There's Plenty of Room at the Bottom:
Opportunites and Challenges for Microrobotics

Arianna Menciassi, PhD
Scuola Superiore Sant’Anna, Pisa (Italy)

Roma, February 26th 2024

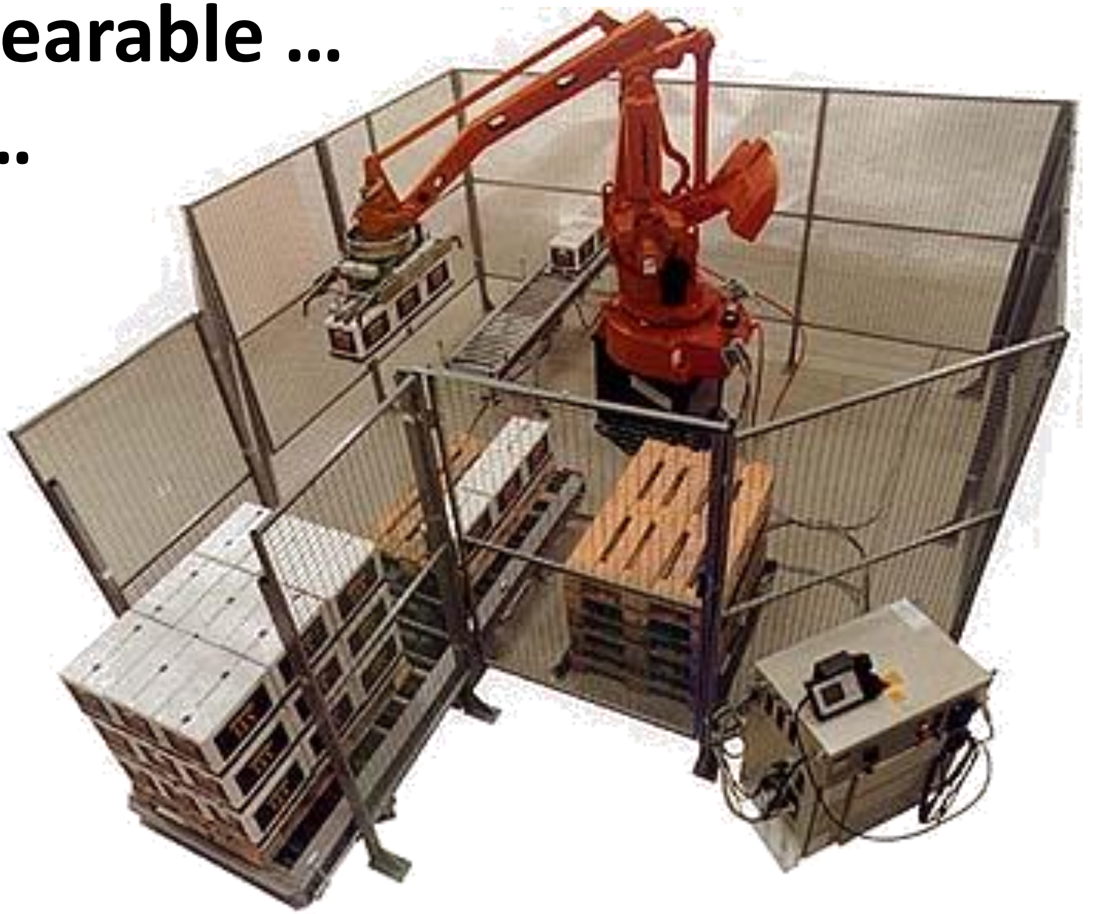
Robots are more and more outside the cages…

they can be wearable …

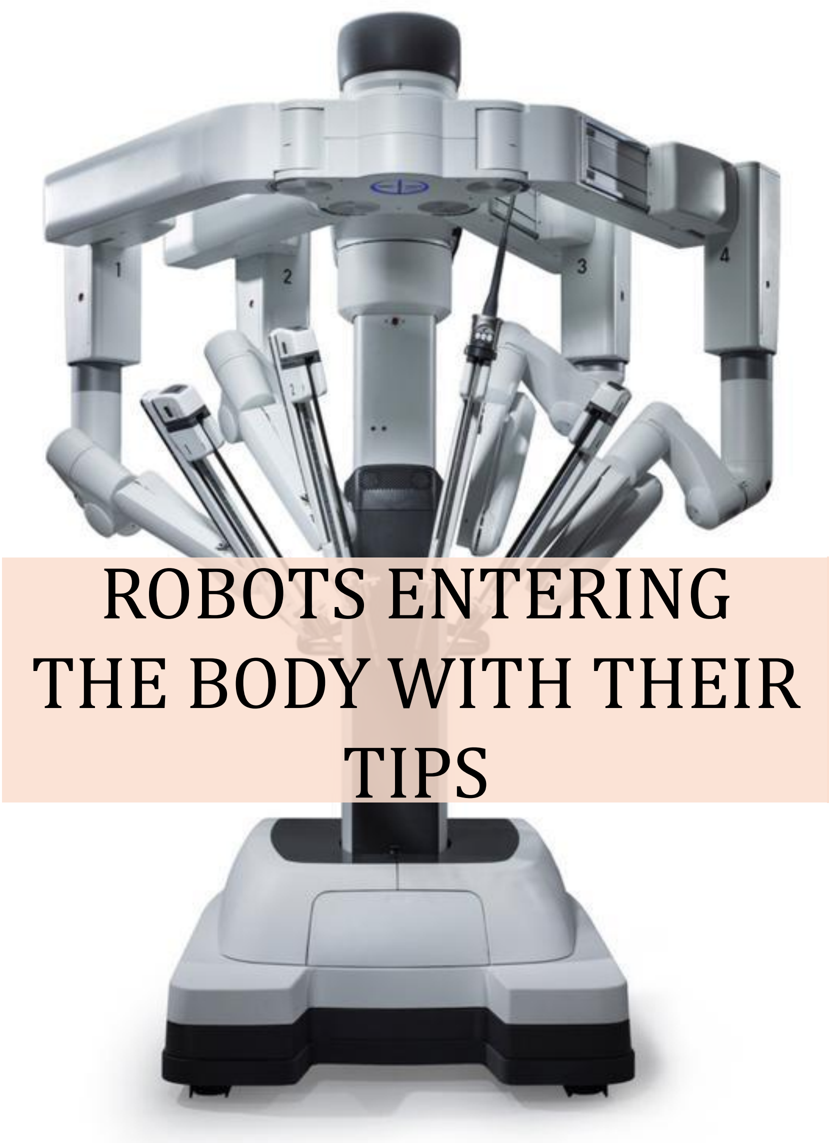
and …

Dustbot, robot for urban hygiene (SSSA)

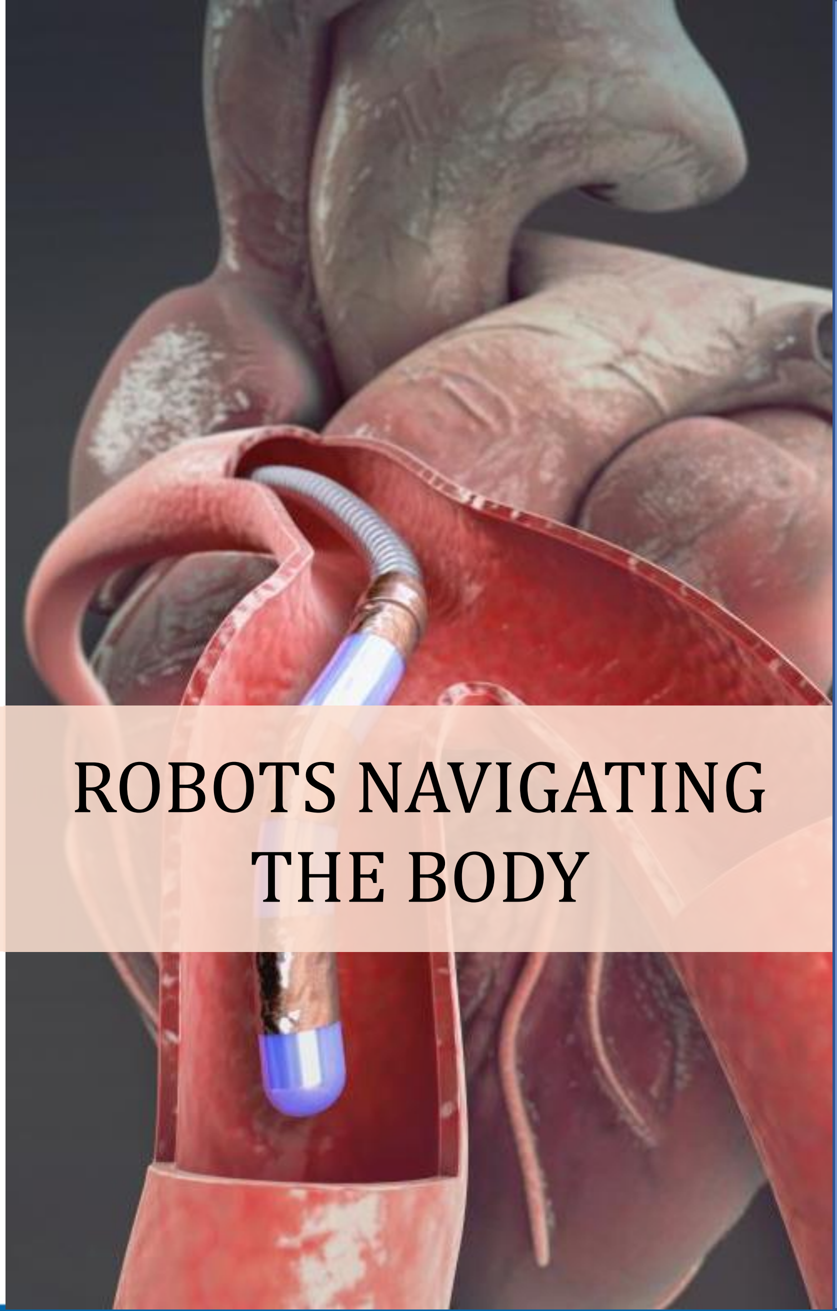
MATE, wearable robot for motion augmentation (IUVO-COMAU)



… robots can work inside the body for chronic and acute interventions



ROBOTS ENTERING THE BODY WITH THEIR TIPS



ROBOTS NAVIGATING THE BODY

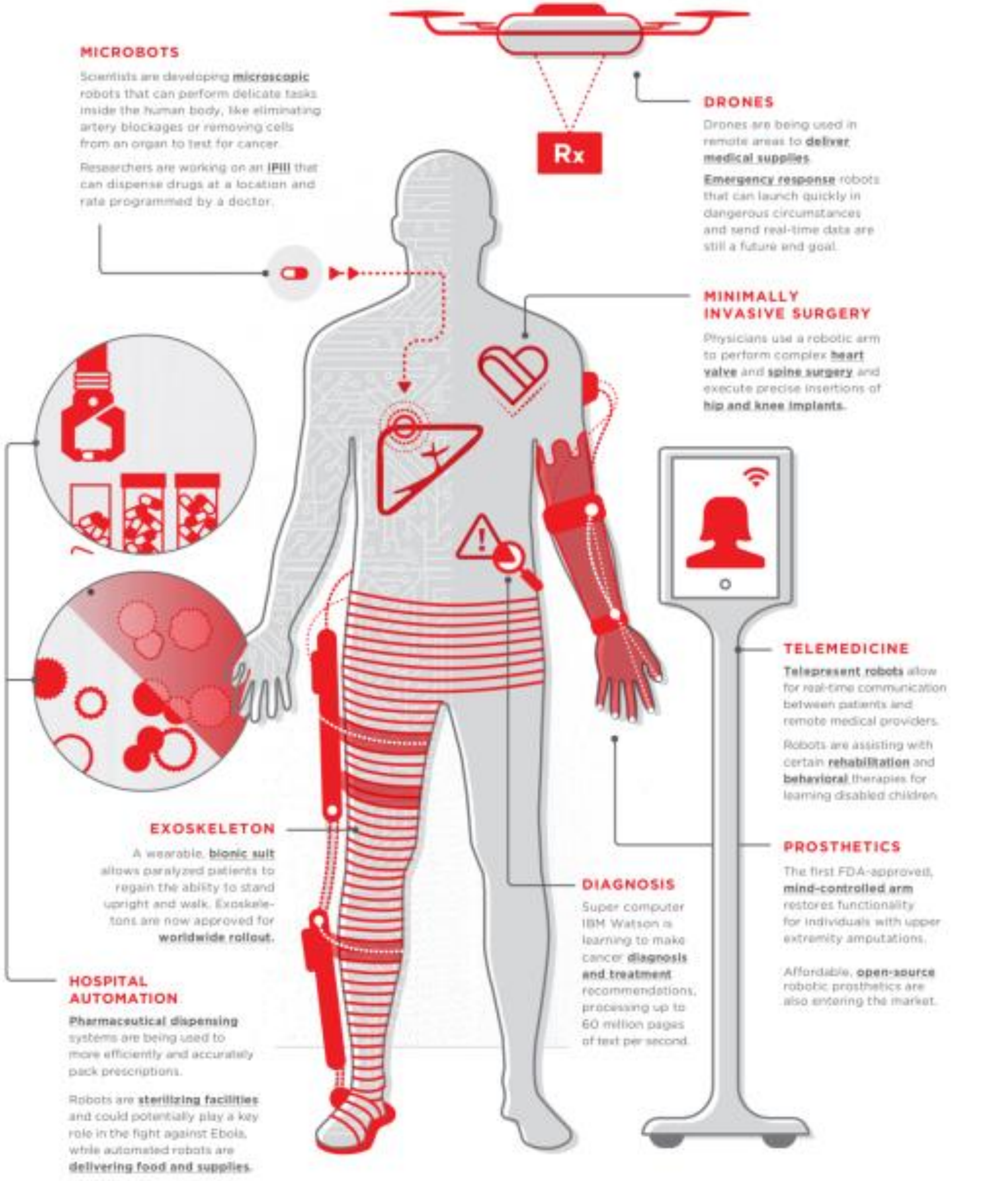
ROBOTS RESIDING IN THE BODY

Health and Robotics …

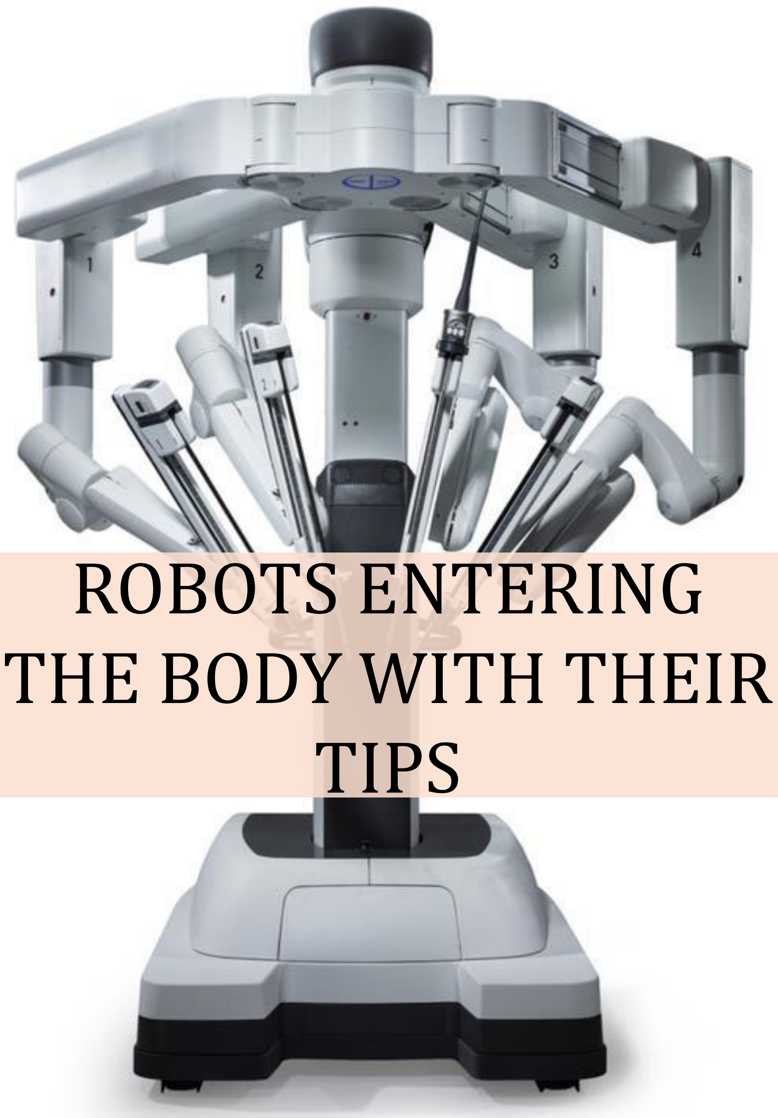
No longer science fiction, robotics has emerged as a leading alternative for many healthcare applications

Dr. Daniel Kraft - "*What's next in healthcare?*"

Daniel Kraft is a physician-scientist, inventor and innovator. He is chair of the Medicine track for Singularity University and Executive Director for FutureMed, a program which explores convergent, exponentially developing technologies and their potential in biomedicine and healthcare

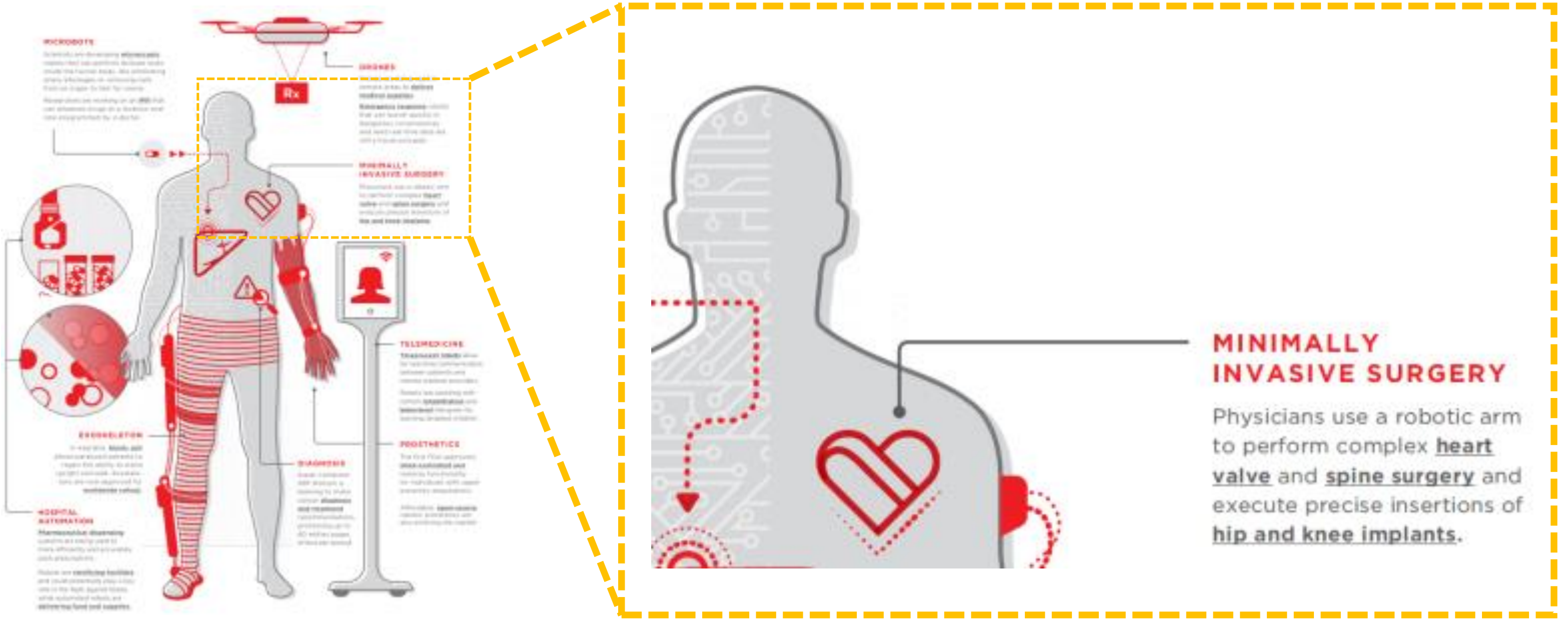


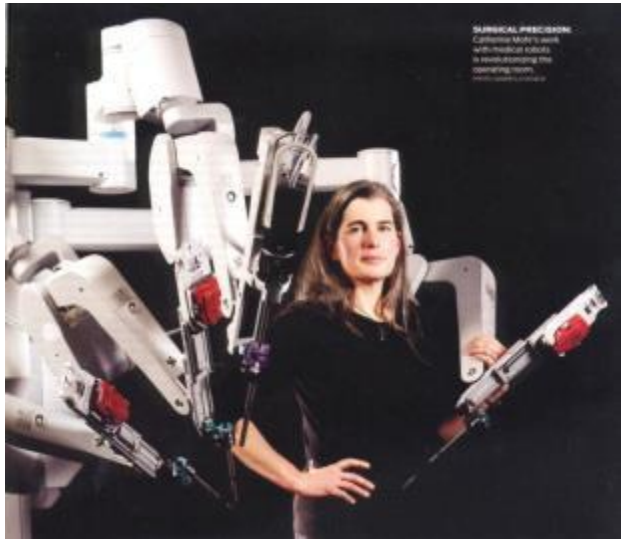
Worrell Infographic, vol. 1, no. 3, figure 01, 2015



ROBOTS ENTERING THE BODY WITH THEIR TIPS

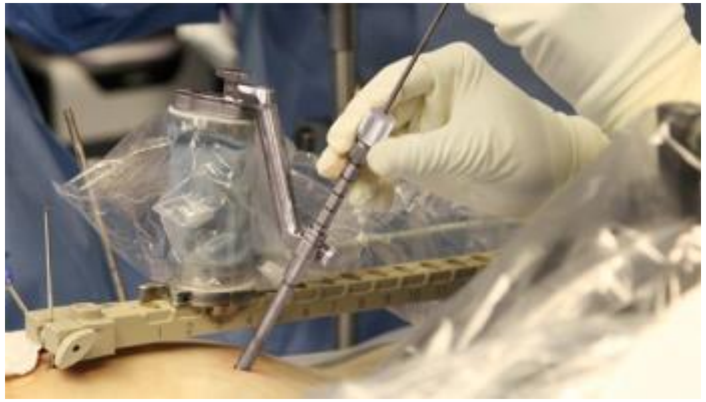
Robotics and Minimally Invasive surgery





Catherine Mohr - Intuitive Surgical

Mazor's New Renaissance Robotic Spinal Surgery System



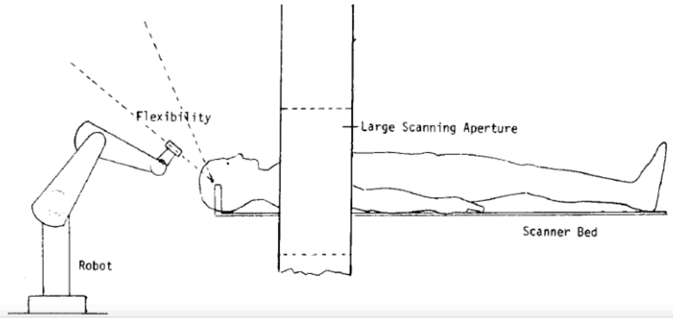
Robotic technologies to make surgery more accurate and less operator depending, to reach unreachable areas of the body without scars…

The beginning:
Industrial Robotics meets Clinical Imaging

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



Computer Assisted Surgery – CAS
Robotic Assisted Surgery – RAS
Computer Integrated Surgery - CIS

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.

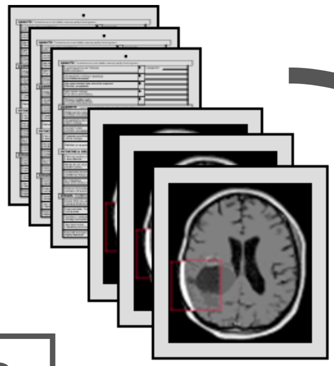
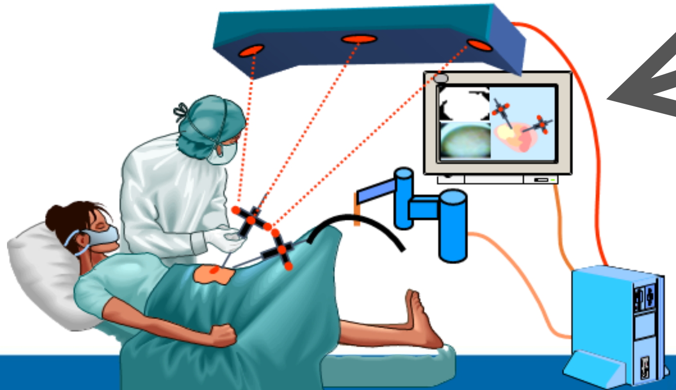


Image Acquisition

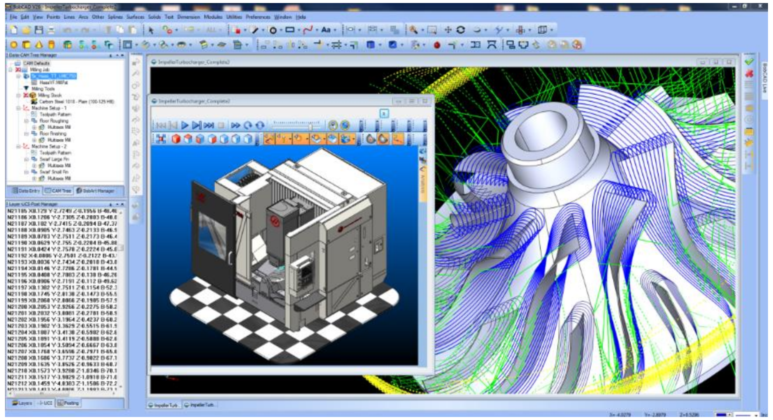
Planning in Virtual Environment

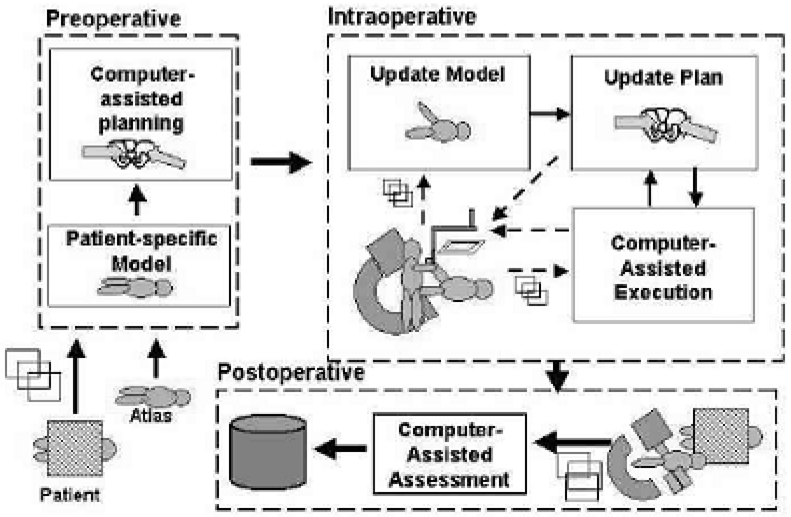
Computer-assisted surgery

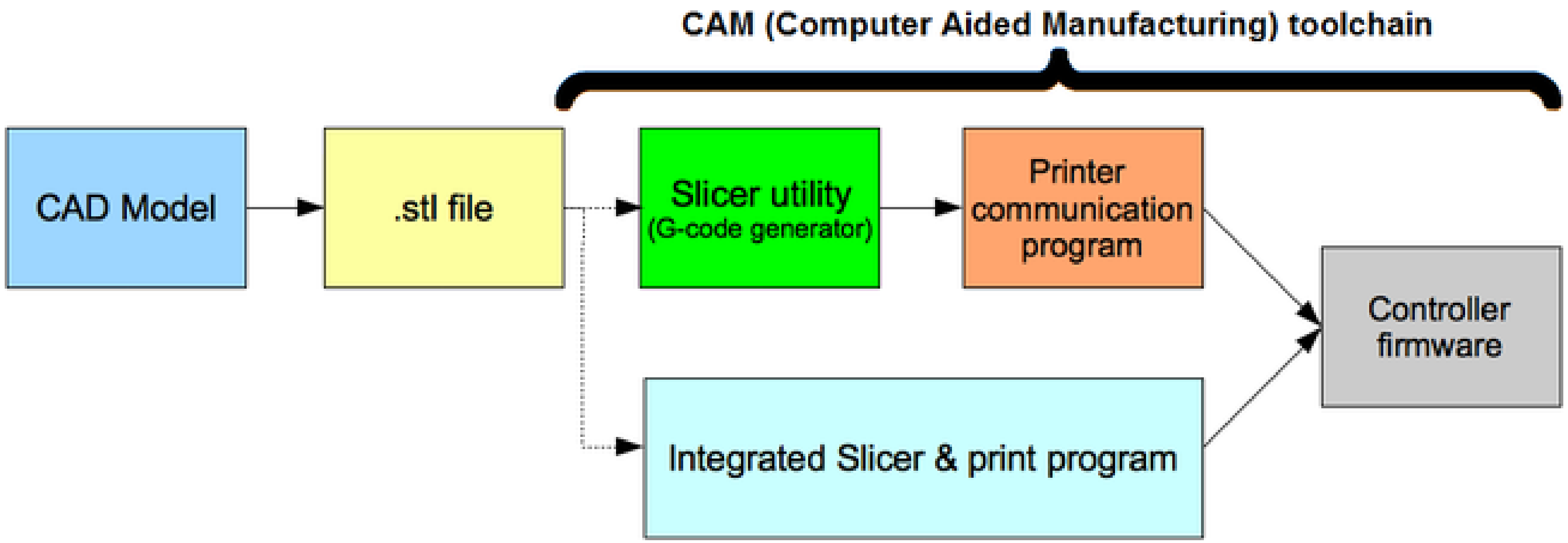


Y. S. Kwoh, CT Research, Department of Radiology, Memorial Medical Center, Long Beach, CA, USA

Medical Images make possible the typical CAD-CAM process … in surgery

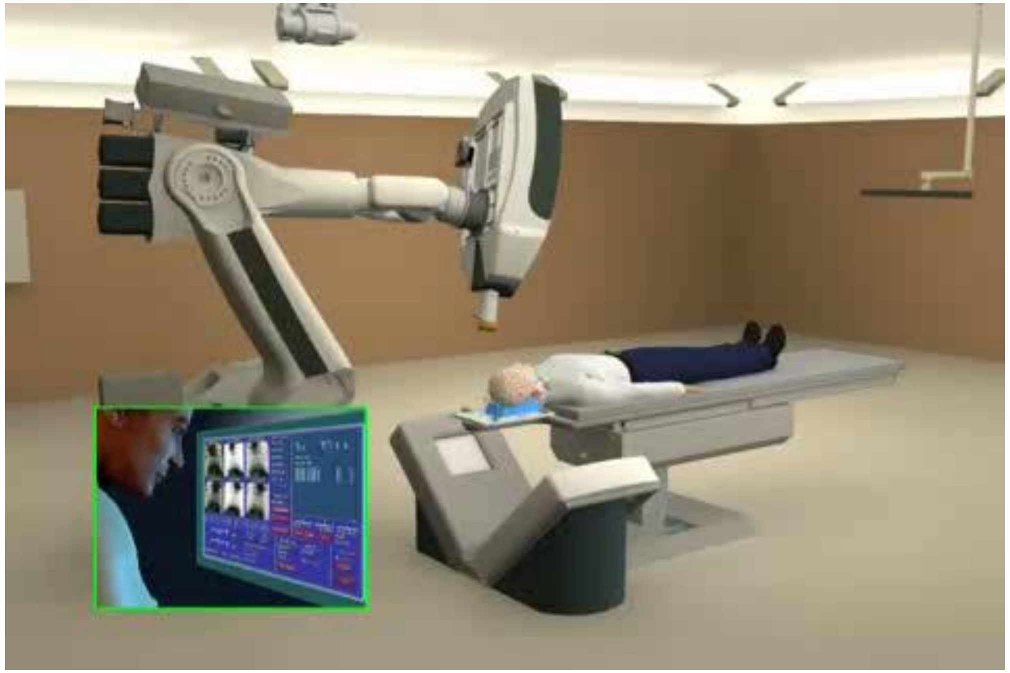






The framework today

INTUITIVE™



Two exercises in the last two years:
The first one…

SCIENCE ROBOTICS | REVIEW

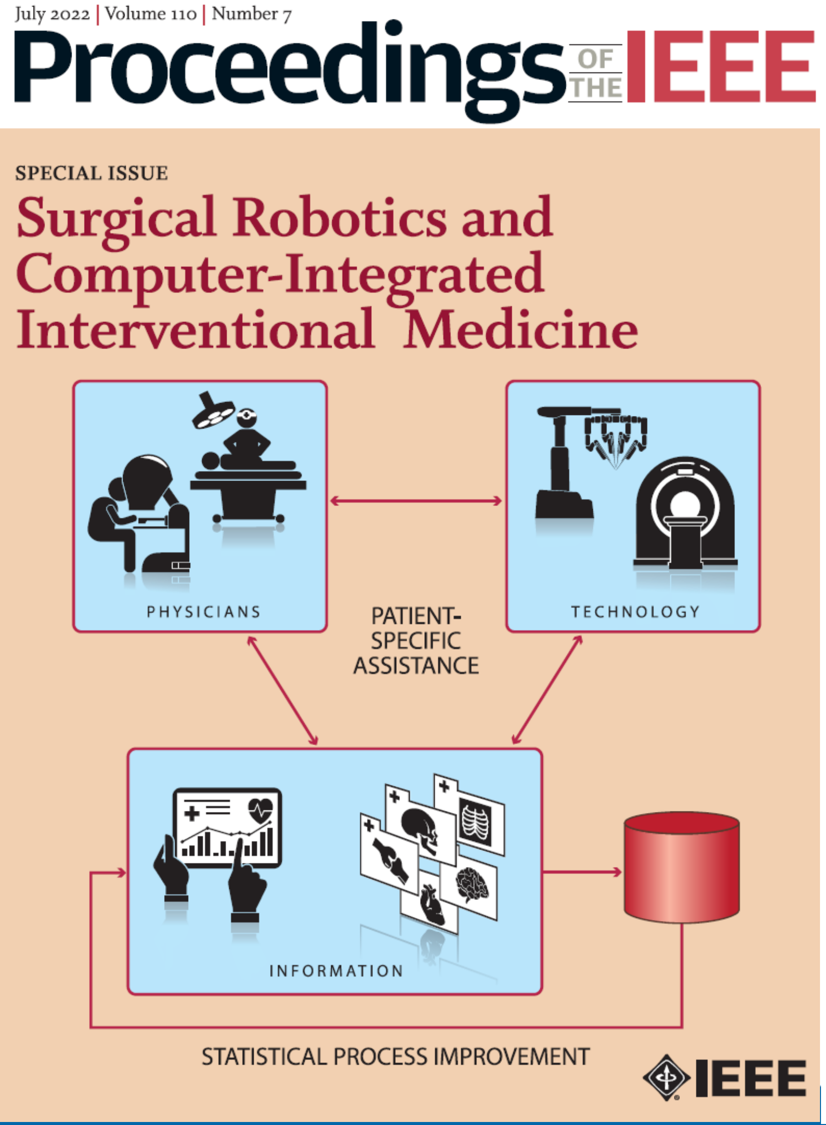
MEDICAL ROBOTS

A decade retrospective of medical robotics research from 2010 to 2020

Pierre E. Dupont[1]*, Bradley J. Nelson[2], Michael Goldfarb[3], Blake Hannaford[4], Arianna Menciassi[5], Marcia K. O'Malley[6], Nabil Simaan[3], Pietro Valdastri[7], Guang-Zhong Yang[8]

Robotics is a forward-looking discipline. Attention is focused on identifying the next grand challenges. In an applied field such as medical robotics, however, it is important to plan the future based on a clear understanding of what the research community has recently accomplished and where this work stands with respect to clinical needs and commercialization. This Review article identifies and analyzes the eight key research themes in medical robotics over the past decade. These thematic areas were identified using search criteria that identified the most highly cited papers of the decade. Our goal for this Review article is to provide an accessible way for readers to quickly appreciate some of the most exciting accomplishments in medical robotics over the past decade; for this reason, we have focused only on a small number of seminal papers in each thematic area. We hope that this article serves to foster an entrepreneurial spirit in researchers to reduce the widening gap between research and translation.

