Medical Robotics

Marilena Vendittelli

Usually this is one of the topic of the projects

da Vinci® surgical system

SAPIENZA
UNIVERSITÀ DI ROMA

sources for this lecture

- http://www.intuitivesurgical.com/products/
- http://investor.intuitivesurgical.com/phoenix.zhtml?c=122359&p=irol-IRHome
- http://www.iwmr.polimi.it (presentation by Mike Yramategui)

difficulties of “manual” MIS

Summarize the challenges of MIS

(Source : US Surgical Corporation)

- Widely used in abdominal surgery

- **Some difficulties:**
  - 3 hands are mandatory
  - monocular vision (usually)
  - comfort of the surgeon
  - eye-hand coordination (fulcrum effect)
  - loss of internal mobility due to kinematics constraints induced by the trocar
  - restricted workspace
  - no force feedback (friction in the trocar)
  - …

- **Advantages of robots:** may solve (more or less) most of these difficulties

The manipulator in the hands of the surgeon manipulates the tools in the patient

system overview

https://www.youtube.com/watch?v=VJ_3GJNz4fg

standard da Vinci® surgical system (introduced in 1999) of the MIS

goal preserve the benefits to the patient of endoscopic surgery skills while giving back to the surgeon the dexterity of open surgery

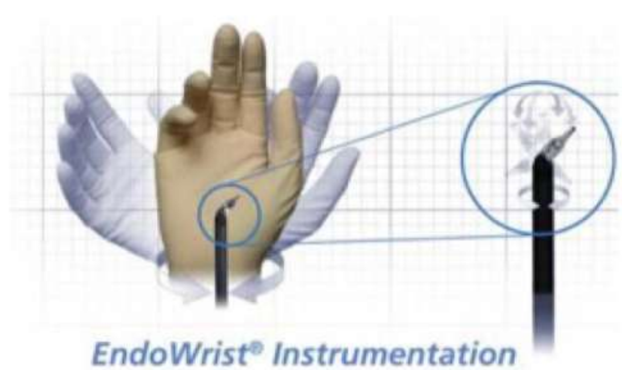
In MIS we use all the dof

- eye-hand coordination, stereoscopic vision ($\rightarrow$ depth)

- intuitive motion

With this manipulator it's possible for the surgeon to have all the motions of the wrist and there is an additional dof that allows for ex. to open and close some surgical tools.

- 7 dof at the tool tip



produced by INTUITIVE SURGICAL

Here we have some info about intuitive surgical

http://www.intuitivesurgical.com/

- founded in 1995, public company in 2000
- headquarters in Sunnyvale, CA
- 5582+ da Vinci systems worldwide (2019)
- ~1.2 million da Vinci procedures performed in 2019
- ~7.2 million da Vinci procedures to date
- primary Markets: Urology, Gynecology, General Surgery, Cardiothoracic
- average cost ($ 1,0M - 2,3M) varies with instruments and accessories and service agreements

Evervie of the installations

system installation through 2019

different colored points are the
differen version of the Davinci

50
States

67
Countries

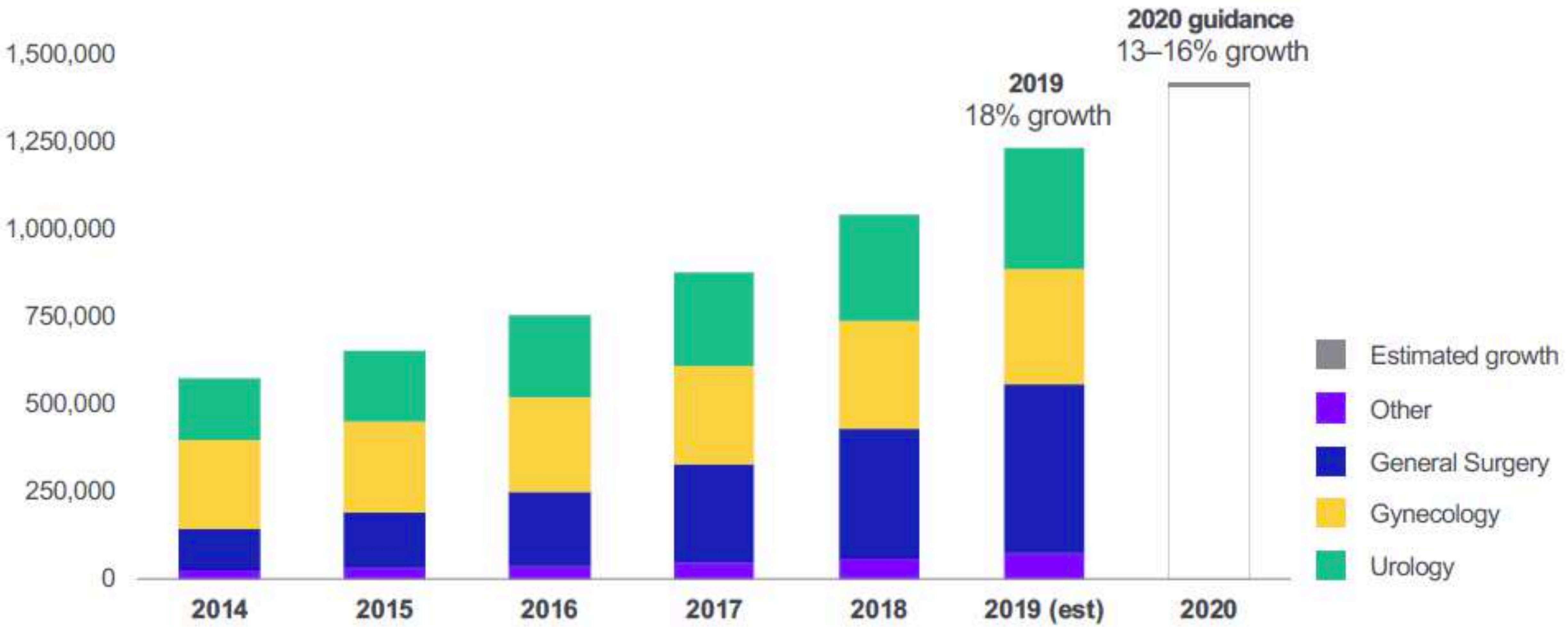
5,582
Number of da Vinci systems around the world.

7.2 million+
Number of minimally invasive da Vinci procedures completed worldwide through 2019.

1.2 million+
Number of da Vinci procedures performed in 2019.

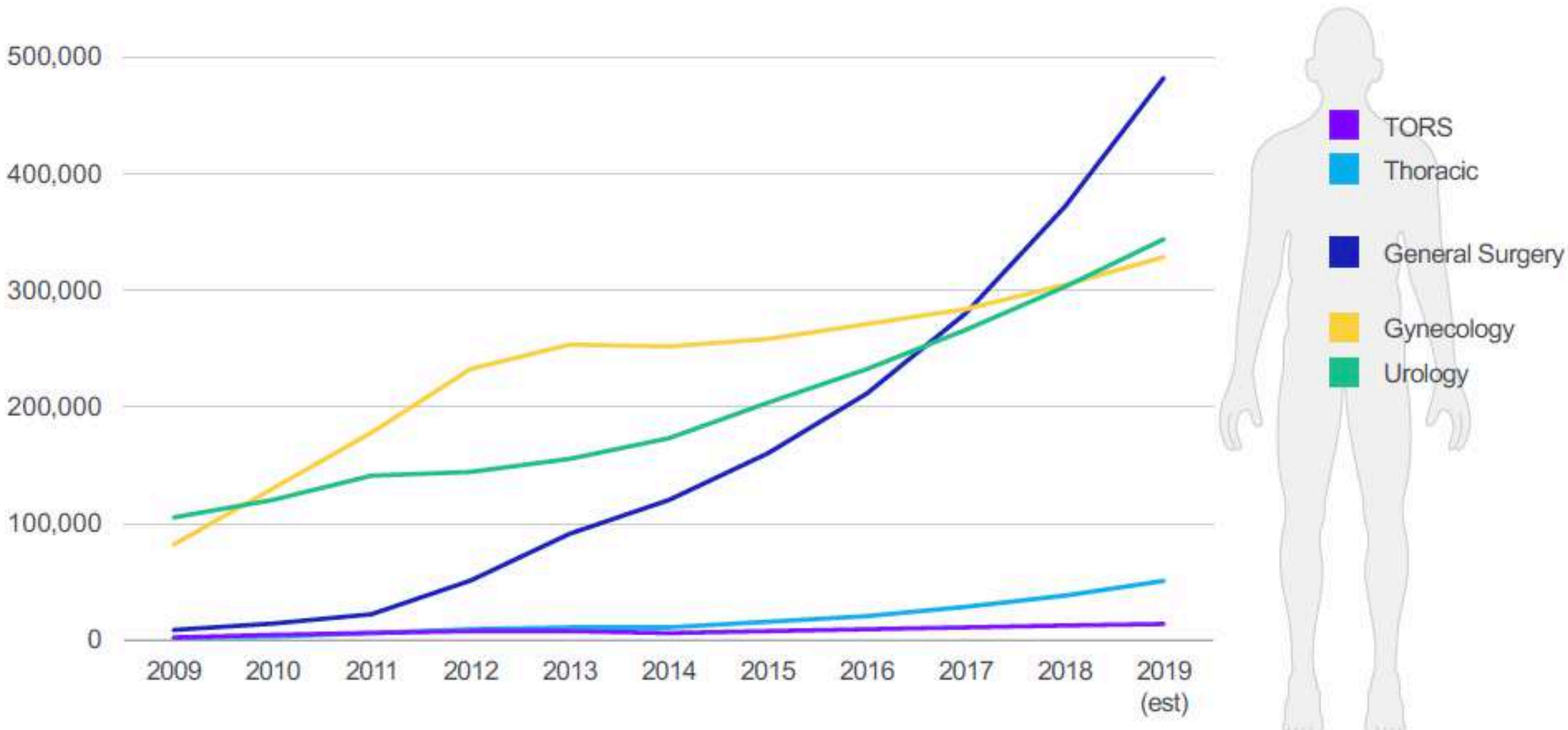
26 seconds
How often a surgeon starts a da Vinci procedure.

