Medical Robotics

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Introduction to Surgical Robotics

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Outline

- what is a robot?
- robots in health care: a note on terminology
- a short historical perspective on medical robotics
- surgical functions and robots
- what's next in surgical robotics?

There is some confusion between robot and a machine that is capable of some reasoning(ARTIFICIAL INTELLIGENCE). In many examples robots is able to interact but not in phisical way (ROBOTICS).

what is a robot?

the surgeon point of view

"The Robot is just a Million Dollar Needle Holder"

definition by Jim Moser MD, Robotic Surgeon@BIDMC

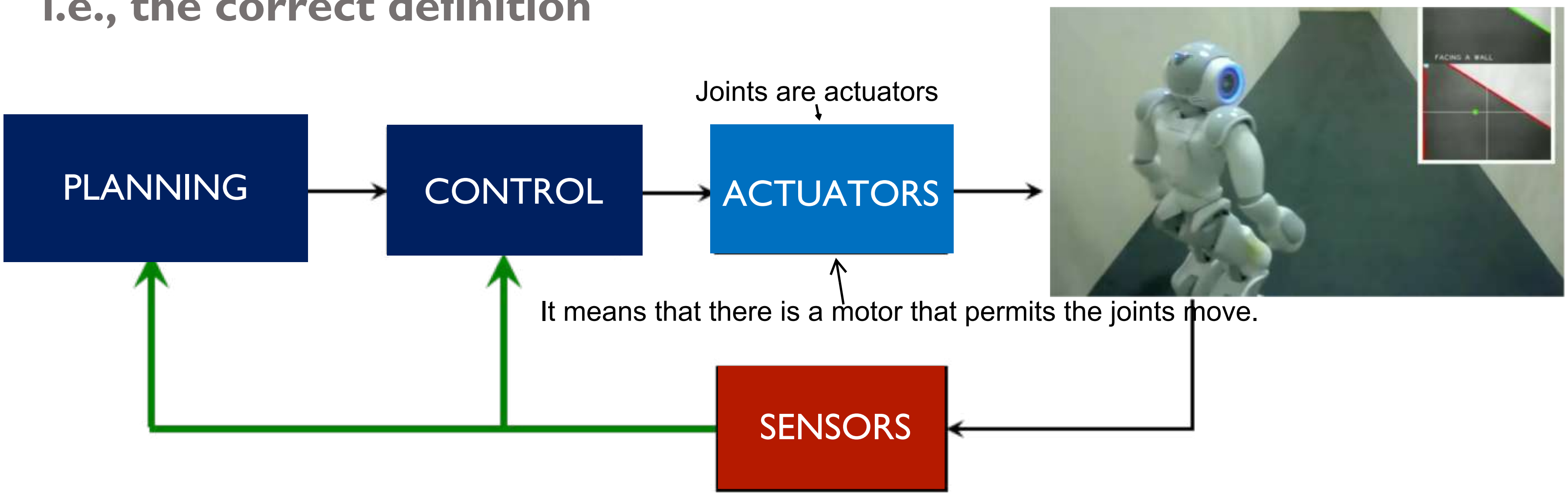
is this a correct definition?

A robot is an object, in SLIDE 4 it's a small human robot, made by mechanical part that we called LINKS, and these links are joint together by articulations.

what the roboticists mean by 'robot'

i.e., the correct definition

Joints are actuators



It means that there is a motor that permits the joints move.

Some sensors perceive from the internal of the robot(where are the joints), others from the external

"intelligent connection between perception and action"

We talk about electromechanical system.

Balancing is a problem. The second thing is walking. Actuator move the robot but to do this we need to perceives the environment around (SENSORS).

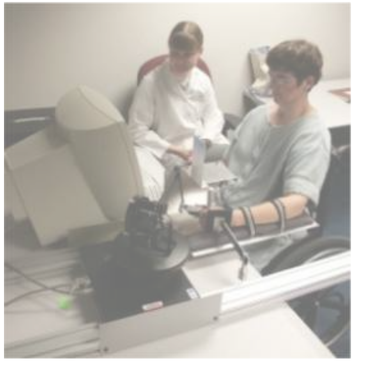
generalized use of feedback provided by sensors

(involves mechanics, automatic control, computer science, artificial intelligence,…)

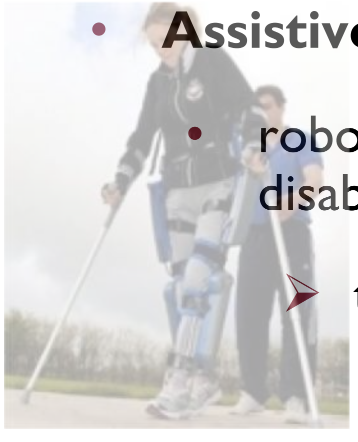
In medical robotics there is almost always the human interaction.

a note on terminology

- **Medical Robotics**
  - robotics for surgery, exploration, diagnosis, therapy…
    - ➢ tools for clinicians/surgeons