Two exercises in the last two years:
The second one…



SPECIAL ISSUE

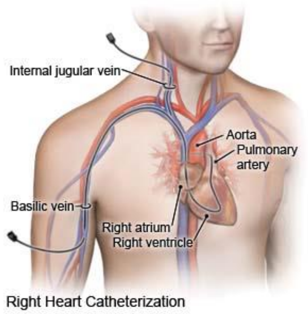
SURGICAL ROBOTICS AND COMPUTER-INTEGRATED INTERVENTIONAL MEDICINE

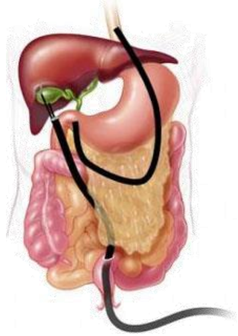
Edited by R. H. Taylor, N. Simaan, A. Menciassi, and G.-Z. Yang

Main challenges and main needs

- Being targeted, i.e. helping the surgeon to reach «unreachable» areas – *targeted* therapy
- Bringing dexterity inside the body with minimal access and high performance actuators
- Being safe in interaction
- Moving towards scarless operations

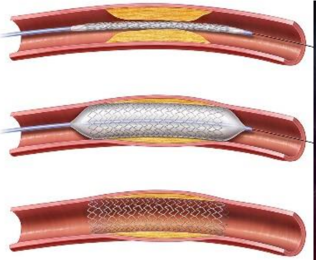
Targeted therapy means…

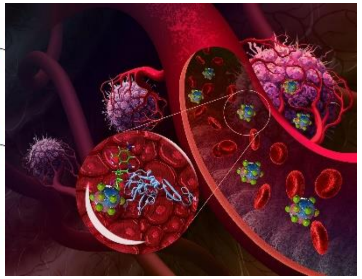




Target reaching

Therapy or therapeutic tool delivery





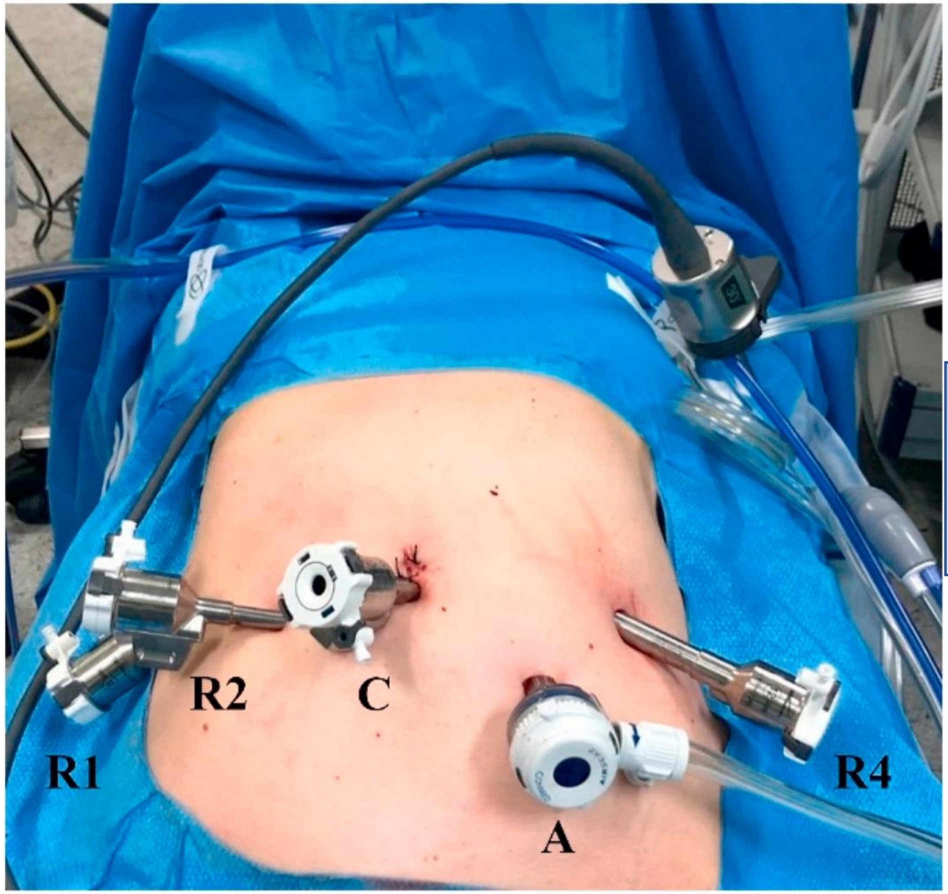
Targeted therapy

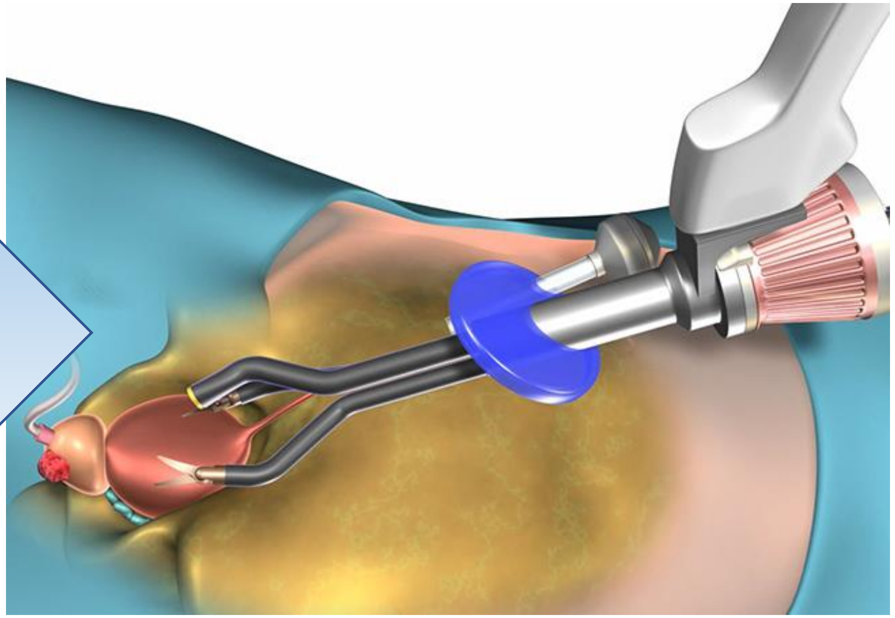
Minimally invasive approach

Reduced side effects

High accuracy, precision and reliability

The problem: reducing the invasiveness, augmenting the dexterity at the distal part

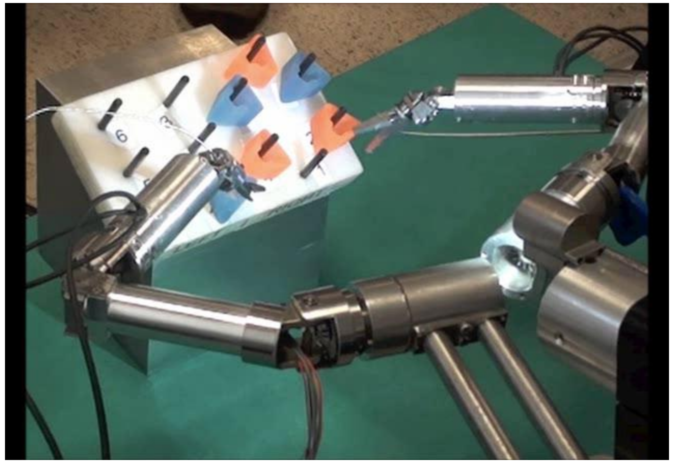


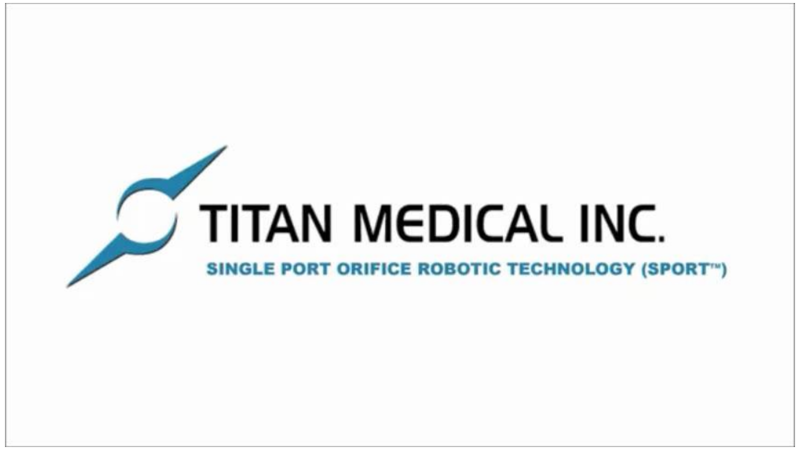


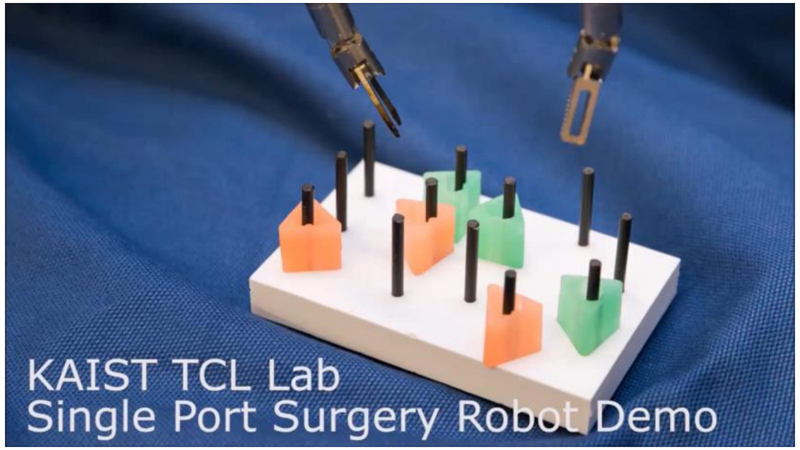
The problem: reducing the invasiveness, augmenting the dexterity in the distal part

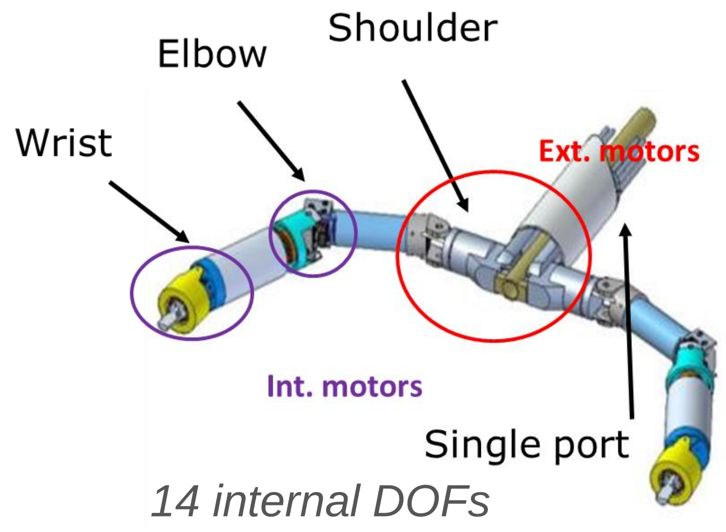
The problem: reducing the invasiveness, augmenting the dexterity in the distal part

SINGLE-PORT ROBOTIC SYSTEMS

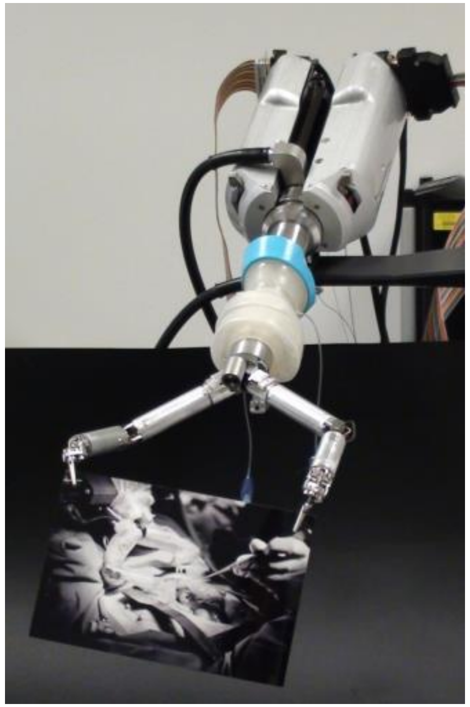






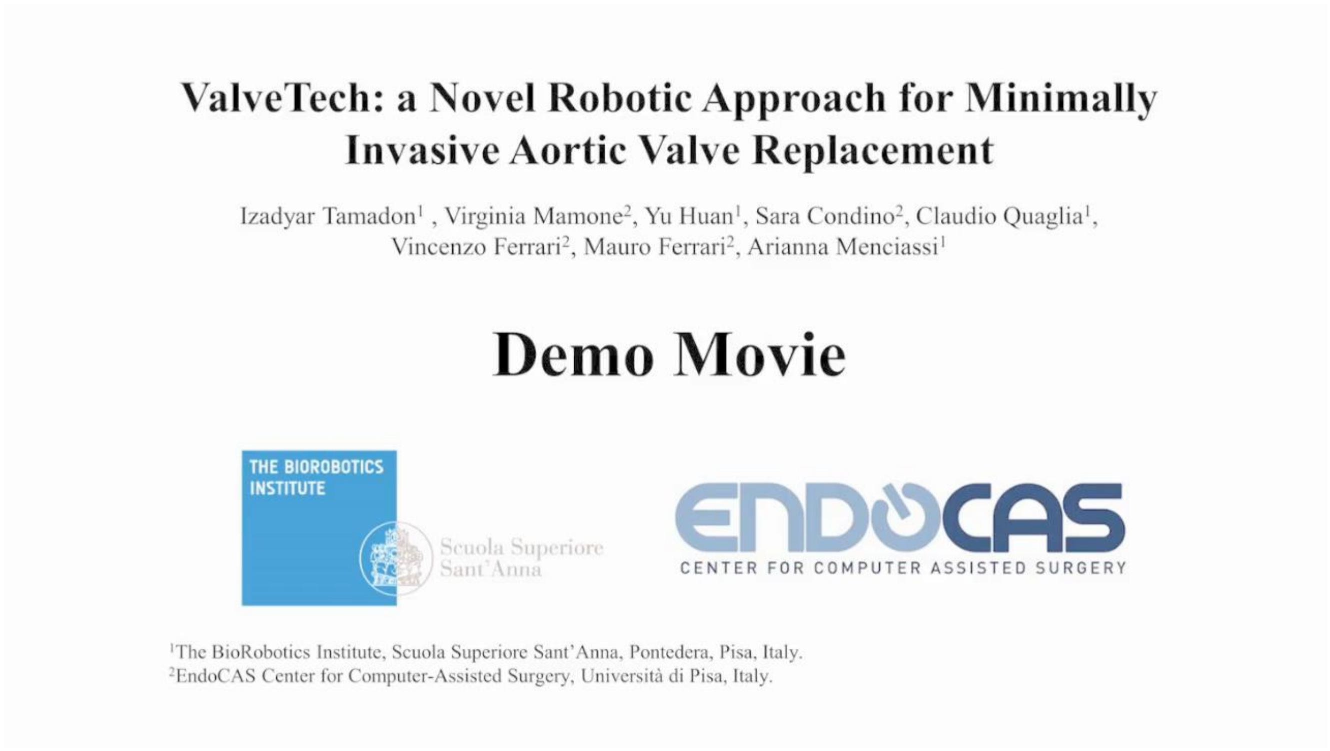


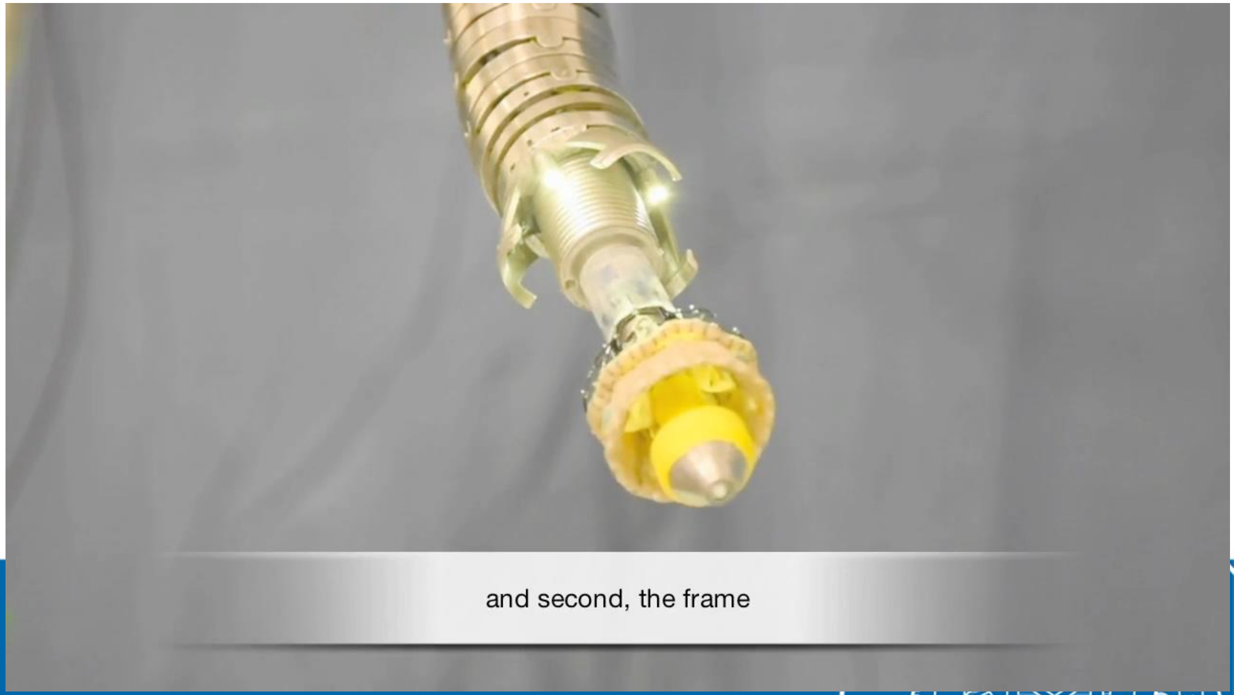
Single port modular surgery: how to deploy many degrees of freedom through a small hole

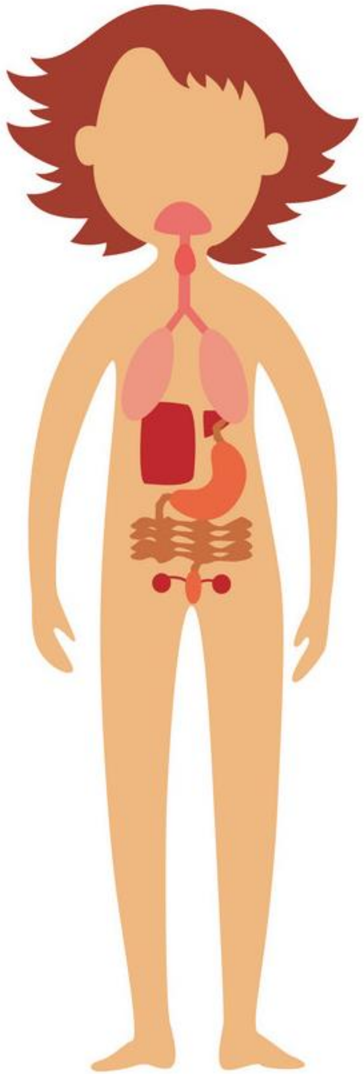


A.R.A.K.N.E.S.
Array of Robots Augmenting the KiNematics of Endoluminal Surgery

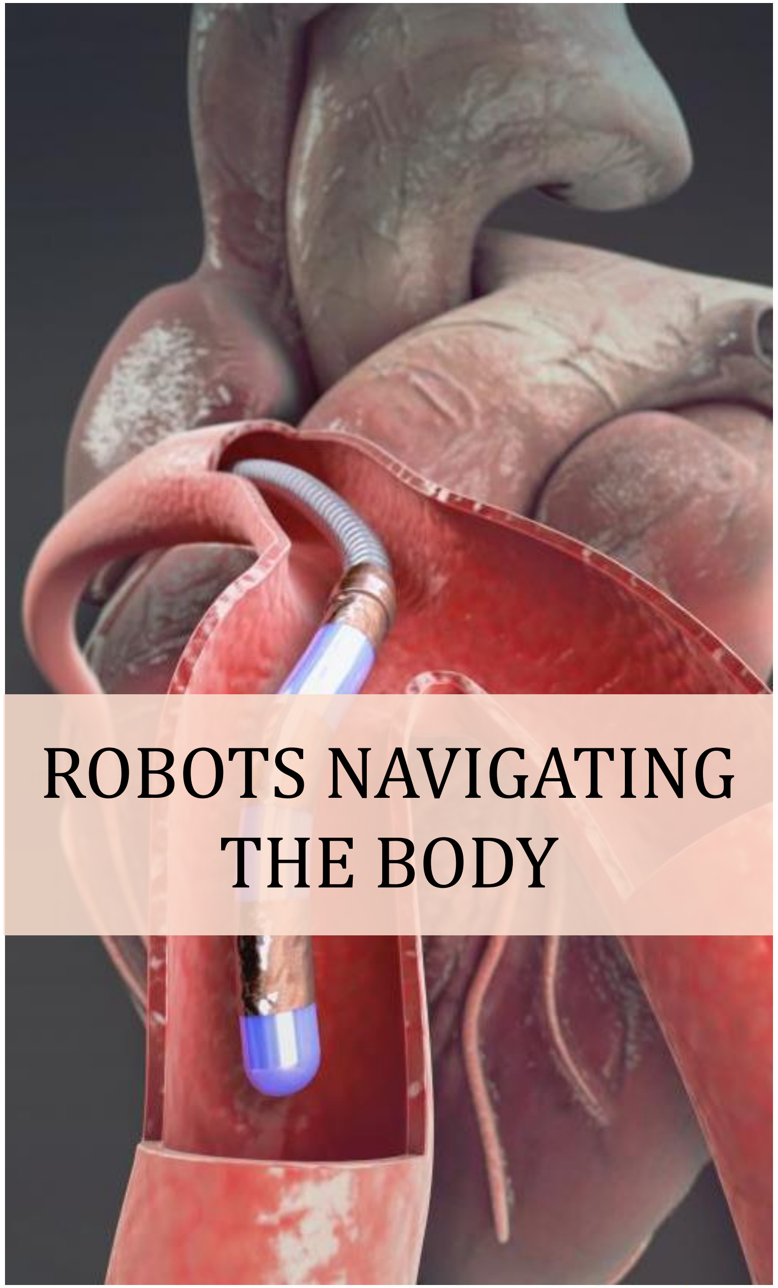
Multiarticulated platform for Minimally Invasive Aortic Valve Replacement



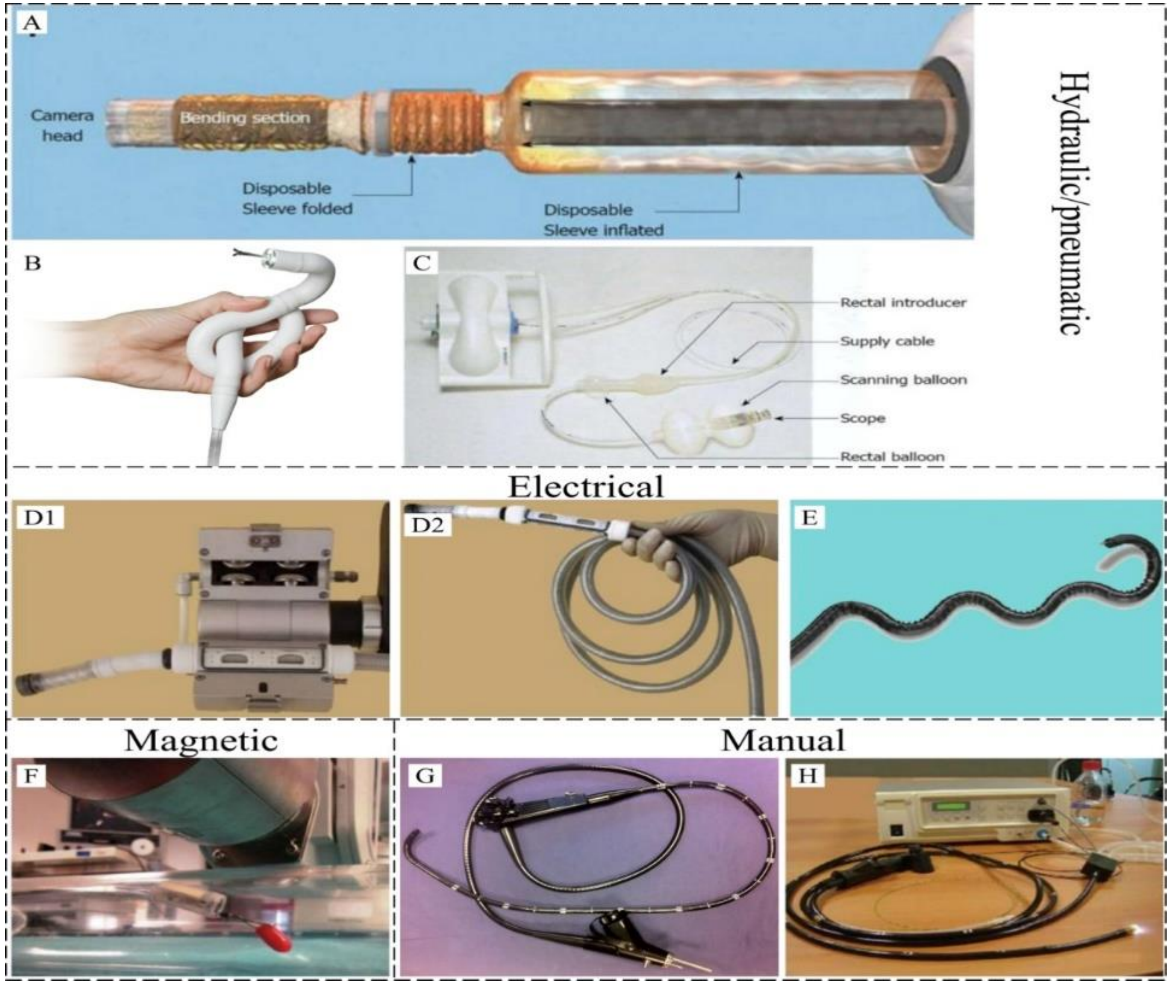


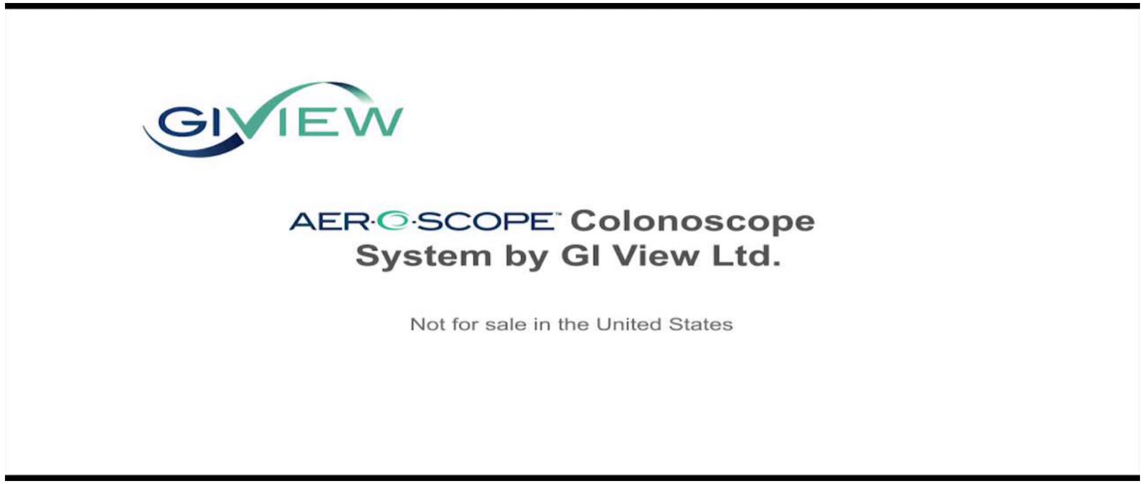


The easiest navigation environment without incisions - Miniature robots navigating in the GI tract…



Smart flexible endoscopes



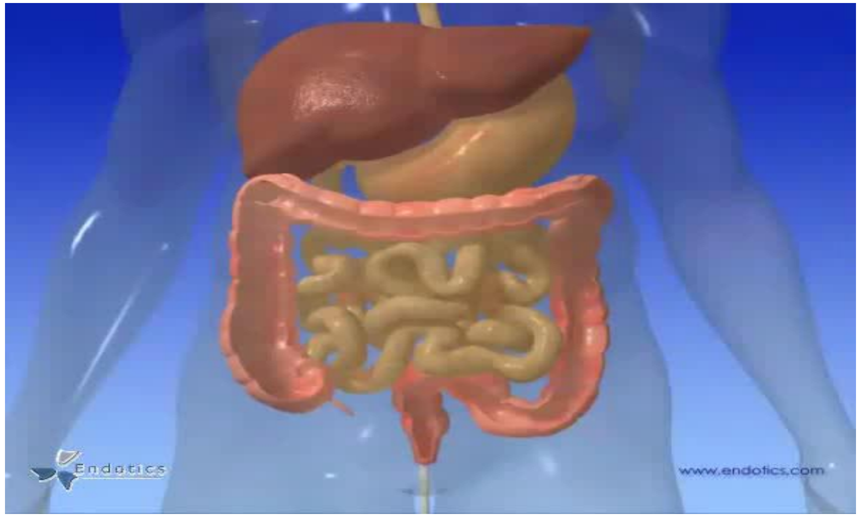


Aer-O-Scope

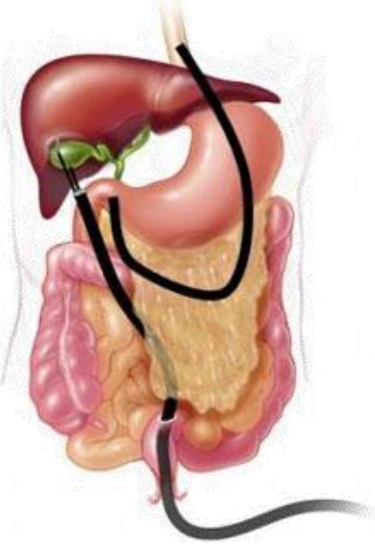
Invendo™ endoscope

Sliker, Levin J., and Gastone Ciuti. "Flexible and capsule endoscopy for screening, diagnosis andtreatment." Expert review of medical devices 0 (2014): 1-18.