procedure trend



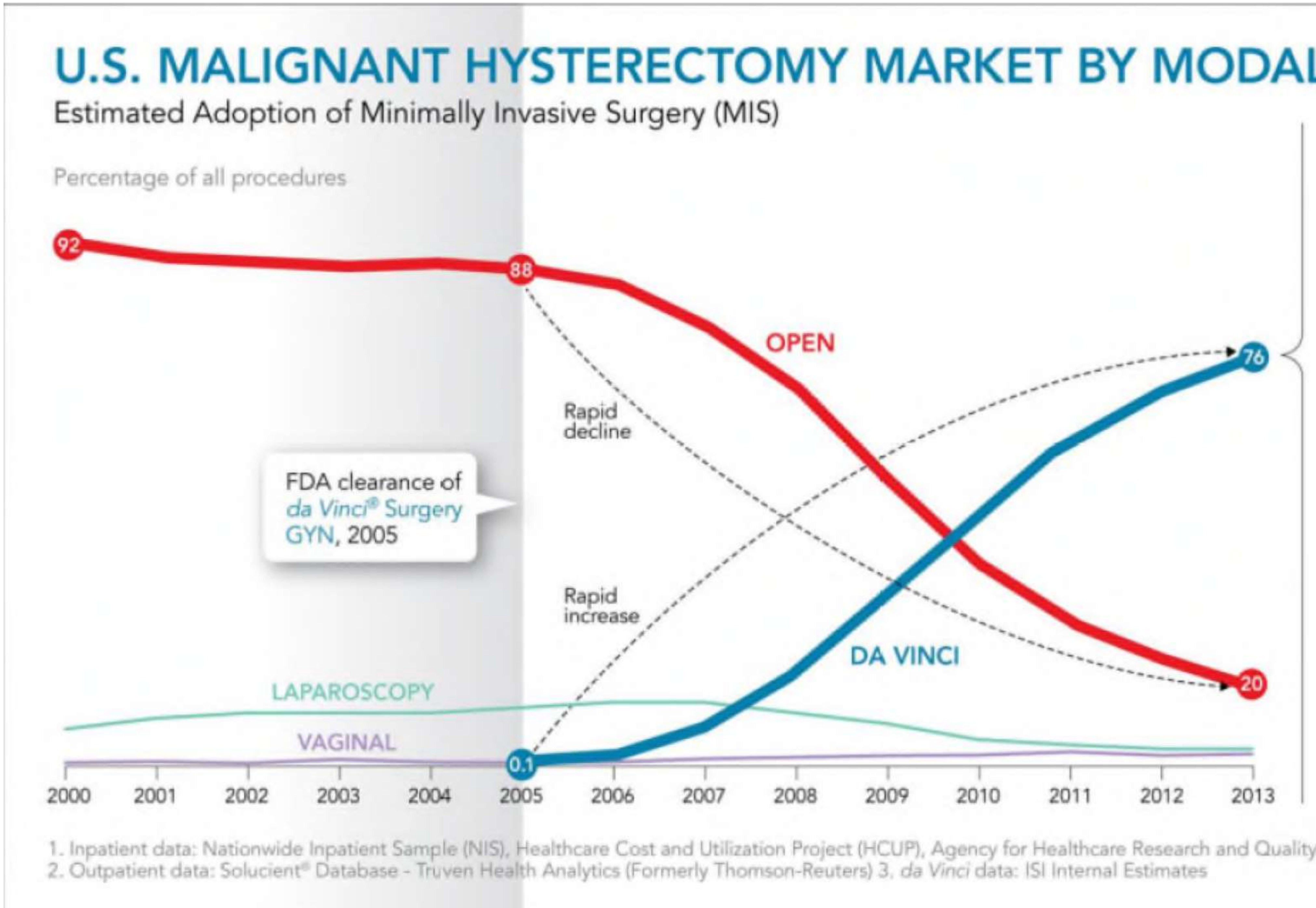
There was an increment in general surgery

growth in procedure categories

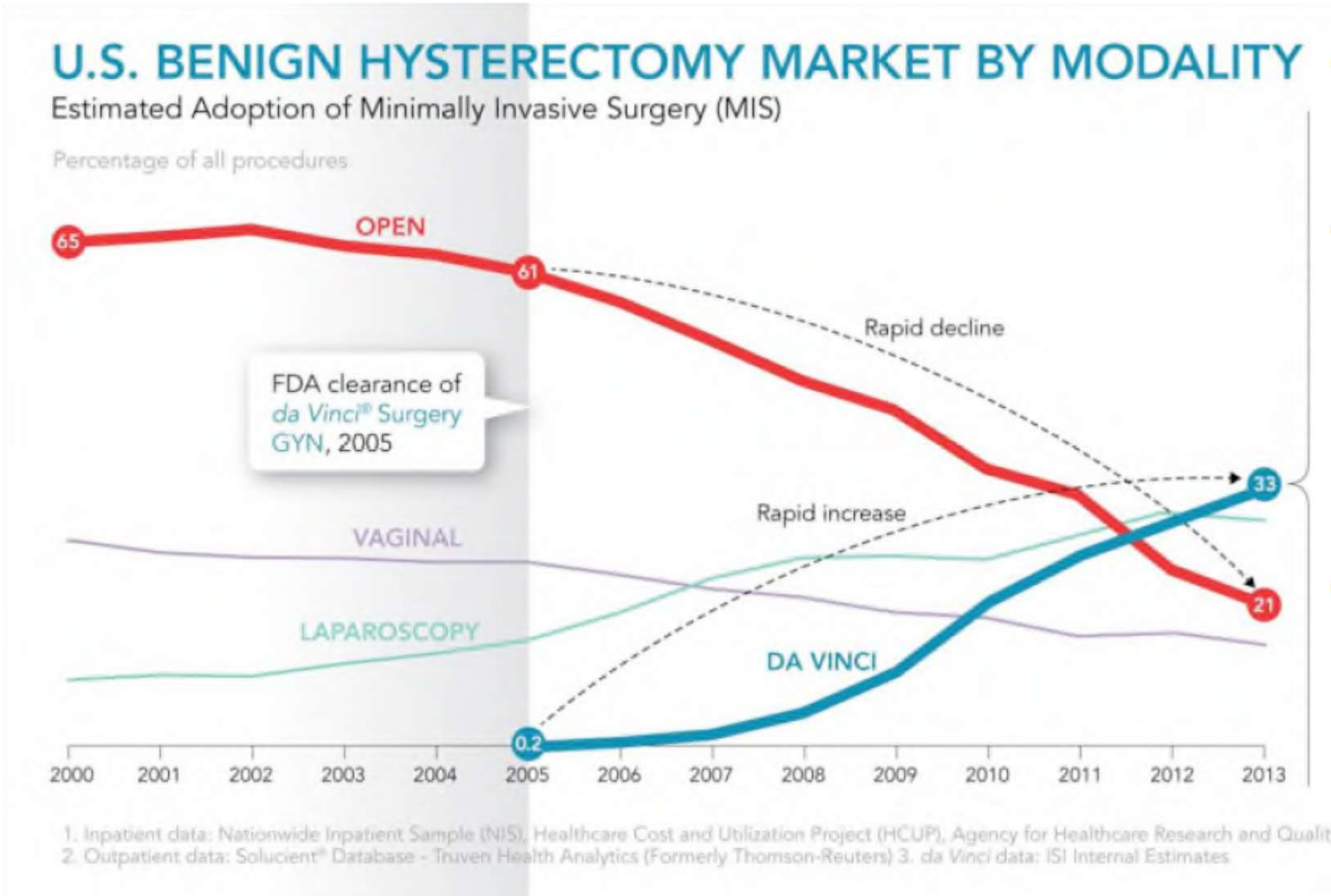


Source: Intuitive 2019 earnings report

Ginecology was one of the first field in which it was used.



- *da Vinci* primarily displaces open surgery
- Prevalence of lap hysterectomy for cancer less than 15% at its peak
- Open surgery is now used in only about 20% of surgeries for cancer



- *da Vinci* primarily displaces open surgery
- After the introduction of da Vinci, the prevalence of MIS (lap, vaginal and da Vinci) grew.
- Open surgery is now used in only about 20% of benign hysterectomies

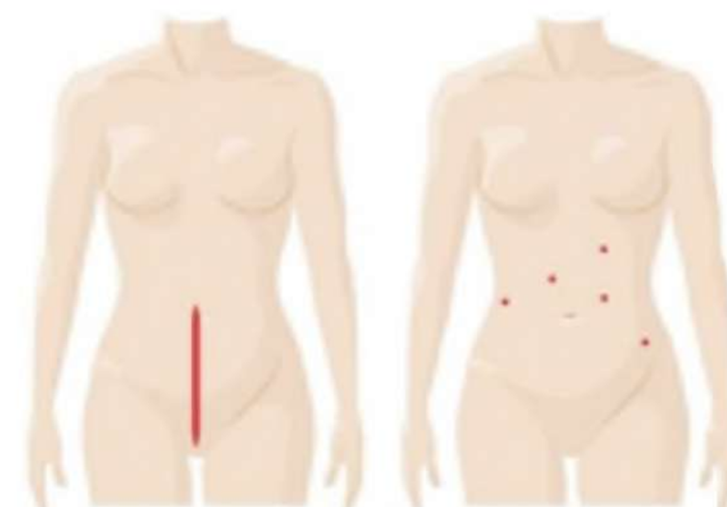
© Di Maio, 2014

A risk is that some cancer cells remain in the body

Outcomes and Cost Comparisons After Introducing a Robotics Program for Endometrial Cancer Surgery

OBSTETRICS & GYNECOLOGY
VOL. 119, NO. 4, APRIL 2012
Lau et al. Jewish General Montreal

- Minimally invasive procedures increased from 17% to 98% in 2 years
- Historic cohort n=160; Robotic cohort n=143
- Robotic cohort:
  - Longer OR time (233 vs 206 minutes)
  - Fewer adverse events (13% vs 42%)
  - Less blood loss (50 ml vs 200 ml)
  - Reduced median hospital stay (1 vs 5 days)
  - Lower overall hospital costs ($7644 vs $10,368)
    - with amortization/maintenance, ($8,370 vs $10,368)
  - Reduced recurrence rates (11 cases vs 19)