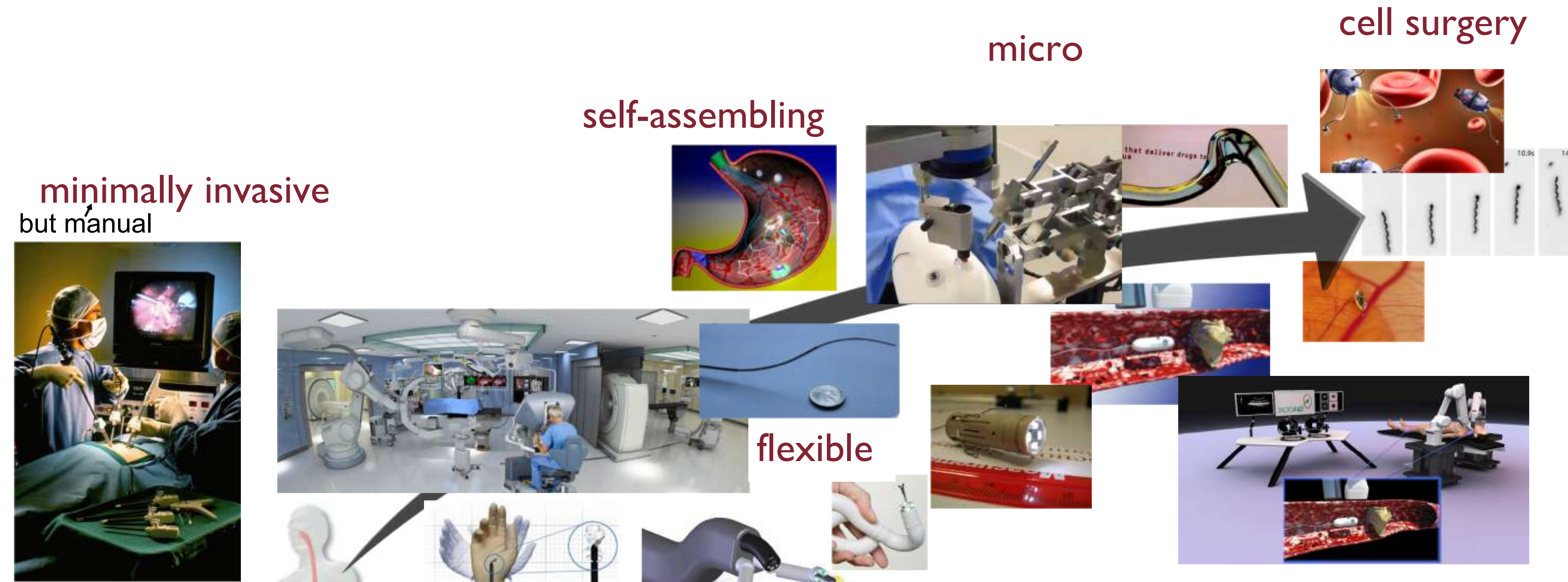


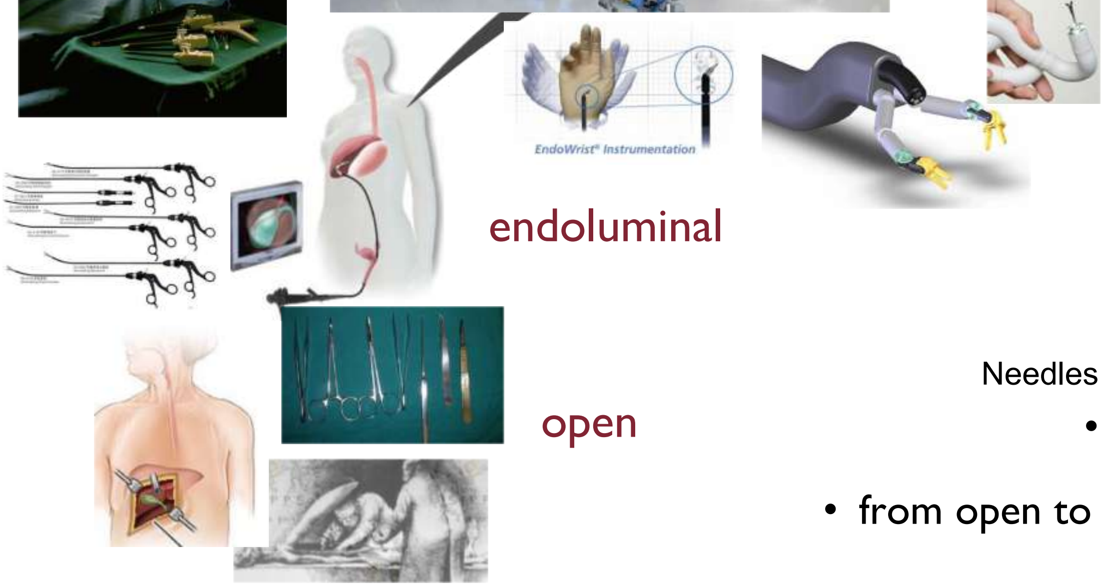
- **Rehabilitation robotics**
  - robots and mechatronic tools for therapy, training…
    - ➢ tools for therapists



- **Assistive technologies**
  - robots and machines that improve the quality of life of elderly and disablee people mainly by increasing personal autonomy
    - ➢ tools for patients

the evolution of surgery





flexible
- from rigid to soft
- from macro to micro

Needles have no dexterity
- with increasing dexterity and autonomy
- from open to minimally invasive to ingestible/injectable

surgical robotics: a historical perspective

Hundreds of patients

Installed bases > 850

New York - Strasbourg

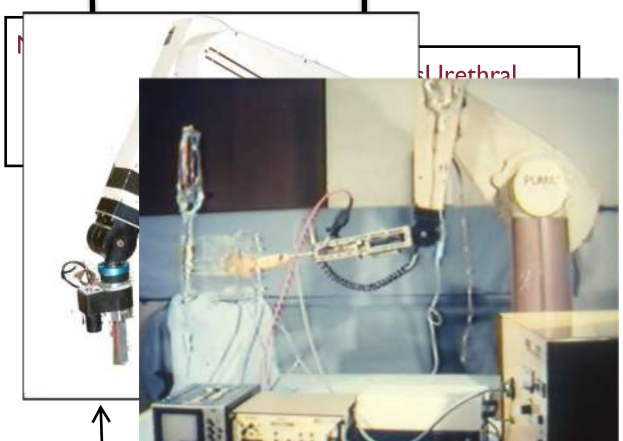
First NOTES procedure
(IRCAD)

1985 1989 1992 1994 1997 1998 2001 2003 2007

Urethral

(Cc

(C



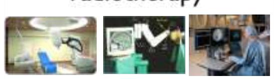
Bone-mounted robot
MARS
(M

It was the only robot competitive with DaVinci

This is an antropomorphic robot(ROBOTICS I)

surgical function and robot specifications

Orthopedics for ex. s related to operation like bone implant.

domain of use	function	kinematic architecture	control modality	sensors and actuators
orthopedics 	machining of rigid surface	conventional (SCARA, anthropomorphic, spherical) 5 (drill) or 6 (cut) dof	autonomous cooperative or "hands-on"	conventional vel: **mm/s** force: until **100N**
MIS 	constrained manipulation	passive joints mechanical RCM (parallelogram, spherical linkages, ...) 5 or 6 external + extra internal dof	teleoperation shared control	conventional vel: **cm/sec** (high acceleration in case of beating hearth surg) force: **few N**
neurosurgery, interventional radiology, radiotherapy 	constrained targeting	conventional + front-end with dedicated architecture 5 or 6 dof	semi-autonomous teleoperation autonomous	MR/CT compatible (pneumatic, piezo, ultrasonic) force: **few N** insertion (usually) manual (undetermined in case of neurosurgery)
microsurgery 	micromanipulation	dedicated kinematic architecture	shared/cooperative teleoperation	piezo, ultrasonic actuators force: **few mN** vel: **0.70m/s** (manual procedure)
tele-echography, TMS, skin harvesting 	surface tracking	conventional + dedicated wrist architecture	autonomous teleoperation	conventional vel: **mm/s** force: **few N**

It's the first domain in which medical robots are used

machining of rigid surfaces (orthopedics)

It's very similar to industrial manipulation
because is related to rigid structure.

- example: total knee replacement

Here there is a knee

cutting/milling/drilling

The prosthesis to be implanted

Prosthesis shoud be inserted on the top of the tibia by means of two screws(viti-that aren't visible). We need to cut the bone and insert the prosthesis.

- risk of misplacement of the mechanical axis, further loosening of the prosthesis

The object reflect the light that is captured by the optical system and then it localize that tool(object) in space.

machining of rigid surfaces (cont'd)

how can robots be of help?

Why a robot is useful in medicine?

However there are some problem for ex. the rosthesis are a limited life.

