# Medical Robotics

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# Robots and Robotic Technologies for Interventional Radiology

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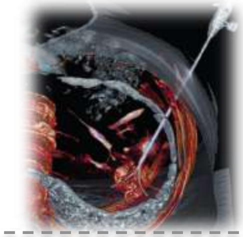
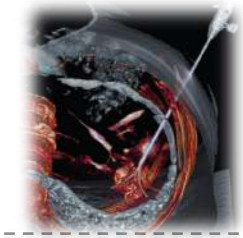
# outline



- “manually executed” interventional radiology (IR) procedures
- value added by robotic systems
- challenges in IR robotic systems design
- a (nonexhaustive) catalogue of existing systems
- open problems
- toward teleoperated needle insertion

# IR procedures



- mininimally invasive procedures: needles, probes or catheters, are used to reach the surgical target through or to deliver some kinds of therapy
  - the patient skin → percutaneous procedures
    - e.g., core biopsy of tumors, embolization, tumor ablation
  - anatomical structures → vascular procedures
    - e.g., angioplasty and stenting

- performed under the guidance of imaging systems:
  - ultrasound (US) there is a probe that admits ultrasounds signal which is reflected depending on the impedance of the tissue and it is reflected back to the probe and based on the delay, the image is reconstructed
    - mainly soft tissues and superficial anatomical structures
  - fluoroscopy (XA) x-ray imaging with a contrast medium

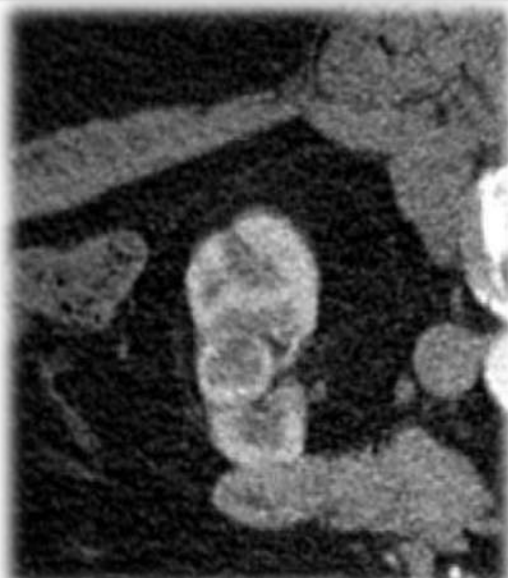
    real-time image acquisition
  - computed tomography (CT) 3D reconstruction of the part of human body that is being image through the acquisition of several slices (NO REAL-TIMEit requires elaboration of images)
  - magnetic resonance (MR) usually it is not real-time but today most modern system provide a quasi-real-time image accquisition

# percutaneous procedures

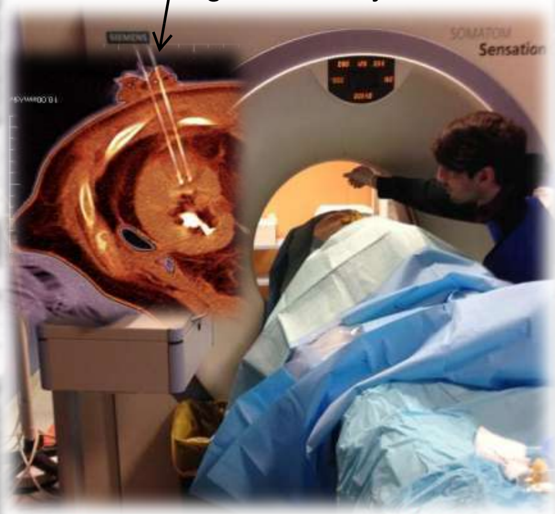
## criticalities of traditional procedure

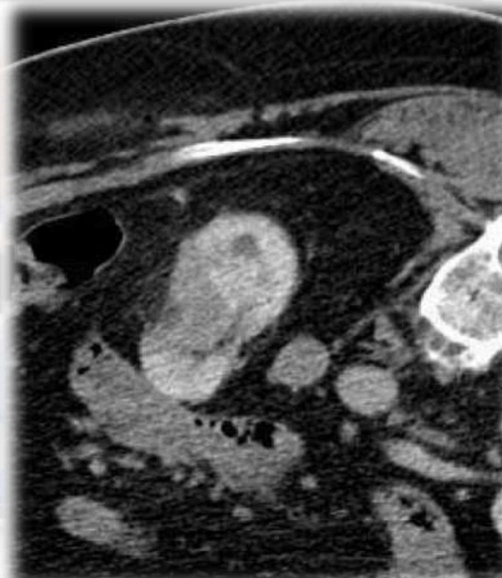
the needle is not inserted in one step but gradually