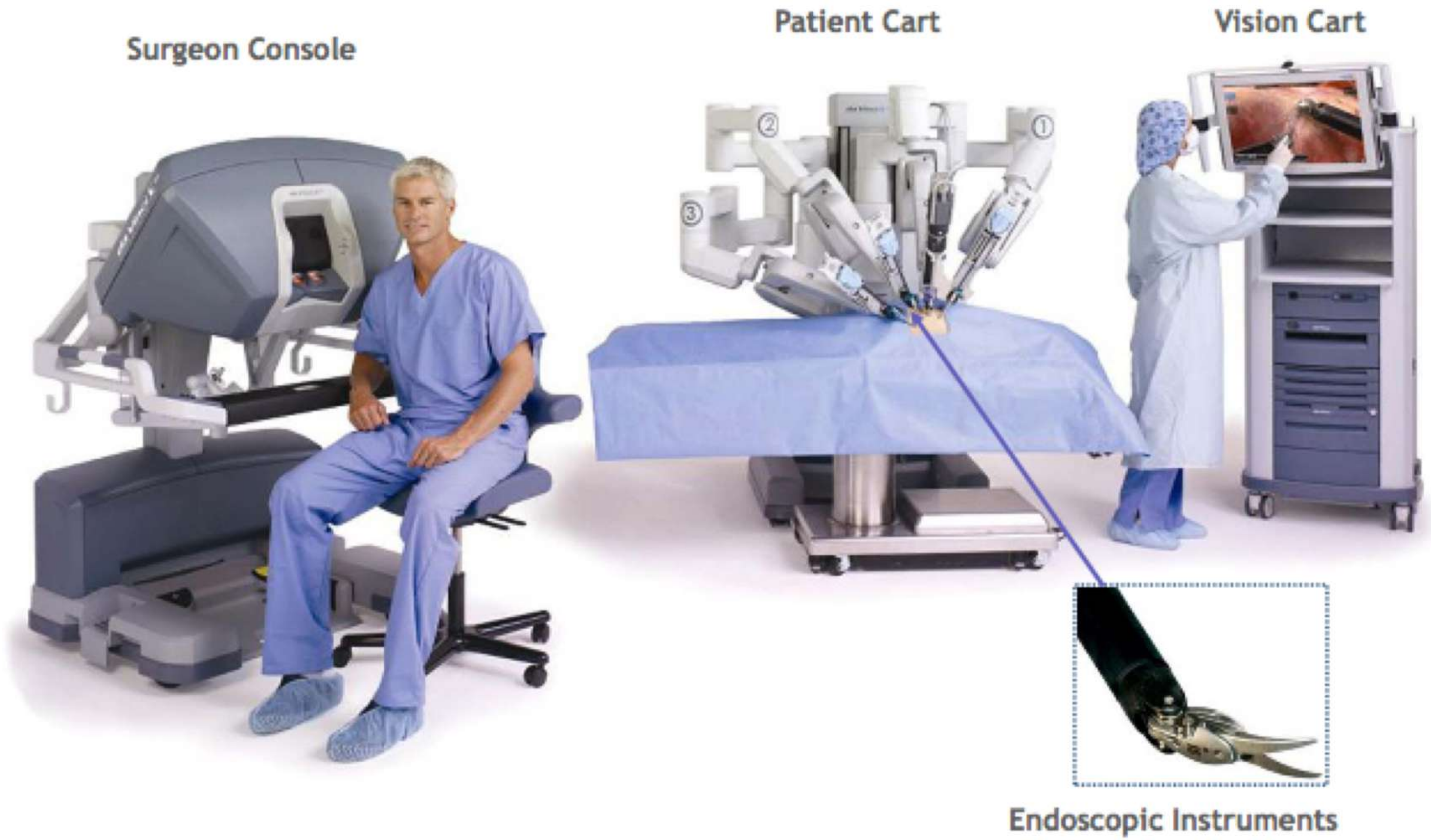


robotics surgery costs more than manual laparoscopy but less than open surgery (considering all the aspect such as the hospitalization)

still, costs are such that

manual laparoscopy < robotic < open surgery

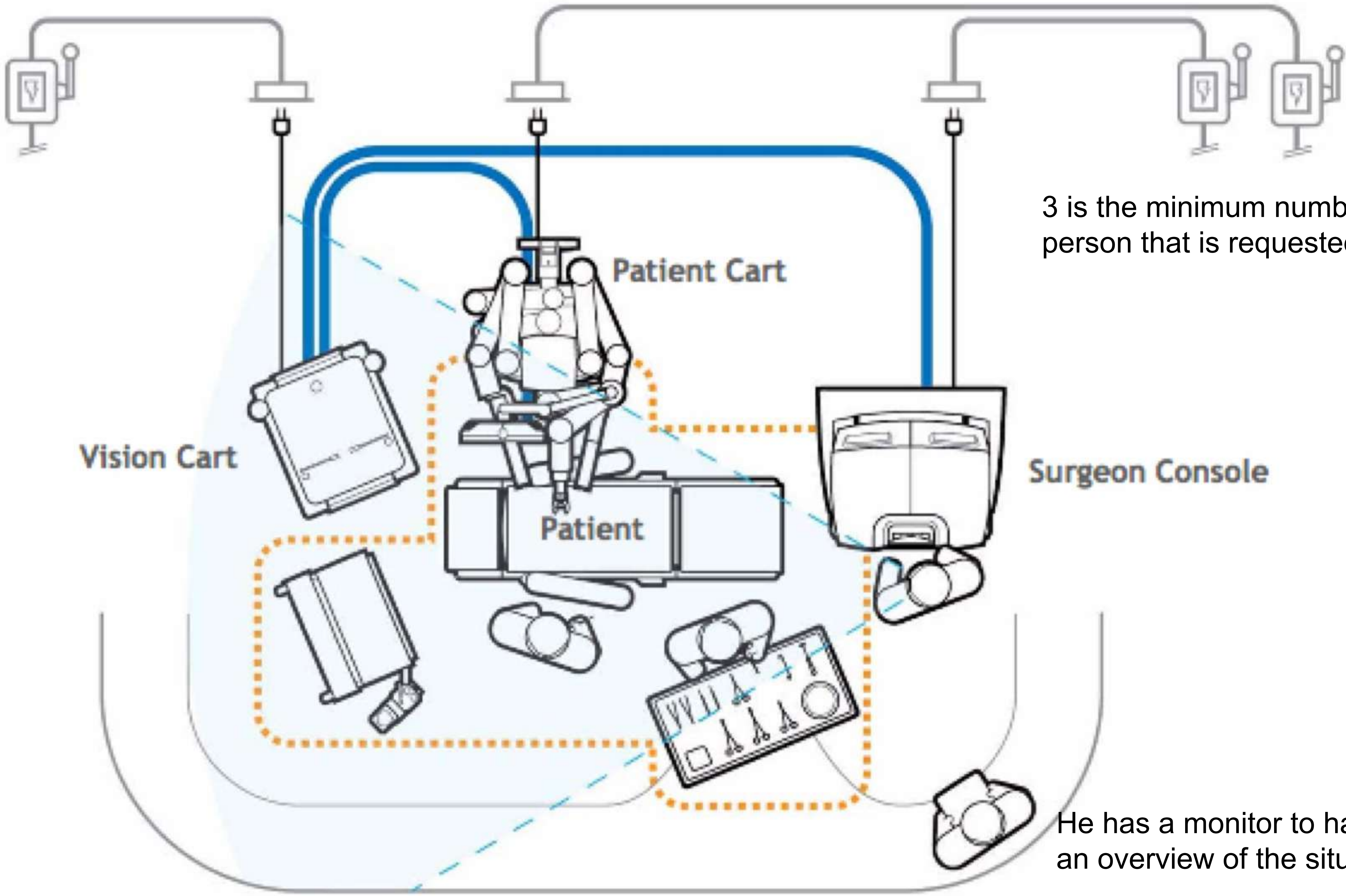
system overview



OR layout

provided by intuitive surgery for the installation

There are versions of daVinci with 2 consoles.



3 is the minimum number of person that is requested

He has a monitor to have an overview of the situation

We are talking about input devices

master console

- the serial manipulators operated by the surgeon act as a high-resolution input device
- the images of the surgical site are sent to the surgeon through two independent vision channels
- the virtual image plane is positioned right above the hands
- switches and foot-actioned buttons allow the surgeon to control the position of the endoscope, reposition the master and adjust the camera focus

used for ex. for repositioning the endoscope

images are sent to the surgical side

3D vision system

- two optical channels with two independent 3-chip CCD
- two independent vision channels connected to two high-definition monitors with a frame rate of thousands of frames per second
- temperature at the endoscope extremity is automatically regulated
- image zooming, contrast improvement, noise reduction
- repositioning possible

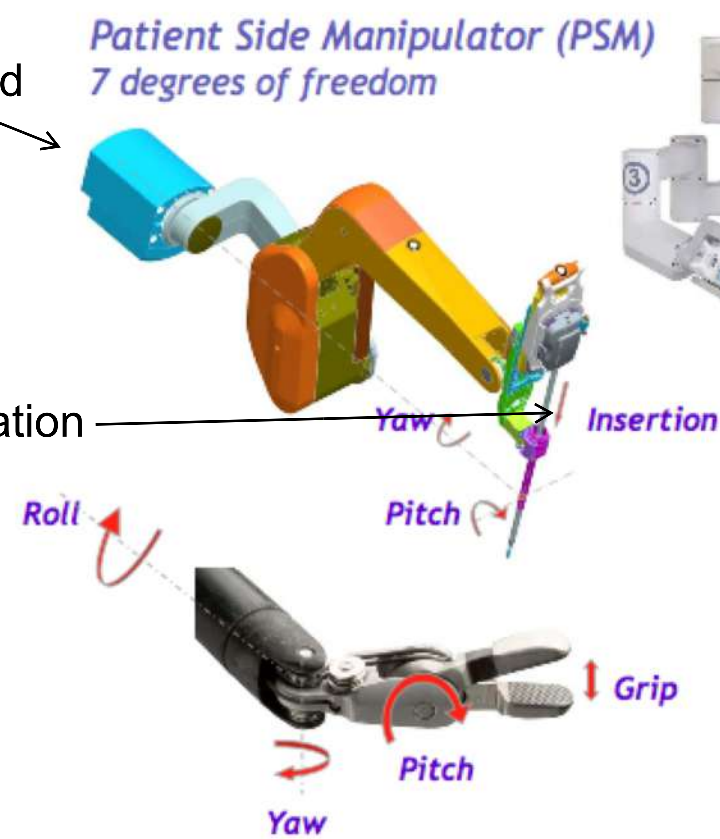
slave robot

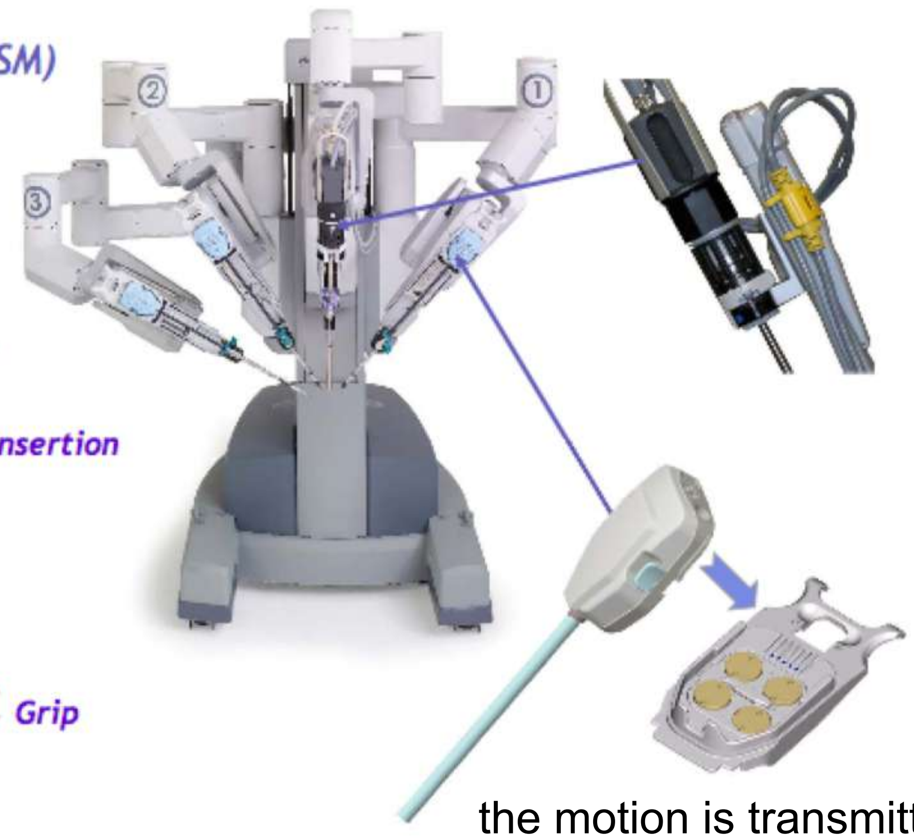
It's a cart that carries 3 or 4 slave arms.