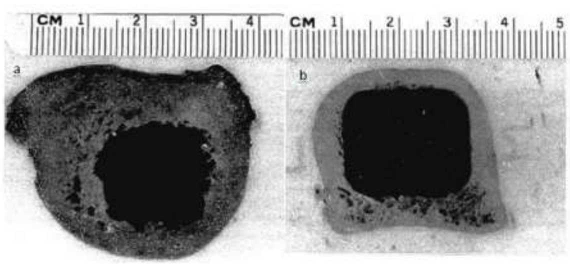
navigation systems / 3D localizers for image-guided surgery (not robot)

Before the surgery operation it gives a 3D model

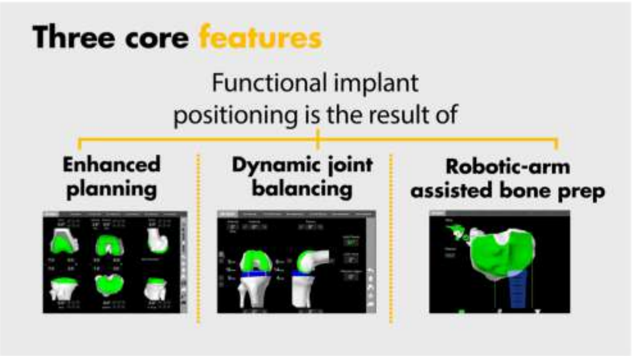
This registration procedure is not invasive

autonomous systems: Tsolution One, THINK Surgical (former ROBODOC)

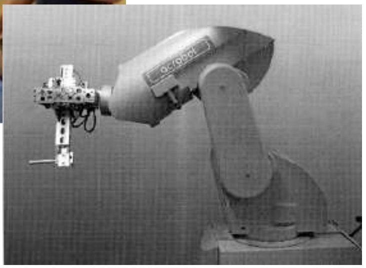
It's one of the few autonomous robot.



"hands-on" systems: MAKO, Stryker (former ACROBOT)



today

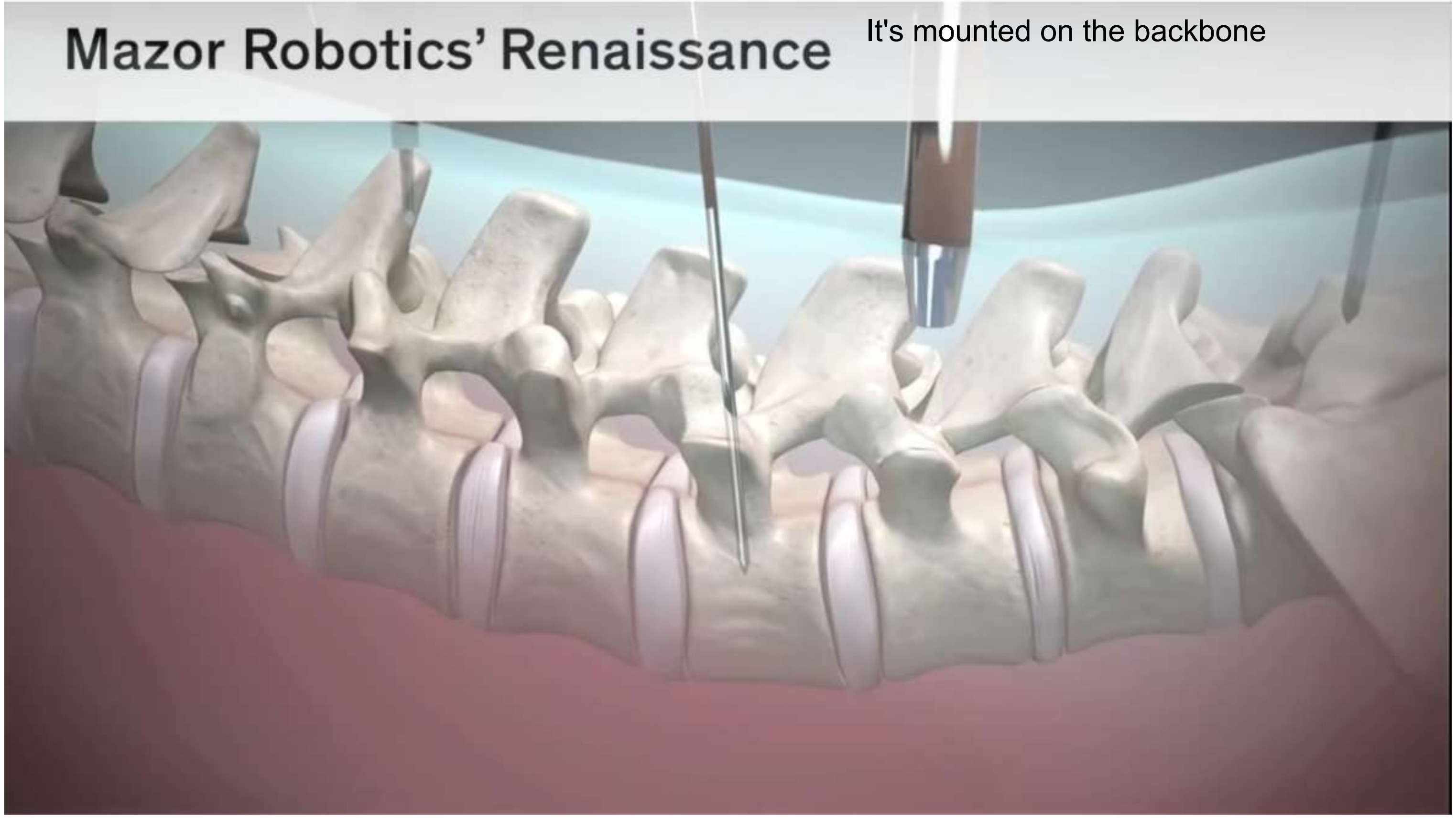


research prototype (20 years ago)

main advantage: accuracy

machining of rigid surfaces (cont'd)

bone-mounted robot: a completely different approach



https://www.youtube.com/watch?v=MrQR6o9iZ3U

main advantages: minimal obstruction, no patient immobilization, small workspace, intrinsically safe

constrained manipulation (MIS)

associated to minimal invasive operation

Result of the endoscopic camera

challenges

They are introduced through a devise called TROCAR

- necessity of 3 hands 2 surgical tools and and endoscopic camera
- usually monocular vision The camera has one single channel.
- surgeon's comfort It is not most confortabe position to do a task
- eye-hand coordination (fulcrum effect)
- loss of internal mobility (constraints induced by trocar)
- restricted workspace
- no force feedback (friction in the trocar)
- …

We need to move the endoscopic camera.

a robot may solve most of these difficulties

For ex. a robot could move the endoscopic camera.

constrained manipulation (cont'd)

active endoscope holder: the 3° hand

AESOP, Computer Motion
voice controlled, no longer on the market

It's the only competitor of intuitive surgical. It produce and commerce also de Da Vinci system

SOLOASSIST, AKTORmed, Germany
joystick controlled

FreeHand, Prosurgics, UK
head controlled

Camera controlled by head movements

KaLAR, KAIST, Korea
control based on knowledge of the surgical gesture, bendable tip, research prototype