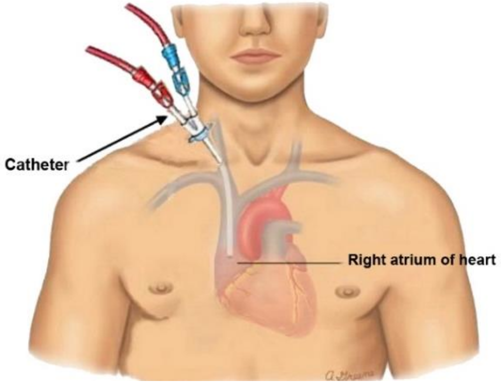
An endoscope with biomimetic locomotion (2000-2010)

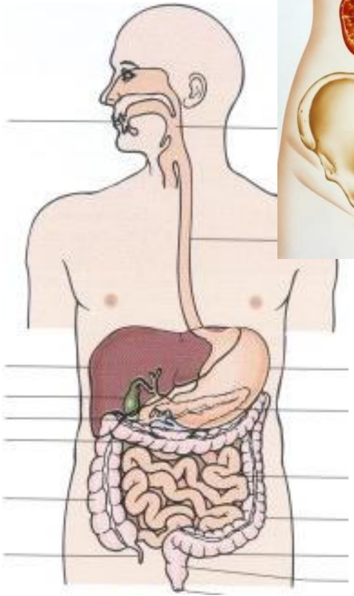


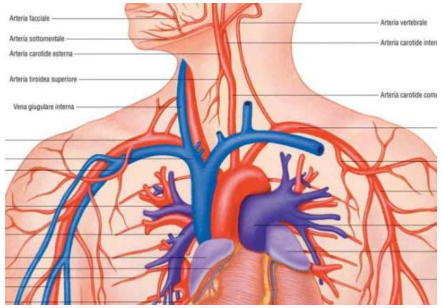
Endoscopes and surgical tools without tails… the trend to capsule-like robots



Flexibility of **traditional wired devices limits access** to some target areas (i.e. limitation to targeted therapy)





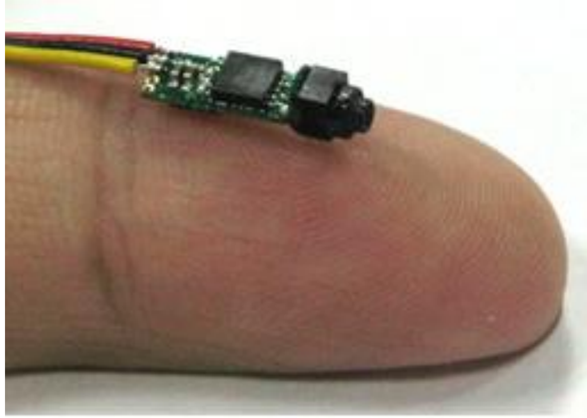


Small diameter and remote districts can be reached **only by wireless or softly tethered devices**

The idea of bringing therapeutic and advanced diagnostic solutions where they are needed: the endoscopic capsule

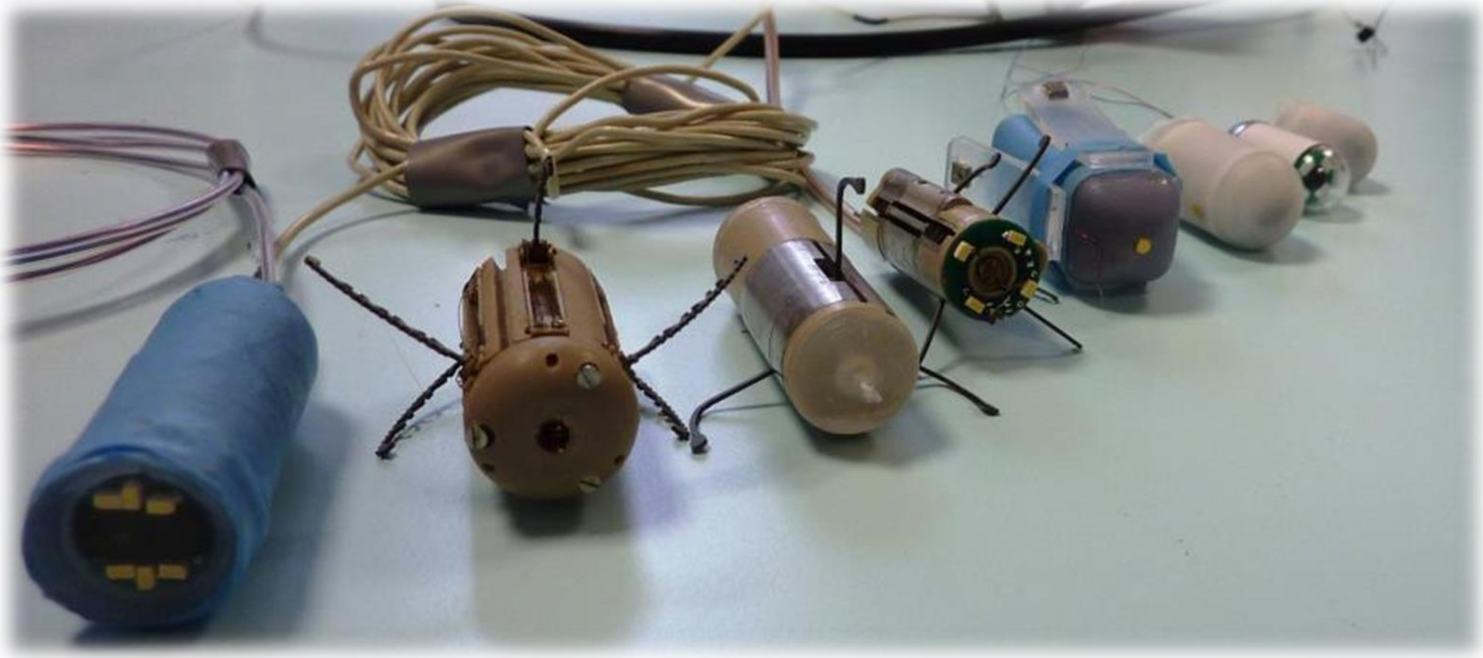
Available wireless capsules: visual investigation of normally not explored areas

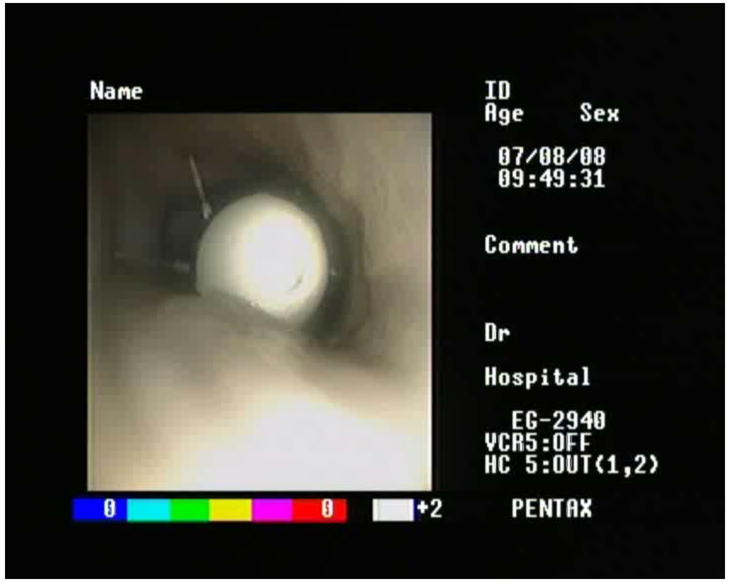
G. Iddan and P. Swain. History and development of capsule endoscopy. *Gastrointestinal Endoscopy. 14: 1-9 (2004)*

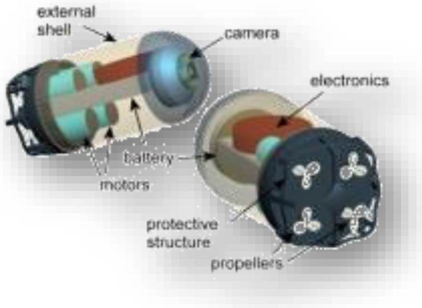


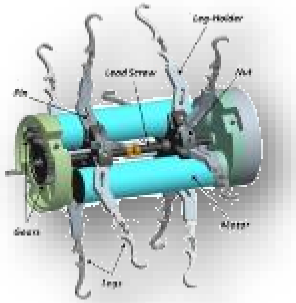
Active/teleoperated locomotion for giving “legs” to advanced diagnostic and therapeutic solutions

ACTIVE capsules with on-board PROPULSION





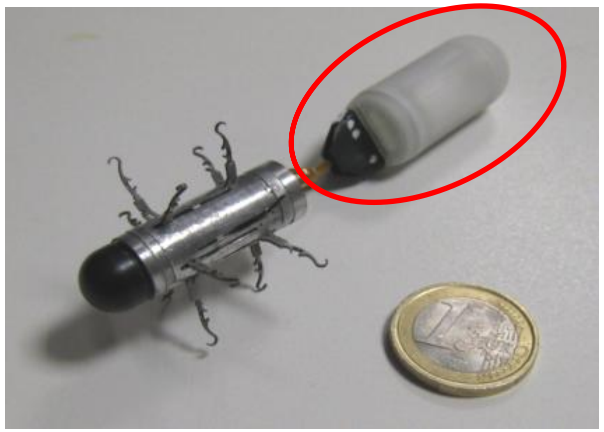




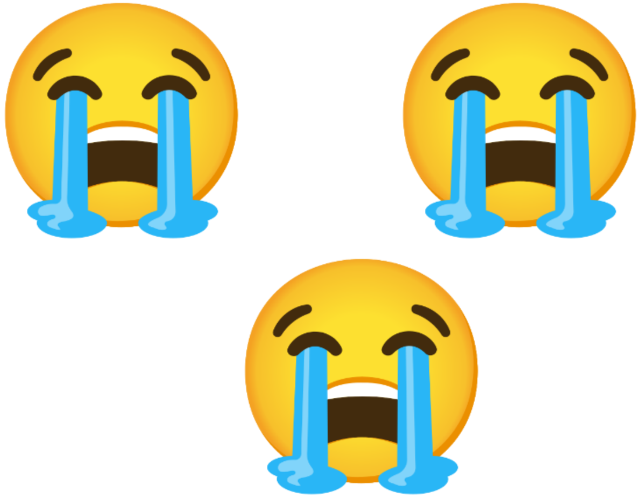
The EU VECTOR Project
Korean IMC Project

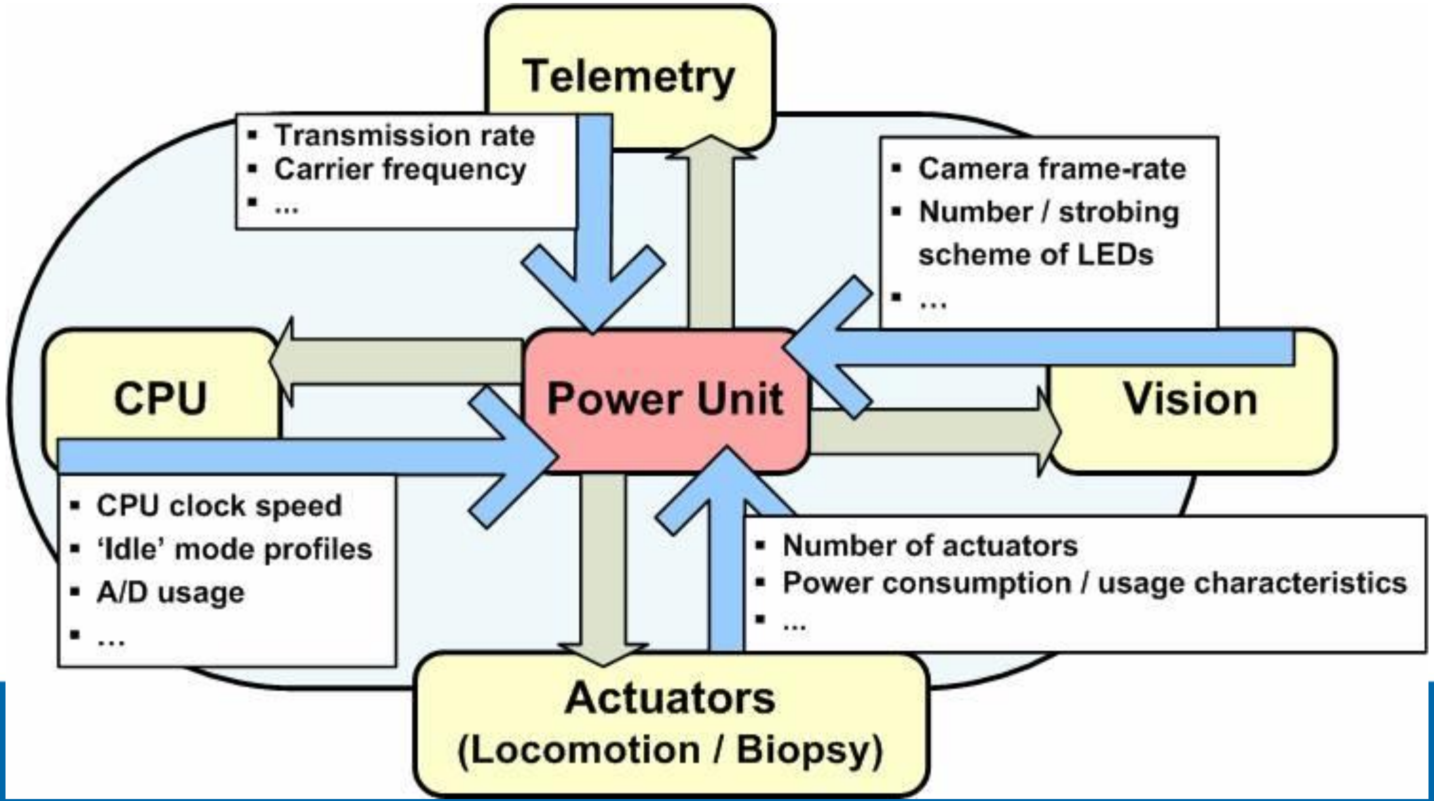
P. Dario and A. Menciassi. *Scientific American*. 303: 62-65 (2010)

Bottleneck for active on-board propulsion



POWER!

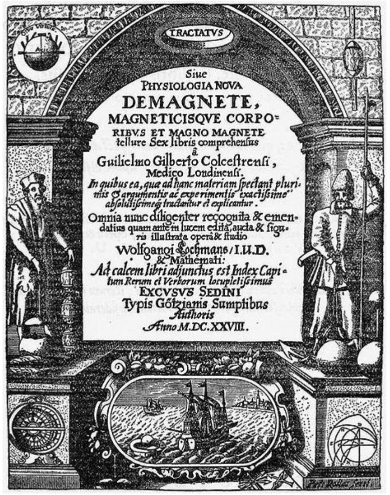




A legged capsule incorporating state-of-art batteries could only walk for less than 30 minutes along the GI tract

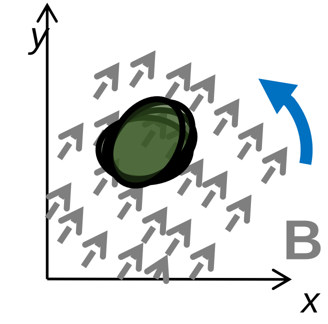
Which solutions for a real scarless intervention and limiting actuation/powering problems at distal level?

Which solutions for a real scarless intervention and limiting actuation/powering problems at distal level?



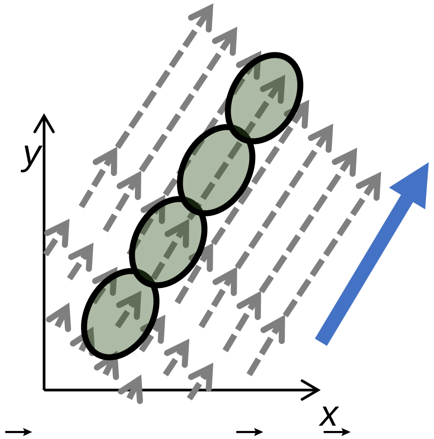
William Gilbert , 1600
De Magnete, Magneticisque Corporibus, et de Magno Magnete Tellure *(On the Magnet and Magnetic Bodies, and on That Great Magnet the Earth)*

Torque



$$\vec{\tau} = V\vec{M} \times \vec{B}$$

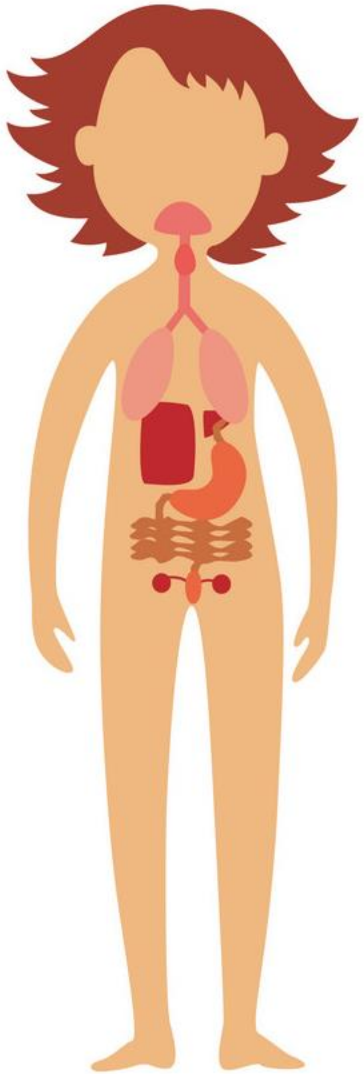
Force

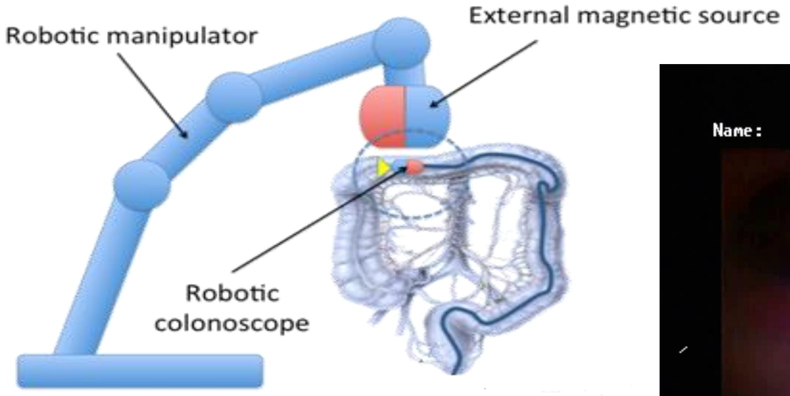


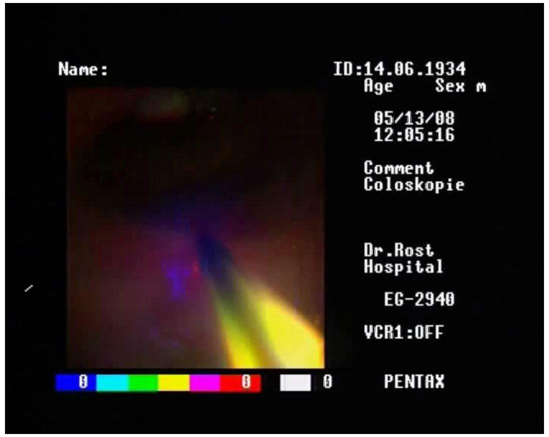
$$\vec{F} = V\nabla(\vec{M} \cdot \vec{B})$$

Magnetic endoscopic capsules, magnetic retraction systems, magnetic catheters, magnetic particles for drug delivery and drug targeting…

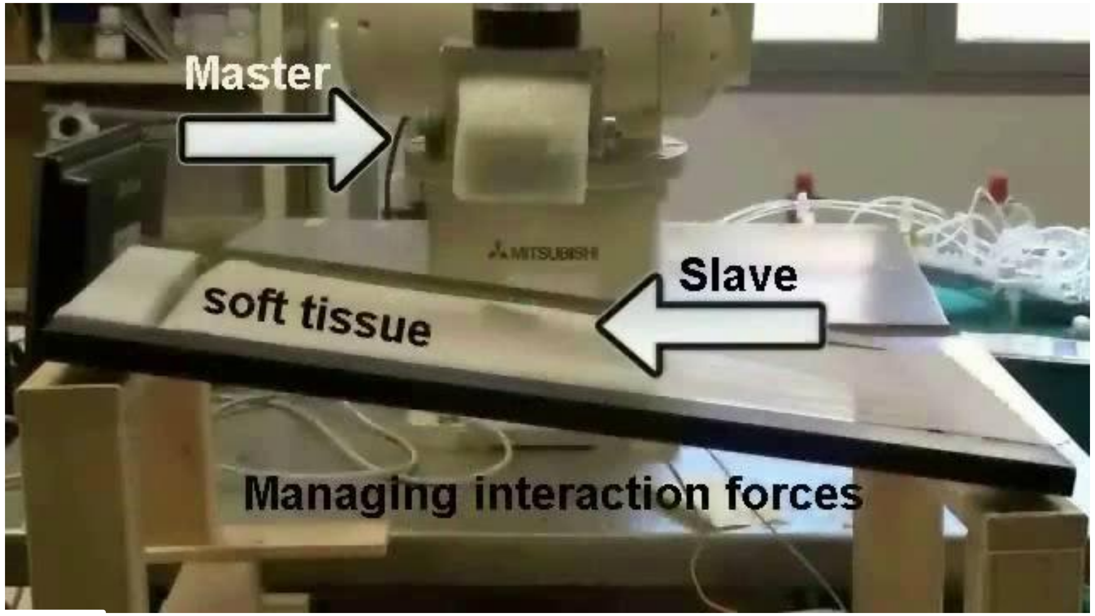
The easiest navigation environment - Miniature robots navigating in the GI tract…

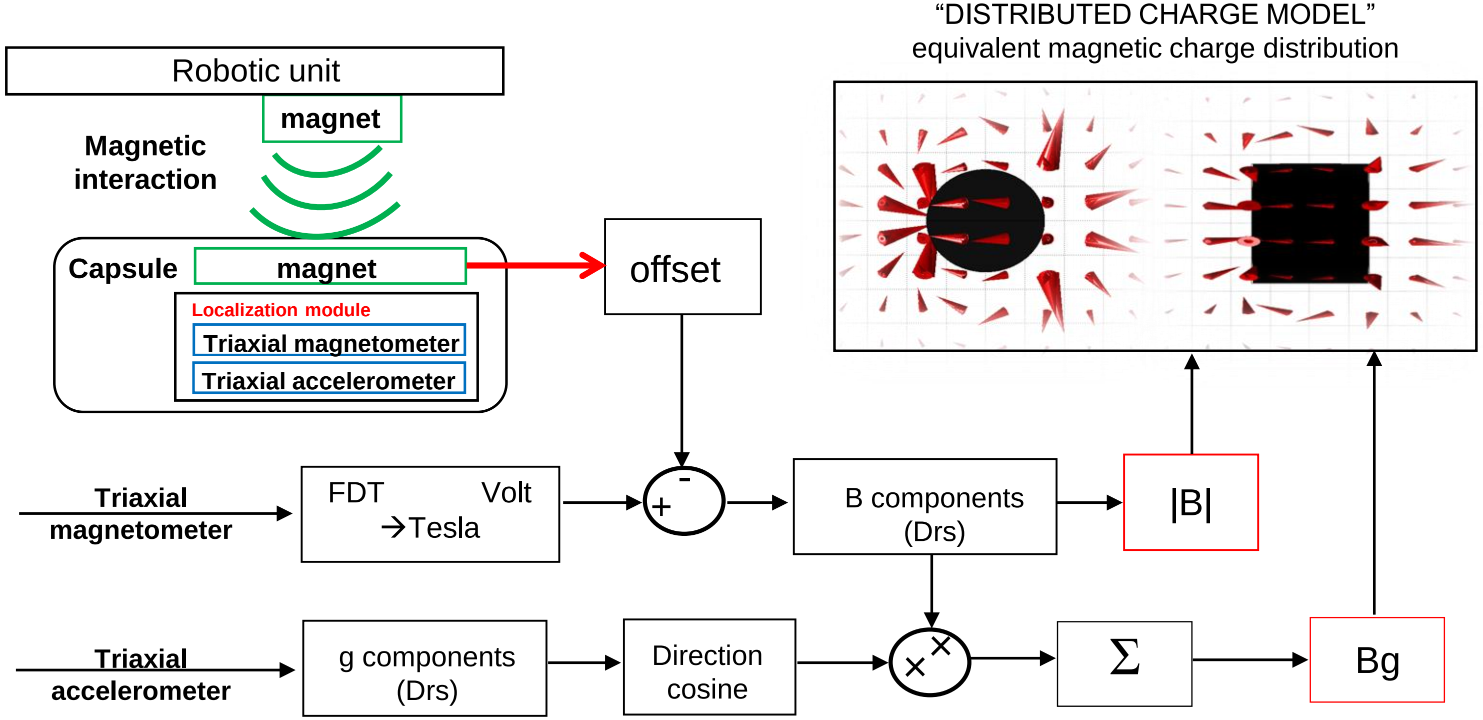






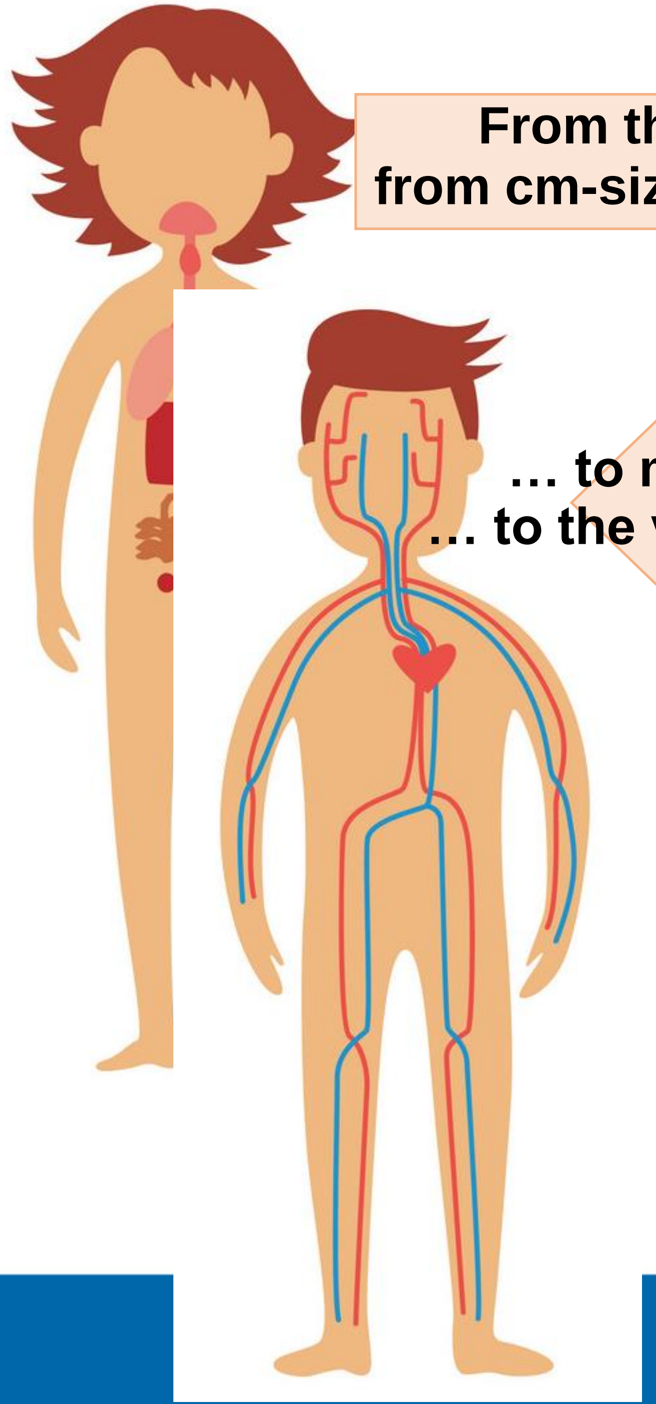
…wireless magnetic dragging is not for free: localization issues open!





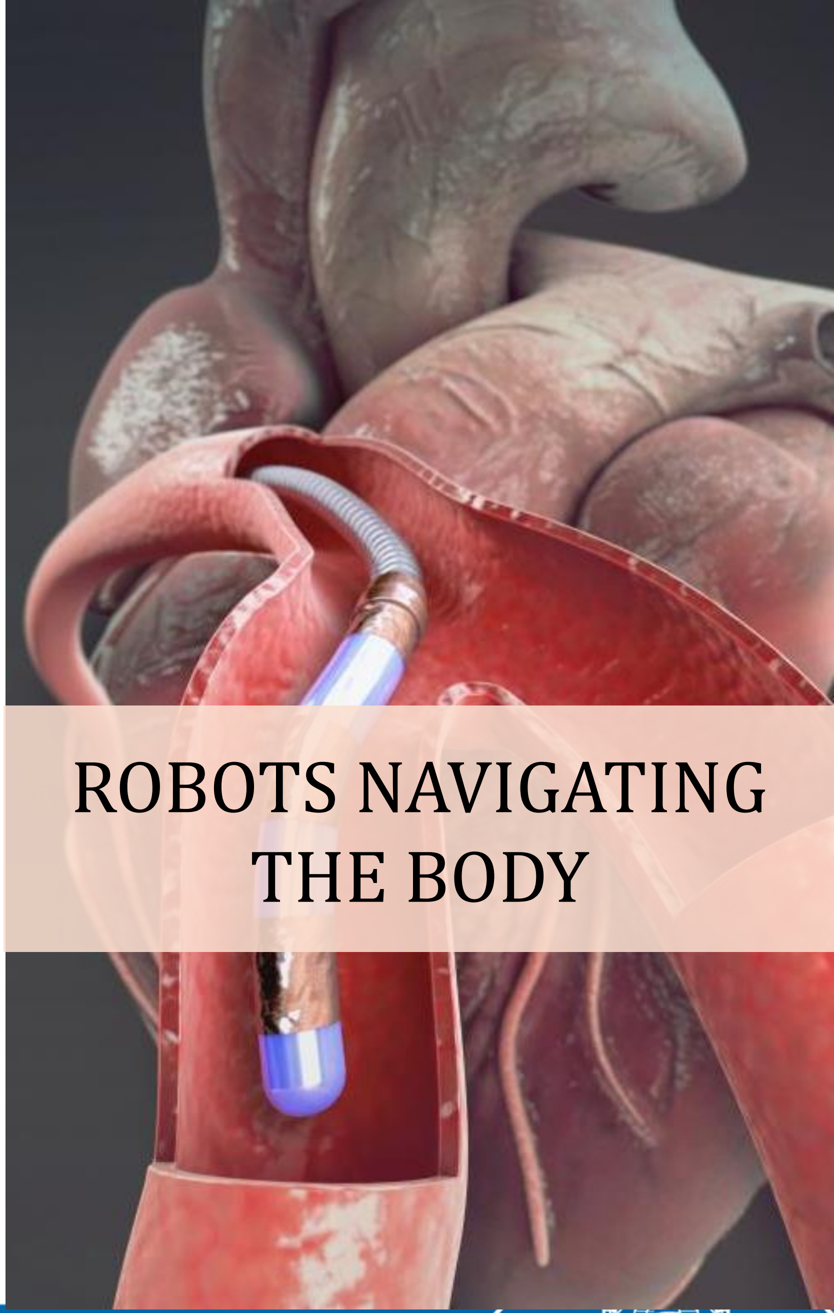
M. Salerno et al., «A discrete-time localization method for capsule endoscopy based on on-board magnetic sensing», Measurement Science and Technology 23 (1), 2011

and also Jake Abbott, Pietro Valdastri, etc…

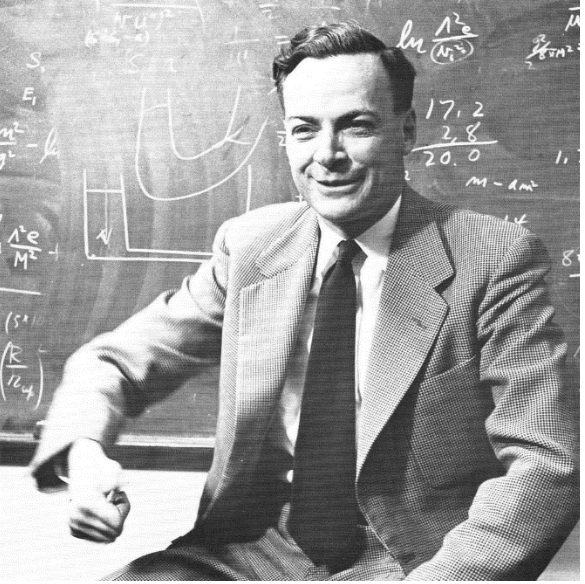


From the GI tract…
from cm-size lumen…

… to mm-size lumen
… to the vascular system



ROBOTS NAVIGATING THE BODY



JOURNAL OF MICROELECTROMECHANICAL SYSTEMS VOL. 1, NO. 1, MARCH 1992

There's Plenty of Room at the Bottom

Richard P. Feynman

I imagine experimental physicists must often look with envy at men like Kamerlingh Onnes, who discovered a field like low temperature, which seems to be bottomless and in which one can go down and down. Such a man is then a leader and has some temporary monopoly in a scientific adventure. Percy Bridgman, in designing a way to obtain higher pressures, opened up another new field and was able to move into it and to lead us all along. The development of ever higher vacuum was a continuing development of the same kind.