identify the target and plan the procedure → manually perform the procedure → assess results and complications



reach the target manually





| Phase risks | Phase risks | Phase risks |
|---|---|---|
| poorly planned access, inappropriate probe route, "no-touch" structures, real-time imaging visualization limitations | patient movements, operator fatigue, in-procedure complications, need for repositioning (iterative process) | subjective assessment of procedure outcome, lack of quantitative post-procedure validation |

this process is not automatical

# percutaneous procedures

## how robots can help

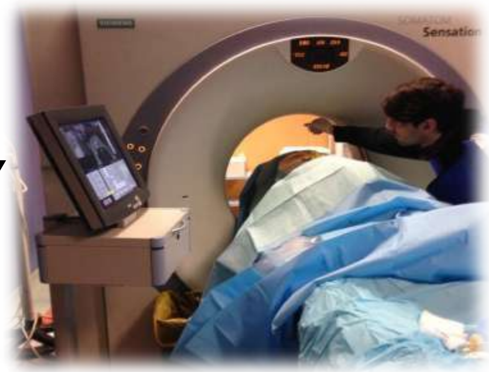
this reduces the risk and the errors related to the operator. The problem is that there are some system (ex ROBIO) to which miss the flexibility and sensitivity (i.e. intelligence)

the setup of these system is more expensive in terms of time, organization and economic

we want to combine the flexibility and intelligence of the human operator with the aspect of accuracy, reproducibility and also the possibility to add some features to help the operator

today imaging guided interventions → today robotics-based alternatives → tomorrow imaging guided interventions

CT scan



manipulator at the patient side which performs the needle insertion in the patient. It is not completely authomatic because there is an operator in the operating room that guiding the needle under the guidance of images and also using an haptic interface to feel the forces that are exchanged between the needle or probe and the tissue

| performed by human operators | mainly guidance systems | automated or hybrid human-robot procedures |
|---|---|---|
| + operator experience factor<br>+ high flexibility/adaptability<br>+ high sensibility/discernibility<br><br>- operator training and costs<br>- subjective result evaluation<br>- mental stress<br>- exposure to ionizing radiation | + reduced operator-related costs and risks<br>+ high reproducibility<br>+ reduced stress-related errors<br><br>- less flexibility<br>- non-Intelligent Platforms<br>- high development costs | + reliability, reproducibility, procedure monitoring and optimization<br>+ post-operative data analysis<br>+ reduced training and personnel costs and risks<br>+ improved comfort for operators<br>+ remote control when trained operator not available<br>+ more procedures per session<br>+ less complications |

# introduction

## technical challenges

need of

- robot kinematic architectures
  - fitting the workspace constrained by the imaging device
  - complying with the fixed point of access to the patient body
- sensors and actuators
  - compatible with the imaging modality
- modeling and control methodologies for
  - tool motion planning and steering
  - compensation of physiological motions and tissue deformation
  - constrained planning and motion

probe and needle deformation can due to a deviation from the plan

# introduction

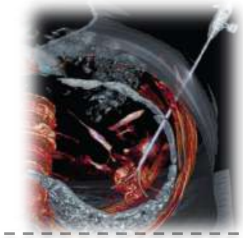
## technical challenges (cont’d)

- pre- and intra-operative image fusion
- force sensing and rendering

can compromise sometimes transparency but can also improve other kind of properties in particular stability. Stability and transparency are in contrast each other

- user interfaces providing
  - haptic and visual feedback
  - augmented information

which kind of feedback



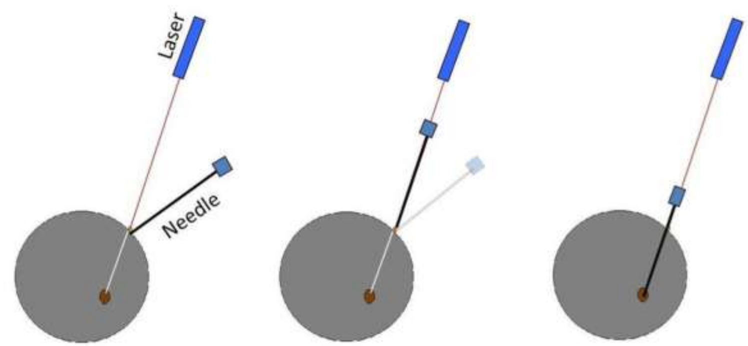
- commercial devices

**SimplyCT** (Neorad)

this navigation system helps the operator to allign the needle with the projected laser ray that points to the internal target

how is obtain this direction that the laser follows?


laser guide




Patient Cross Section with lesion (brown)