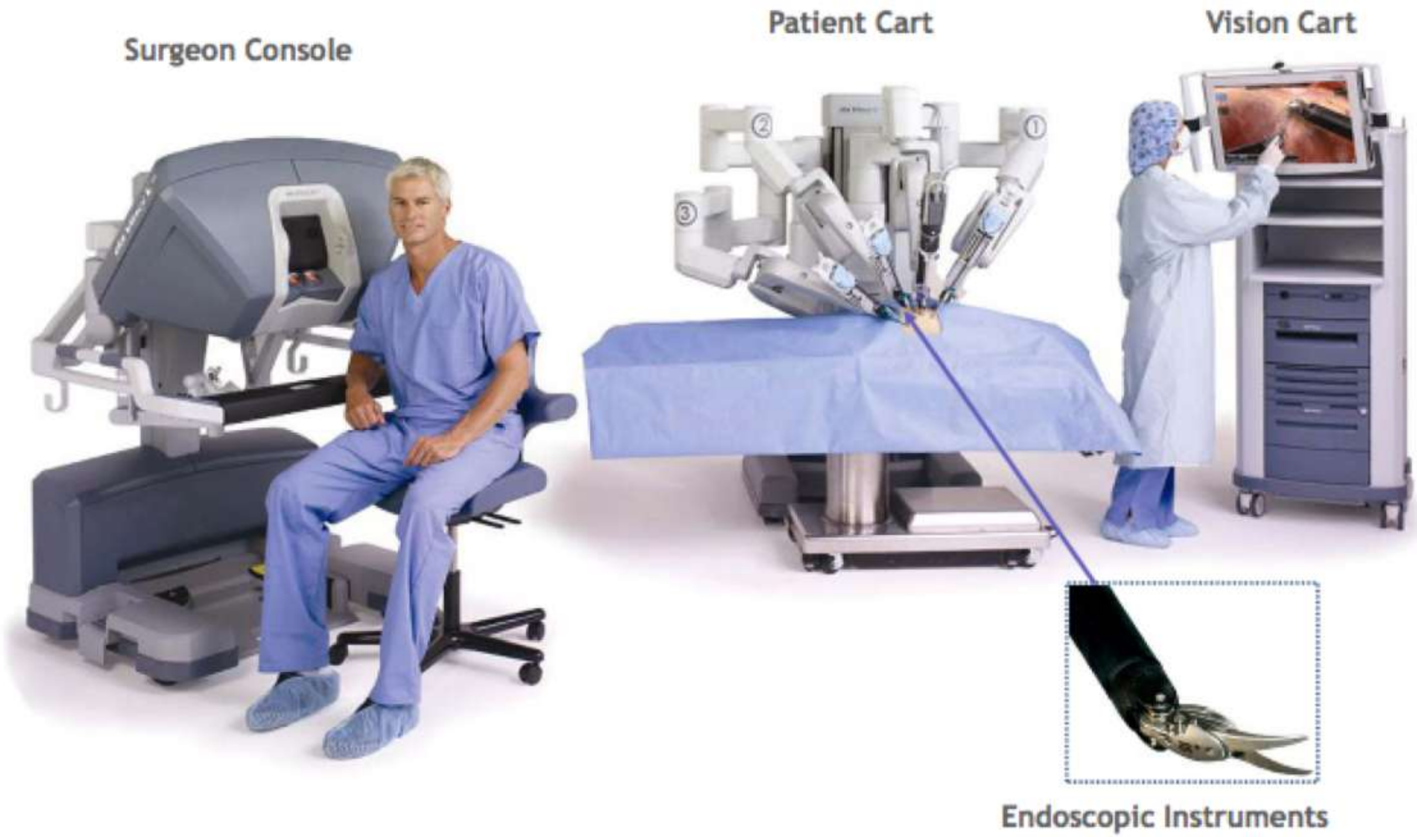
control through visual servoing, research

possibly with a dedicated kinematics to comply with the RCM constraint

constrained manipulation (cont'd)

master-slave systems: the da Vinci Surgical System

system overview



constrained manipulation (cont'd)

master-slave systems: the da Vinci Surgical System

da Vinci Surgical System, Intuitive Surgical, US

- currently dominating the market, preserves the benefits of MIS for the patient and the dexterity of open surgery for the surgeon
- eye-hand coordination, stereoscopic vision

- intuitive motion

With this interface we command the degree of freedom of the surgical tool. It has the same degree of freedom of the human hand.

- 7 dof at the tool tip, wrist dexterity brought inside the patient

- mechanical RCM

remove center of motion

constrained manipulation (cont'd)

master-slave systems: the da Vinci Surgical System

- produced by INTUITIVE SURGICAL
- founded in 1995, public company in 2000
- headquarters in Sunnyvale, CA
- 4440+ da Vinci systems worldwide
- ~875.000 da Vinci procedures performed in 2017
- ~5 million da Vinci procedures to date
- according to Intuitive Surgical estimation, **every 36 seconds** a surgeon starts a da Vinci procedure worldwide
- primary Markets: Urology, Gynecology, General Surgery, Cardiothoracic
- average cost ($ 1,0M - 2,3M) varies with instruments and accessories and service agreements

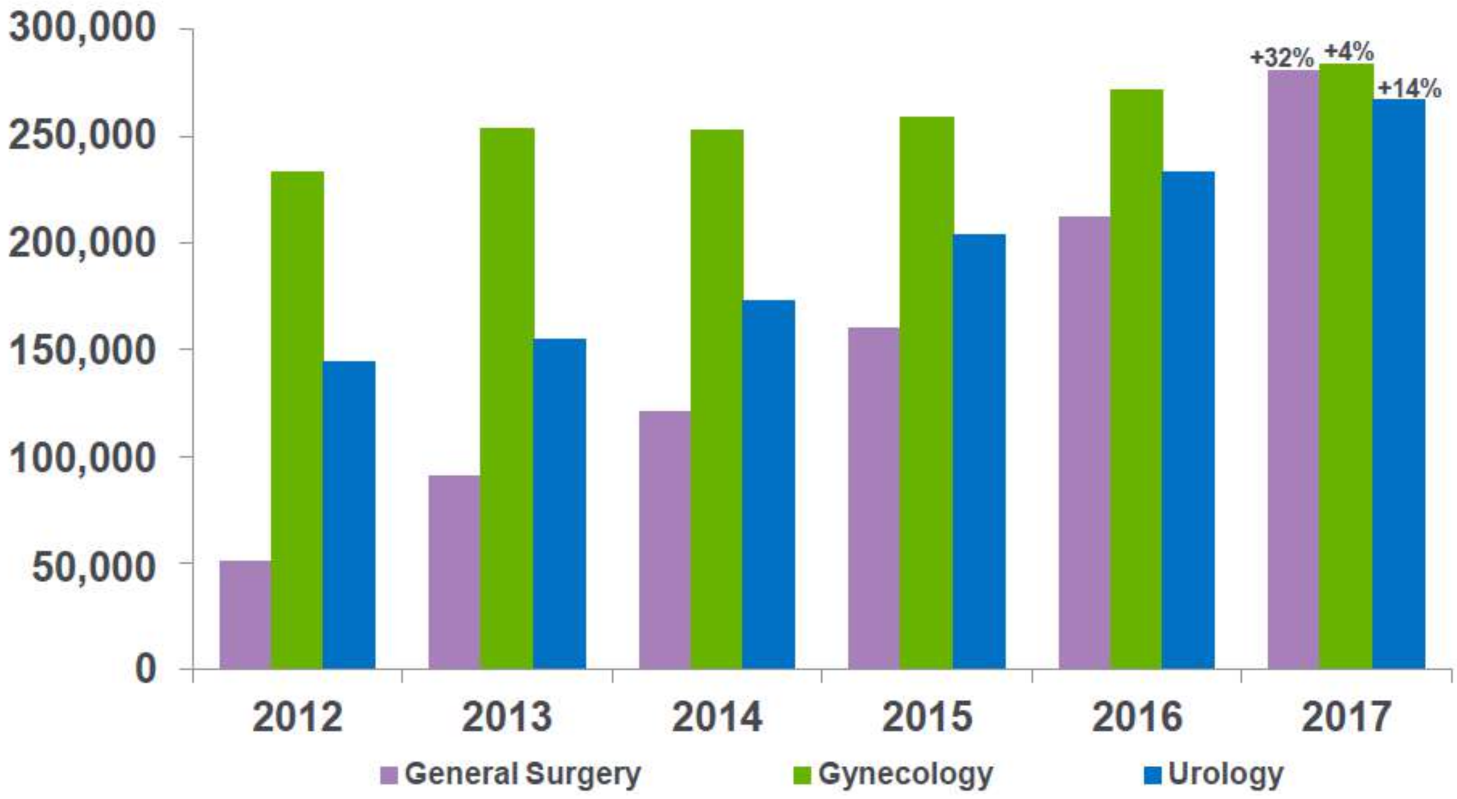
constrained manipulation (cont'd)

master-slave systems: the da Vinci Surgical System

system installations

constrained manipulation (cont'd)