I would like to describe a field, in which little has been done, but in which an enormous amount can be done in principle. This field is not quite the same as the others in

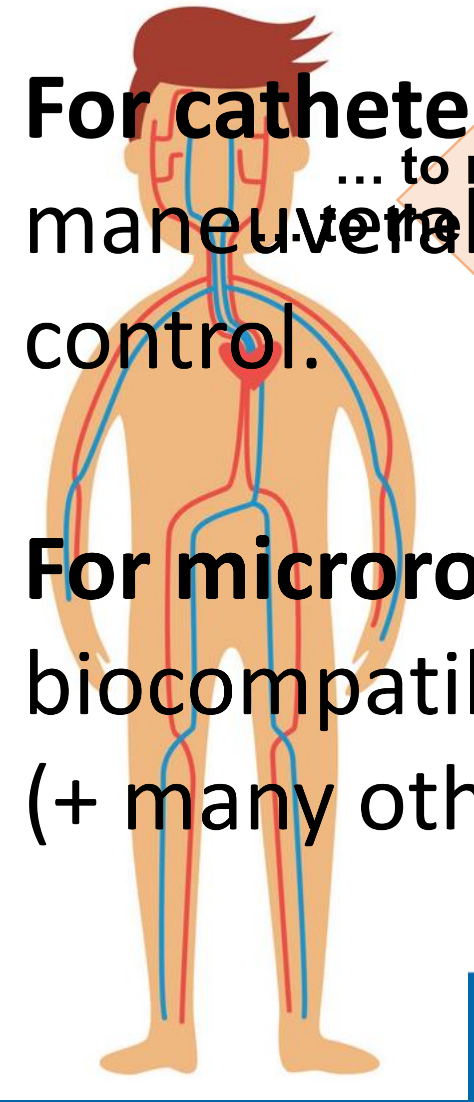
dots on the fine half-tone reproductions in the Encyclopaedia. This, when you demagnify it by 25 000 times, is still 80 angstroms in diameter—32 atoms across, in an ordinary metal. In other words, one of those dots still would contain in its area 1000 atoms. So, each dot can easily be adjusted in size as required by the photoengraving, and there is no question that there is enough room on the head of a pin to put all of the Encyclopaedia Britannica.

Furthermore, it can be read if it is so written. Let's imagine that it is written in raised letters of metal; that is, where the black is in the Encyclopaedia, we have raised letters of metal that are actually 1/25 000 of their ordinary size. How would we read it?

From the GI tract…
from cm-size lumen…

Main Challenges:

… to mm-size lumen
… to the vascular system



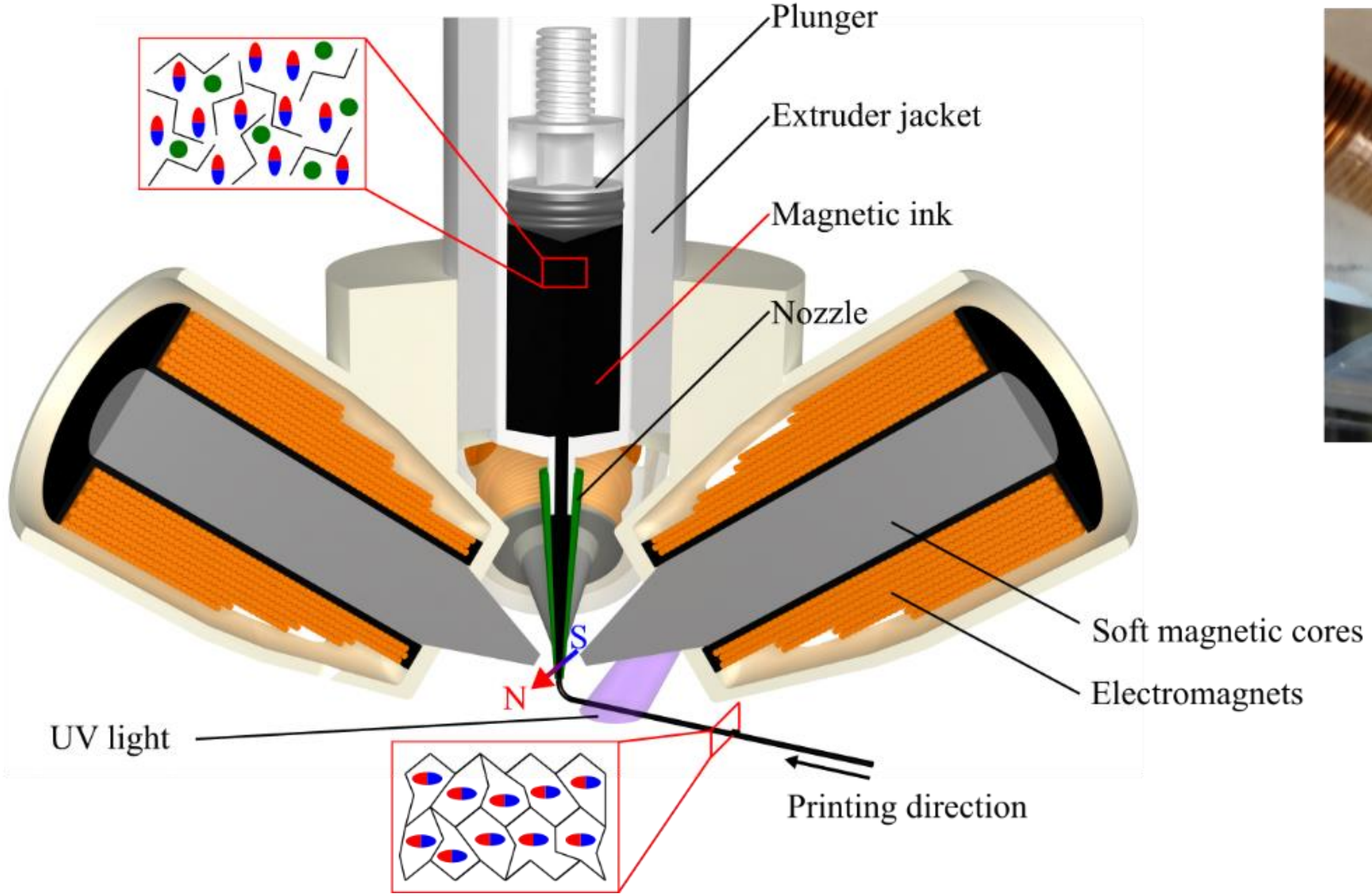
- **For catheters**: flexibility, maneuverability and tip control.

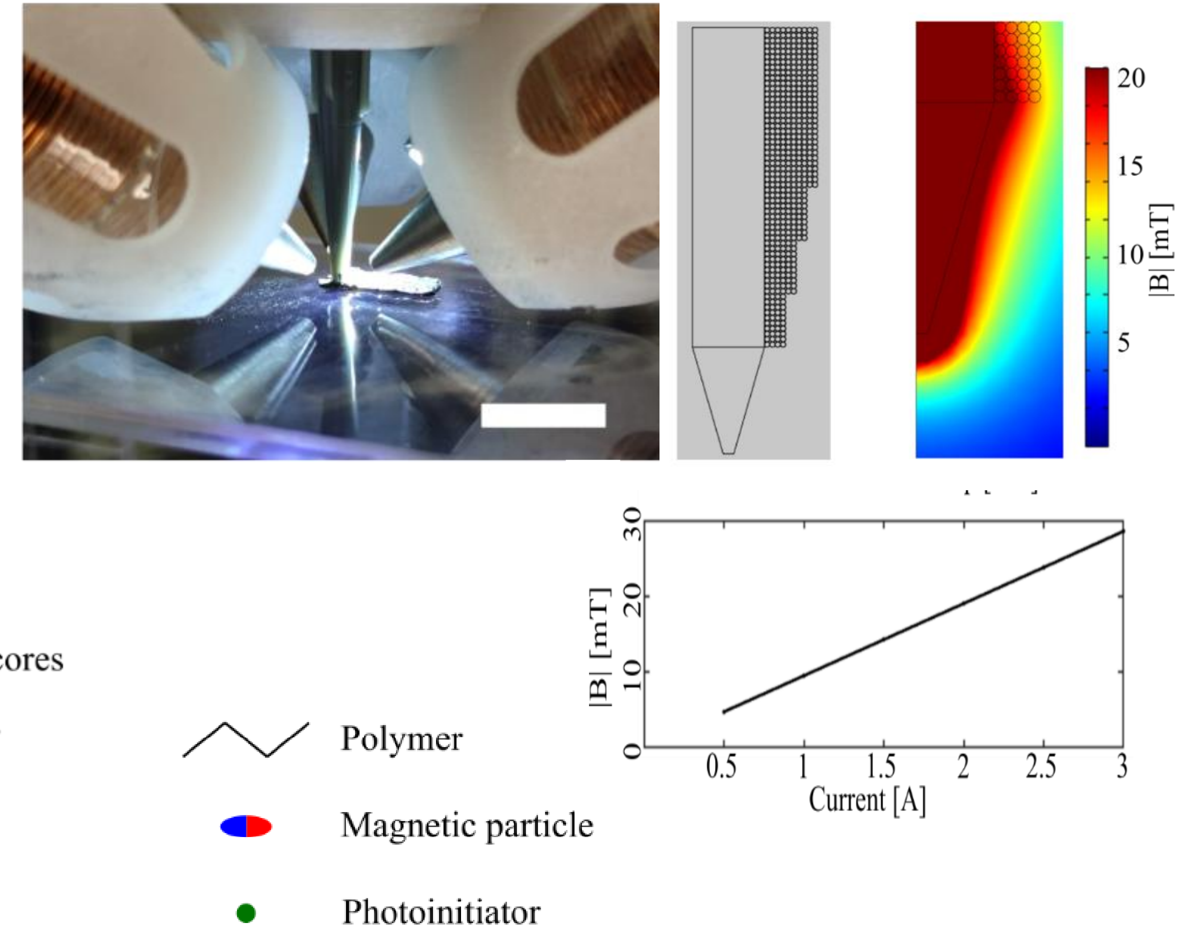
- **For microrobots**: control, biocompatibility, tracking (+ many others!)

NAVION, ETH

Microparticles in the blood flow (Fantastic Voya\ge)

3D Printing of Small-Scale Soft Robots with Programmable Magnetization





HMD Ansari et al., Adavanced Functional Materials, 2023

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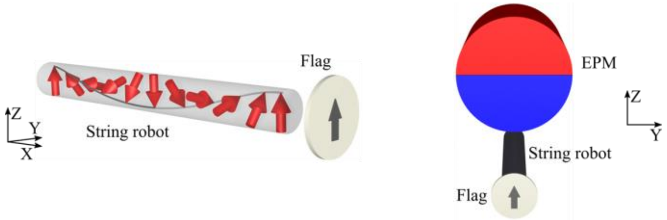
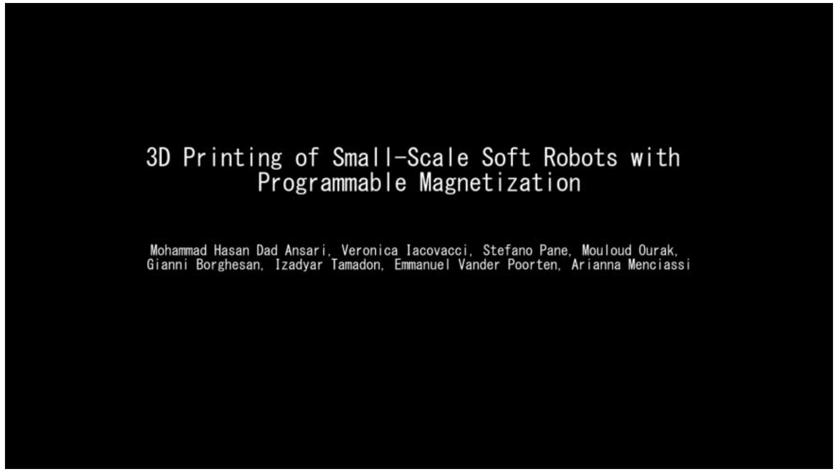
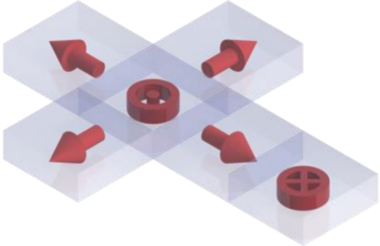
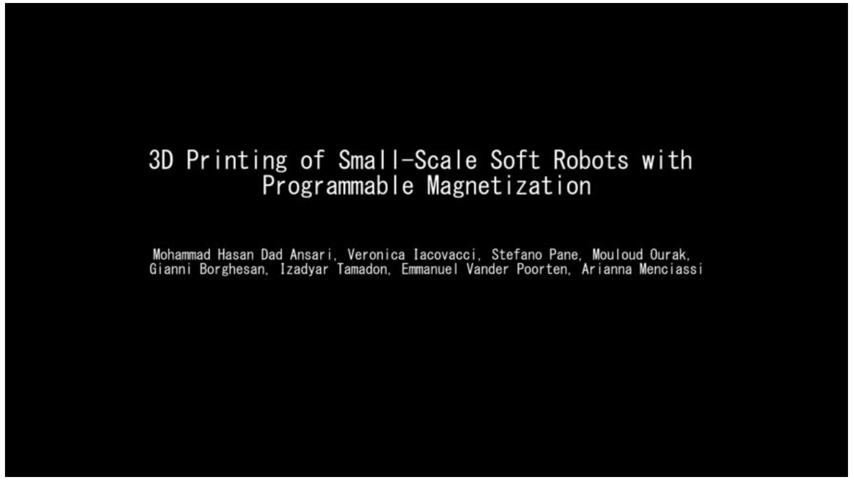
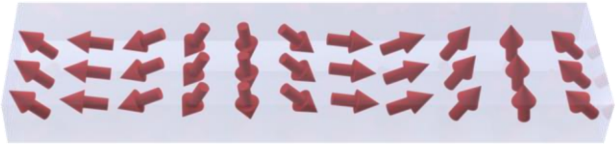
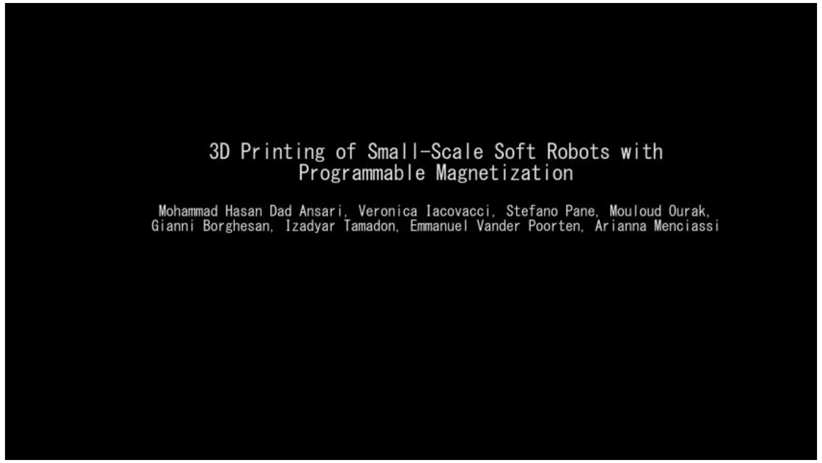








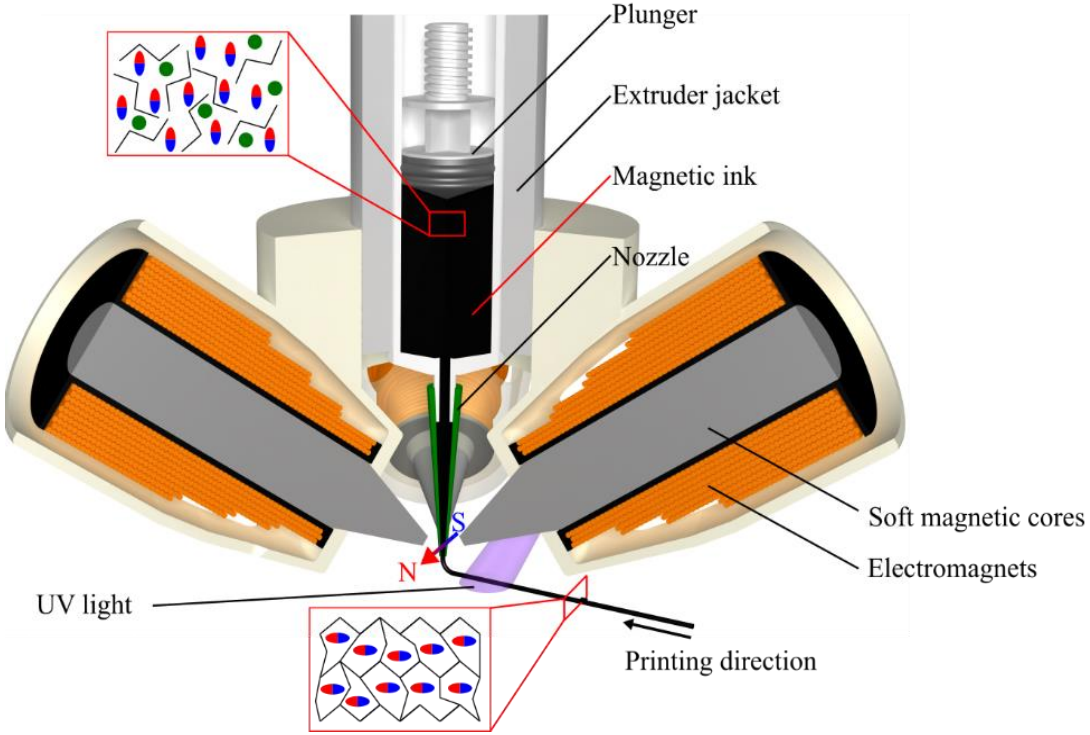


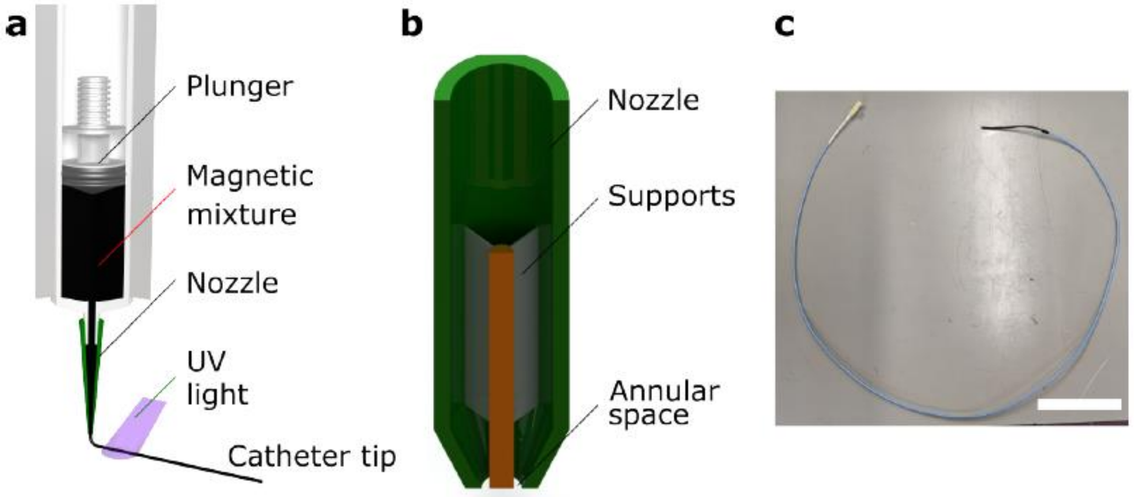


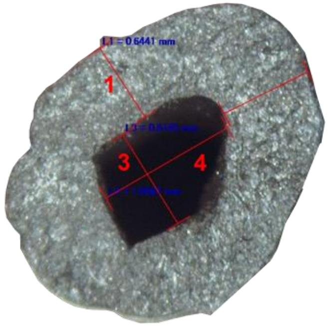
HMD Ansari et al., Adavanced Functional Materials, 2023

Magnetic catheters with programmable magnetization

- Distributed magnetic particles – miniaturization
- Magnetic anisotropy – programmed bending – patient-specific
- 3D printing – different materials, sizes, shapes – versatile



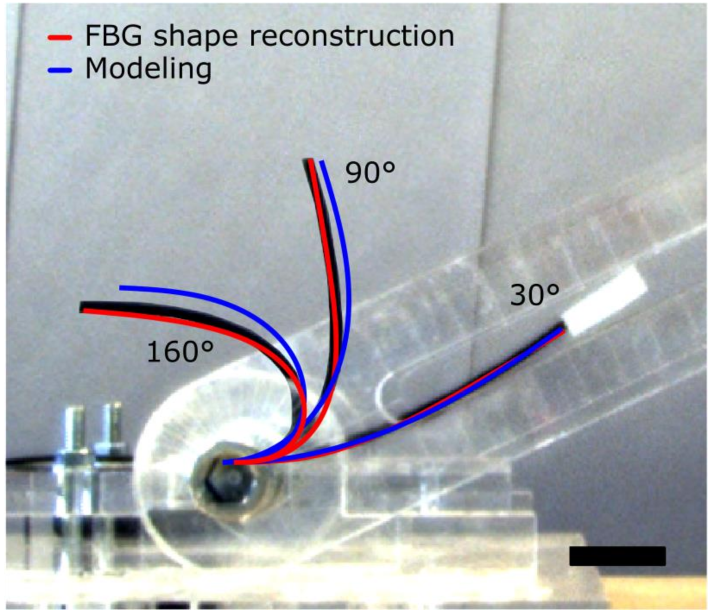


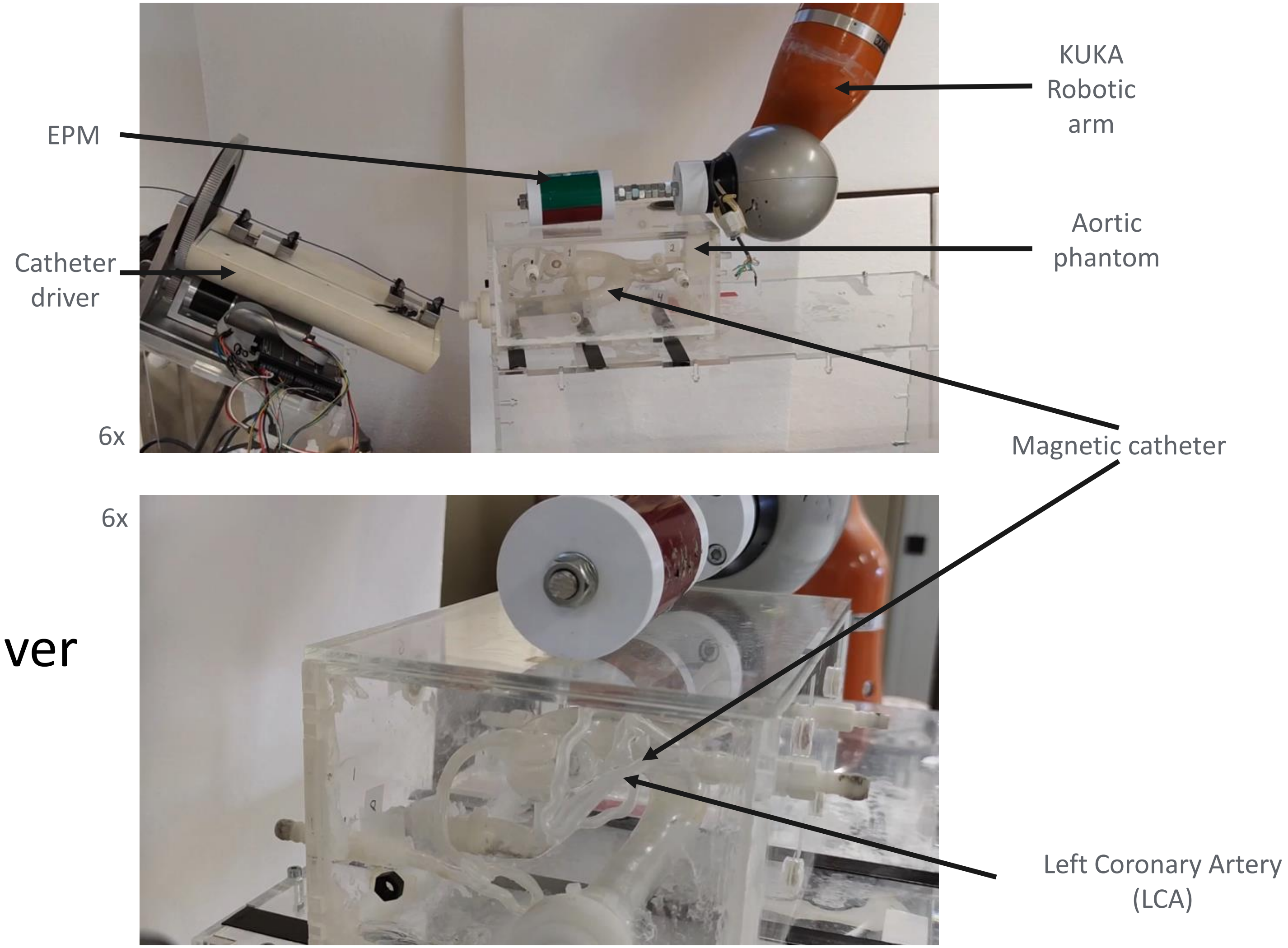


1	0.6441mm
2	0.7325mm
3	0.8145mm
4	1.0967mm

Ansari et. al. *Actuators, 2023*

Robot-assisted guidance of the magnetic catheter





Robot assisted catheterization

- Automatic insertion using catheter driver
- EPM path defined using several waypoints
- EPM moved along the path based on visual feedback of the operator
- Success rate = 83.3% (5/6)

Ansari et. al. *Actuators, 2023*

Main Challenges:

- **For catheters**: flexibility, maneuverability and tip control.

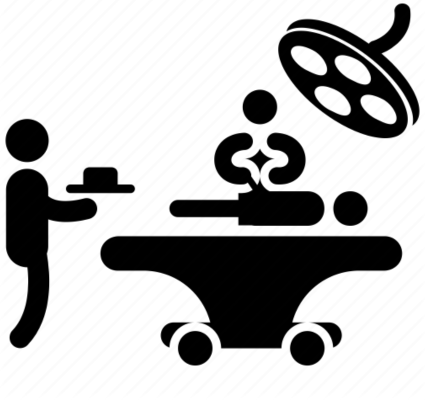
- **For microrobots**: control, biocompatibility, tracking (+ many others!)

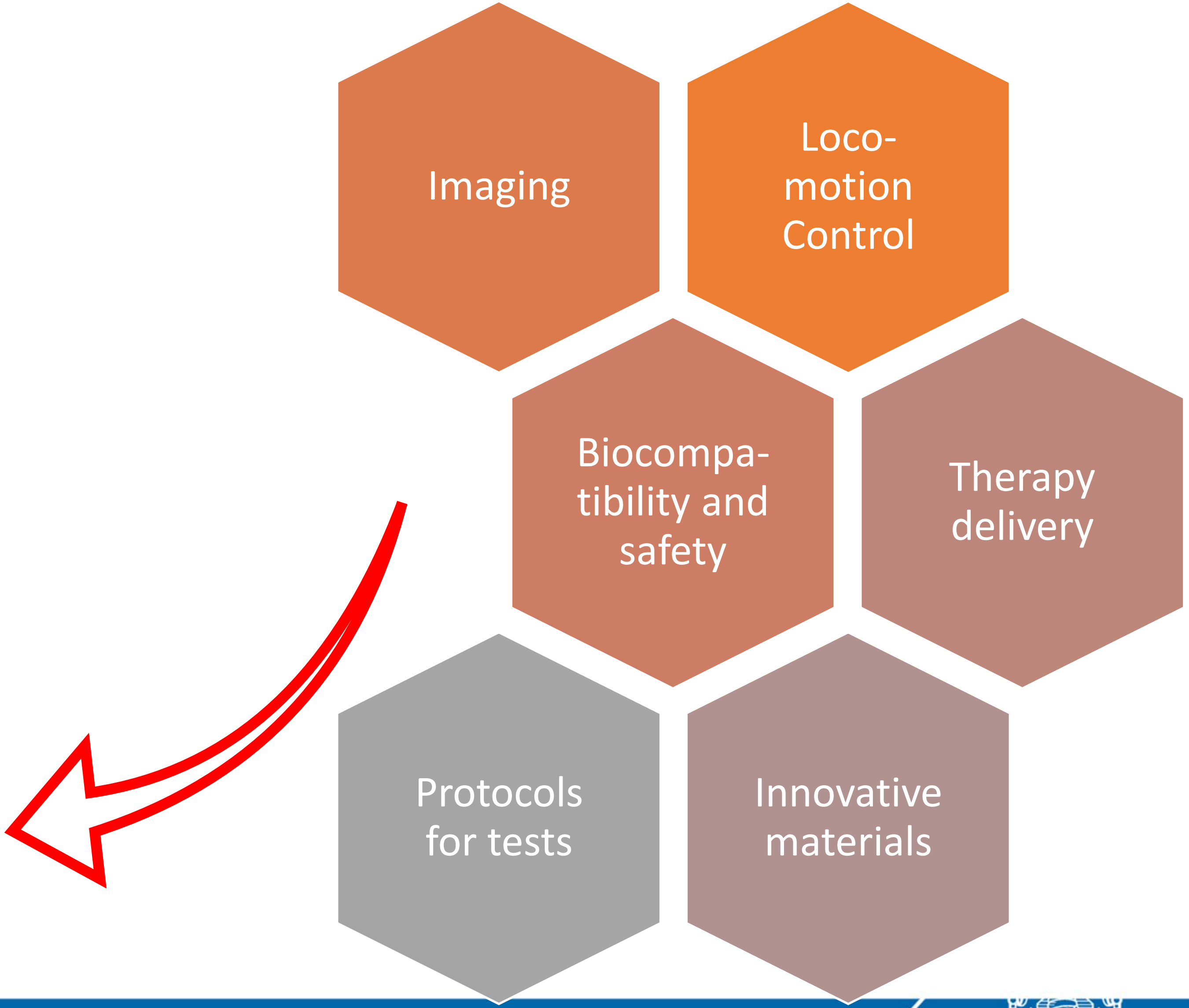
- Space constraints
- Need for higher spatial resolution
- Need for higher temporal resolution
- Need to shift from microscope-based lab settings to tissue-compliant imaging modalities
- Lower contrast mismatch between microrobots and tissue

Microparticles in the boold flow (Fantastic Voya\ge)

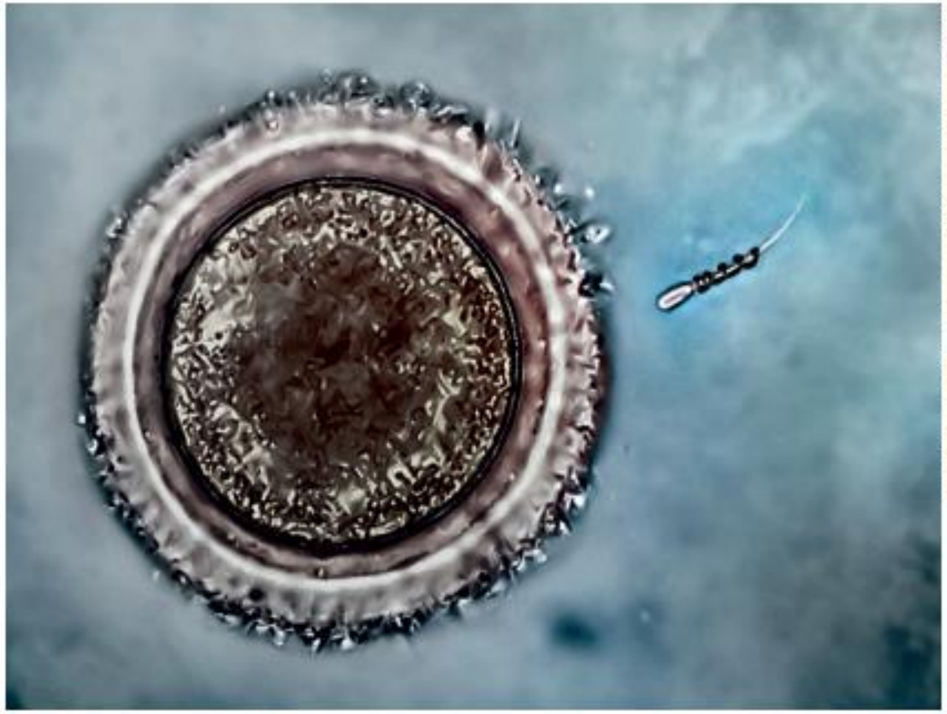
Let’s focus on challenges for microrobots in the vasculature

TRANSLATION TO RELEVANT CLINICAL SCENARIOS





(Magnetic) Microrobots for in vivo applications – Open Challenges



A helical micromotor helps an immotile but healthy bovine sperm cell get to an egg in culture.