Laser at hub of needle

Needle progression along laser light

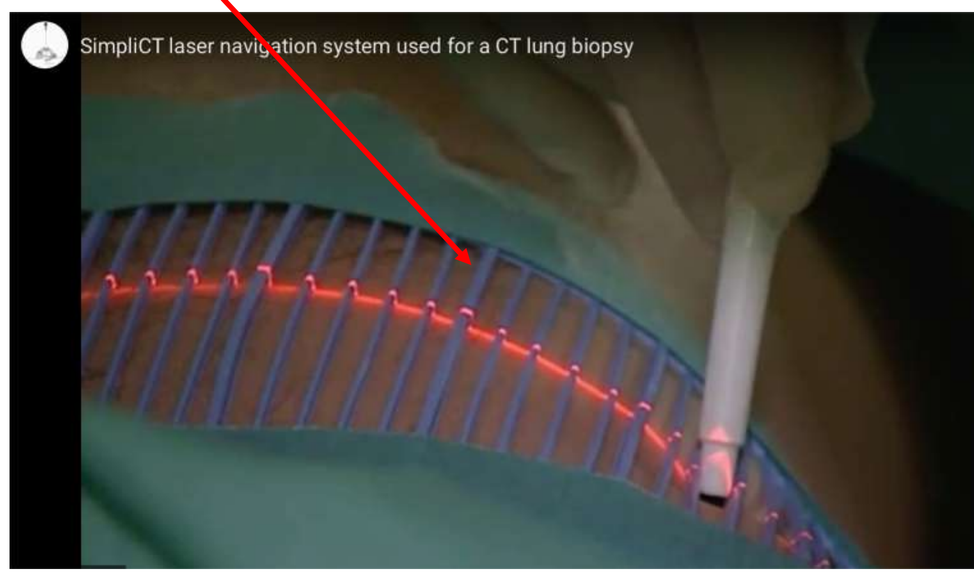
## SimplyCT

planning phase (relies on previous laser/CT scan calibration)

the operator plans the needl trajectory to reach this target and since this point, visible in the CT scan, and the guided grid is on the patient, this point is directly marked on the patient skin with a special marker like a pen

guiding grid

this is visible in the CT scan

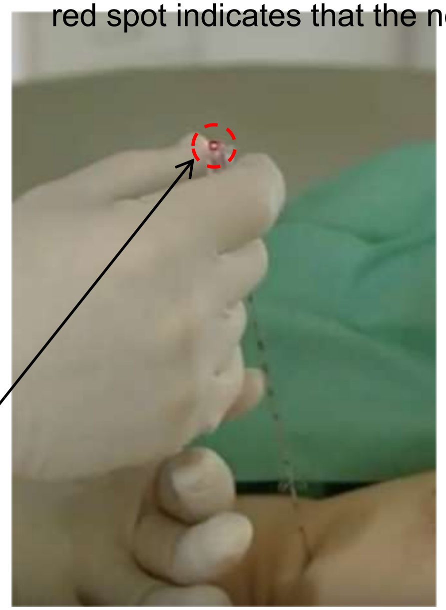



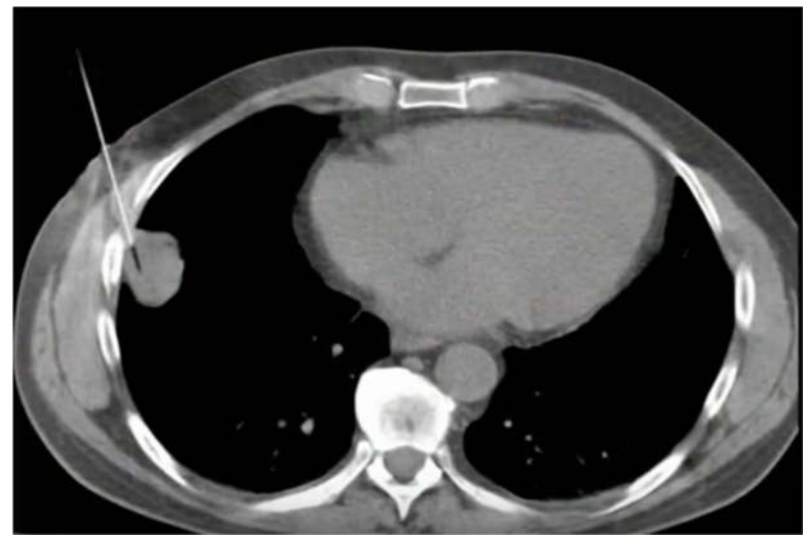
from one reference system to another. If we know where this pointt is in the reference frame of the imaging system and by using the calibration between the imaging system and the laser, we can express the coordinates of this point in the reference frame of the laser. The laser can points directly to the internal target

**SimplyCT**

alignment, insertion, verification → sampling

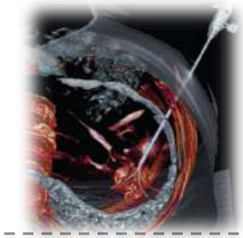
red spot indicates that the needle is alligned with the laser bean