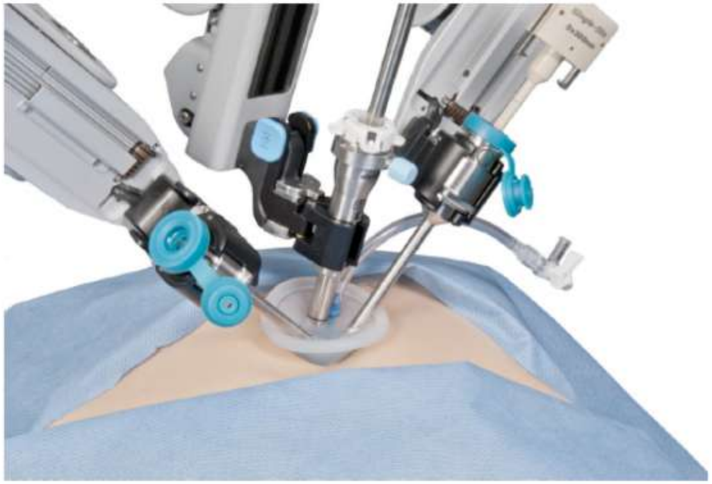
master-slave systems: the da Vinci Surgical System



procedure trend

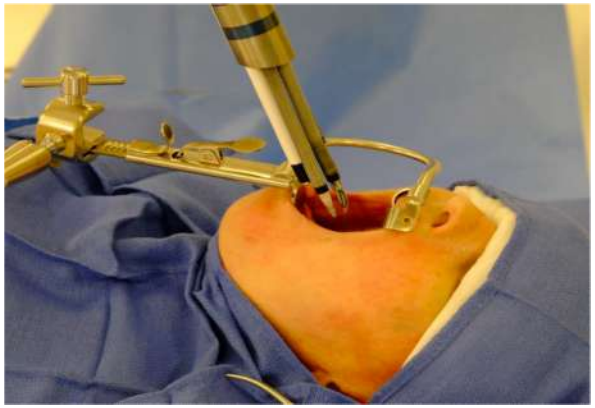
constrained manipulation (cont'd)

da Vinci evolutions: single port access



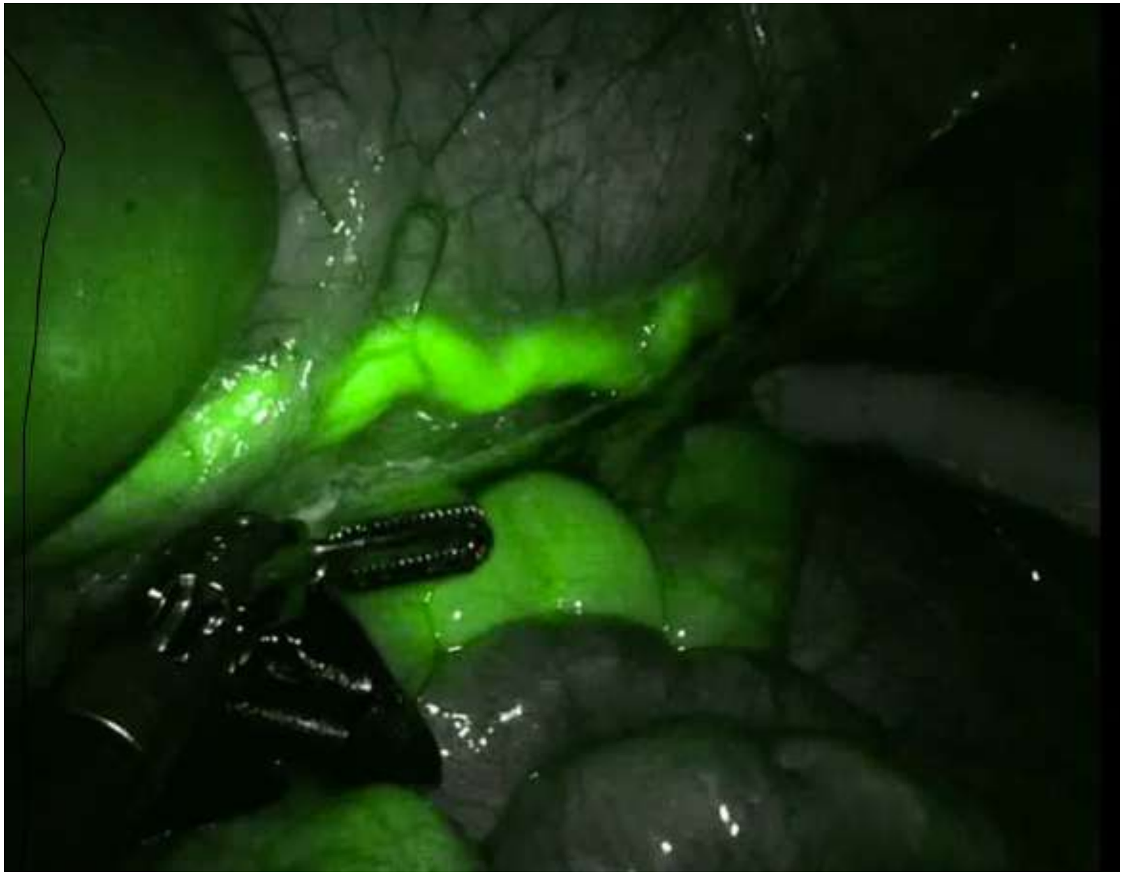
da Vinci single-site instruments

- surgery through a single umbilical port
- FDA Cholecystectomy Clearance Dec 2011
- benign hysterectomy / Salpingo Oophorectomy 510K filed Q3 12
- 450^{+} US hospitals have purchased Single-Site products through Q4 12



constrained manipulation (cont'd)

da Vinci evolutions: enhanced imaging



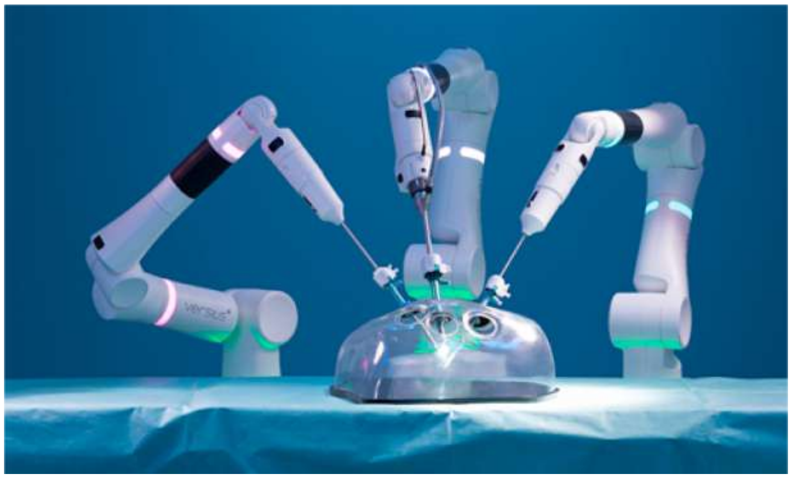
constrained manipulation (cont'd)

da Vinci evolutions: flexible catheter based system

https://www.intuitive.com/en-us/products-and-services/ion

constrained manipulation (cont'd)

da Vinci's competitors



Versius, CMR Surgical, UK, 2018

FlexDex, US (not a robot)