Medical microbots need better imaging and control

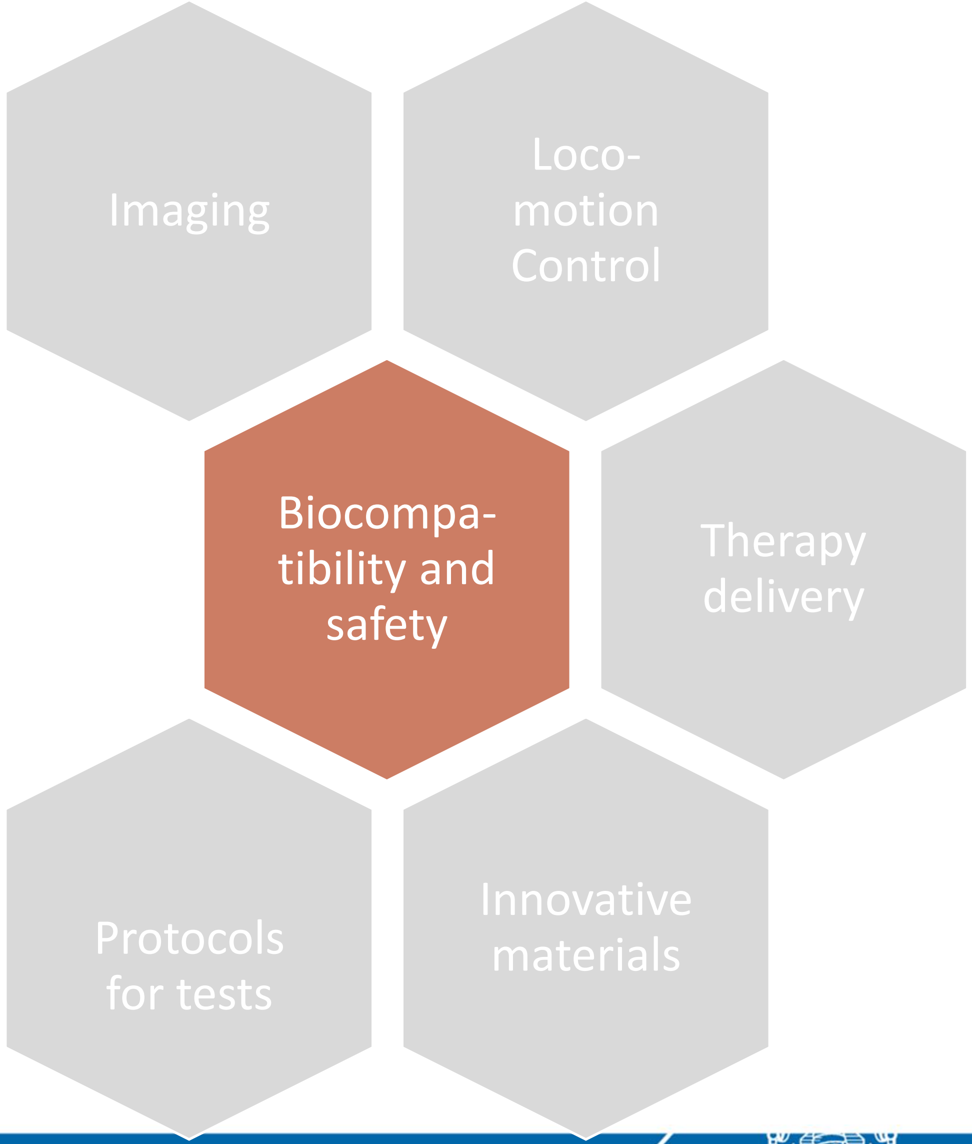
Mariana Medina-Sánchez and **Oliver G. Schmidt** set priorities for more realistic tests of tiny machines that could be used to diagnose and treat conditions.

So far, most microbot experiments have been done *in vitro* under conditions very different from those in the human body. Many devices rely on toxic fuels, such as hydrogen peroxide. They are simple to steer in a Petri dish, but harder to control in biological fluids full of proteins and cells, and through the body's complex channels and cavities.

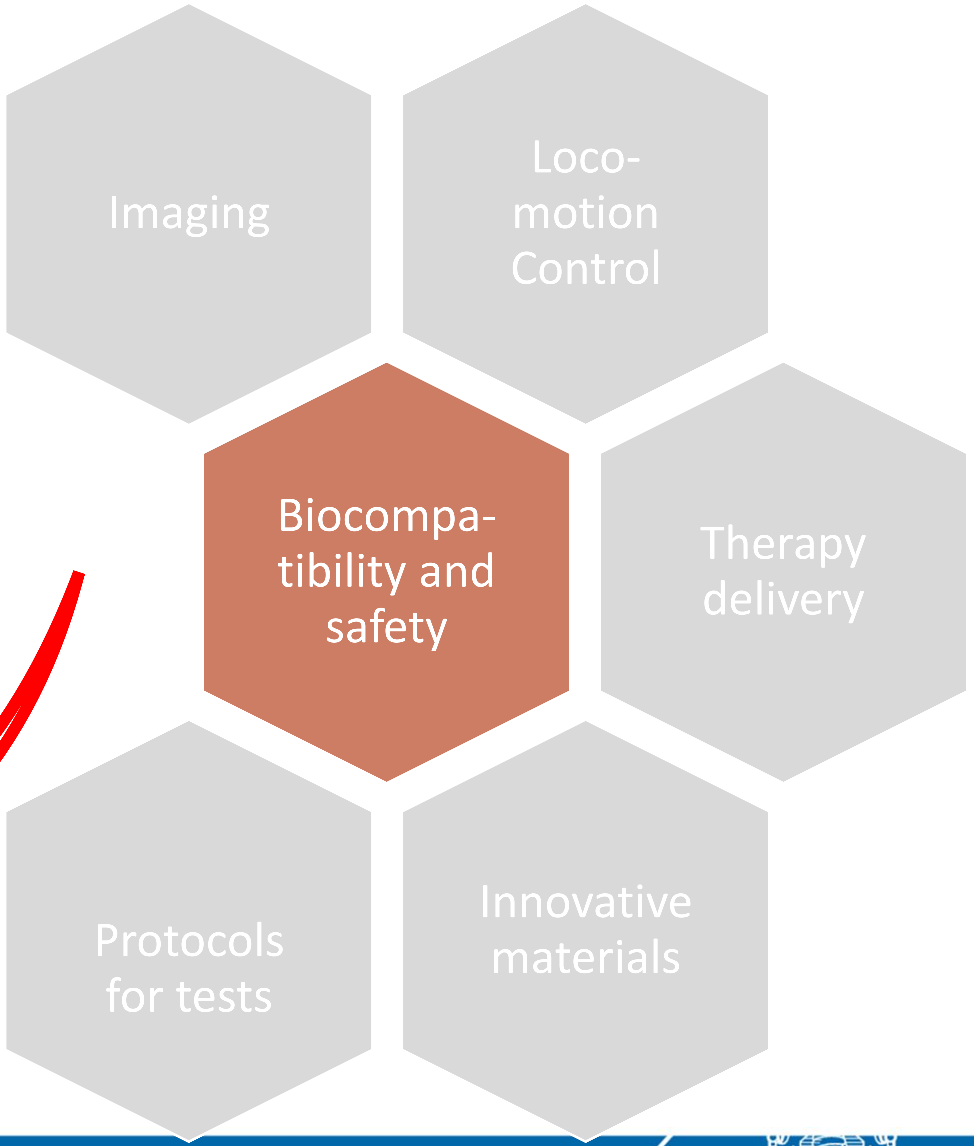
To enter clinical trials, microbots must clear two major hurdles. First, researchers need to be able to see and control them operating inside the body — current imaging techniques have insufficient resolution and sensitivity. Second, the vehicles need to be biocompatible and be removed or stabilized after use. Achieving both aims would set the stage for further improvements — in steering and mobility, materials and capabilities.

We call on microrobotics researchers, materials scientists and bioimaging and medical specialists to work together to solve these problems. And regulatory agencies need to put in place directives for testing therapeutics that are based on microbots.

Micro & Nanorobotics towards in vivo applications: challenges

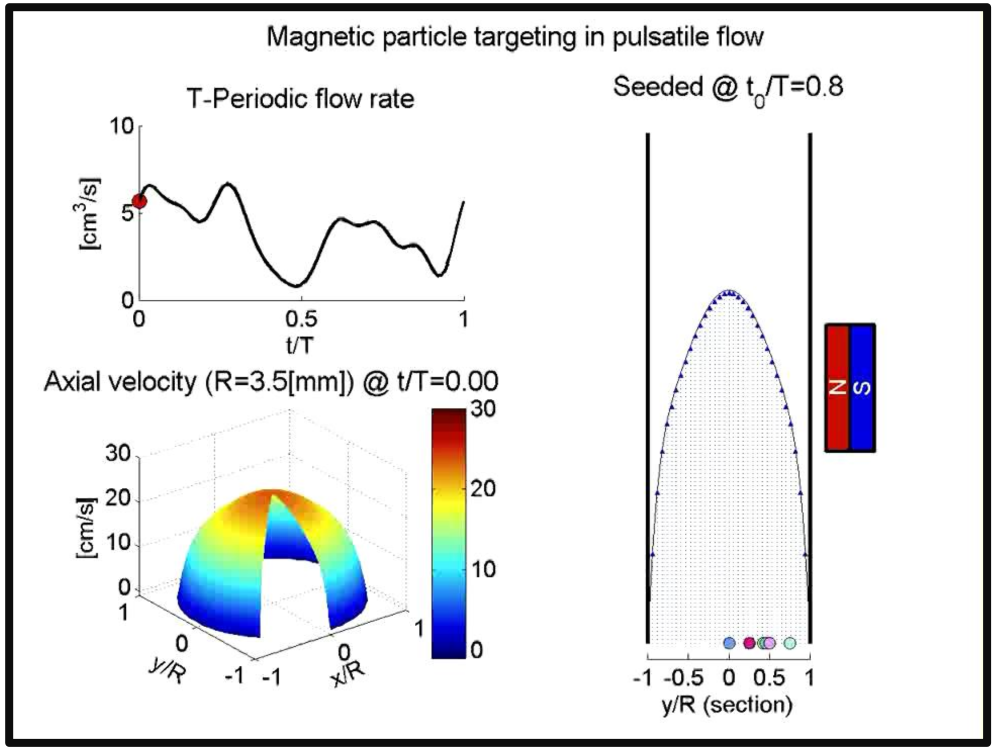


Micro & Nanorobotics towards in vivo applications: challenges



How facing the bio-distribution of magnetic particles in the body?
How managing the magnetic particles not contributing to the therapy?

Micro & Nanorobotics towards in vivo applications: challenges



Berselli, L. C., P. Miloro, et al. (2013) "Applied Mathematics and Computation **219**(10): 5717-5729.

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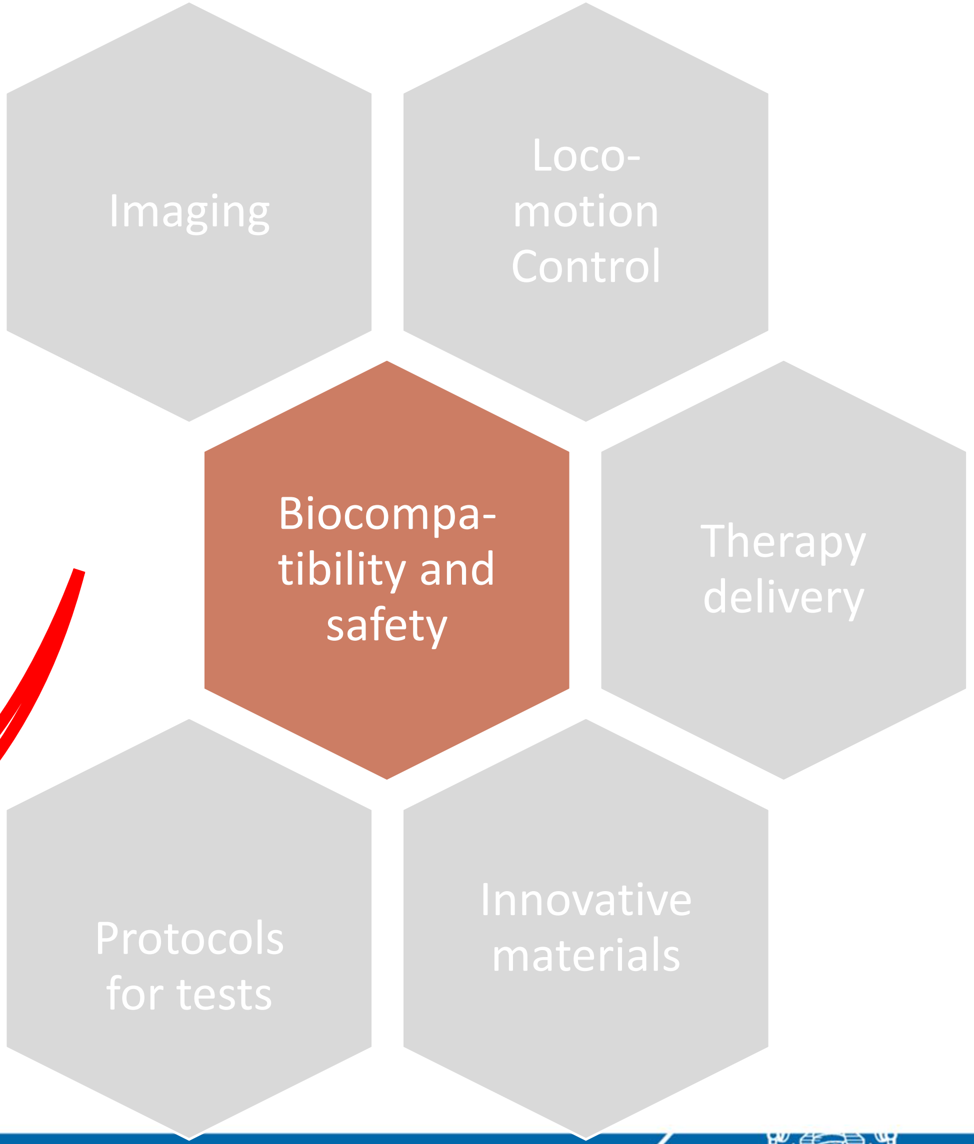
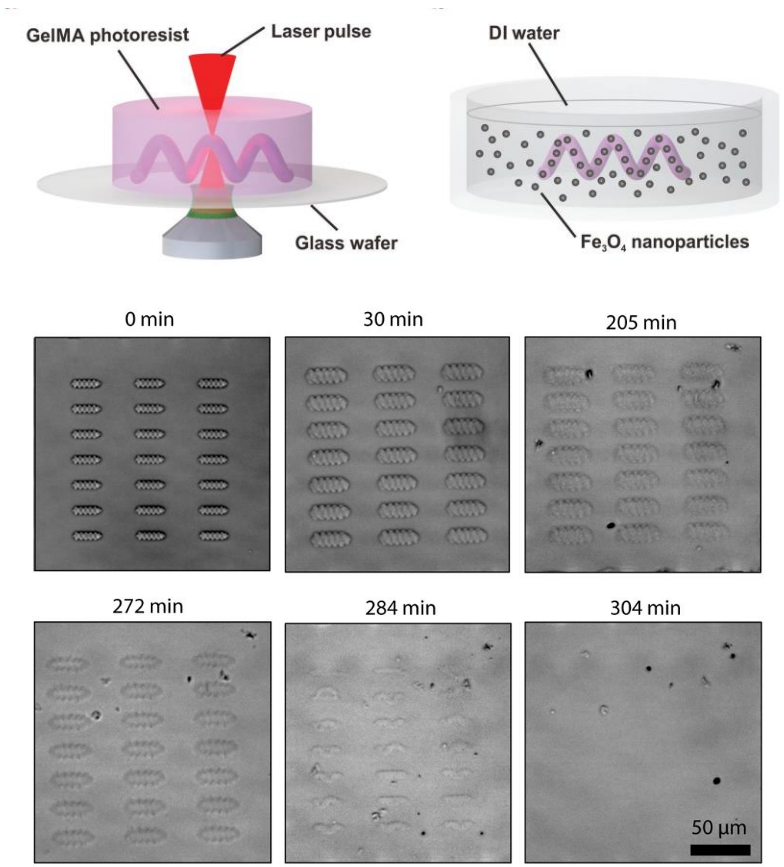


(Magnetic) Microrobots for in vivo applications – Open Challenges

Development of fully degradable structures



Loaded drugs and magnetic particles are biodistributed in the body after degradation

So far, most microbot experiments have been done *in vitro* under conditions very different from those in the human body. Many devices rely on toxic fuels, such as hydrogen peroxide. They are simple to steer in a Petri dish, but harder to control in biological fluids full of proteins and cells, and through the body's complex channels and cavities.

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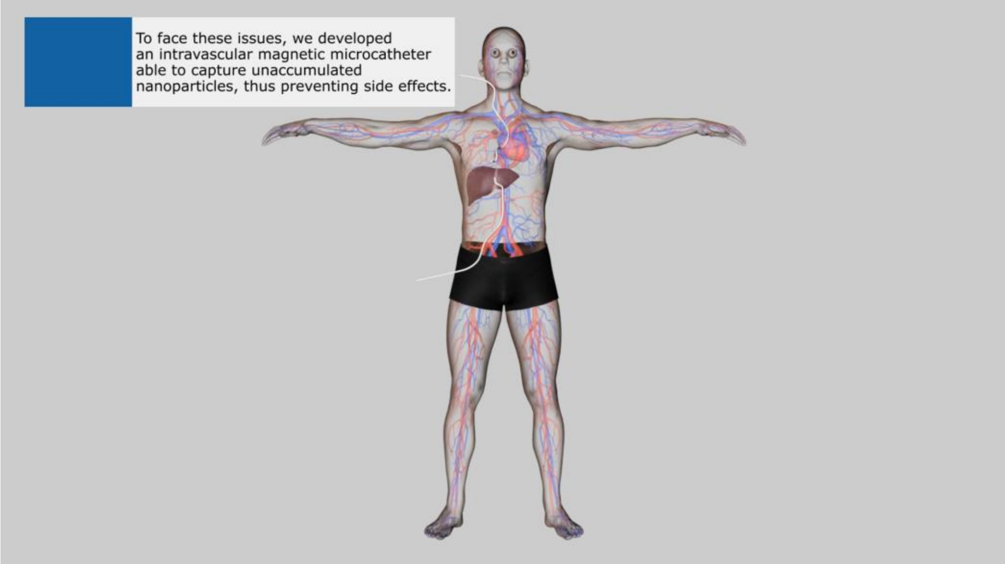
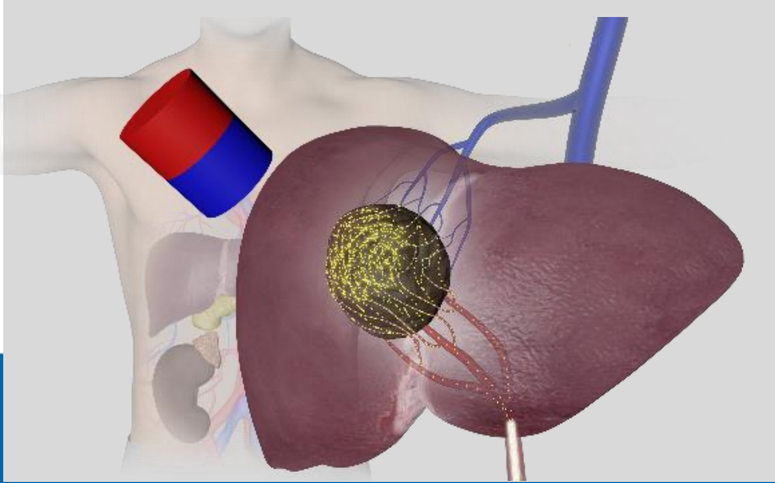
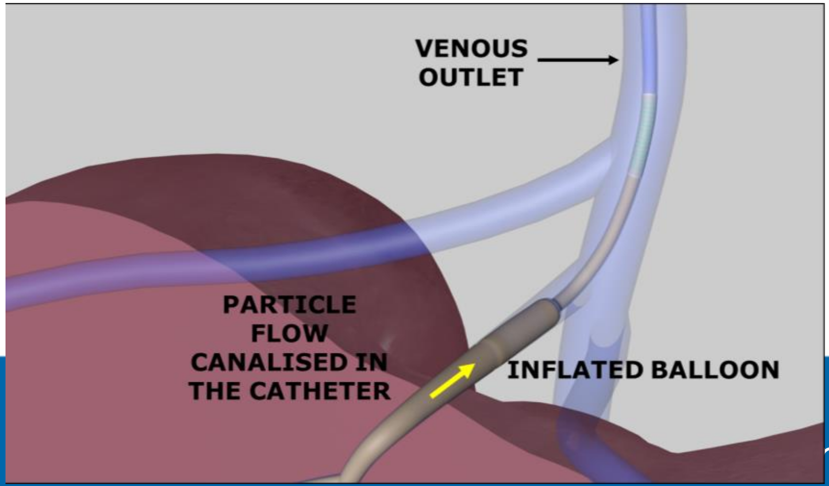
Intravascular magnetic catheter to retrieve micro and nanoagents from the bloodstream

Iacovacci, V., et al. Adv. Sci. 2018
Iacovacci, V., et al. ICRA 2019

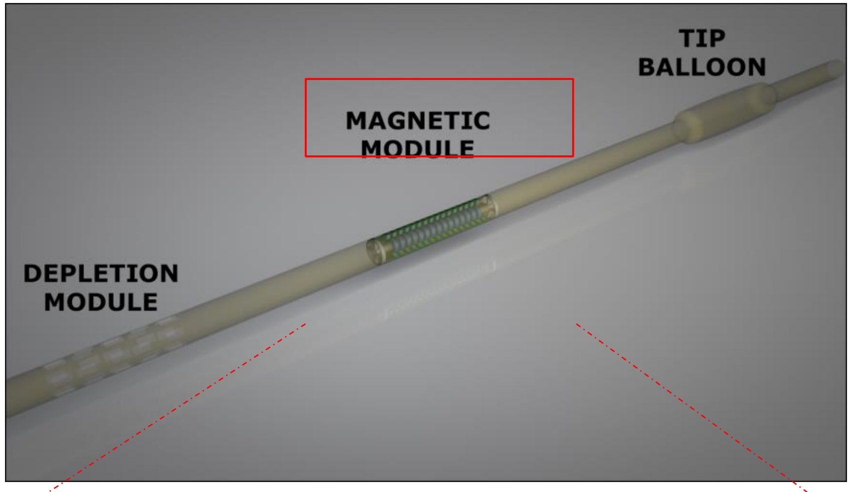
TARGET: ORGANS FEATURED BY TERMINAL CIRCULATION (e.g. LIVER, KIDNEY, PANCREAS)

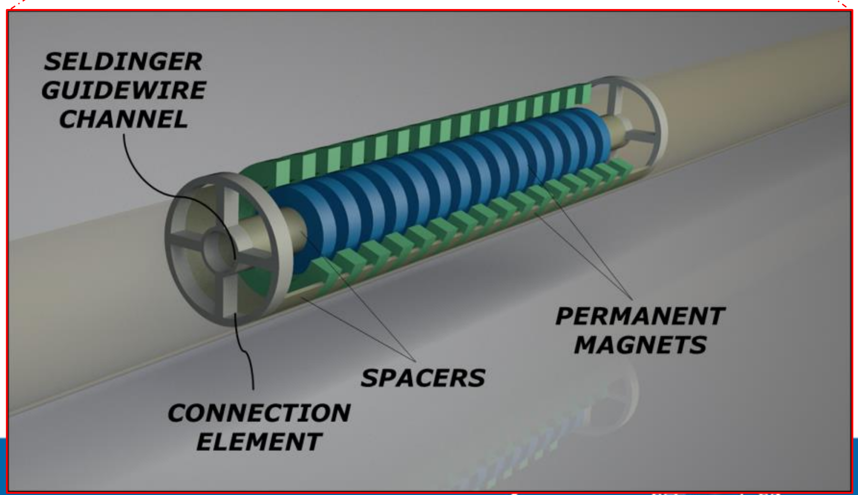






MODULAR CATHETER STRUCTURE





Magnetic module design – FEM modeling

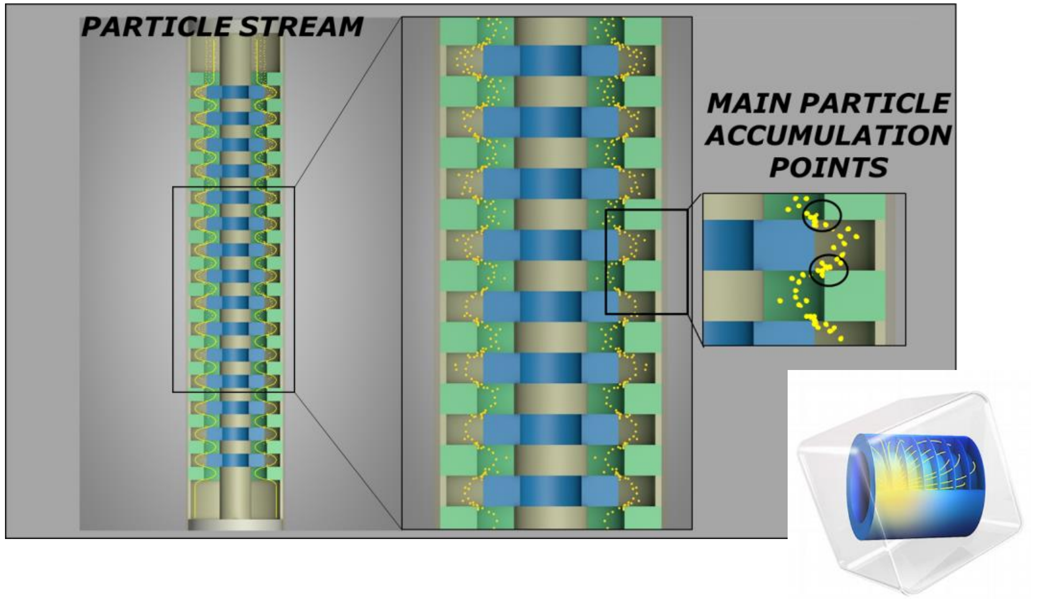
- ***SPHERICAL PARTICLE***
- ***POINT DIPOLE APPROXIMATION***
- ***LAMINAR FLOW IN A CHANNEL***

$$\boldsymbol{v}_p = \boldsymbol{v} + \zeta f(H)(\boldsymbol{H}\cdot\nabla)\boldsymbol{H}$$

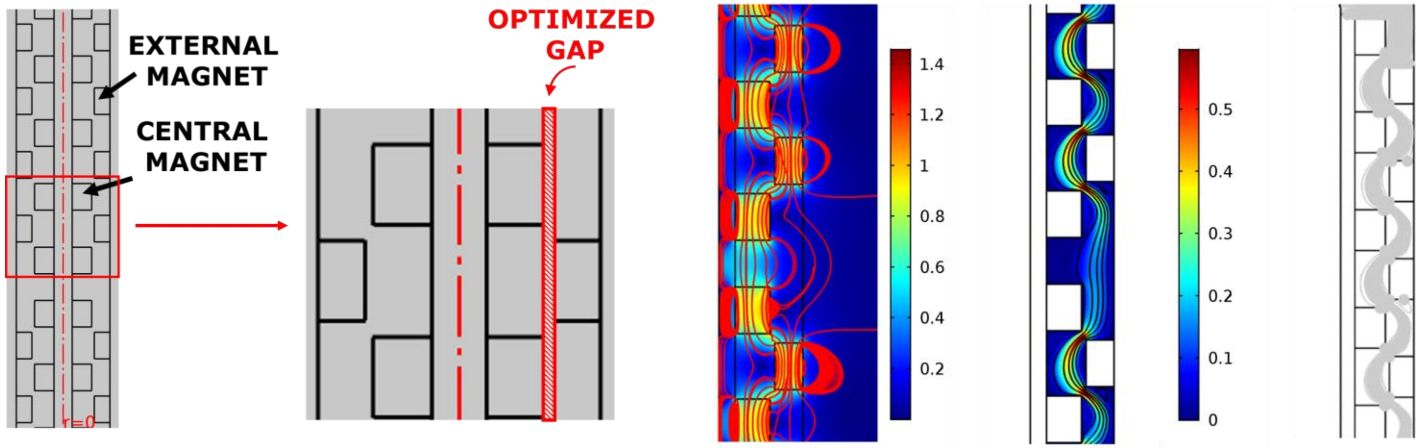
$$\zeta = \frac{\mu_0(1+\chi_f)}{6\pi\eta_f}\frac{V_{mag}}{r_h}$$

PARTICLE IN A FLUIDIC AND MAGNETIC FIELD SIMPLIFIED MODELING

$$f(H) = \begin{cases} \dfrac{3(\chi_p-\chi_f)}{(\chi_p-\chi_f)+3(1+\chi_f)} & \dfrac{M_{sp}}{H} > \dfrac{3(\chi_p-\chi_f)}{(\chi_p-\chi_f)+3(1+\chi_f)} \\ \dfrac{M_{sp}}{H} & \dfrac{M_{sp}}{H} \leq \dfrac{3(\chi_p-\chi_f)}{(\chi_p-\chi_f)+3(1+\chi_f)} \end{cases}$$

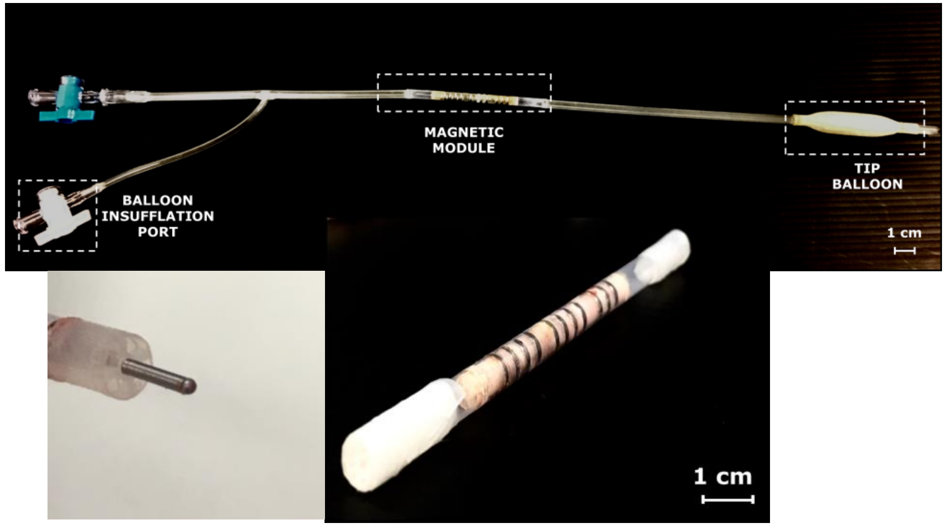


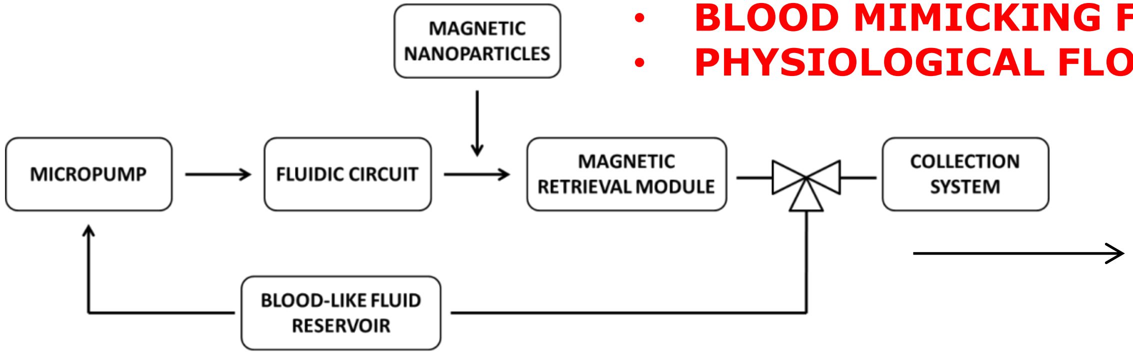
- ***CATHETER DIAMETER (12 F, 15 F)***
- ***MAGNET NUMBER, GROUPING***
- ***PARTICLES DIMENSION***



Iacovacci, V., et al. Adv. Sci. 2018
Iacovacci, V., et al. ICRA 2019

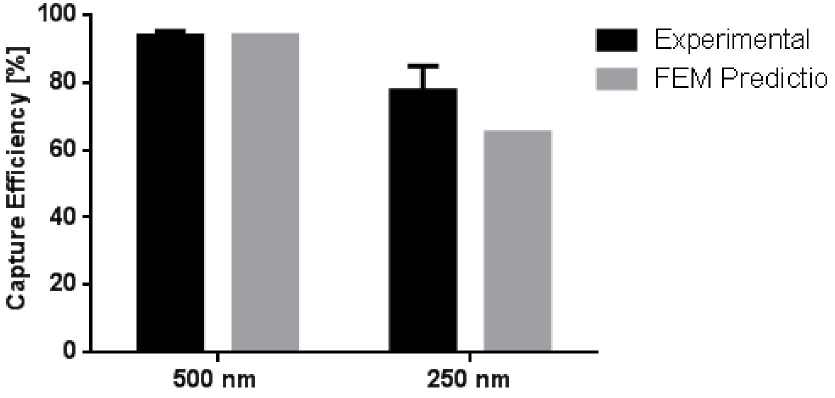
Experimental validation





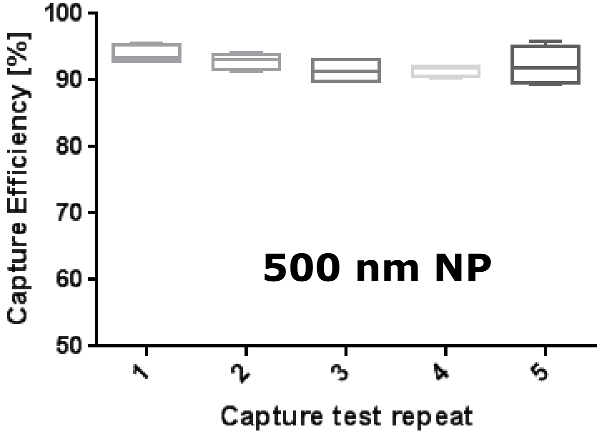
- BLOOD MIMICKING FLUID
- PHYSIOLOGICAL FLOW RATE