inside the patient there is another dof

The dof that are commanded by the master are those of this parallelogram

an additional dof is the translation





the motion is transmitted through the cables

- three/four articulated arms mounted on a base
- some joints are manually regulated at the beginning of the surgery and remain fixed during the surgery
- the remaining joints are actuated and remotely controlled by the surgeon (plus filtering and motion scaling)
- two/three arms hold the surgical tools while the third/fourth holds the endoscope
- standard sterilization procedures of the surgical tools are allowed

are important

These tools becomes always more small and make the procedure less and less invasive.

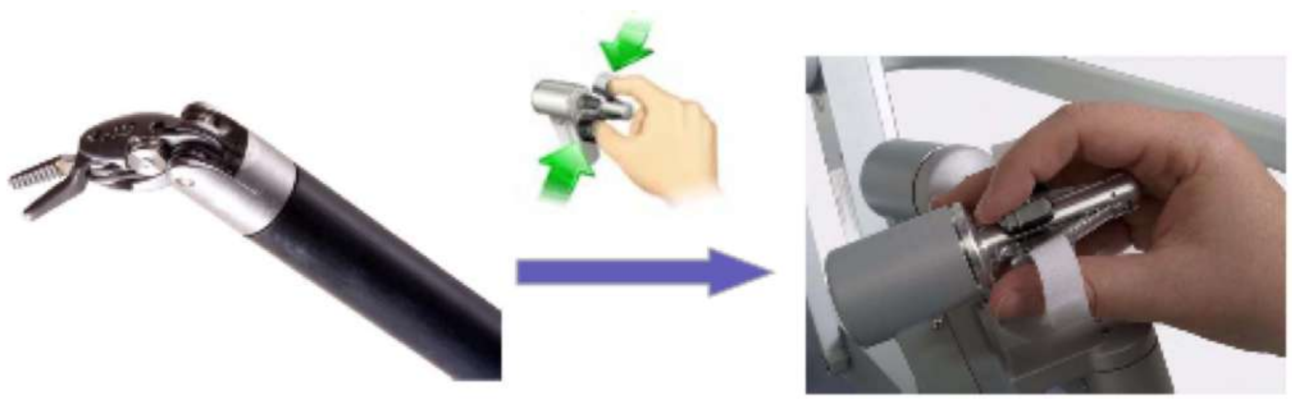
Endo Wrist® tools

- about 40 different types of forceps, needle drivers, scalpel, scissors, cautery instruments,. . . (5 mm, 8 mm)
- enhanced dexterity, precision and control
- 7 degrees of freedom, 90° degrees of articulation
- intuitive motion and finger-tip control
- ease of use: after an instrument is mounted to the da Vinci System, the interface recognizes the type and function of the instrument, and displays the number of uses

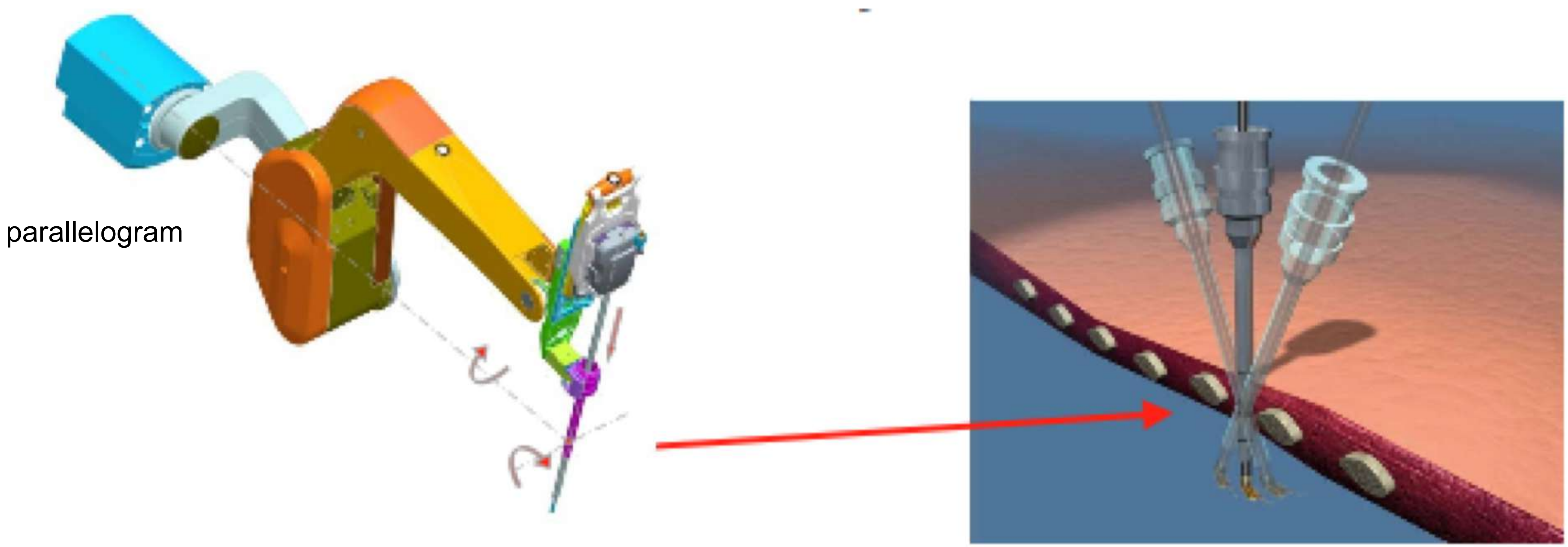
safety

- redundant sensors, hardware watchdogs, real-time fault detection
- transition to “safe state” before hazardous motion
- system can be easily removed from patient in fault condition
- no autonomous motion of instruments

- instrument motion is under surgeon view and control



mechanical RCM

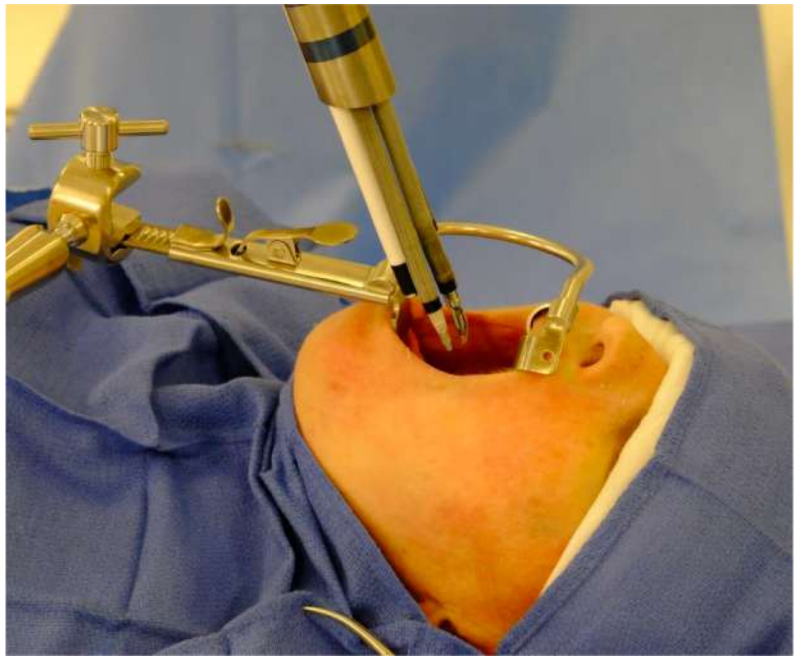


- slow motion outside the body $\Rightarrow$ assistant can anticipate and avoid contact