SPORT, Titan medical, Canada
single port access, flexible instruments

Senhans, TransEnterix, US
(eye tracking, haptic feedback)

constrained manipulation (cont'd)

da Vinci's competitors: research platform

Raven, Washington Univ.
(featured in *Ender's Game*)

It is teleoperated not autonomous

The idea is the same of the da Vinci. Robotically assisted and remotely controlled

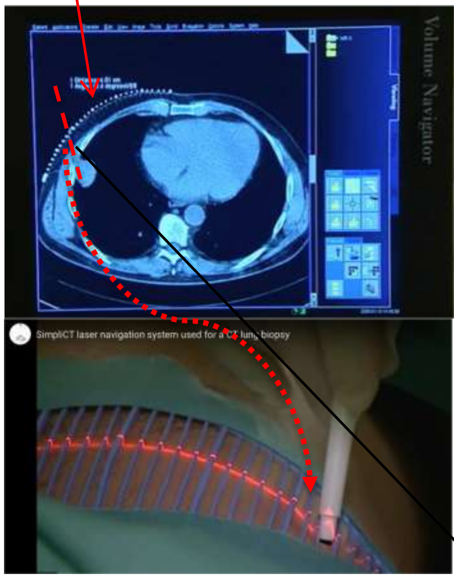
MiroSurge, DLR, Germany
(open research system with force sensors at the instruments tip)

Function related to interventional radiology

The traditional procedure is like this: you have the image of the patient, there is a greed that is visible in the image. The trajectory to follow is signed.

constrained targeting (interventional radiology)

greed

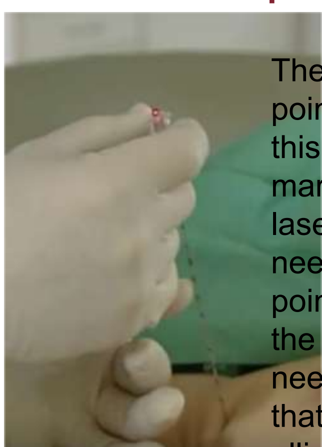


planning

alignment

challenges

- fixed access point (but without trocar)
- guide of imaging necessary
- soft tissue + non-rigid needle
- smaller and smaller target
- avoid critical areas



There is a little red point(not visible in this images) that marks where the laser intersects the needle. When this point is exactly on the top of the needle, this means that the needle is alligned with the desired orientation

insertion

verification

It follows always the same directory so we could need to rioriented the trajectory.

robots are useful to

- shield the medical staff from radiations
- comply with the small workspace of MR/CT gantry

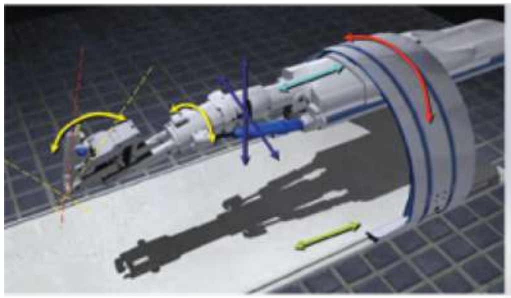
magnetic resonance/computed tomography

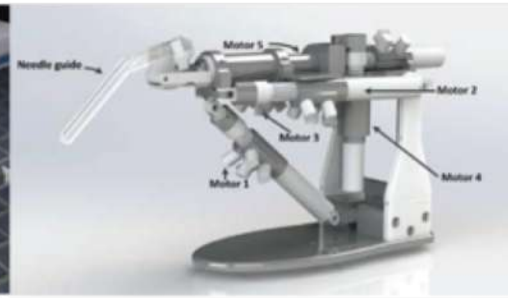
- accurately reach small targets
- compensate for patient's motion

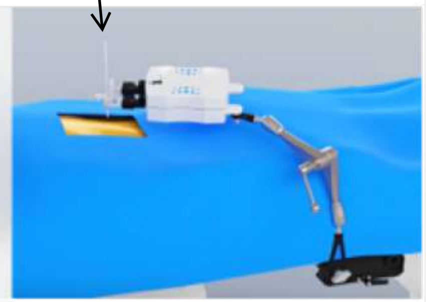
constrained targeting (interventional radiology)

percutaneous procedures

teleoperated by the doctor







INNOMOTION
- one of the first MR-compatible, CE cleared
- 6-dof, pneumatic 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

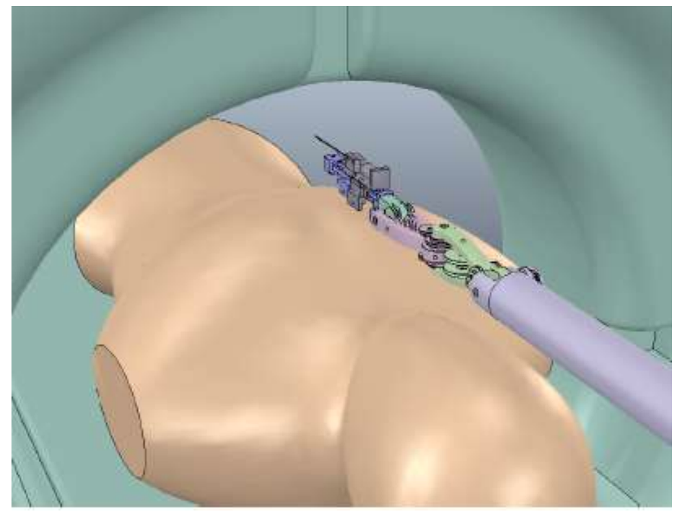
iSYS1
- CT and XA guide
- 2-dof orienting the needle guide
- passive positioning arm
- planning software
- manual insertion