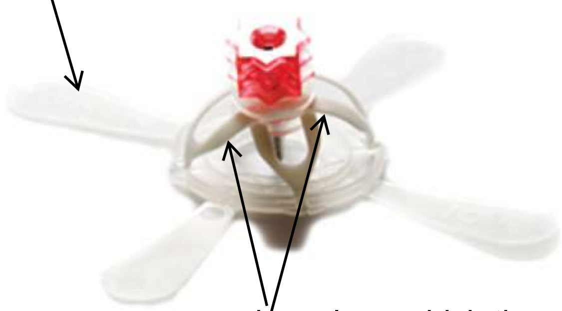
the operator alligns the needle with this laser bean

further verification by taking again another CT scan



- commercial devices mainly passive → not robot

### **SeeStar** (Apriomed)




rotating arches of half spheres for orbital needle positioning

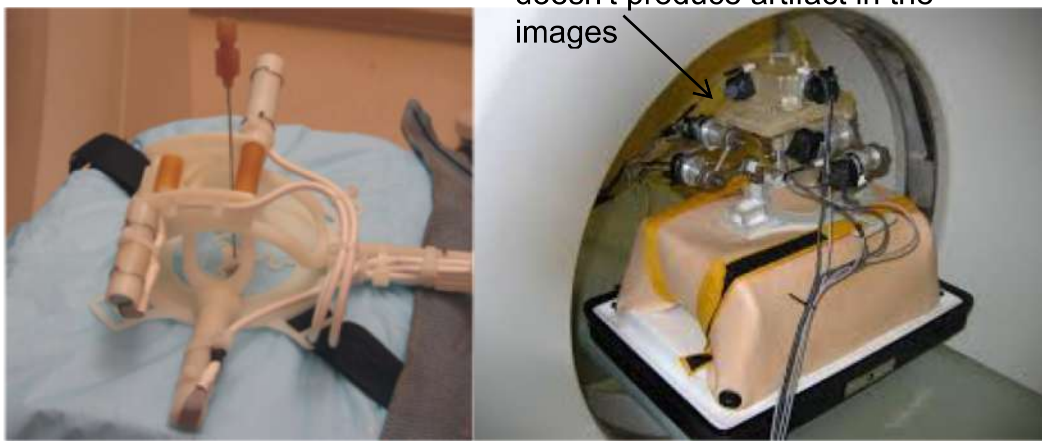
**note**: both for SimplyCT and Seestar the needle is oriented and inserted manually

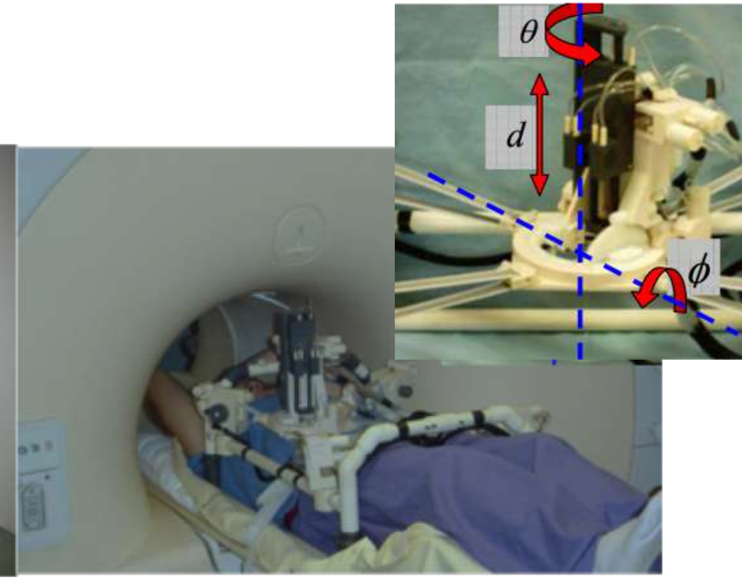
# percutaneous procedures

## patient-mounted systems

- research prototypes

constructed to go in the CT scan. It doesn't produce artifact in the images






**Robopsy**
- orbital positioning
- 2 stepper motors for insertion of the needle
- manual alignment

but the isertion is authomatical through stepper motors

**CT-bot**
- 5-dof, parallel architecture
- ultrasonic piezo motors
- fiducials for registration
- 2-dof steering device for needle spinning and insertion