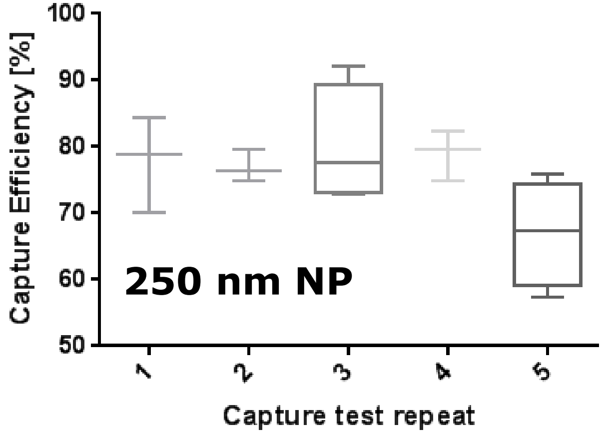
ICP-MS ANALYSIS to quantify the collected samples Iron content



OPTIMAL CORRESPONDANCE AMONG FEM PREDICTION AND EXPERIMENTAL DATA

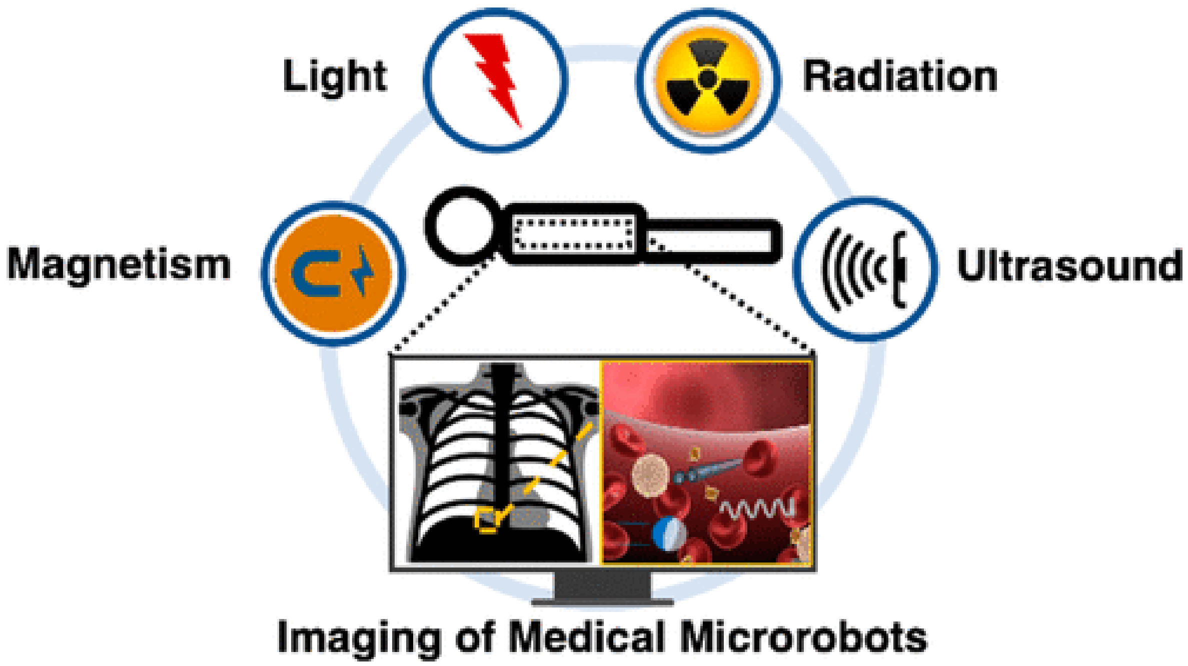
MULTIPLE PASSAGE TESTS

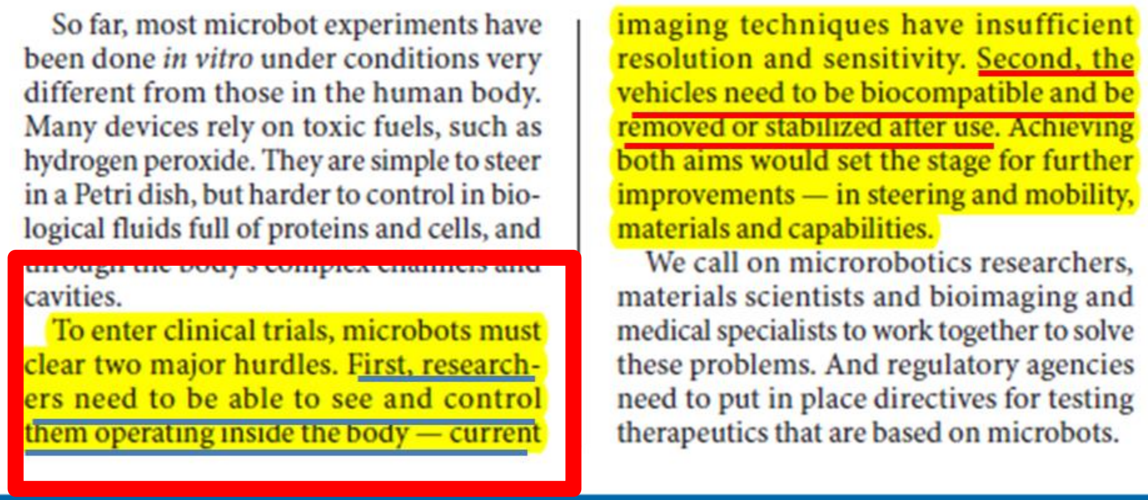




NO SIGNIFICANT HEMORHEOLOGICAL ALTERATION (BLOOD CELLS COUNT AND HEMATOCRIT)

EXTENSIVE CAPTURE EFFICIENCY FOR MULTIPLE USAGE (MASSIVE DOSES)





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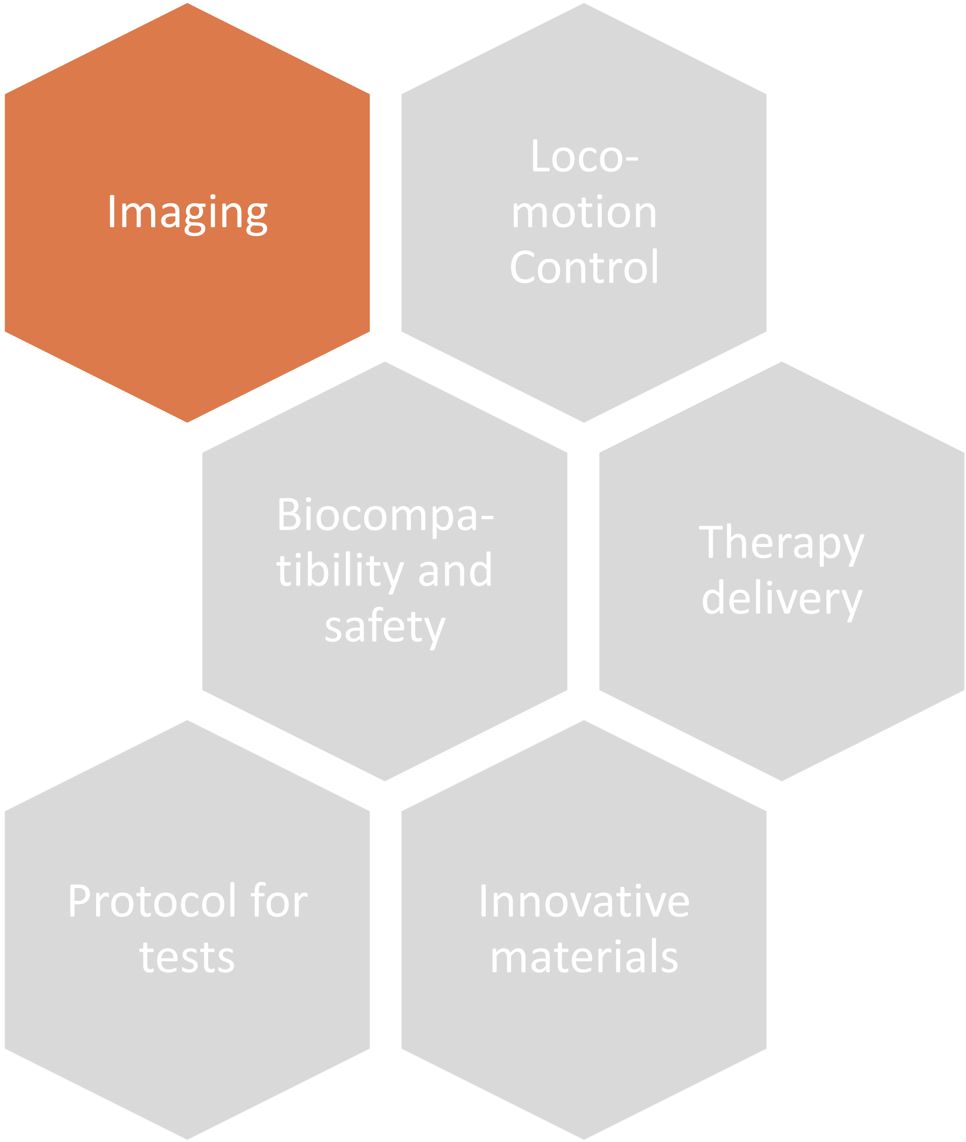
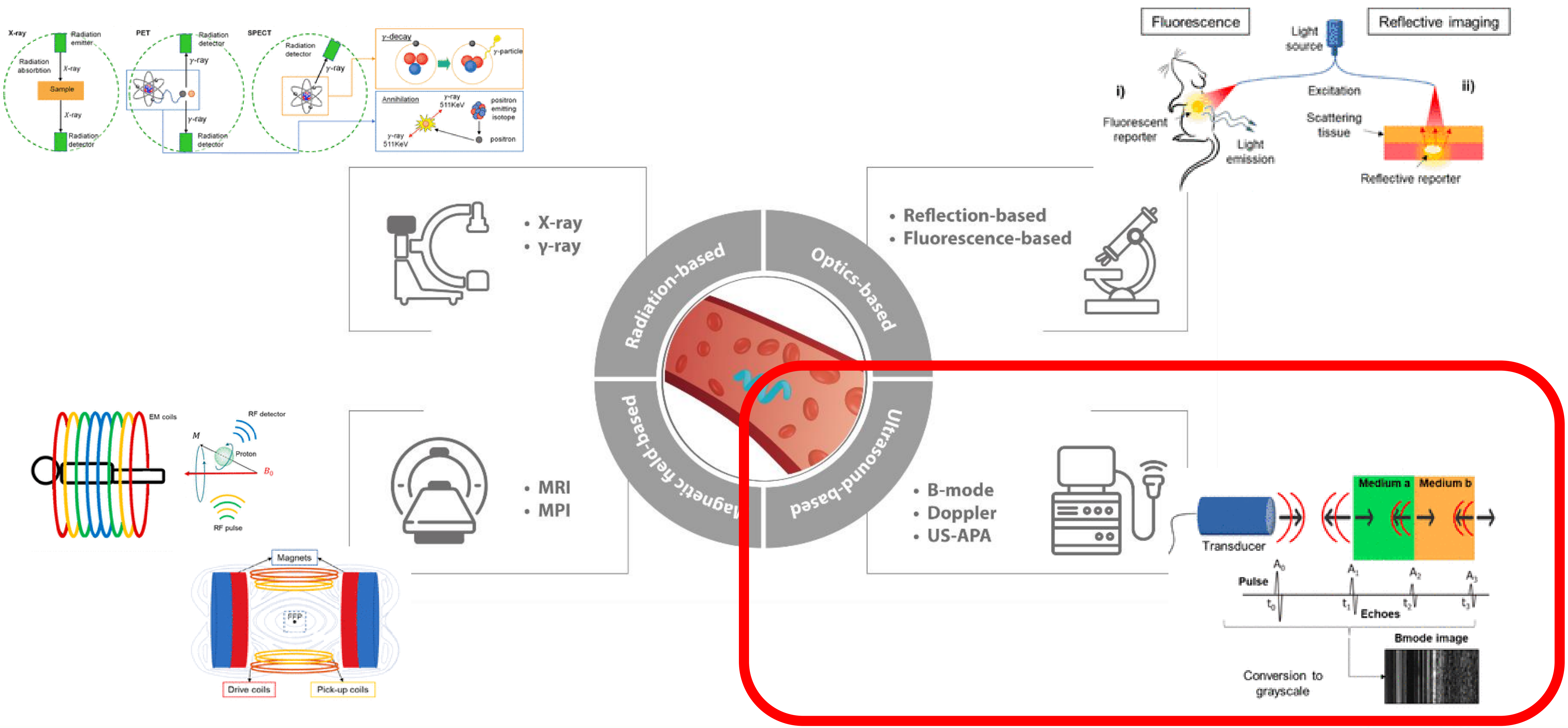
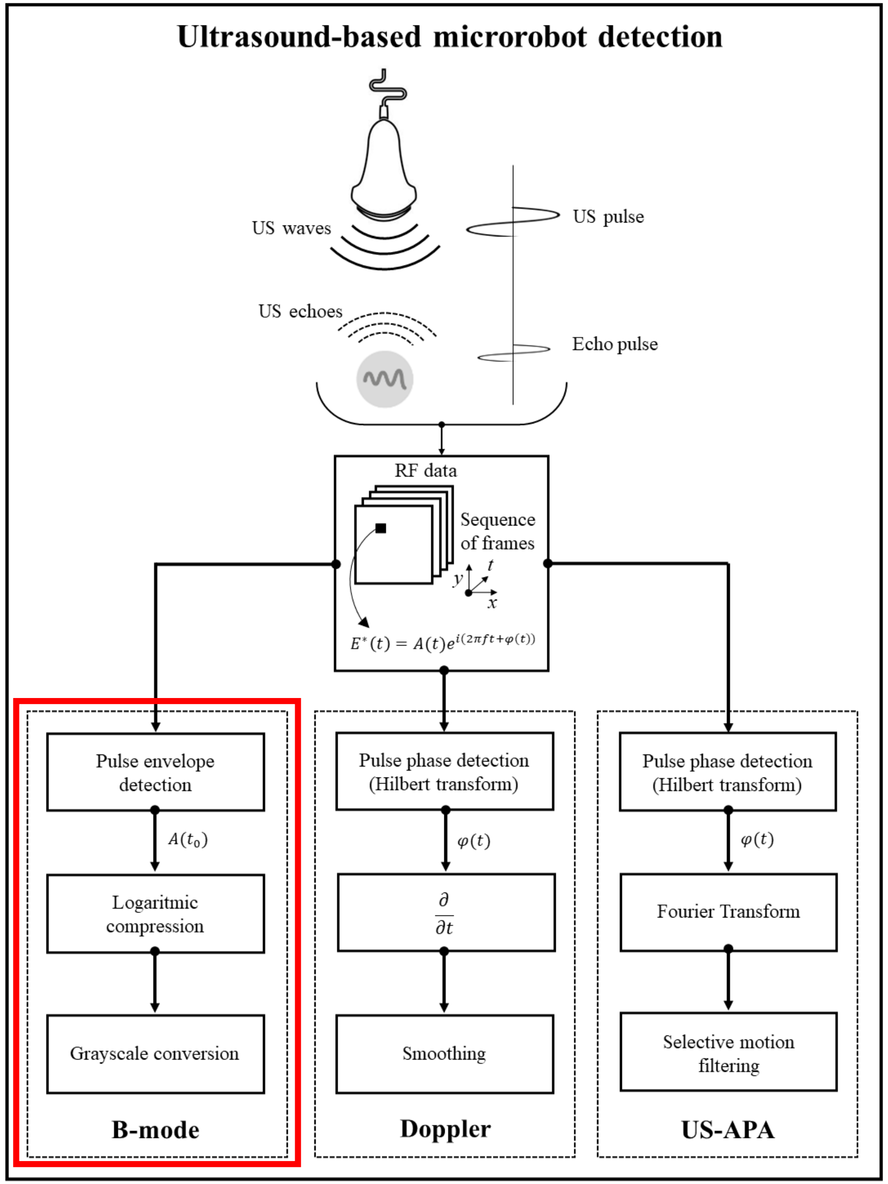


Aziz, A., et al. (2020)

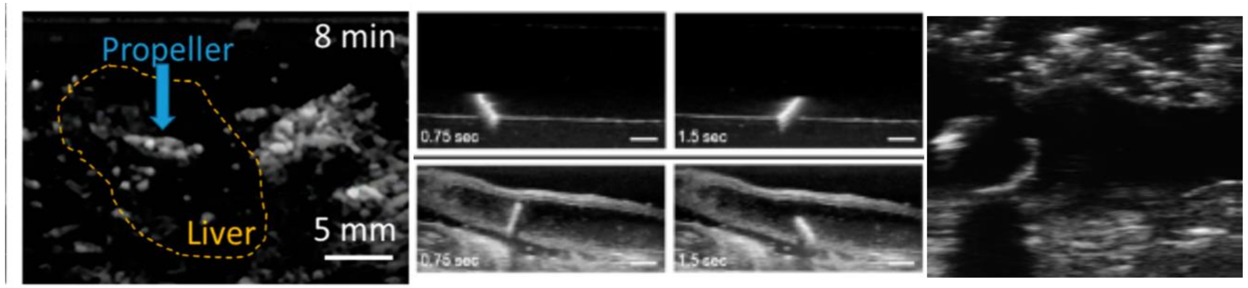
Microrobots imaging – state of the art



Microrobots US imaging – examples



B-MODE IMAGING OF SUB-MILLIMETRIC ROBOTS



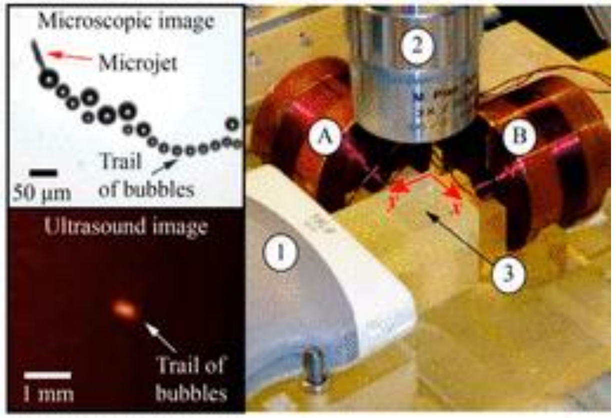
Li et a... 2019

...ure, 2018

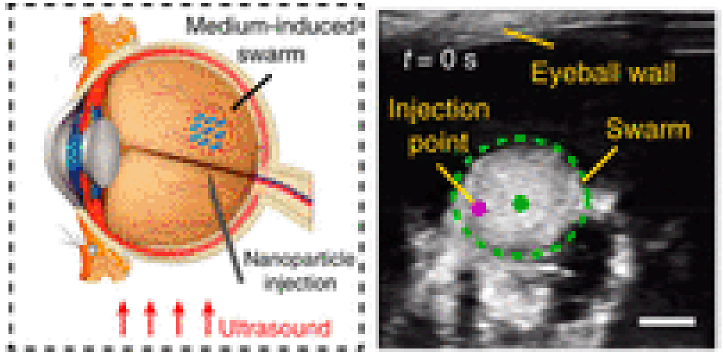
LOW CONTRAST RESOLUTION IN HIGHLY ECHOGENIC MEDIA

MICR...

...SWARM IN VITREOUS

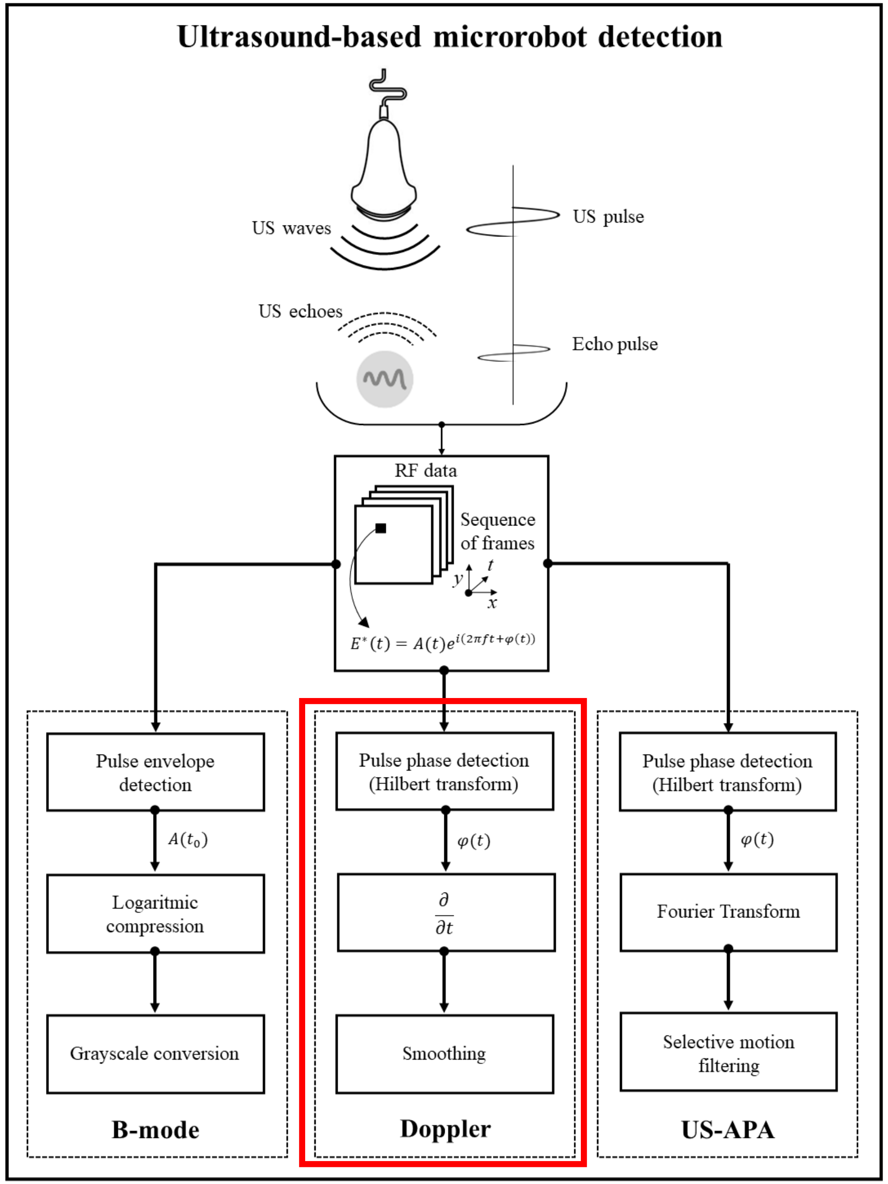


Sanchez et al. , IEEE BioRob, 2014



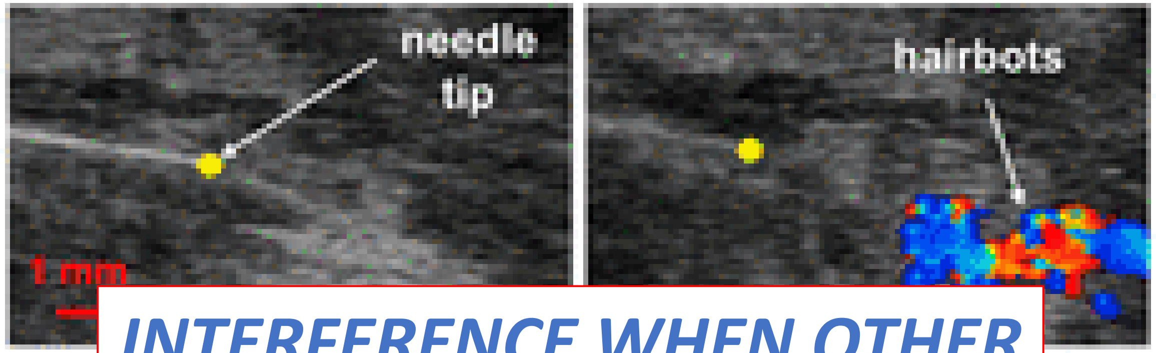
Yu et al. , Nat. Comm, 2019

Microrobots US imaging – examples



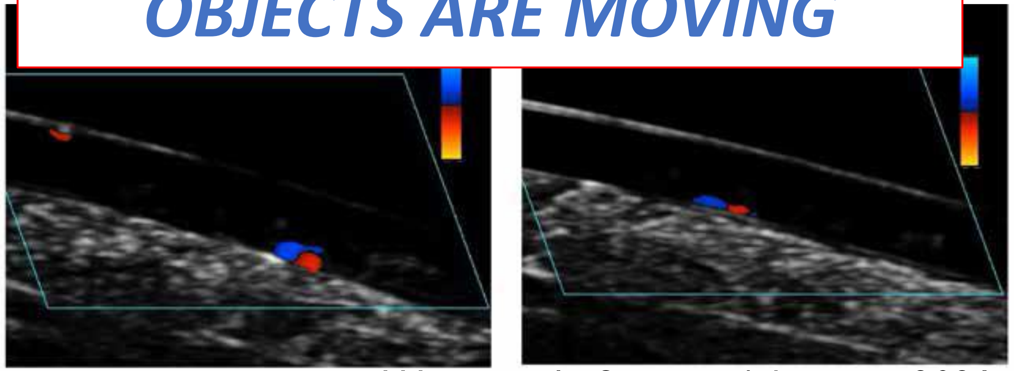
Motion-based analysis can help

OPPORTUNITIES OFFERED BY DOPPLER IMAGING



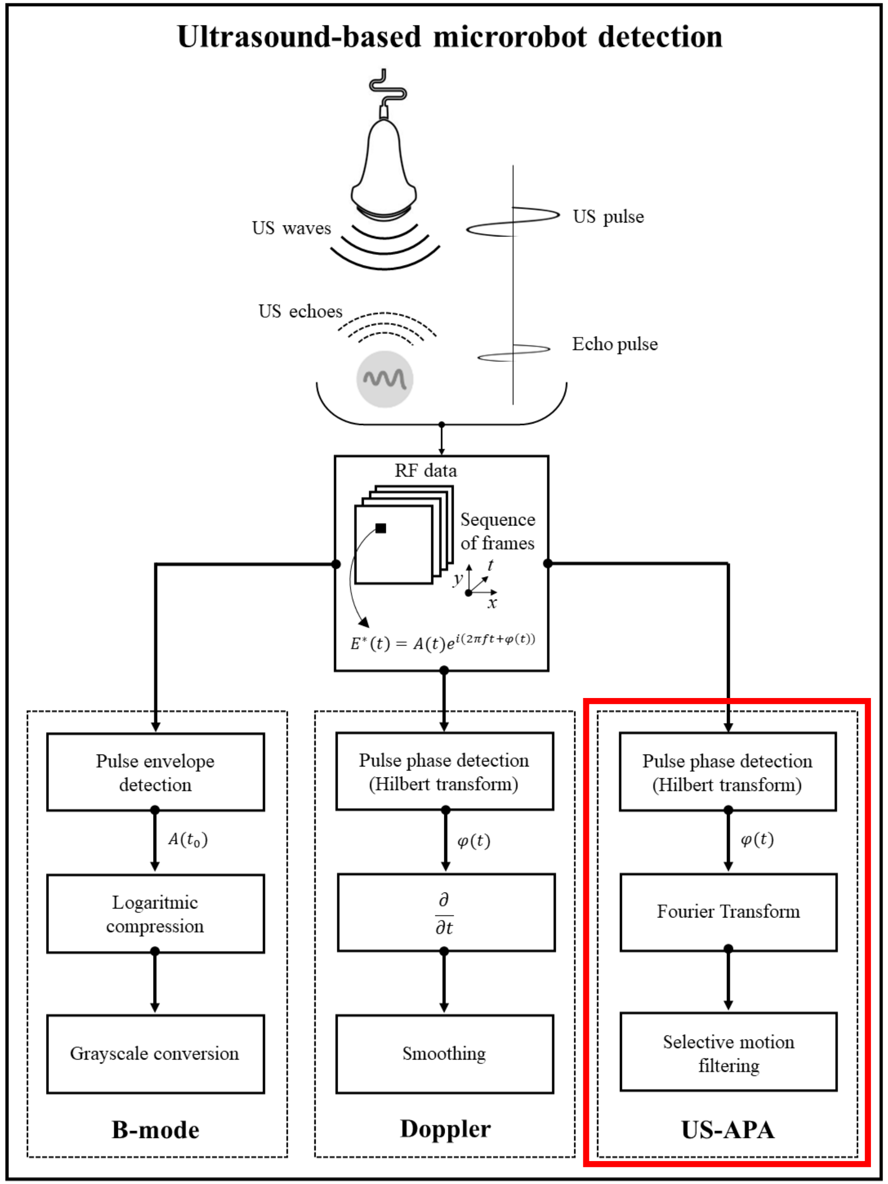
2019

INTERFERENCE WHEN OTHER OBJECTS ARE MOVING



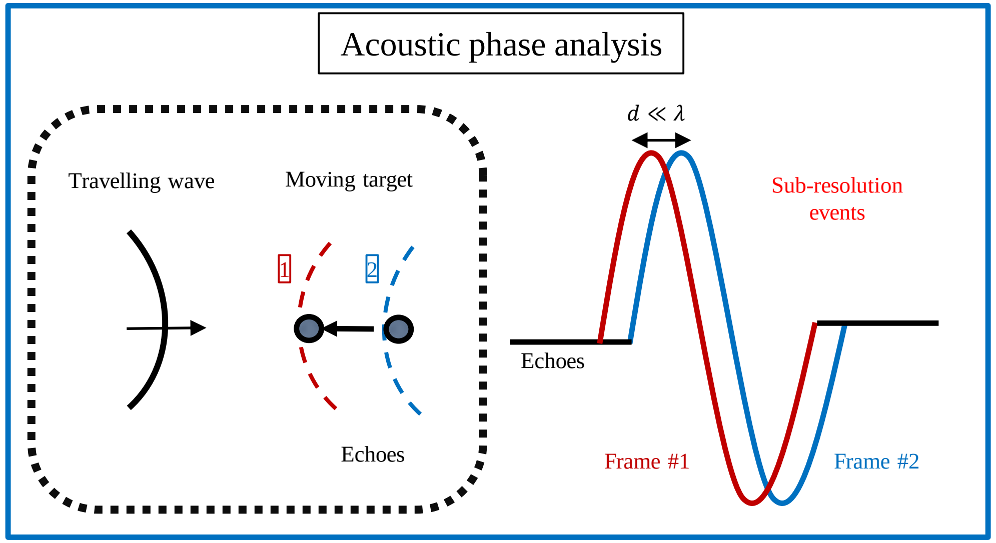
Wang et al., Science Advances, 2021

Microrobots US imaging – examples



Selective motion filtering can improve tracking stability and precision

ACOUSTIC PHASE ANALYSIS (APA)

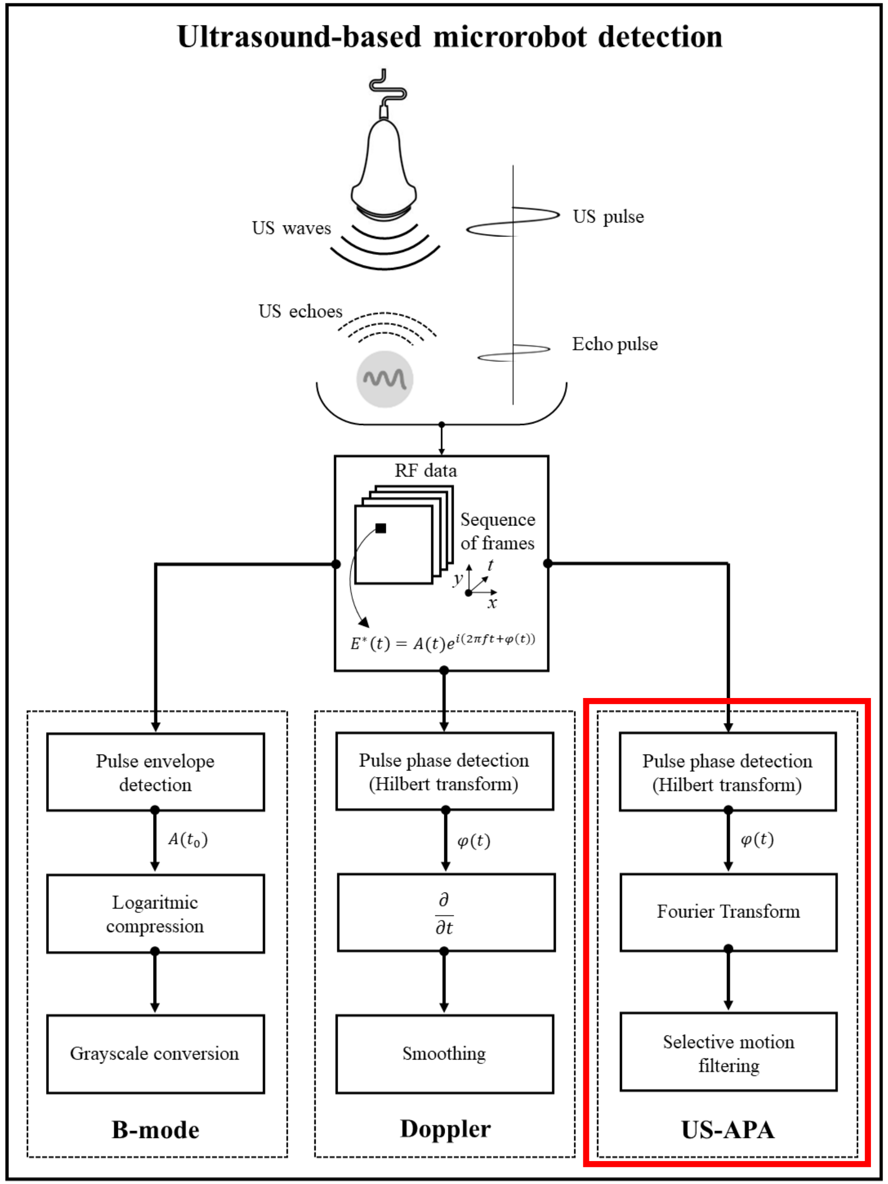


Analytic echo signal

$$E(t) = A(t)e^{\varphi(t)} \longrightarrow \varphi(t) = \frac{4\pi}{\lambda}u(t)$$