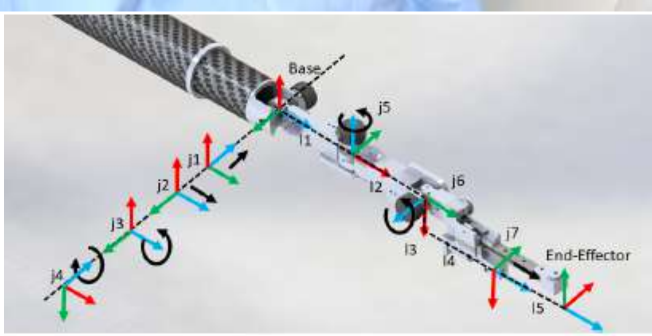
ROBIO
- CT/PET-CT guide
- 5-dof
- floor-mounted
- image-based registration
- manual insertion

constrained targeting (interventional radiology)

percutaneous procedures: one of the many research prototypes

- an open-access CT-compatible prototype





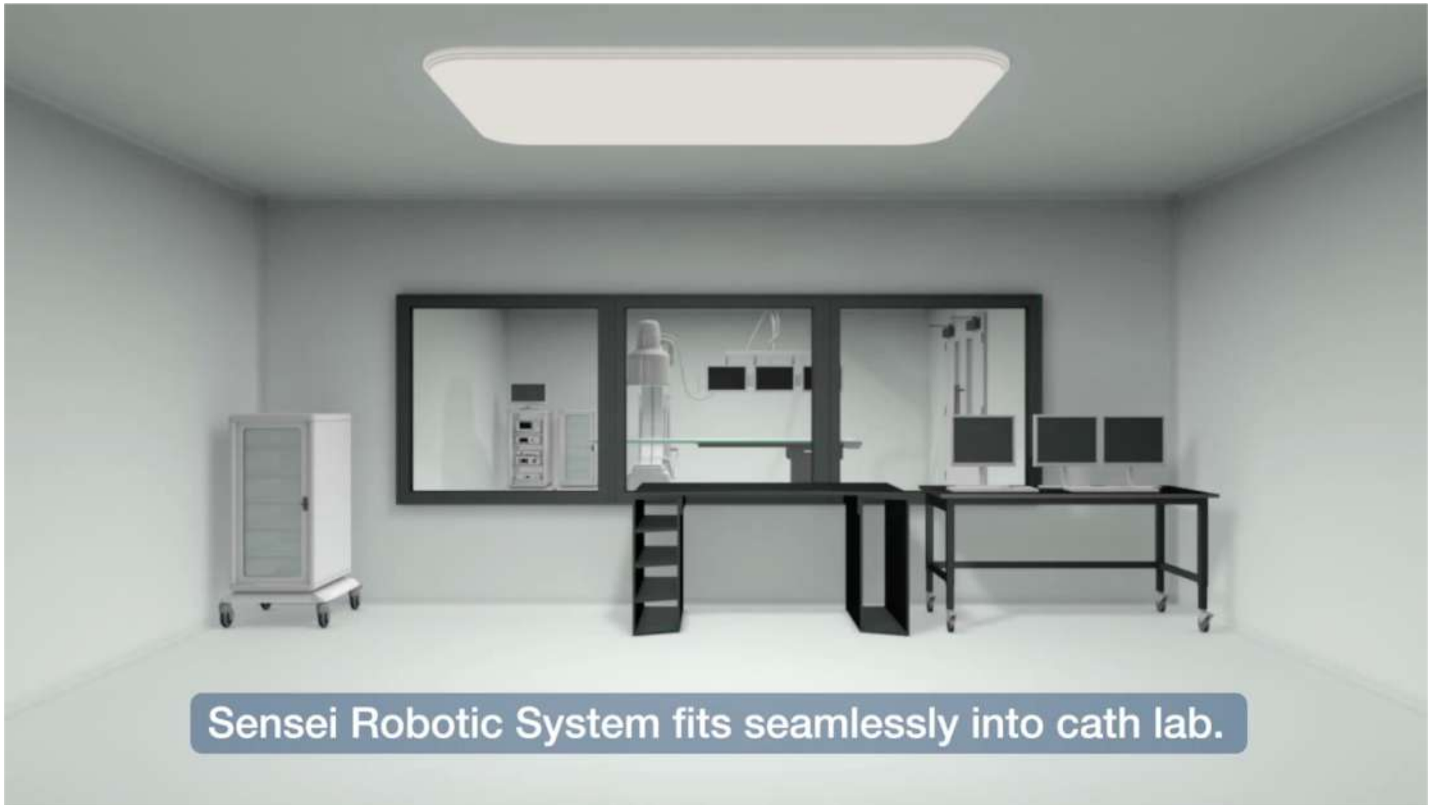
- 7-dof
- belt/cable driven
- user interface for remote control
- V-REP simulator

In percutaneus procedure the needle is inserted through the skin and directly reache the target, while in vascular or endovasculare procedure the needle is inserted in the skin but follows the blood verse.

constrained targeting (interventional radiology)

vascular procedures

The needls have to be more flexible because is inserted in for ex. catheters.



6-dof

Sensei X2, Auris Health, US
(evolution of Magellan)

constrained targeting (interventional radiology)

vascular procedures

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

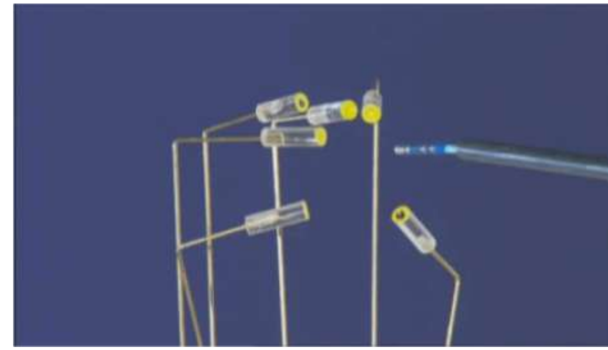
Niobe (Stereotaxis Inc.)

- XA guide
- electrophysiology procedures
- remote magnetic catheter control: uniform magnetic field generated by arms motion for omnidirectional steering of a catheter tip

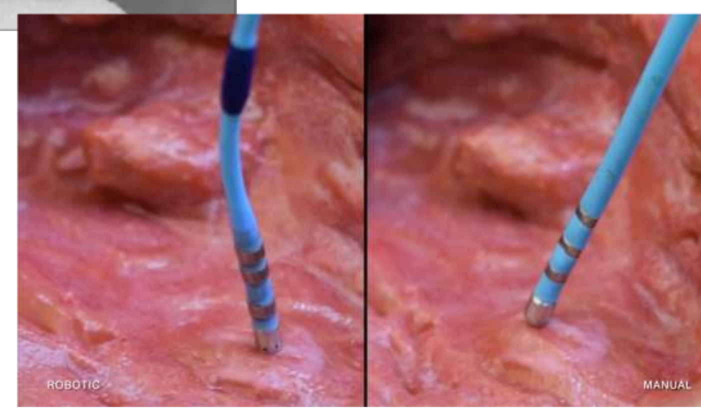
constrained targeting (interventional radiology)

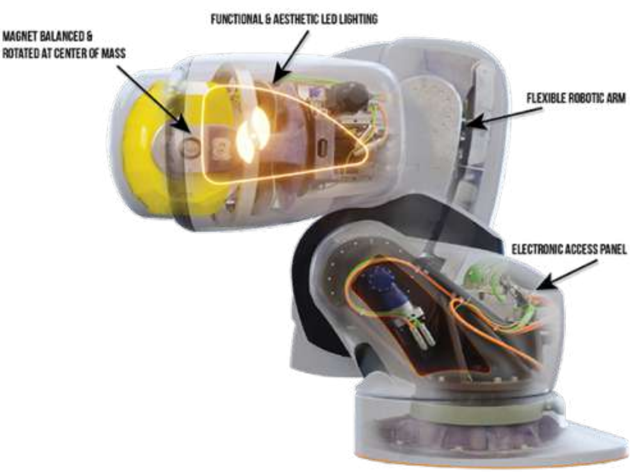
vascular procedures

accuracy



softness





Genesis (Stereotaxis Inc.)