**Light Puncture Robot (LPR)**
- MR-compatible
- 2-dof, pneumatic actuators
- frame fixed to the scanner table
- fiducials for registration
- rapid needle insertion (9cm/s) and release

for insertion and orientation of the needl

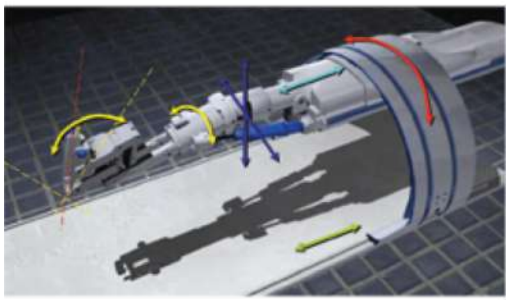
# percutaneous procedures

## gantry/floor-mounted systems

- commercial devices

it provides a guidance for the needl

higher degree of accuracy



**INNOMOTION**

- one of the first MR-compatible, CE cleared
- 6-dof, pneumatic motors 6 motors
- fornt-end accomodates coaxial probes (cannulae, laser probes, endoscopes)
- no longer commercialized

**Soteria**

- MR-guided prostate biopsiy
- 5-dof hybrid parallel-serial architecture
- automatic planning and motion execution

**iSYS1**

- CT and XA guide
- 2-dof orienting the needle guide
- passive positioning arm
- planning software
- manual insertion

**ROBIO**

- CT/PET-CT guide
- 5-dof
- floor-mounted
- image-based registration
- manual insertion

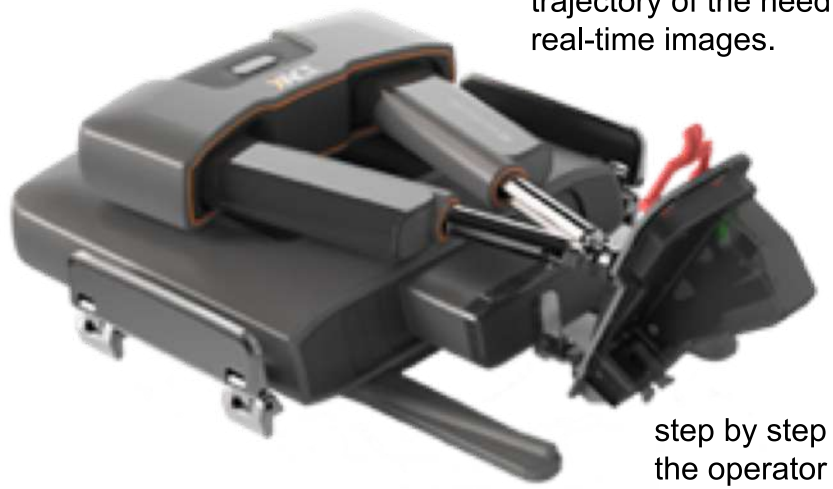
# percutaneous procedures

## gantry/floor-mounted systems

- a very recently commercialized system

no forces sensing

the insertion is authomatical. The operator plans the trajectory of the needle based of preoperative and real-time images.



step by step operation that can be corrected by the operator at a discrete time

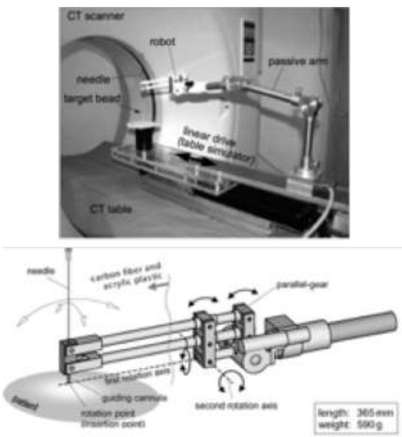
https://www.youtube.com/watch?v=3eJCBAUcIMQ

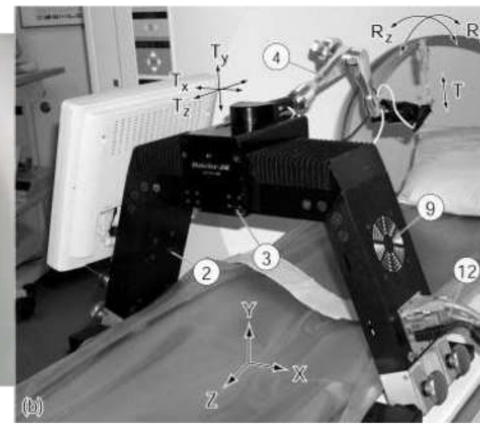
# percutaneous procedures

## gantry/floor-mounted systems

- research prototypes

the main meterial challenge is the compatibility with high magnetic field





**Siemens**

- XA guide
- 2-dof RCM + a needle guide
- controlled by joystick or through visual servoing