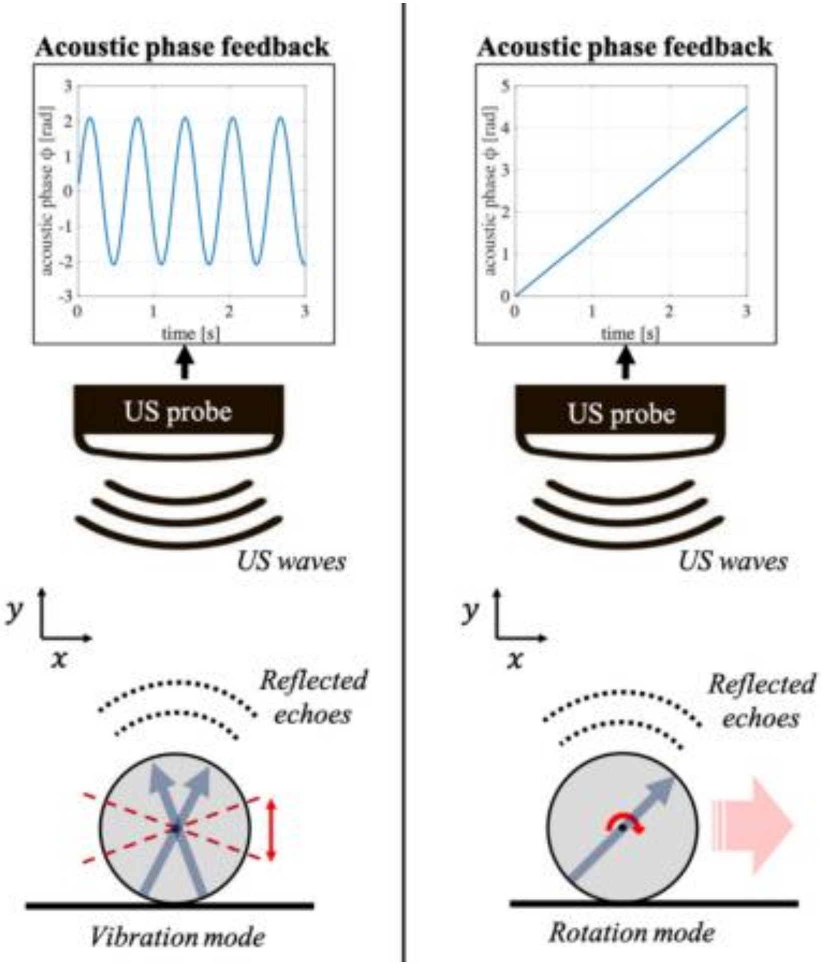
Acoustic intensity **Acoustic phase** **Target Motion projection on pulse axis**

Microrobots US imaging – APA

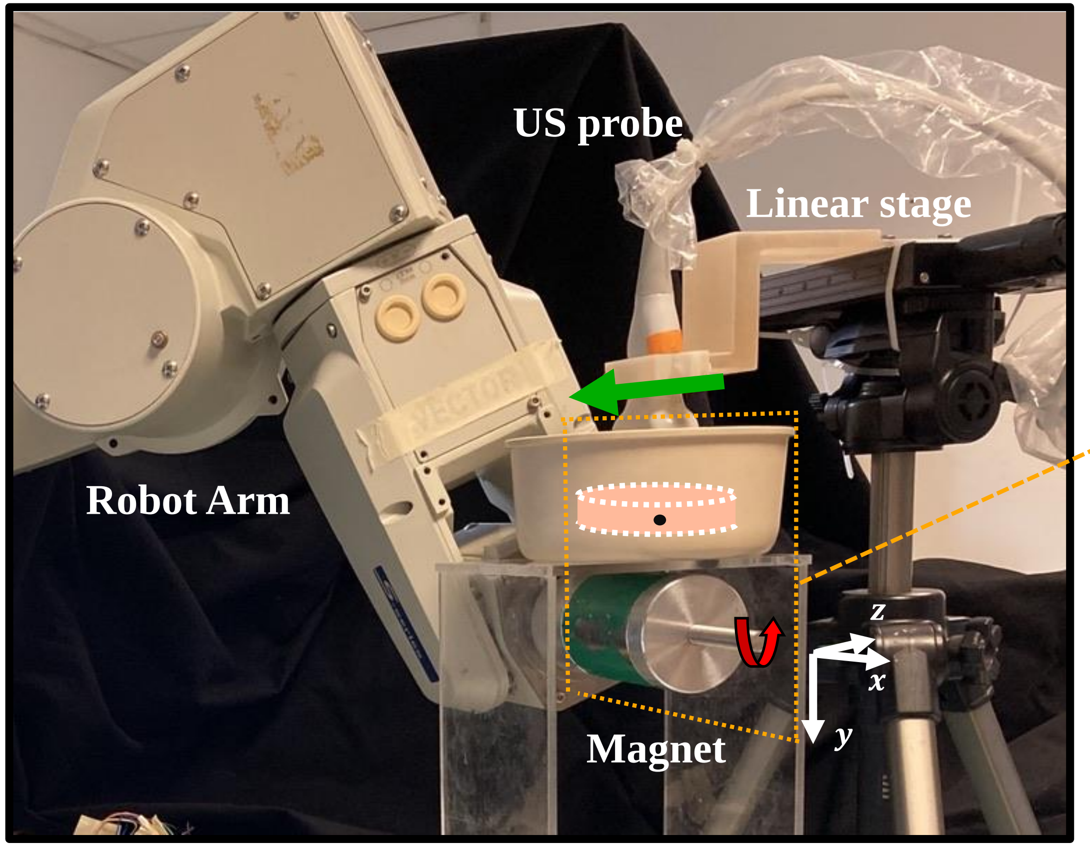


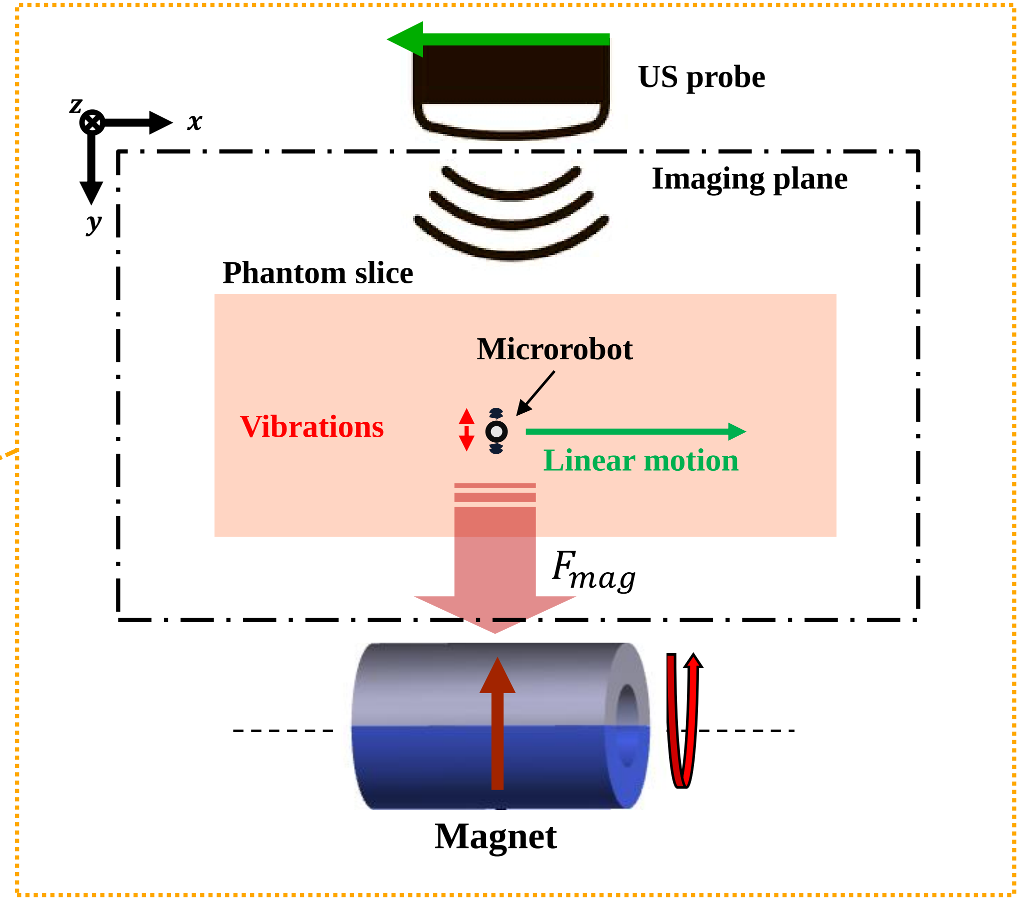
Different microrobot locomotions induce different phase feedback

$$\varphi(t) = \frac{4\pi}{\lambda} u(t)$$

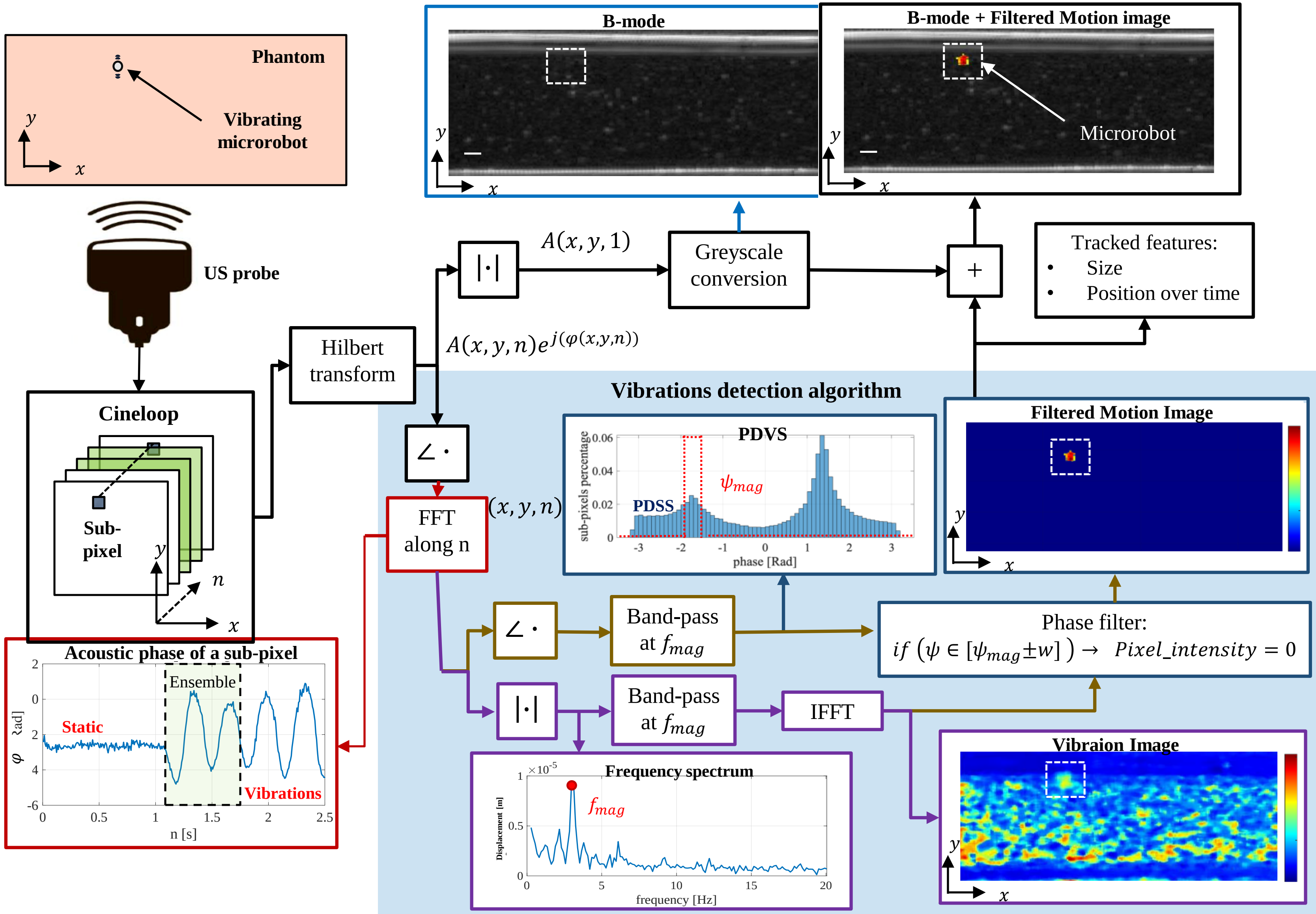


Experimental setup for real-time imaging and tracking





Vibrations detection algorithm



1. Fourier analysis
Analyze the frequency components of the acoustic phase

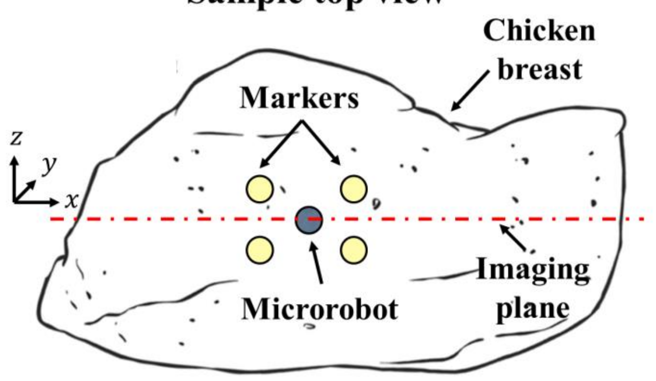
2. Frequency filtering
Isolate vibrations at microrobot frequency

3. Phase filtering
Isolate vibrations in-phase with the magnetic field

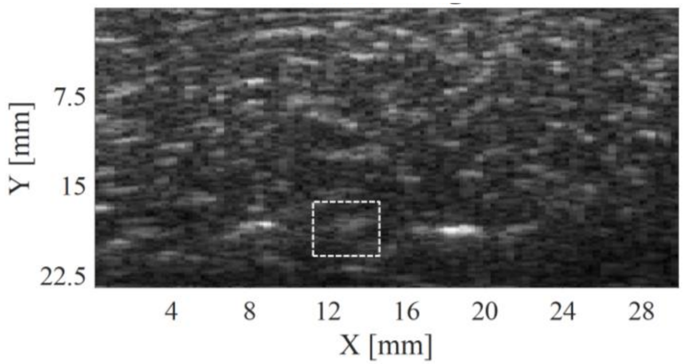
4. Overlap with B-mode

Tracking soft vibrating microrobots in tissues

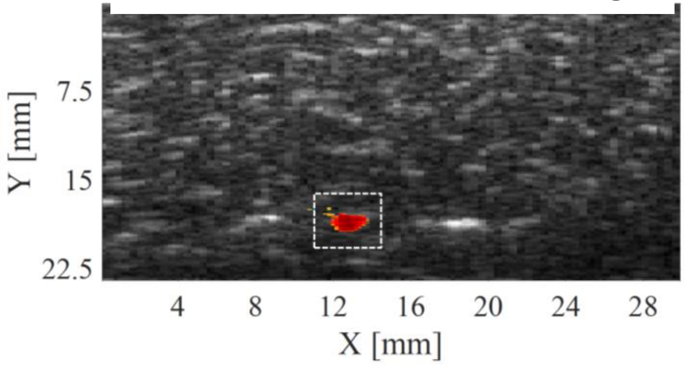
Sample top view



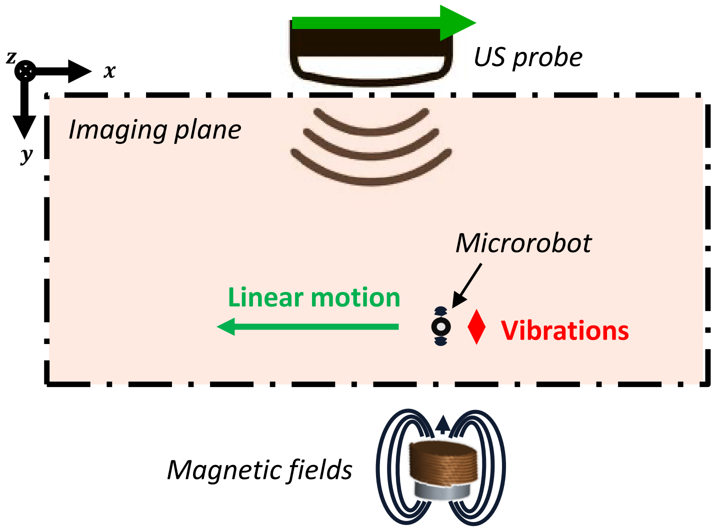
B-mode



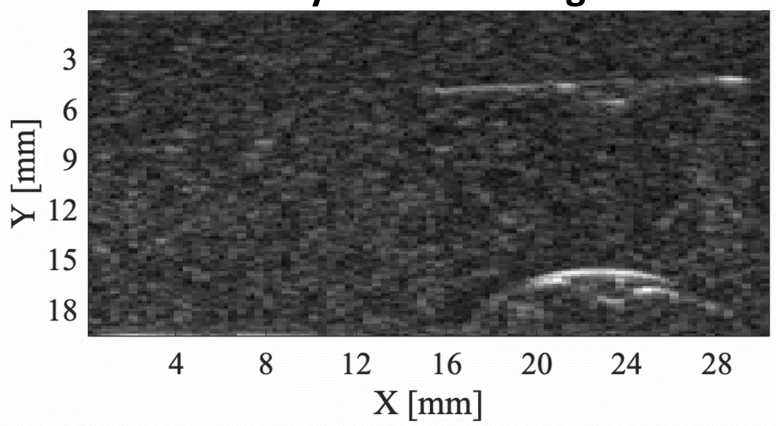
B-mode + Filtered Motion Image



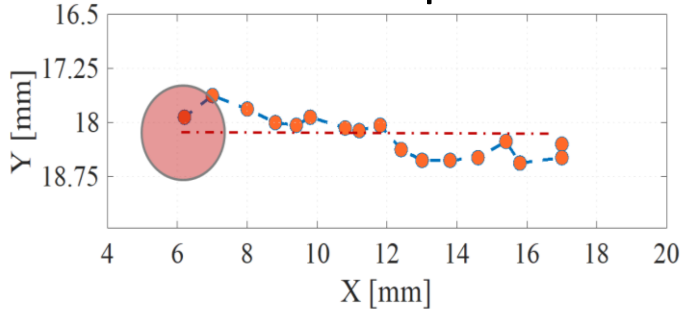
Sample side view



Dynamic tracking



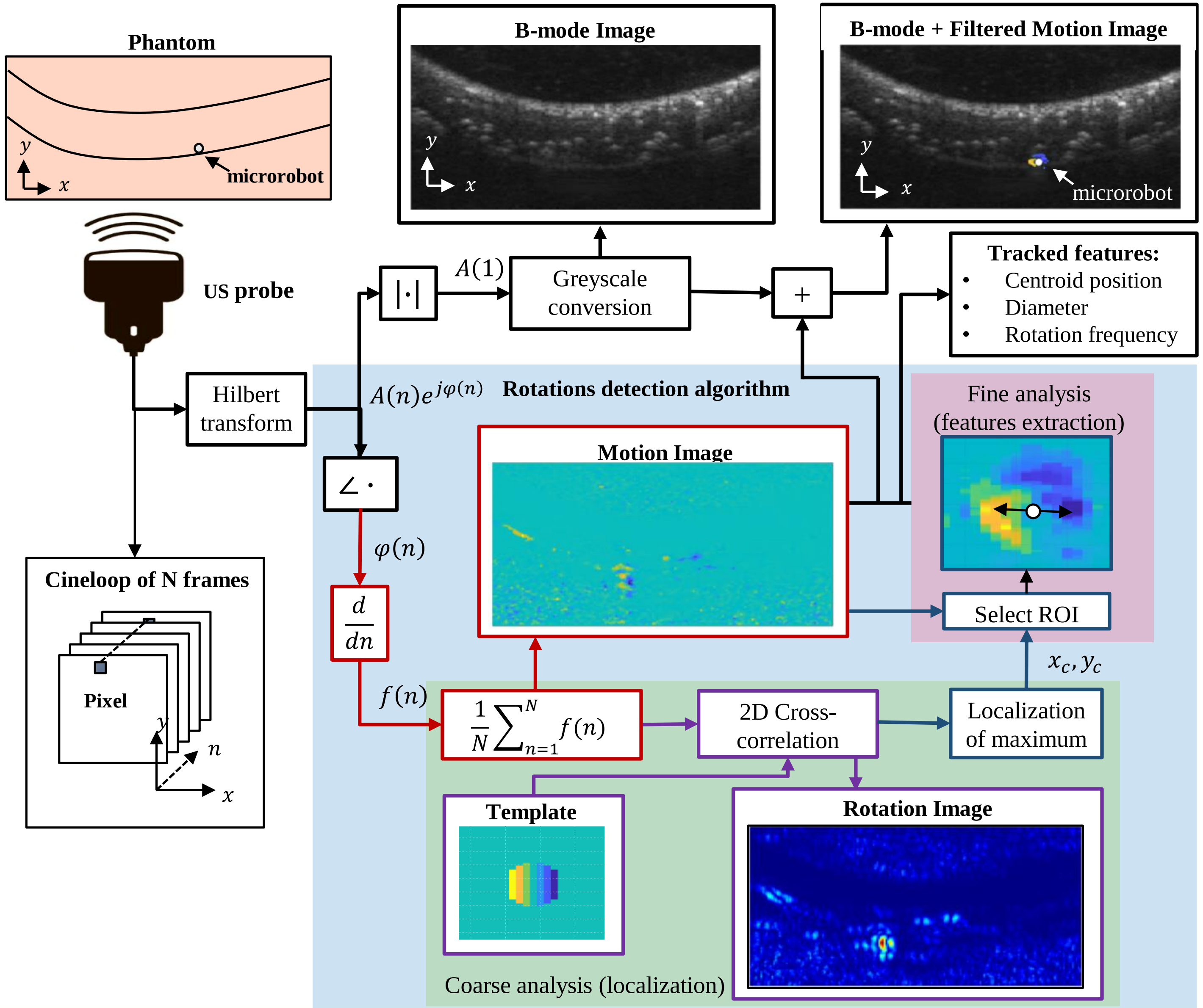
MR centroid positions



MR diameter	1 mm
MR vibration frequency	3 Hz
MR linear velocity	1 body-lenght/s
Position tracking err.	0.25 body-lenght
Tracking frame rate	1.5 fps

Pane, S., et al., *Applied Physics Letters*, (2021)

Rotations detection algorithm



1. Temporal analysis

Analyze the differential phase in the time domain

2. Block-matching

Cross-correlate the mean differential phase with a rotation template

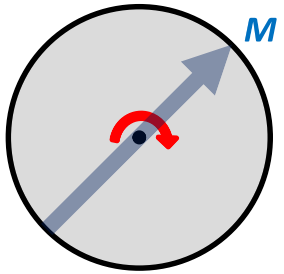
3. Derive microrobot features

Localize the maximum in the cross-correlation map and identify size of motion diagram

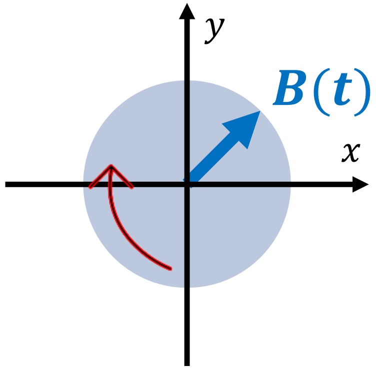
4. Overlap with B-mode

Tracking rotating microrobots in vascular phantom

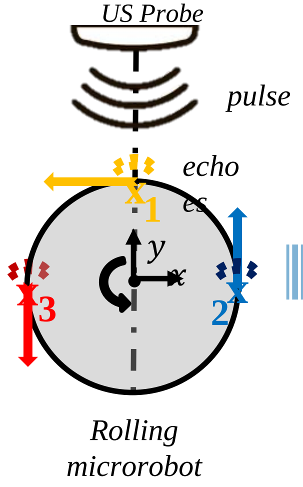
Rotating Microrobot

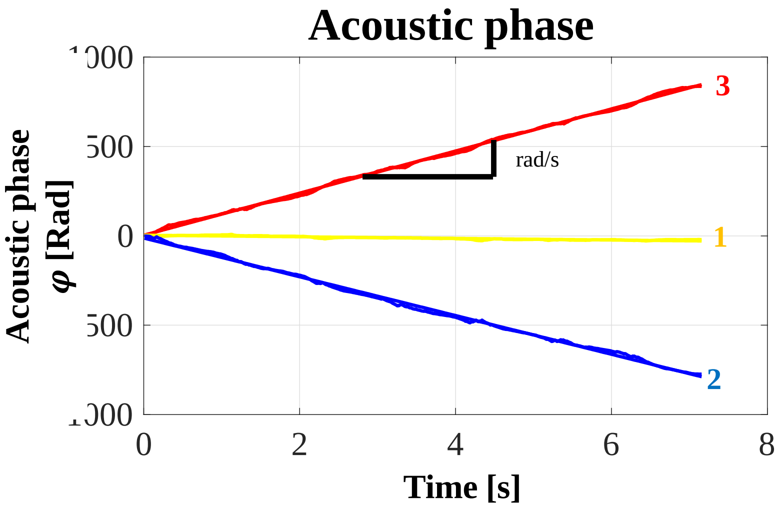


Magnetic field sequence

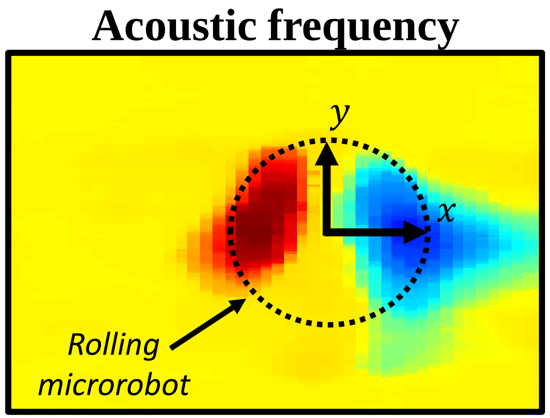


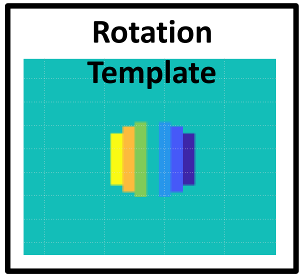
$$\begin{cases} B_x = |B| * sin(2\pi f_{rot} t) \\ B_y = |B| * cos(2\pi f_{rot} t) \end{cases}$$





$d\varphi/dt$

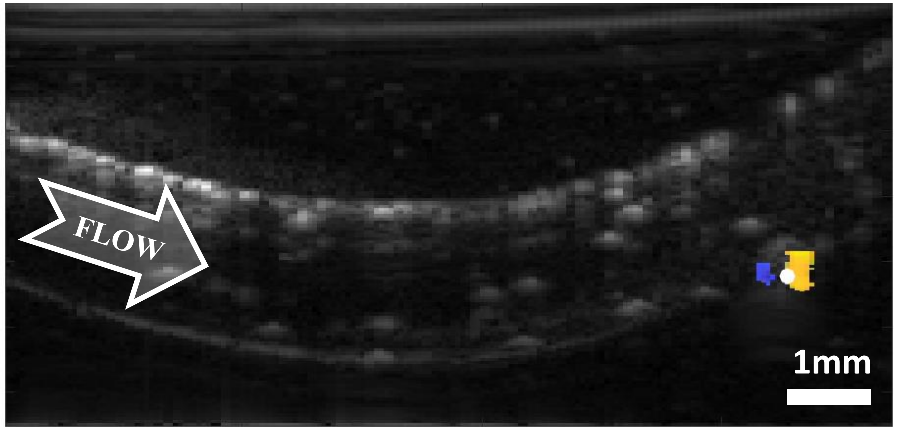




Cross-Correlation

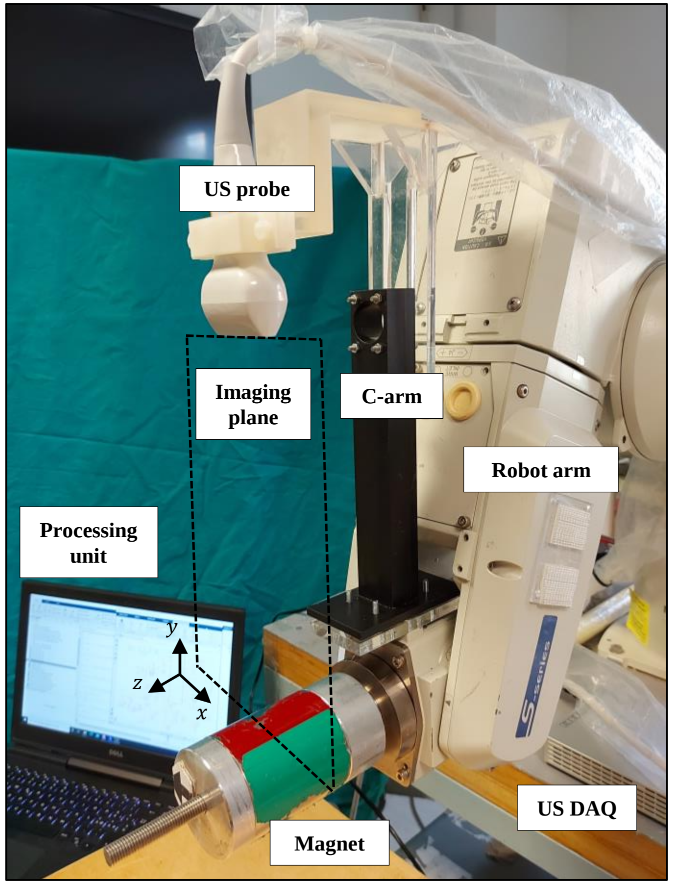
MR diameter	550 µm
MR vibration frequency	5 Hz
MR Rotation frequency	1.5 Hz
Flow rate	3 mL/s
Position tracking err.	130 µm
Tracking frame rate	3 fps