evolution: single-port access

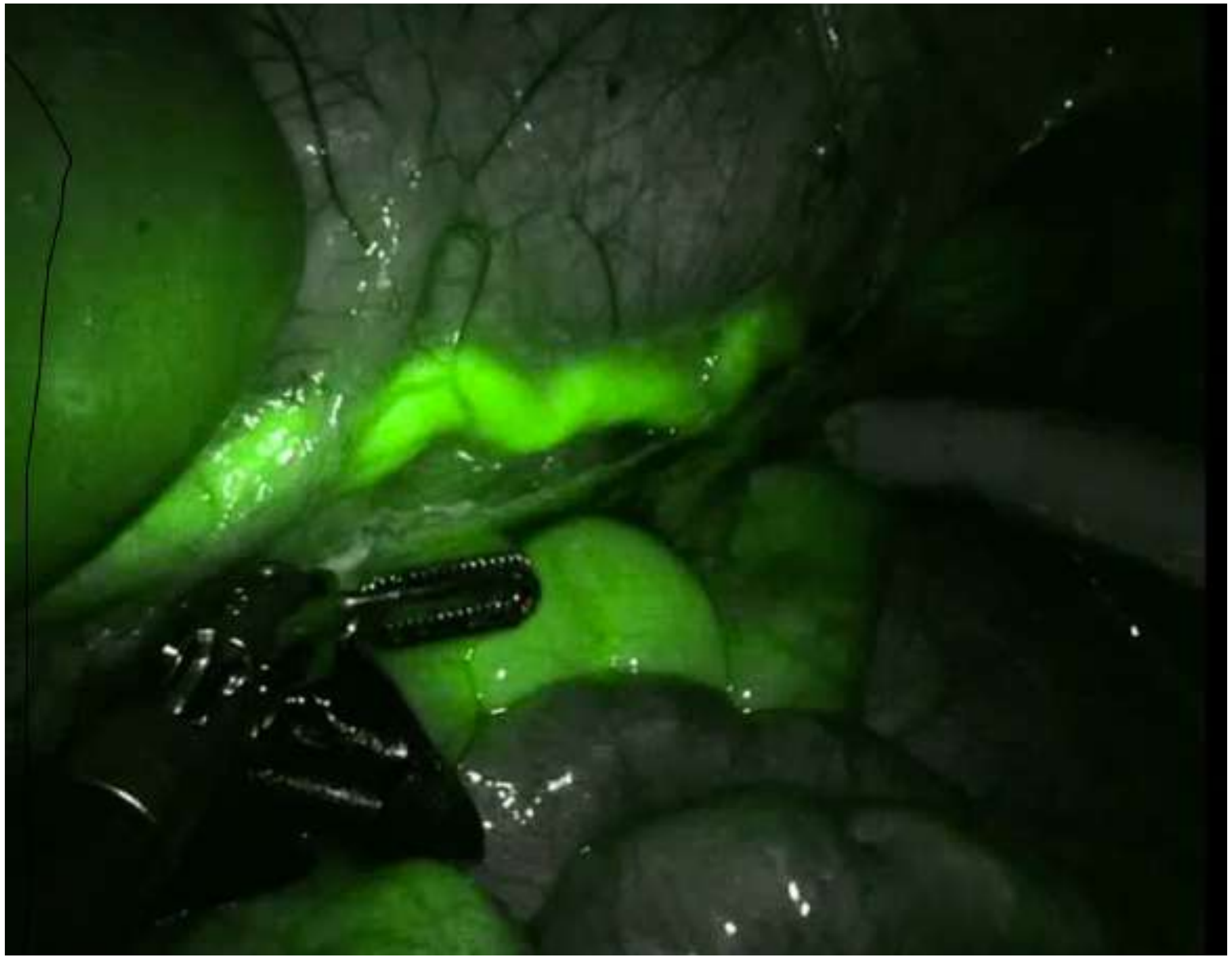
da Vinci single-site instruments

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



- not yet FDA cleared in the US

evolution: enhanced imaging

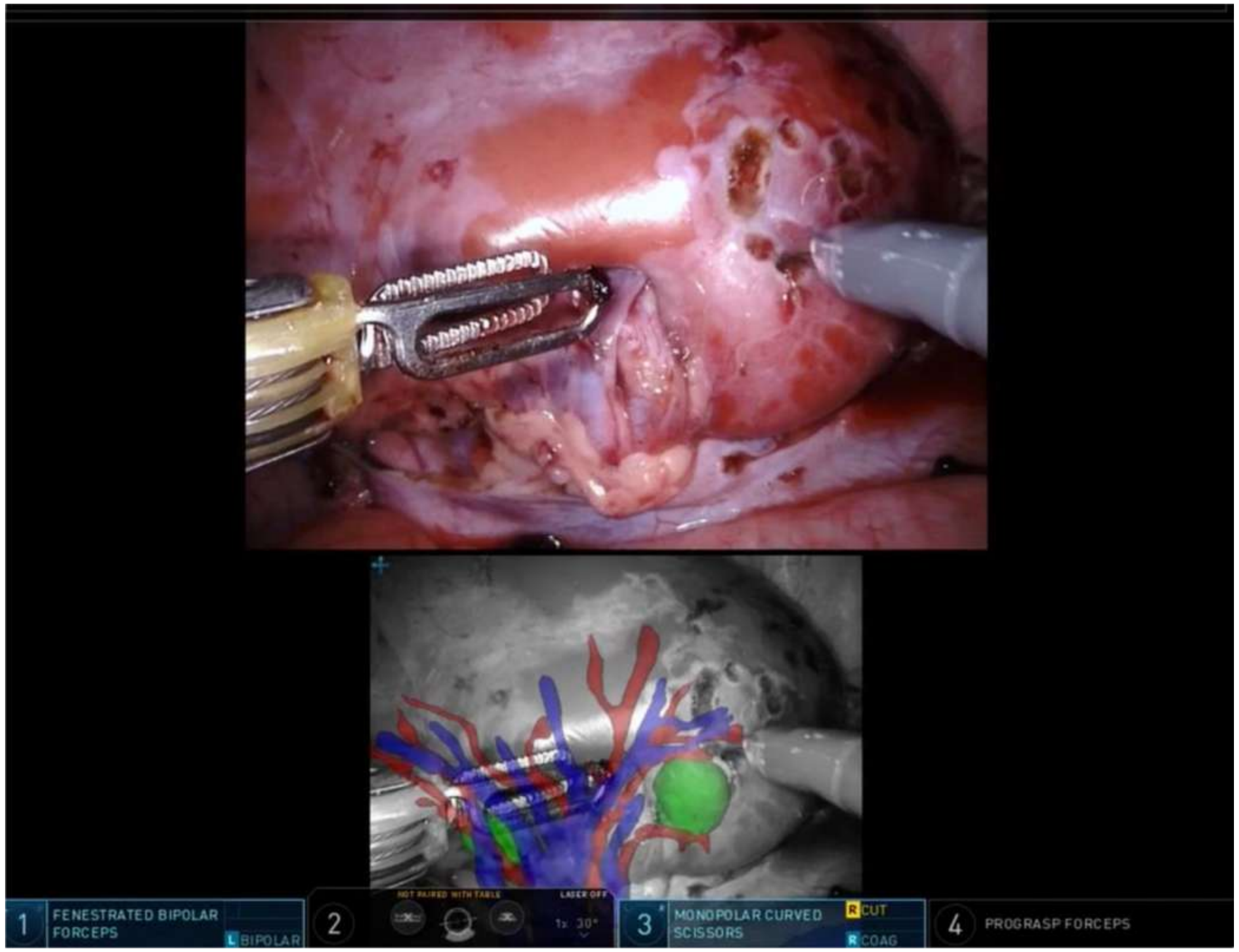


- can help surgeons identify structures during surgery
- not yet FDA cleared in the US