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

constrained targeting (interventional radiology)

open problems

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

- smaller, lighter, intrinsically safe robots
- prediction models One way to reduce radiation is to have a continuous feedback, so a predition model that can predict how the needle will interact with the tissues.
- real-time (re)planning when a needle penetrates in the tessue the forces that are perceived at the base of the needle are due not only the forces exchange at the needle tip but also the forces exchange between the needle shaft and the tessue
- force sensing at the needle tip and haptic rendering
- shape and force sensing on the whole catheter body not at just catheter tip
- compensation of cardiac heart motion Difficulties to keep the chateter tip in contact with the tessue because of the heart motion.
- transmission of sufficient force to execute the treatment

constrained targeting (neurosurgery)

2 examples of tools

PathFinder, Prosurgics, UK

ROSA, MedTech, France

a robot for fine positioning and instrument guide

We have linear accelerator that deliver high energy radiation. (ONCOLOGICAL TREATMENT)

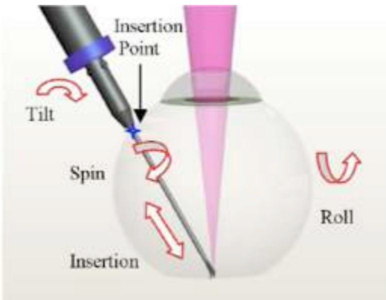
constrained targeting (radiotherapy)

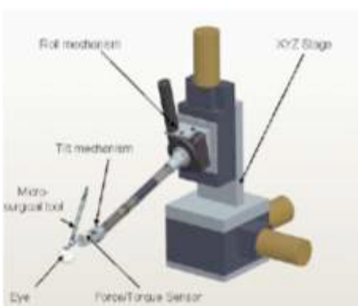
CyberKnife, Accuracy, US

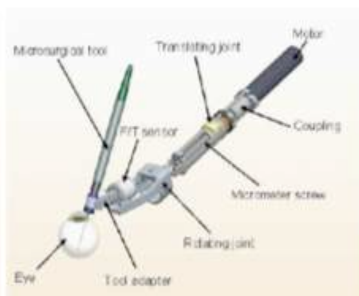
Microcanalation of the retina.

micro-manipulation (microsurgery)

We need at least 4-dof







SteadyHand, JHU

Here we have 3 cartesian degrees of freedom and we have also a roll pitch motion. It has a particular control modality which is called SHARED CONTROL of the manipulator. It means that both the robot and the surger or the operator in general, are in control of the tool.

challenges

- accuracy at the microscopic scale (target size comparable with hand tremor noise induced)
- exchanged forces
- single access point constraint (in this example)

a robot for (in general)

- teleoperation to scale force and motion
- accurately reach small targets
- compensate for patient's motion
- compensate the natural hand tremor

It's very difficult to project a robot that is able to make human actions (and a human is more intelligent) but robots are better in accuracy.

micro-manipulation (microsurgery)

surface tracking

TMS Robot, Axilum Robotics

MELODY, AdEchoTech, France

challenges

- accurate positioning and reproducibility
- control of contact forces
- soft tissue deformation

a robot for

- accurate surface tracking
- contact force control
- patient motion compensation

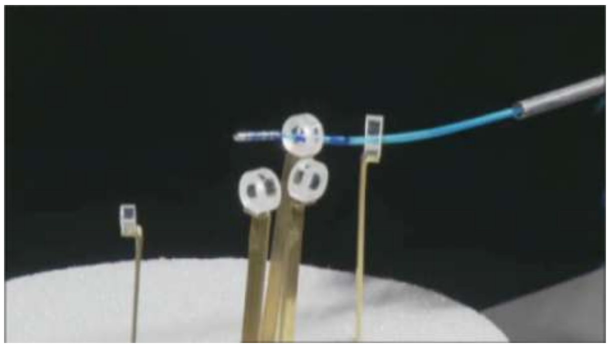
(some) lessons learned

- costs of installation, maintenance, use
- size/footprint/workflow alteration: robotic systems should complement rather than alter the surgical workflow
- increased cognitive load for surgeons and staff
- situation awareness compromised during robotic surgery
- the looooooong way to certification

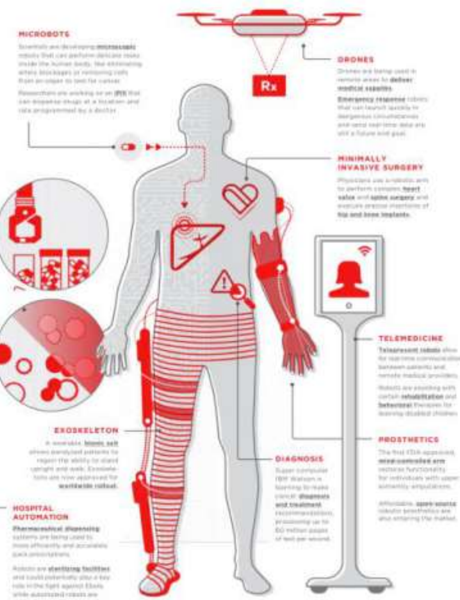
then, what's next?

the future of surgical robots looks…

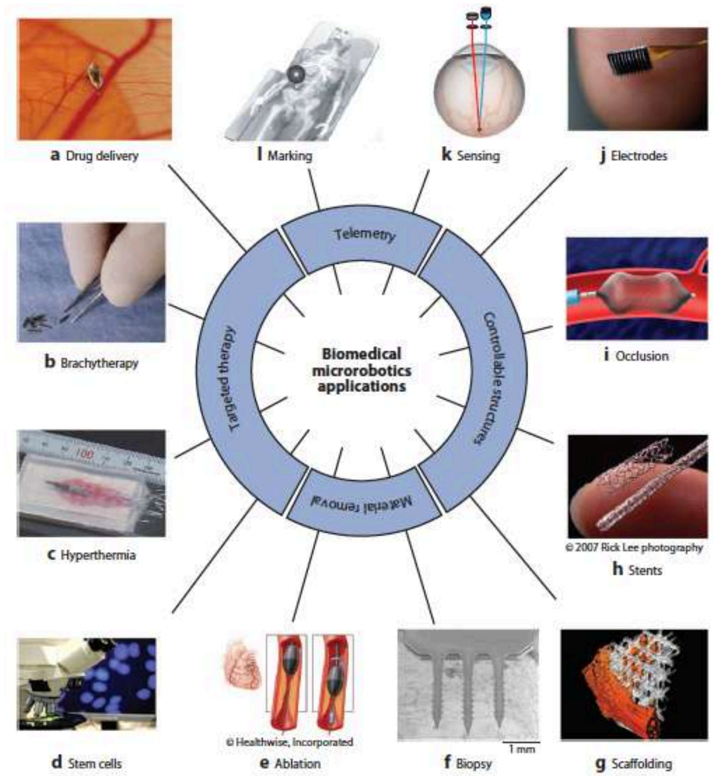
…soft



…connected



…tiny



Nelson et al., Annu. Rev. Biomed. Eng. 2010

- targeted therapy
- material removal
- controllable structures
- telemetry

challenges

- accuracy
- powering, locomotion, localization
- control of tiny structures subject to a variety of forces that become relevant at the micro/nano scale in a highly complex and unstructured enviroment
- combine knowledge of biological processes with control methodologies
- application of appropriate forces

macro/micro robotics technology merging is expected to help in pushing the boundaries of targeted therapies