**B-Rob**

precursor of iSYS

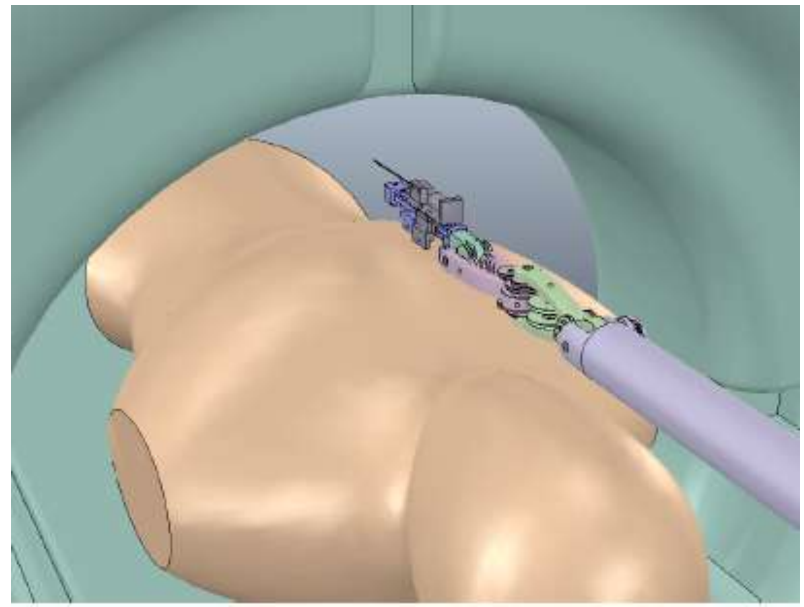
**AcuBot**

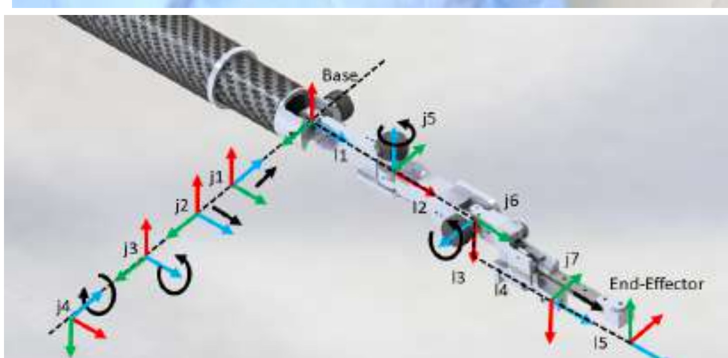
- manual positioning to the entry point relying on the CT laser
- automatic orientation through the RCM module
- registration by alignment with the CT laser

**MrBot**

- MR-guided
- 6-dof, pneumatic stepper motors
- transiperineal access to the prostate for biopsy, thermal ablation, brachytherapy
- registration markers

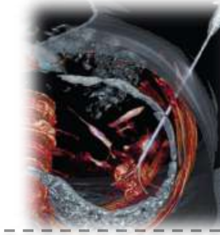
- an open-access CT-compatible prototype





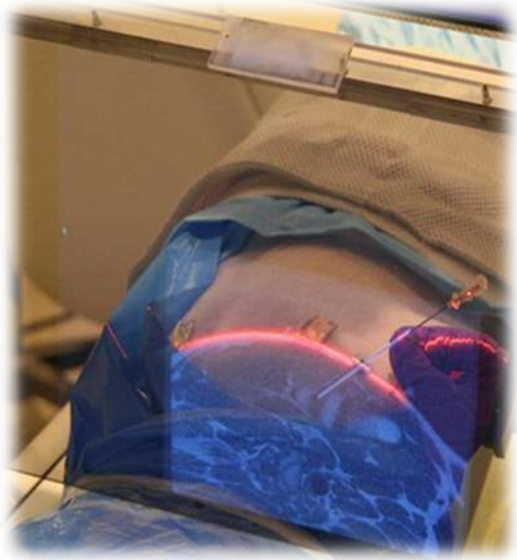

- 7-dof
- belt/cable driven
- user interface for remote control
- V-REP simulator

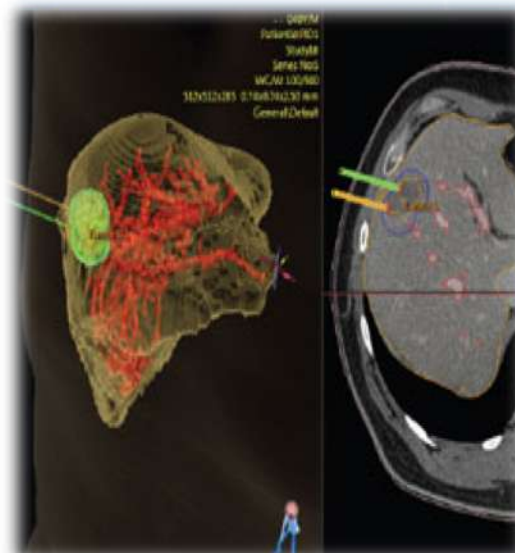
# percutaneous procedures



## summing up: limitations of current systems

**semi-autonomous positioning devices** → **advanced guidance technologies** → **advanced image processing**





| | | |
|---|---|---|
| Limitations: rigid, non-intelligent positioning devices, real-time control of insertion not available, bulky and difficult to position | Limitations: require image registration or patient sensor, no real-time control, patient movement | Limitations: limited to post-procedure phase, not routinely used to modify procedure outcome |