using an infrared caemra

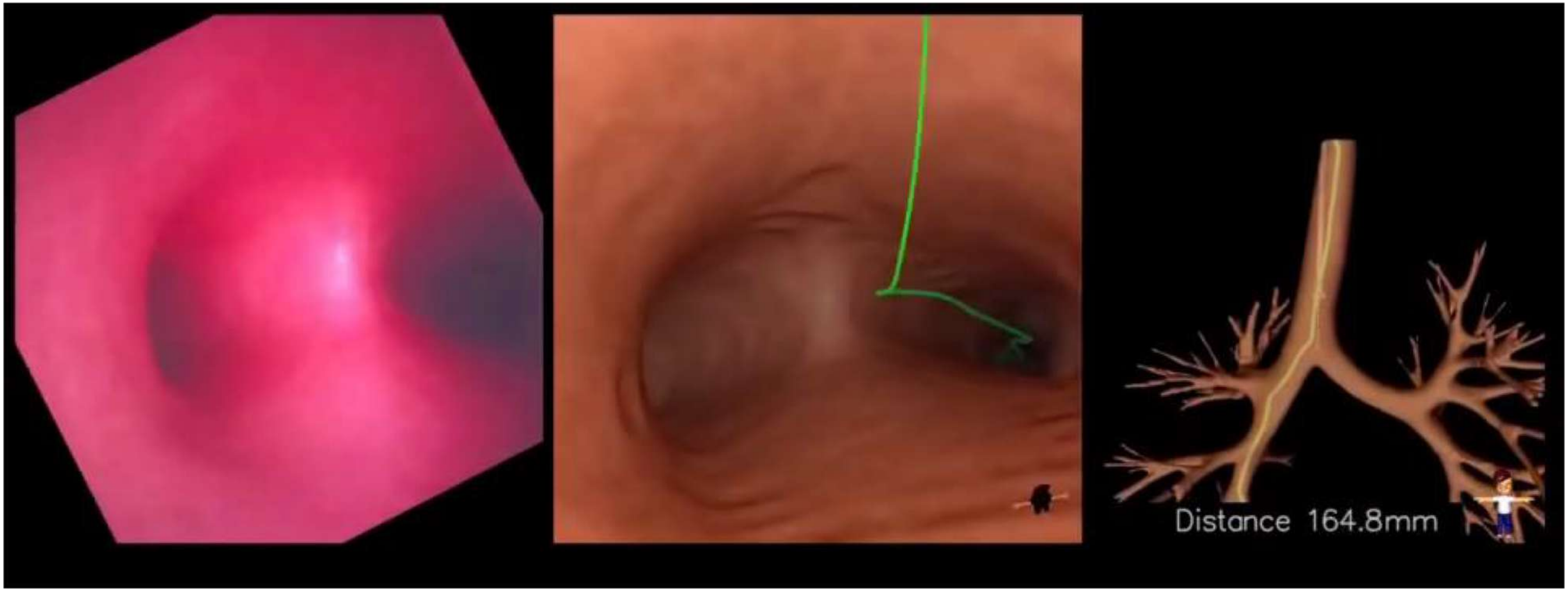
evolution: intelligent systems

It uses a VR visual system tht improves performances



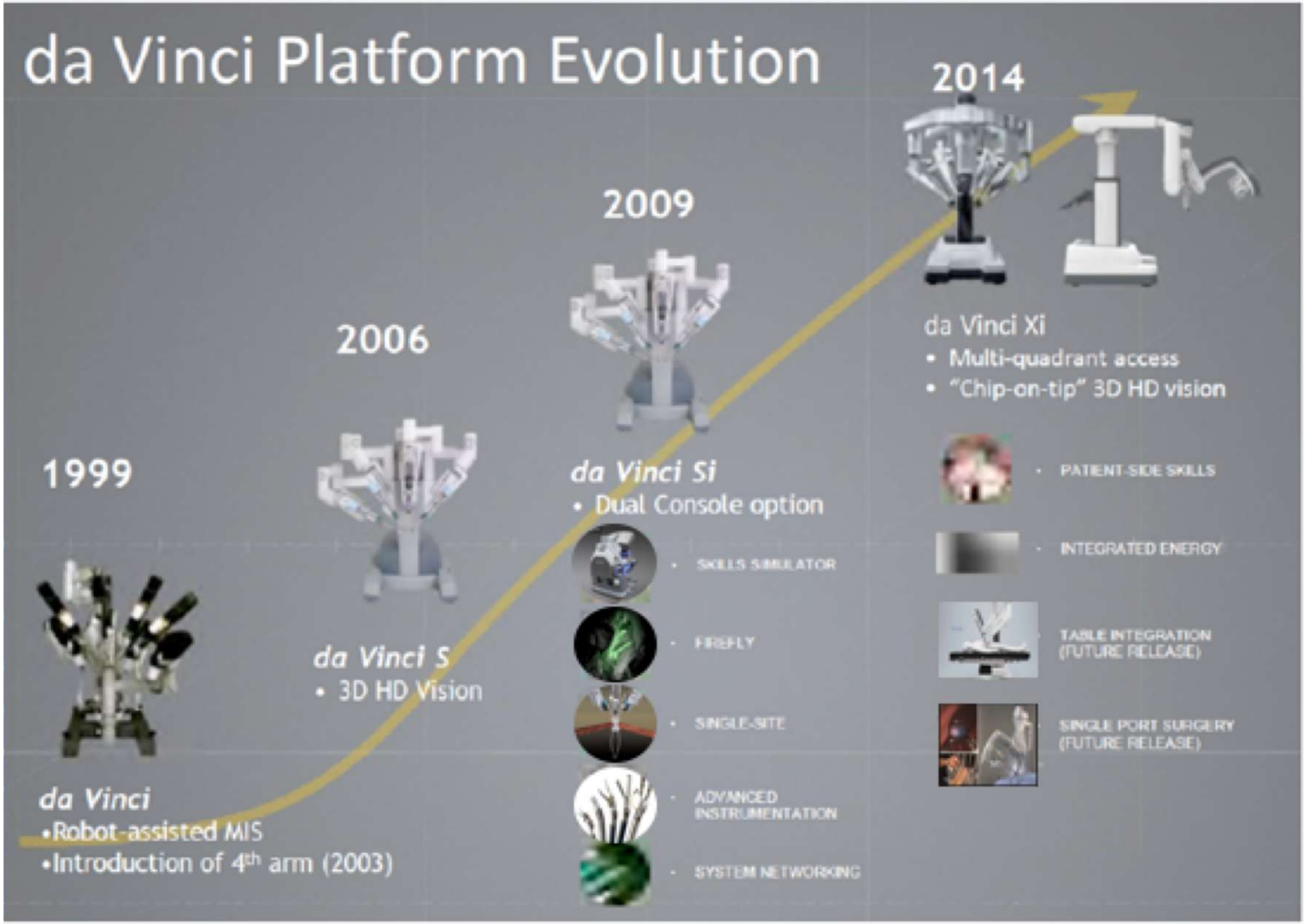
- state-of-the-art measures and sensors that provide real-time feedback can help in identifying structures
- not yet FDA cleared in the US

evolution: flexible catheter based system



• not yet FDA cleared in the US

many functions are added during the years for security and to the images analysis



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Product Development Cost and Complexity

- It took ~9 years and >$250M for Intuitive to reach profitability.
- 2013 R&D investment totaled $167 million, or ~$320 per patient.
- A *da Vinci* system is composed of >35,000 individual components (counting down to resistors) from >300 suppliers (direct).
- There are >2 million lines of embedded run-time code. Almost half of this code is related to safety and redundancy.
- A typical software verification will consist of ~40,000 test cases.
- The formally-maintained design history file is >10,000 pages of documentation.

A V-REP Simulator for the da Vinci Research Kit Robotic Platform

application that allows the use of the daVinci system.

developed by

G. A. Fontanelli*, M. Selvaggio*, M. Ferro**, F. Ficuciello*, M. Vendittelli** and B. Siciliano*

*University of Naples Federico II, ** Sapienza University of Rome

daVinci is very very expensive(2-3 millions of dollars). This, in particular, because it has some function for safety

motivation for developing a simulator

- da Vinci Research Kit (dVRK): repurposed core components donated by IS since 2012 coupled with software and controllers developed by research users
- an already quite wide community sharing the dVRK (32 systems in 28 sites worldwide)

- a simulation tool to
    - overcome the difficulty of replacing components in case of malfunctioning
    - test new tools design
    - validate control strategies
    - integrate learning in a simulation environments
    - provide an easy-to-access educational tool to students

available surgical simulators

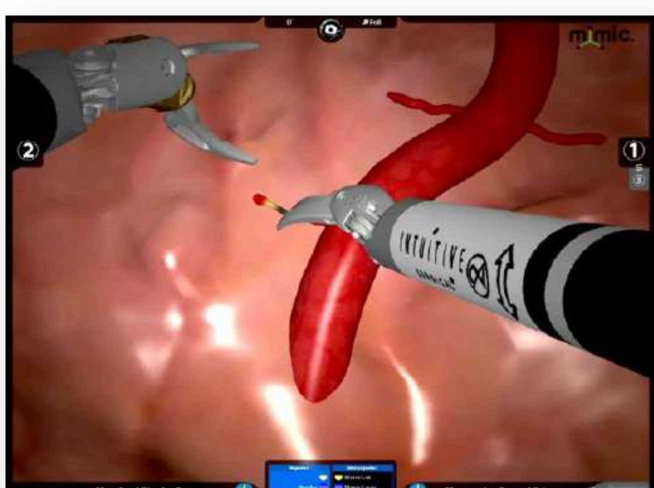
Surgical training simulators

softwares to get practice

Xron

dV trainer

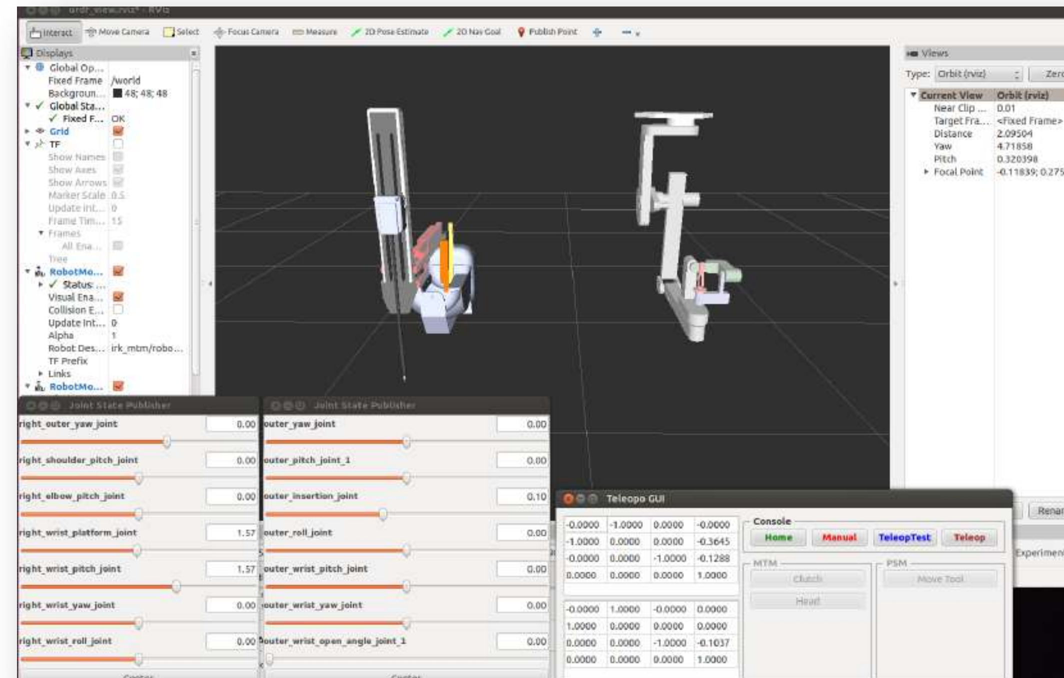
da Vinci skills simulator



robotix mentor

Research simulator

da Vinci Research Kit RVIZ



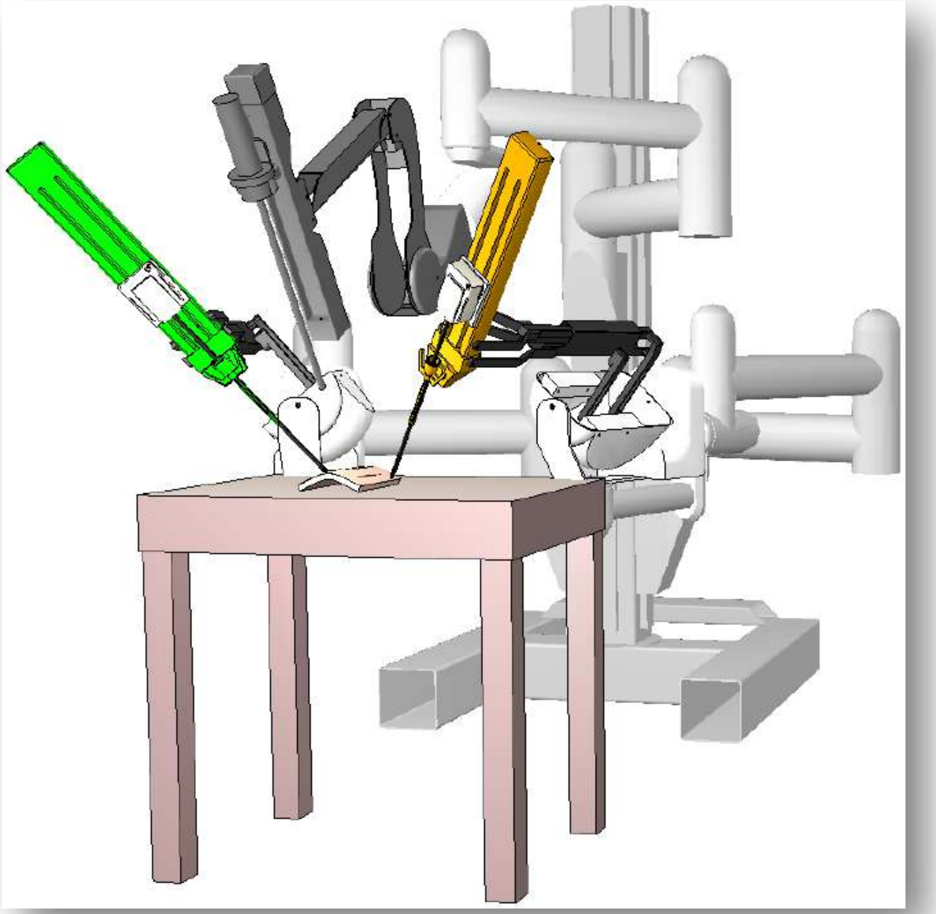
Robot Operating System:allows to design, implement and control robot

- integrated in ROS
- integration with other languages (Matlab, Python) but only using the dVRK code
- no Setup Joint simulated
- only visualizer: no physics
- not easy integration of objects, sensors etc. into the environment

you can simulate only the actuation part not the whole

V-REP simulator for the dVRK

- versatility and simplicity of this software for multi-robot applications
- each object/model can be individually controlled via an embedded script, a plugin, a ROS or BlueZero node, a remote API client, or a custom solution
- controllers can be written in C/C++, Python, Java, Lua, Matlab or Octave
- the simulator can be easily interfaced with the real surgeon master console
- new objects and robots can be imported in the scene by using a graphical interface



The complete simulator* is available at: https://github.com/unina-icaros/dvrk-vrep.git.