Phase-based tracking images

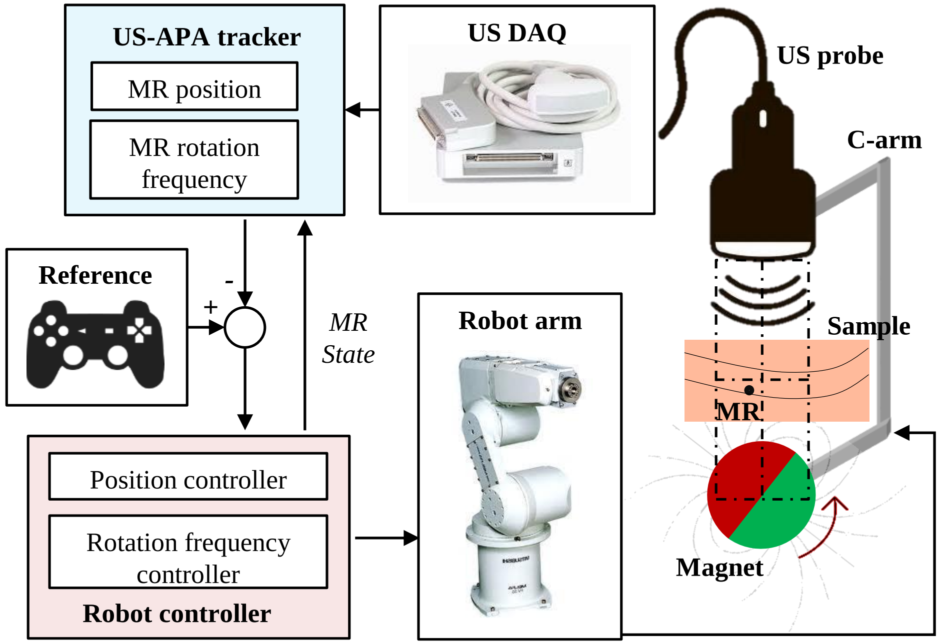


Use APA feedback for control

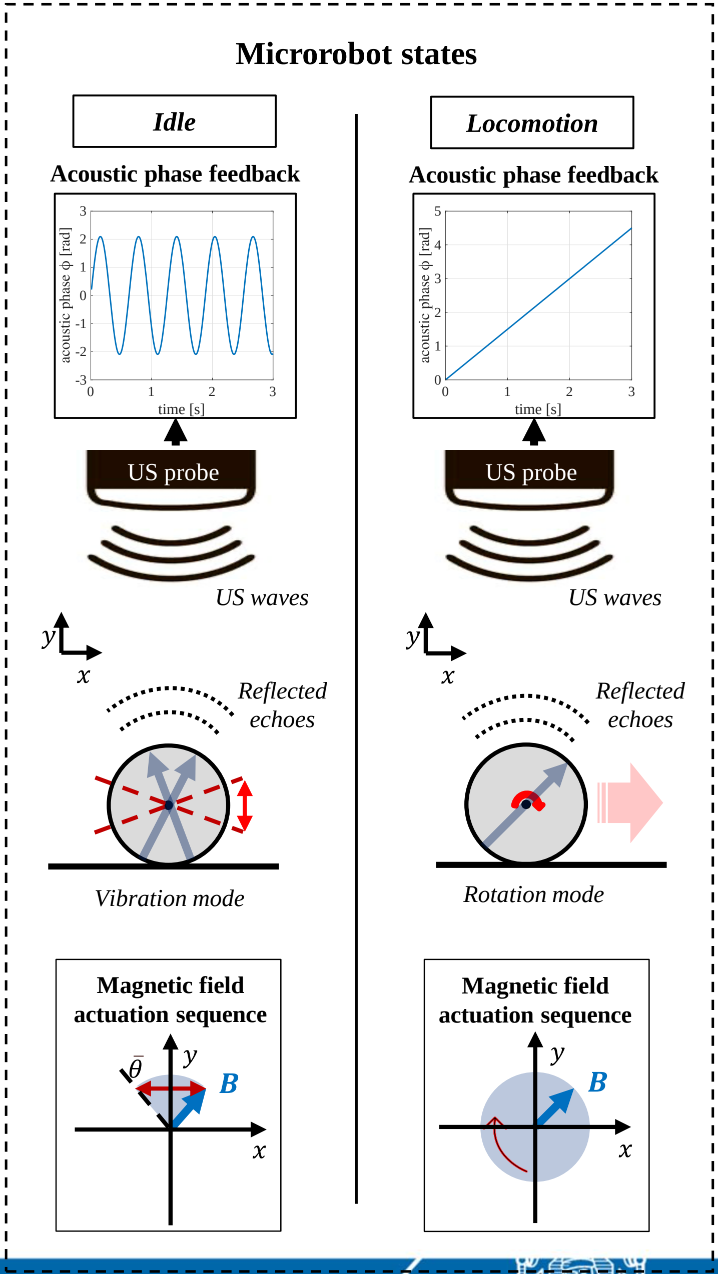
Robotic visual-servoing platform



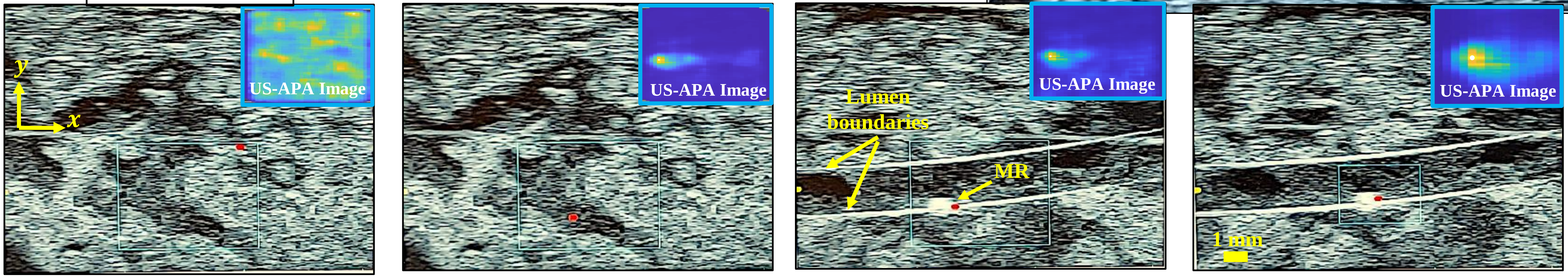
Closed-loop control architecture



User interface



Microrobot blind localization



1. System start: MR not vibrating

2. Controller start: *supervised search mode*

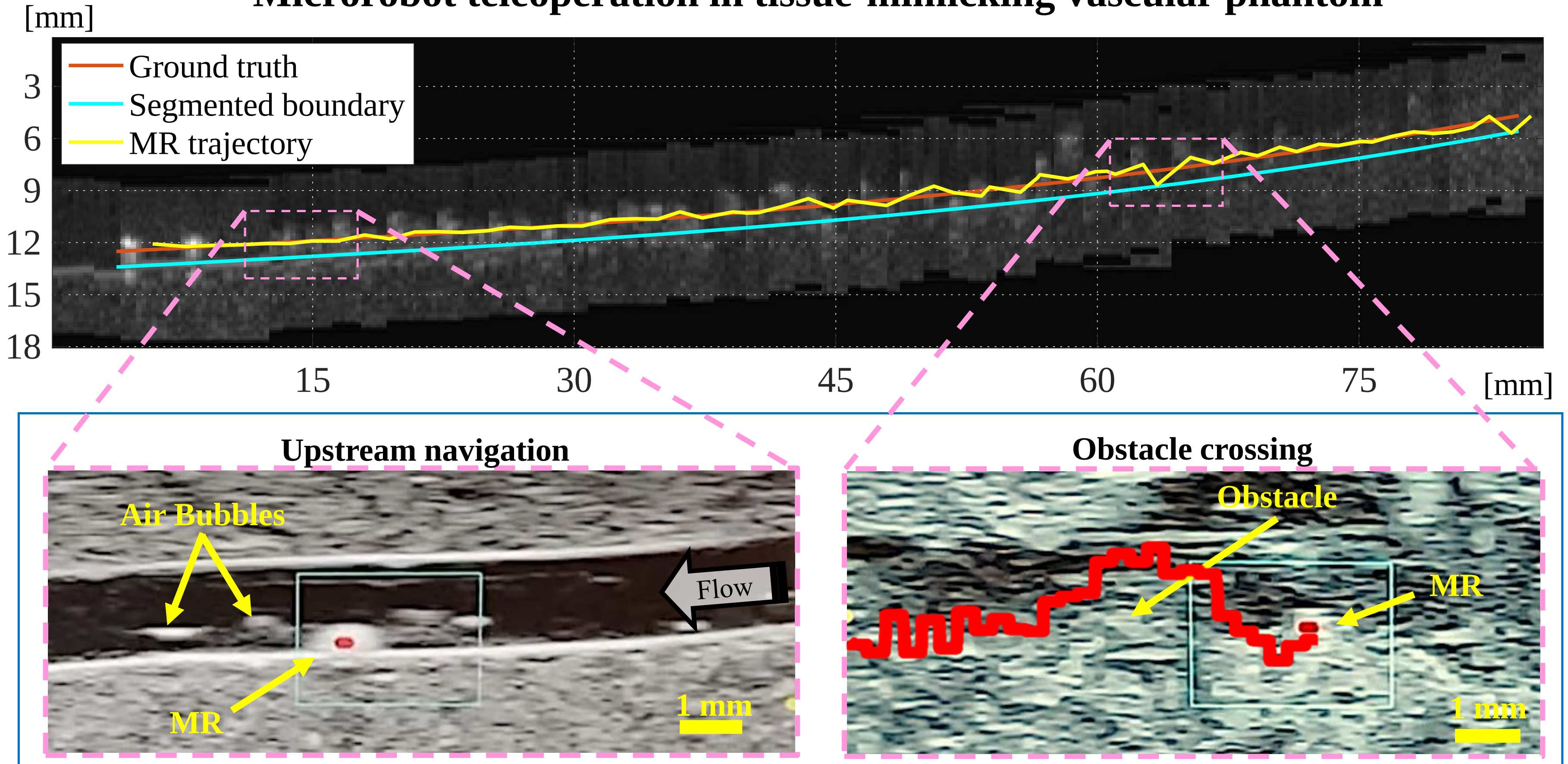
3. MR found: set optimal imaging plane

4. Teleoperation start: *visual-servoing mode*

Pane, S., et al. , *IEEE- Transactions on Robotics,* (2022).

Closed-loop control performances

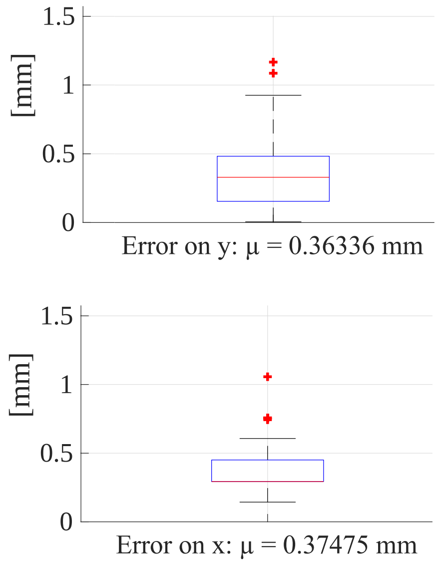
Microrobot teleoperation in tissue-mimicking vascular phantom



Robustness to disturbances from tissues and physiological flow

System performances

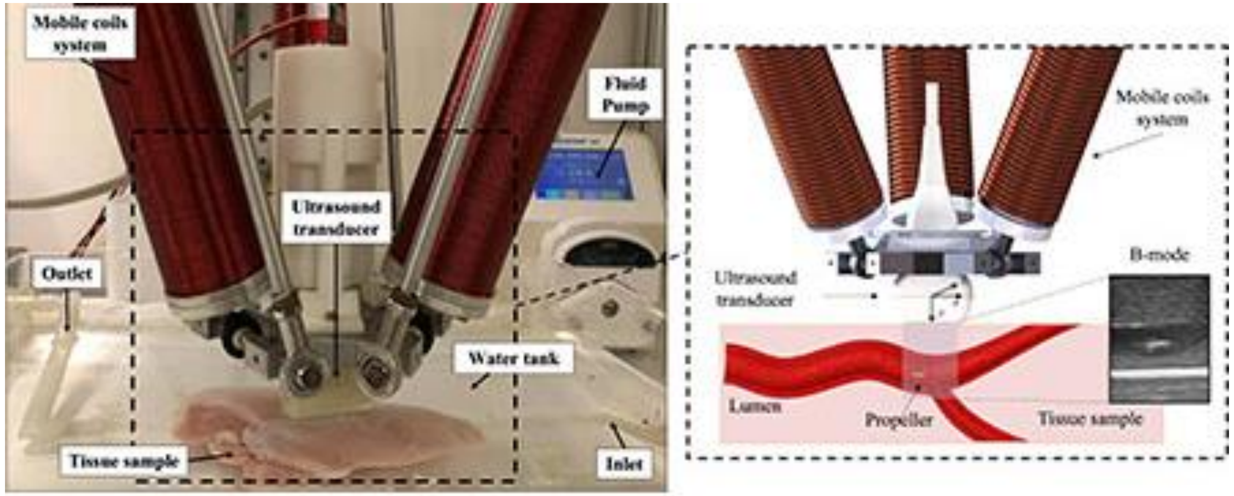
Average tracking error μ



Precision

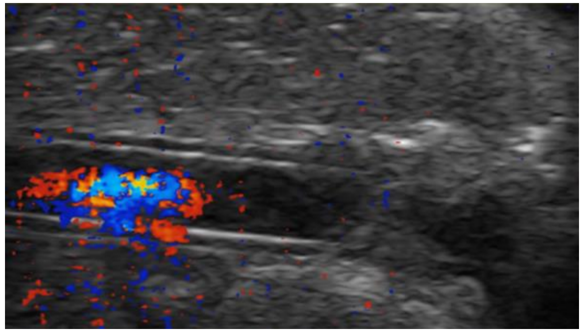
μ < 1 body-lenght

At a glance comparison between APA and Doppler

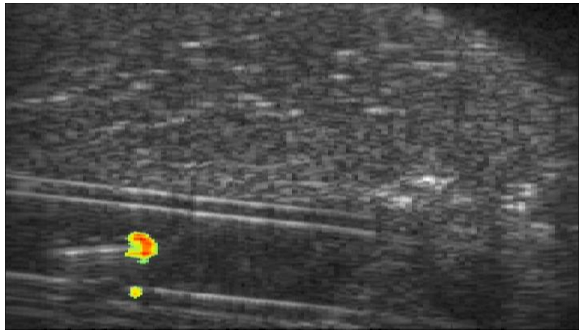


AIP Publishing **APL Bioengineering**

Static background conditions

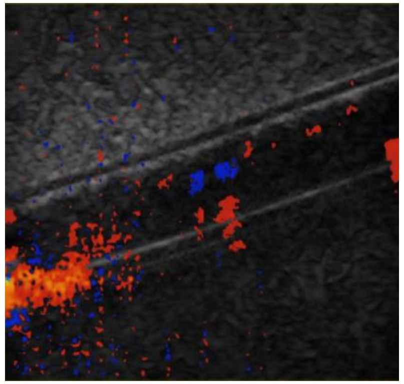


Color Doppler

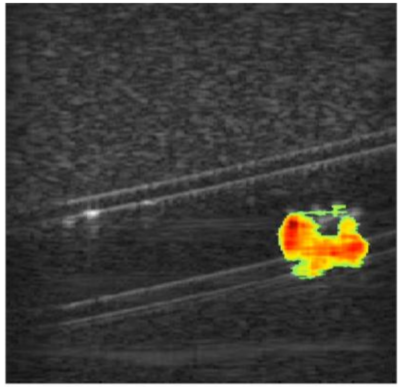


US -APA + B-mode

Disturbance: *fluid flow motion*

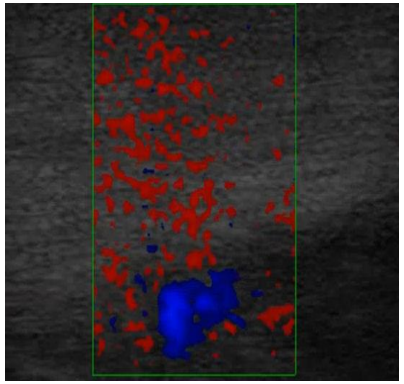


Color Doppler

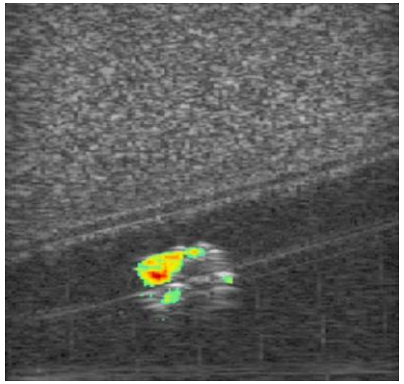


US -APA + B-mode

Disturbance: *tissue motion*

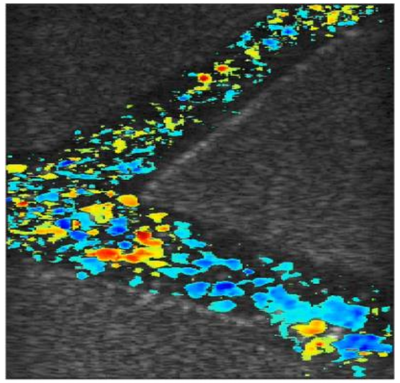


Color Doppler

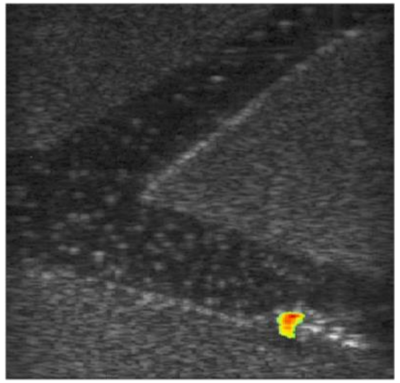


US -APA + B-mode

Disturbance: *fluid flow in bifurcation*

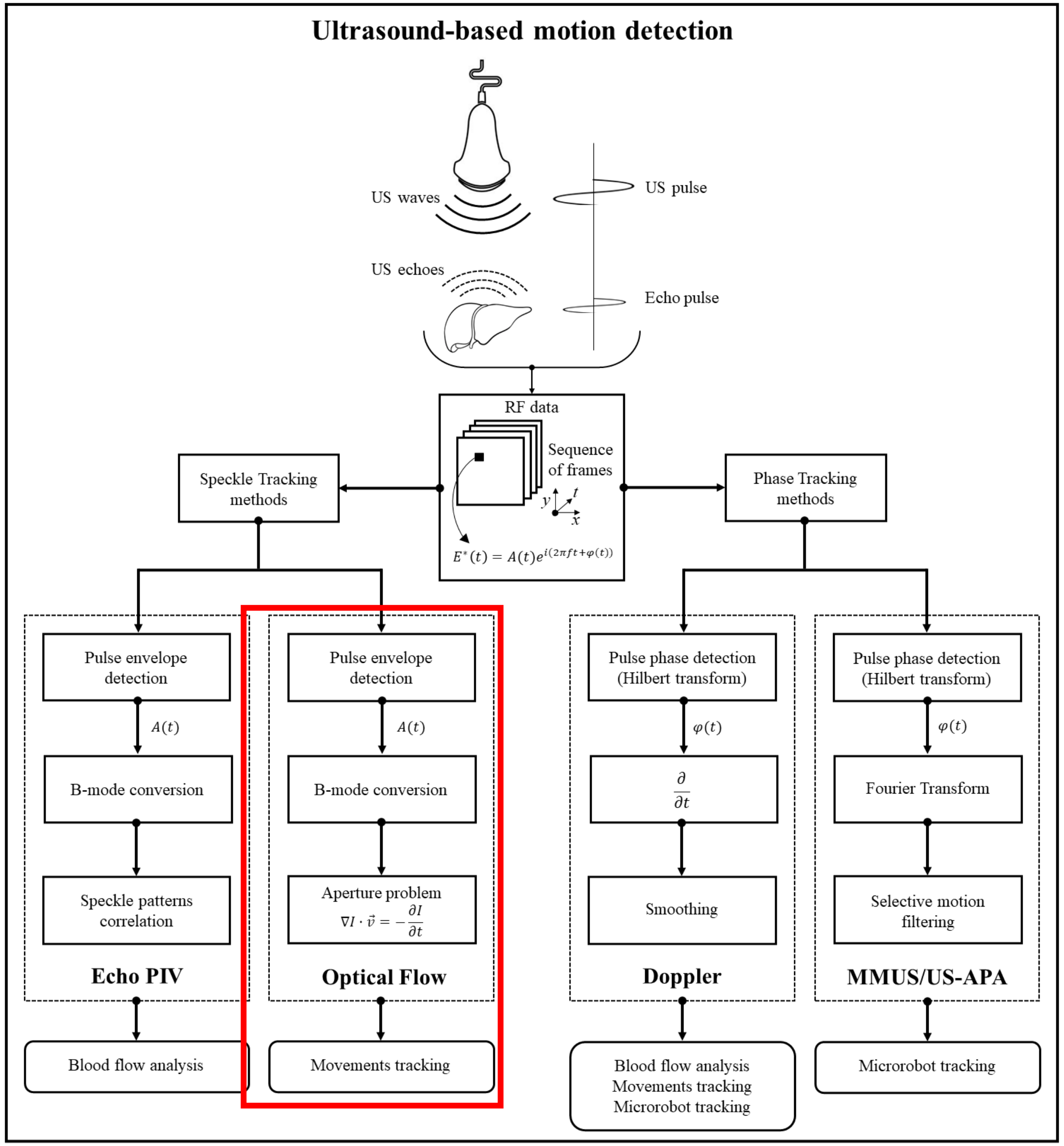


Color Doppler



US -APA + B-mode

S Pane, M Zhang, V Iacovacci, L Zhang, A Menciassi,
APL Bioengineering, (2022).



Motion detection by US imaging: Could more traditional solutions work?

APA requires specific US imaging devices (need for RF data) and low temporal performances (few Hz)

Difficult translation

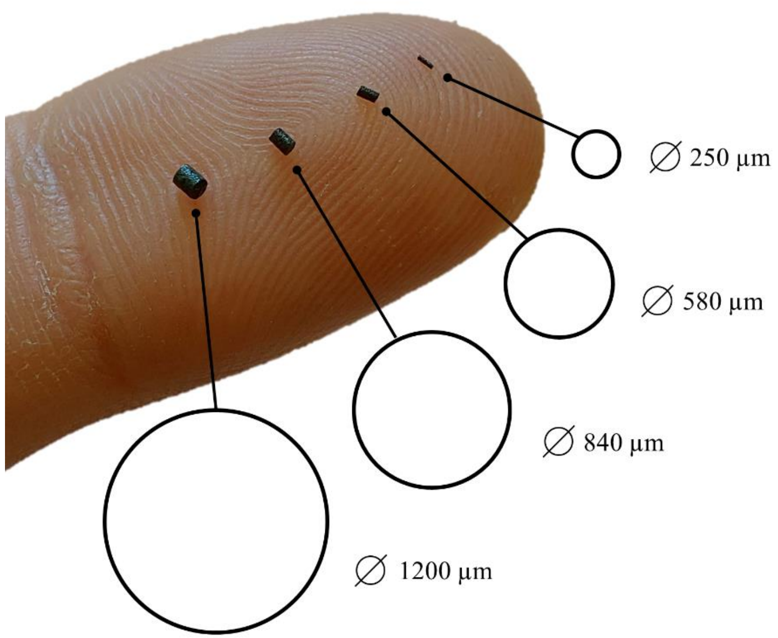
There exist other motion detection strategies with higher output rates and based on standard Bmode

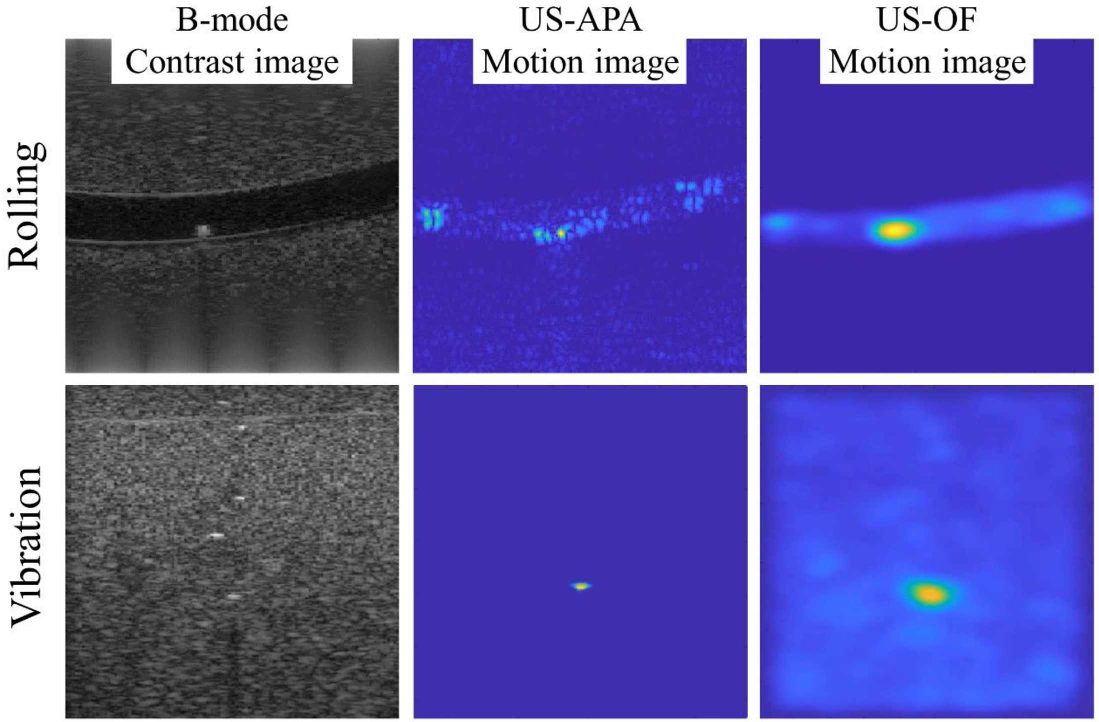
One option is OPTICAL FLOW

Comparison between APA and Optical Flow

The comparison between the two techniques was carried out considering:

- **Different microrobot dimensions (from 1200 to 250 µm in diameter)**
- **Different locomotion patterns (rolling and vibration from 5 to 1 Hz)**
- **Different environmental conditions (vascular and tissue-like)**





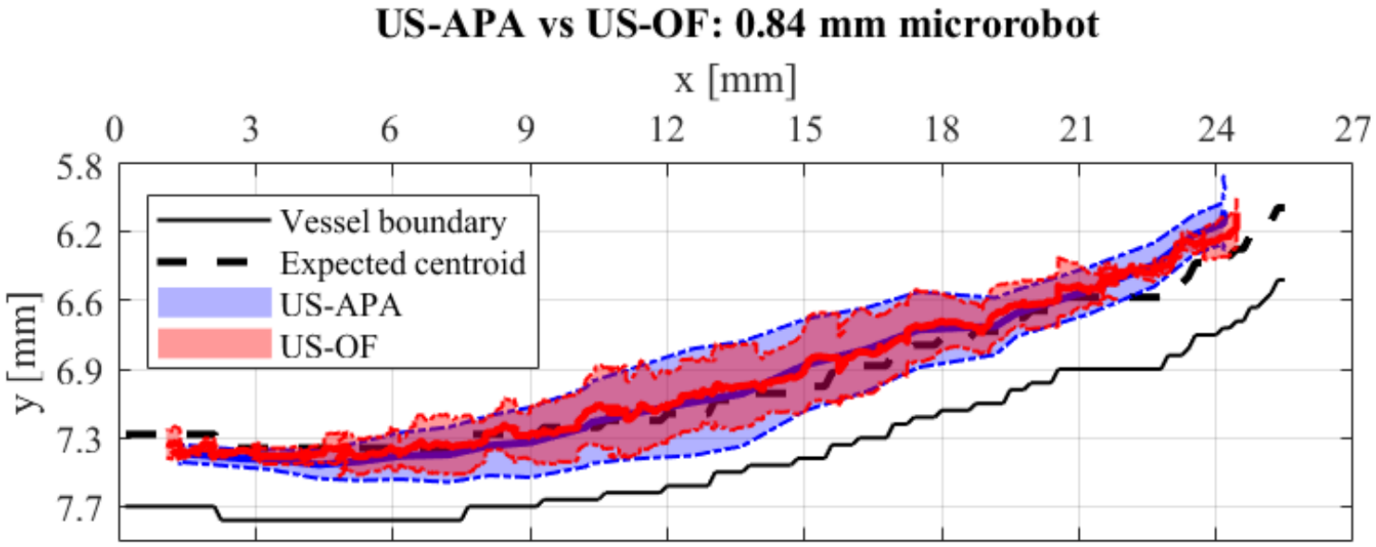
Faoro, G., et al. , *IEEE Robotics & Automation Letters,* (2024).

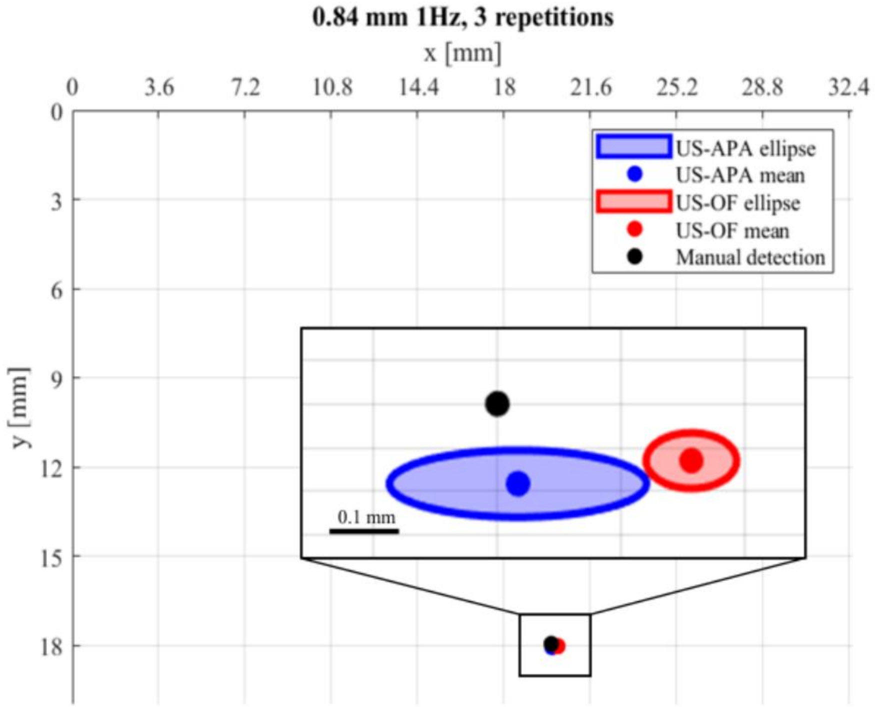
Comparison between APA and Optical Flow

Optical Flow consistently achieved submillimetric tracking accuracies in all tested conditions (error < 0.6 *body length* for rolling ~1 *body length* for vibration)

Spatial performances are comparable to US-APA with no need for RF data

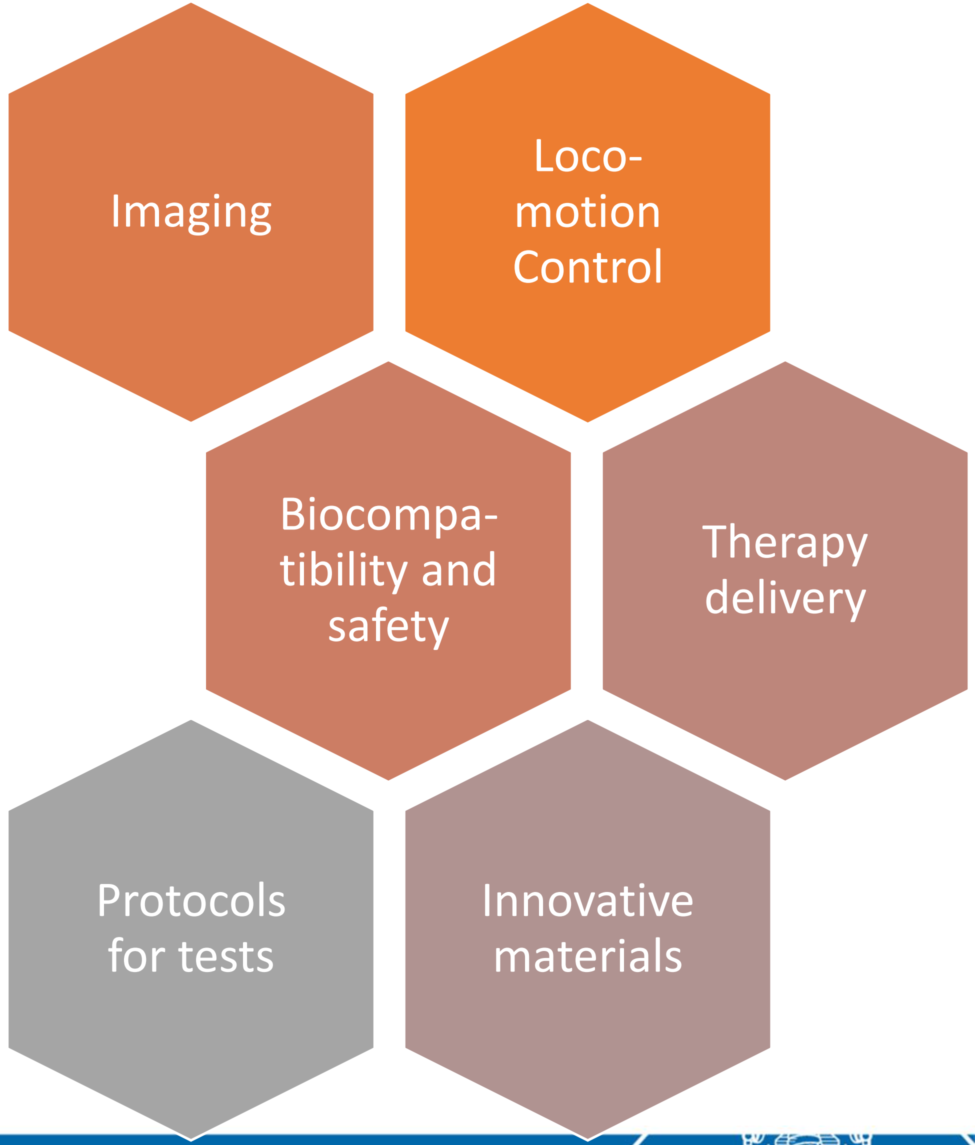
Major increase in output rate from 1-2 Hz up to 40 Hz





Conclusions

- Many challenges are still ahead, but motivations are strong!
- It is time to think about more advanced paradigms for microrobotic control, application, human interaction…
- Open research platforms and published datasets are key for developing / testing new methodologies
- Identifying the correct balance between AI methods and physical modelling in the miniature/micro domain



Thank you for your attention!

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