# percutaneous procedures

## summing up: challenges of tomorrow's interventions

fully autonomous positioning devices → remote, real-time haptic control → advanced procedure monitoring


**Challenge:** advanced robotic arm technology and control methodologies for safe physical interaction with patients and staff

**Challenge:** integrated haptic controller with extra-fine force feedback for robot teleoperation by medical personnel

real-time imaging + prediction models

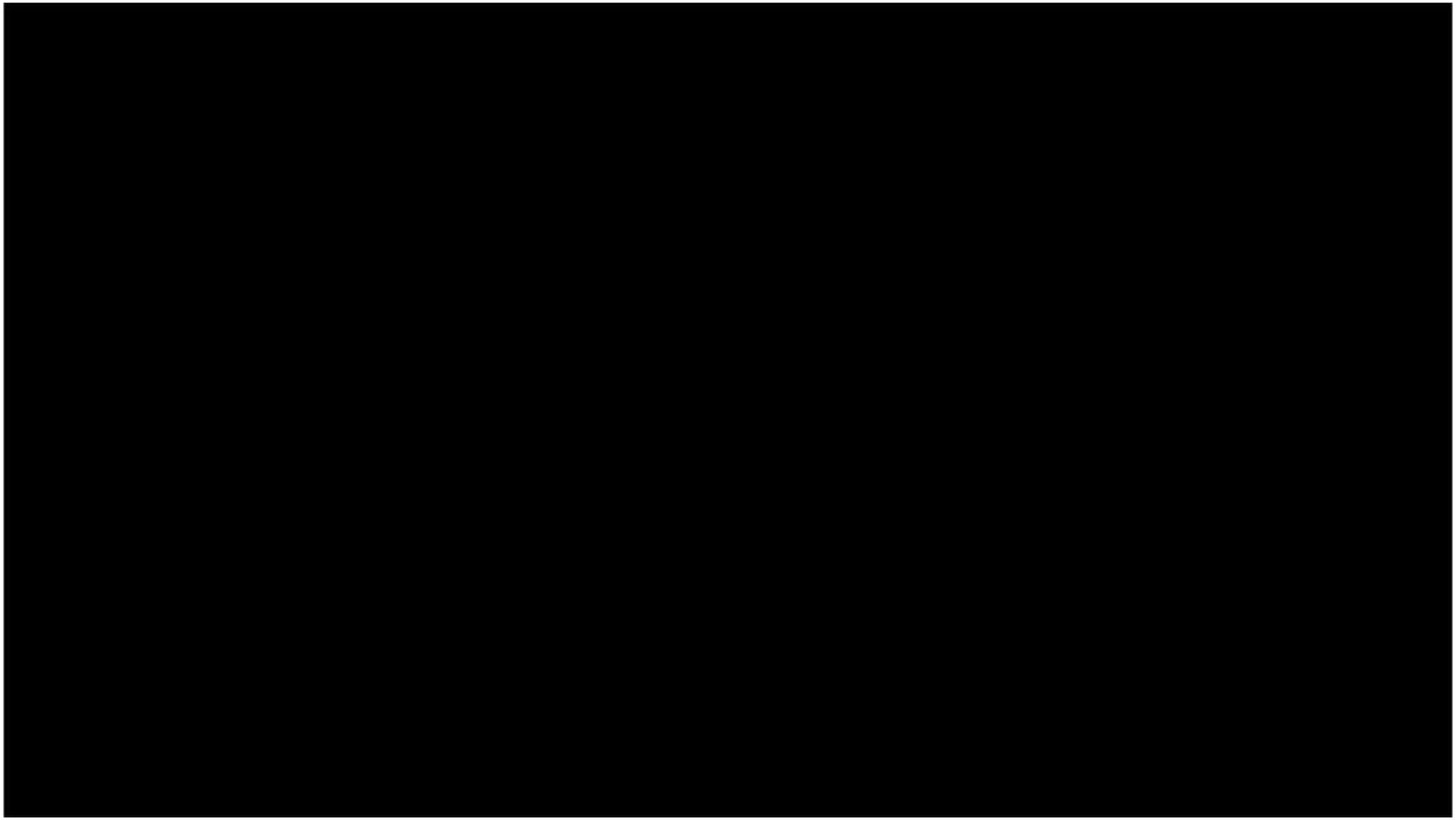
**Challenge:** high-speed communication between scanner and control software, real-time 3D procedure adaptation

# vascular procedures

the flexible probe is guided inside the body through haptic interface. The couple is between the haptic handle and the tip of the probe

## the Sensei X2 system (similar to Magellan)

system to introducing a flexible catheter inside the human body to reach the heart starting from the femoral arteria (for ex. used for treatment of aritmia). The procedure is performed under the guidance of a c arm used for fluoroscopy.