* currently recommended OS/middleware combinations: Ubuntu 14.04+ROS Indigo, Ubuntu 16.04+ROS Kinetic

Consider the whole machine is more complicated because for instance only for the support joint you have 6 joints and for the patient manipulator you have additional others 7 joints. The number of dof is in general quite high.

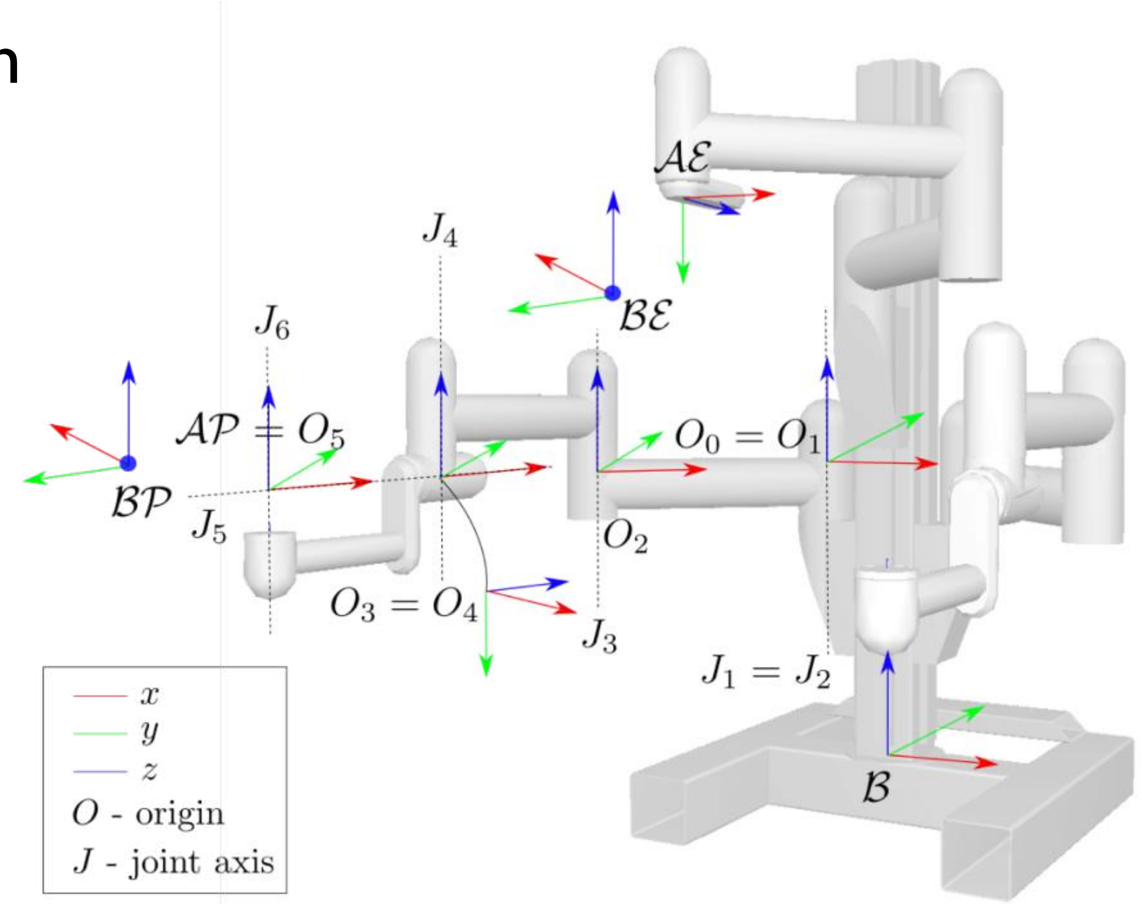
dVRK kinematics: SUJ

Endoscopic Camera Manipulator

- the two PSMs and the ECM are mounted on the SUJ, an articulated robotic structure composed by three arms

Patient Side Manipulator

- the two PSMs are located at the end of two 6-DoFs arms
- the ECM is located at the end of a 4-DoFs arm
- the real SUJ joints are not actuated by motors but it is possible to control breaks in each joint and read the angular position using potentiometers
- the simulated SUJ joints are position controlled



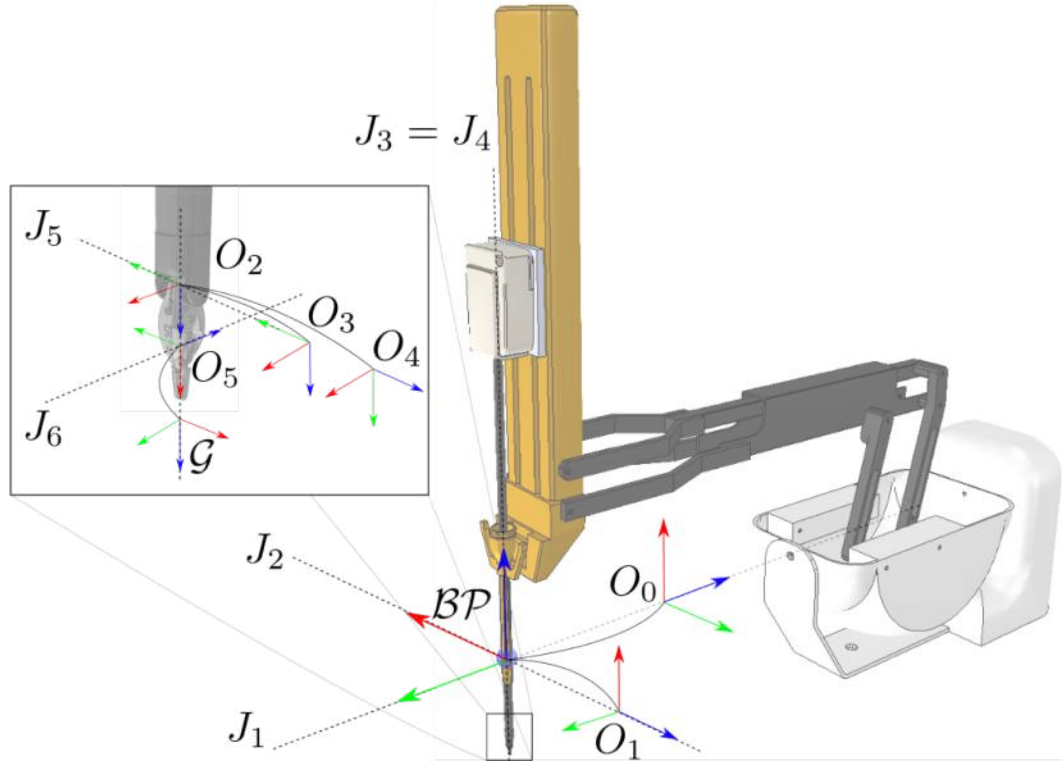
DH PARAMETERS OF THE SUJ

link	joint	a_i	α_i	d_i	θ_i
1	P	0	0	$q_{se,1}$	—
2	R	a_2	0	—	$q_{se,2}$
3	R	a_3	0	—	$q_{se,3}$
4	R	0	$-\pi/2$	—	$q_{se,4}$
5	R	0	$\pi/2$	$-d_4$	$q_{se,5}$
6	R	0	0	—	$q_{se,6}$

dVRK kinematics : PSM

It' a 7-dof arm but it refers to the actuated dof. Actually the full number of dof is higher.

- each PSM is a 7-DoF actuated arm, which moves a surgical instrument about a Remote Center of Motion (RCM)
- the first 6-DoFs correspond to Revolute (R) or Prismatic (P) joints, combined in a RRPRRR sequence
- the last DoF corresponds to the opening and closing motion of the gripper
- torque control possible



In the DH table we have only 6 joint because the last joint for open an close tthe wrist don't effect the kinematics of the robot

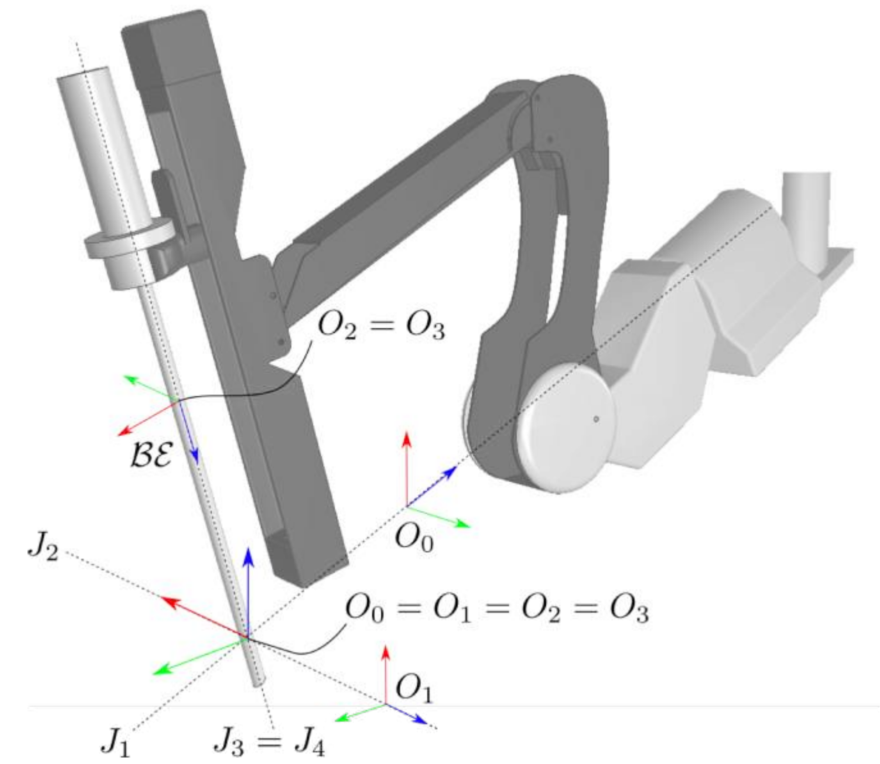
DH PARAMETERS OF THE PSM

link	joint	a_i	α_i	d_i	θ_i
1	R	0	$-\pi/2$	$-$	$q_{p,1}$
2	R	0	$-\pi/2$	$-$	$q_{p,2}$
3	P	0	0	$q_{p,3}$	$-$
4	R	0	$\pi/2$	$-$	$q_{p,4}$
5	R	a_5	$-\pi/2$	$-$	$q_{p,5}$
6	R	0	$-\pi/2$	$-$	$q_{p,6}$

dVRK kinematics : ECM

4-dof actuated arm, here we have not the wrist and the tool to simulate. The first 2 revolute joints are to rotate the structure(roll and pitch angle), the third is a prismatic joint and the last is a revolute joint which rotate around the axis of the tool itself.