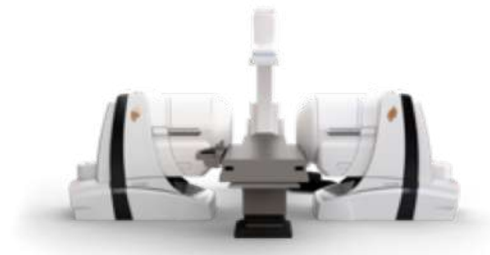
# vascular procedures

## commercial systems

**Magellan** (Hansens)

**CorPath**
- similar to Magellan and SenseiX
- used for coronary and peripheral vascular interventions


**Amigo**
- closer to traditional steering methods (knobs and buttons)
- no possibility of haptic feedback

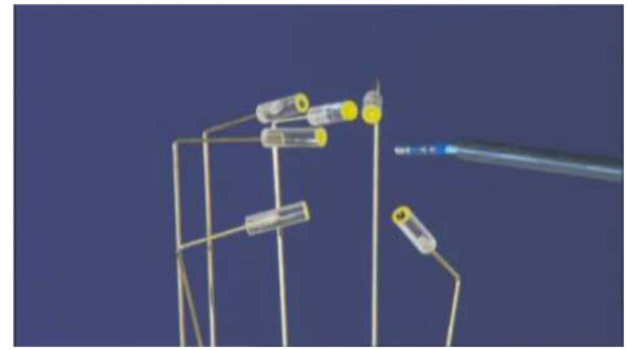


**Niobe** (Stereotaxis Inc.)
- XA guide
- electrophysiology procedures
- remote magnetic catheter control: uniform magnetic field generated by arms motion for omnidirectional steering of a catheter tip

# vascular procedures

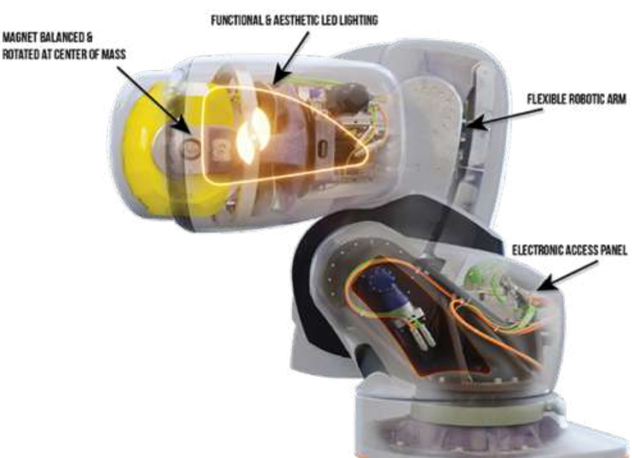
## commercial systems

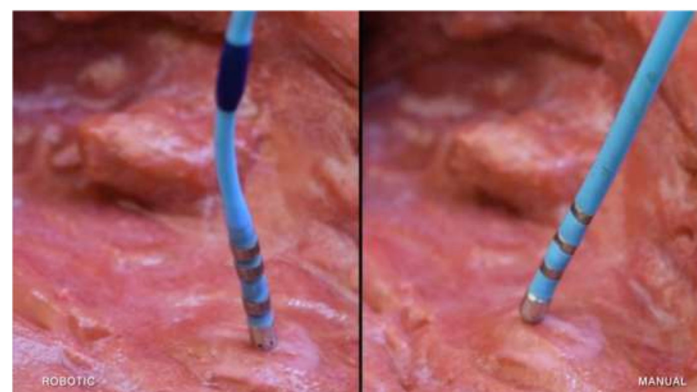
accuracy



softness

stability




**Genesis** (Stereotaxis Inc.)

- 70-80% faster than Niobe
- reduced size
- increased workspace

although the illustrated systems have changed the standard of care in both percutaneous and intravascular procedures, challenging aspects remain, like e.g.,

- smaller, lighter, intrinsicly safe robots
- control techniques for safe human-robot interaction
- prediction models
- real-time (re)planning
- force sensing at the needle tip and haptic rendering
- shape and force sensing on the whole catheter body
- compensation of cardiac heart motion
- transmission of sufficient force to execute the treatment