- the ECM is a 4-DoF actuated arm, which moves the endoscopic camera about the RCM through revolute and prismatic joints, combined in a RRPR sequence
- at the end tip of the endoscope two cameras have been included to simulate the binocular vision system of the real dVRK endoscope
- controlled in position



DH PARAMETERS OF THE ECM

link	joint	a_i	α_i	d_i	θ_i
1	R	0	$-\pi/2$	—	$q_{e,1}$
2	R	0	$-\pi/2$	—	$q_{e,2}$
3	P	0	0	$q_{e,3}$	—
4	R	0	0	d_4	$q_{e,4}$

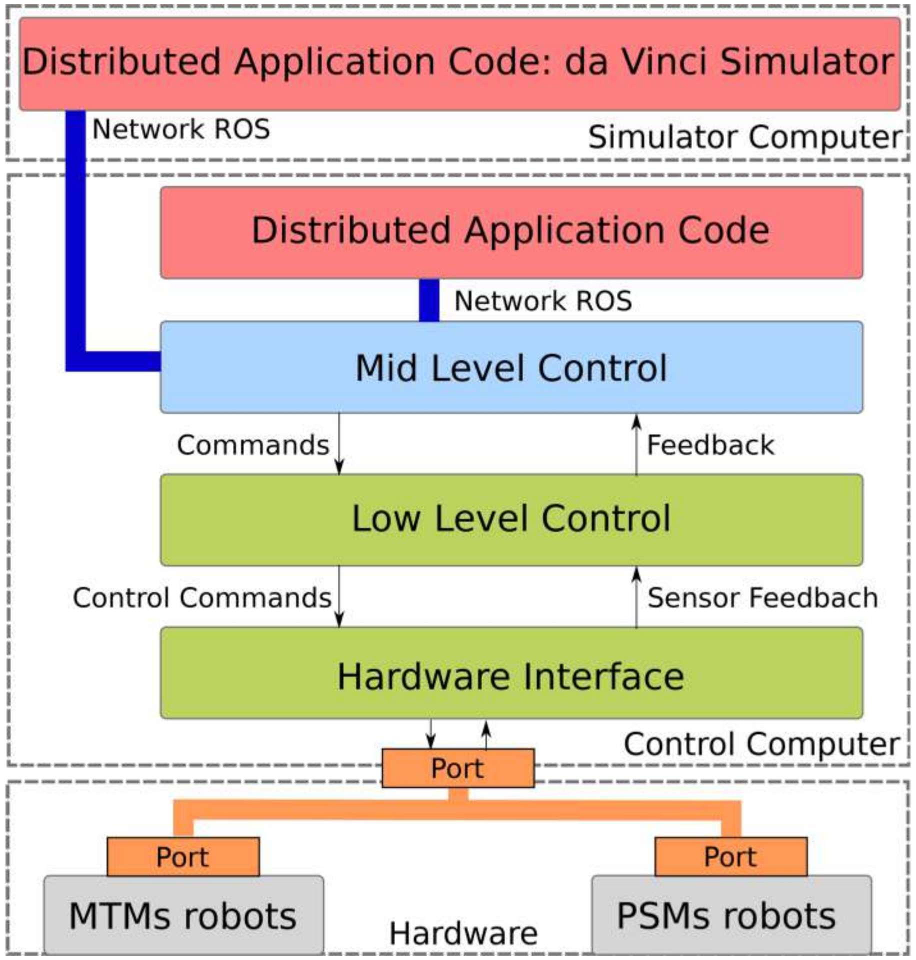
V-REP model of the complete dVRK

- each robot link has been realized by including two type of mesh:
  - one **visual mesh** with structure and texture similar to the real robot link,
  - one simplified **convex dynamic and respondable mesh** used to simulate dynamics and contacts
- the kinematic chain of each robotic arm is realized by linking mesh and joints in a **joint-respondable-visual** sequence
- dynamic parametrs included for each respondable link of the two PSMs
- the resulting complete robot is composed of 10178 triangles

V-REP control architecture

- full integration into the high level ROS framework of the dVRK control infrastructure

- different control modalities:
  - telemanipulated using the dVRK MTMs;
  - in combination with the real robotic PSMs and ECM, to implement augmented reality algorithms;
  - as standalone, by controlling the simulated robot using the ROS framework, (through C++, MATLAB or Python ROS nodes), or directly in V-REP using custom scripts

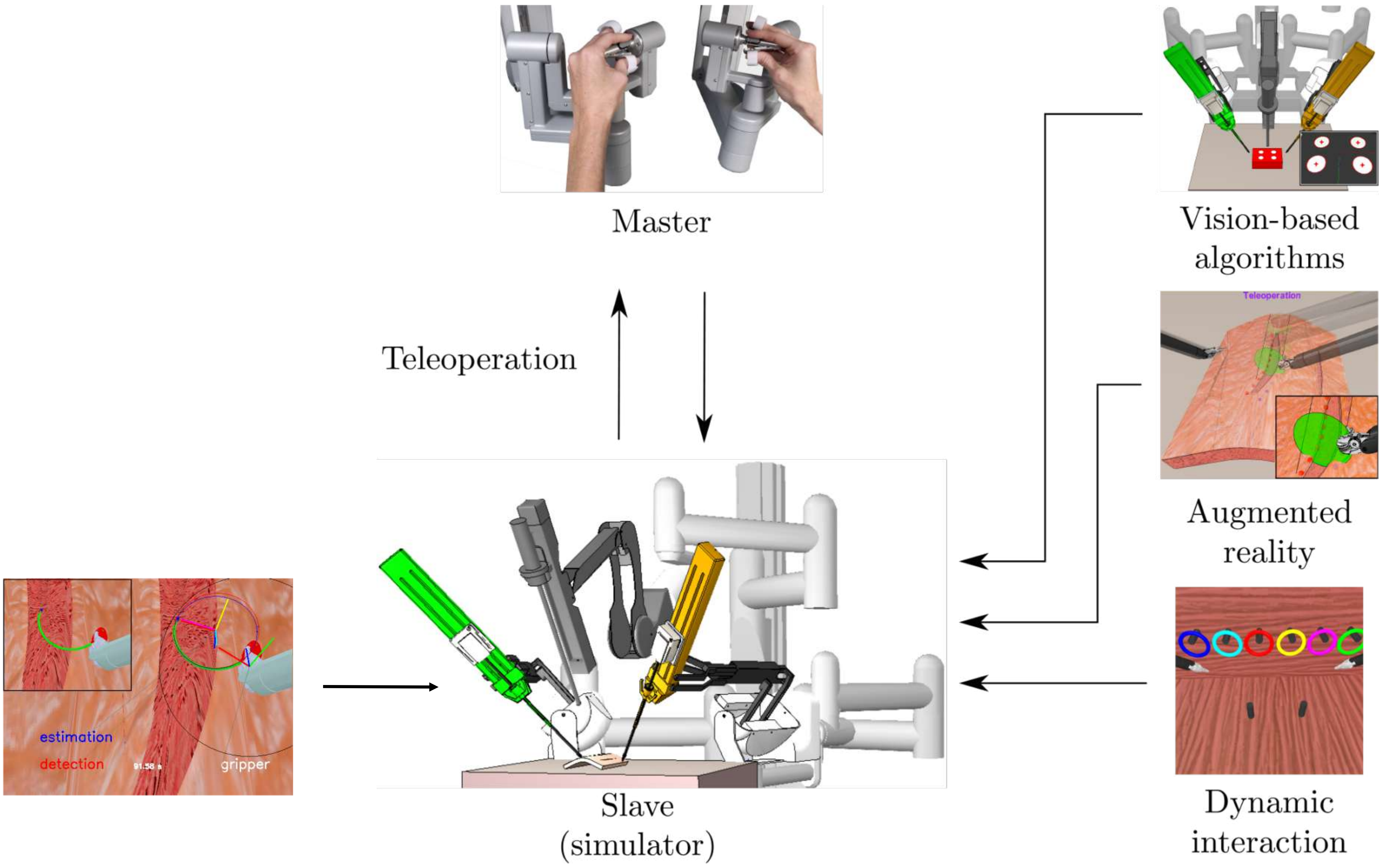


- cameras topics streamed at 60 Hz*

- joints and objects topics streamed at 220Hz

*The simulation requires to be run in threaded-rendering mode, in order to decouple the rendering and the control scripts and speed up the execution.

Example scenes

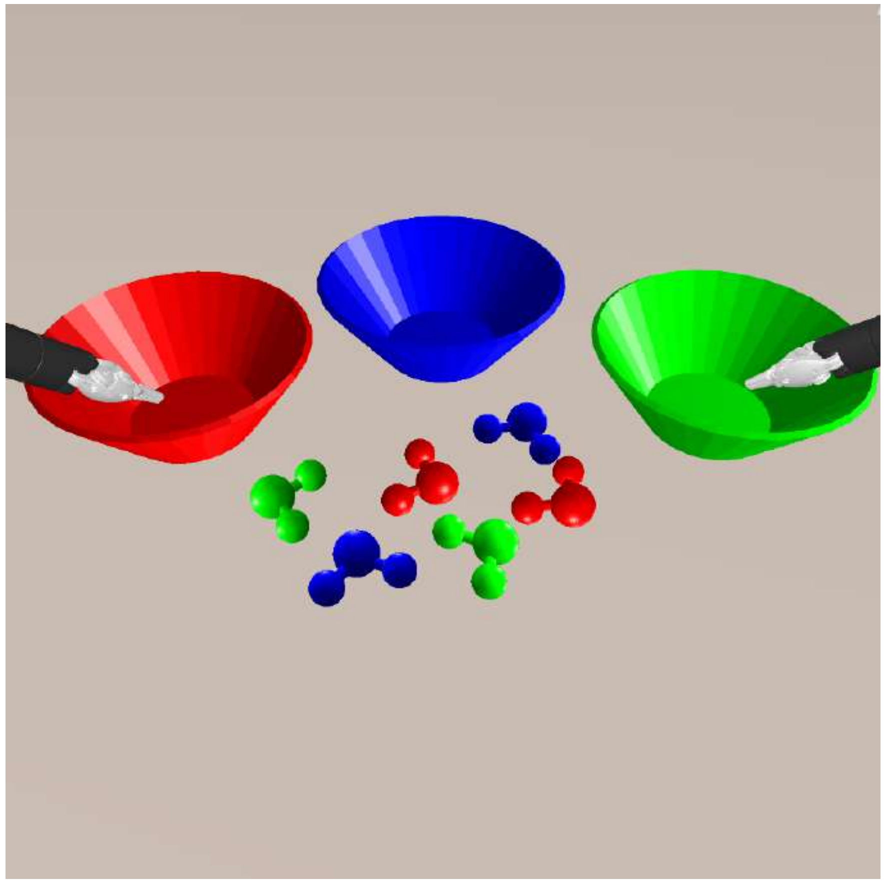


Example scenes: training

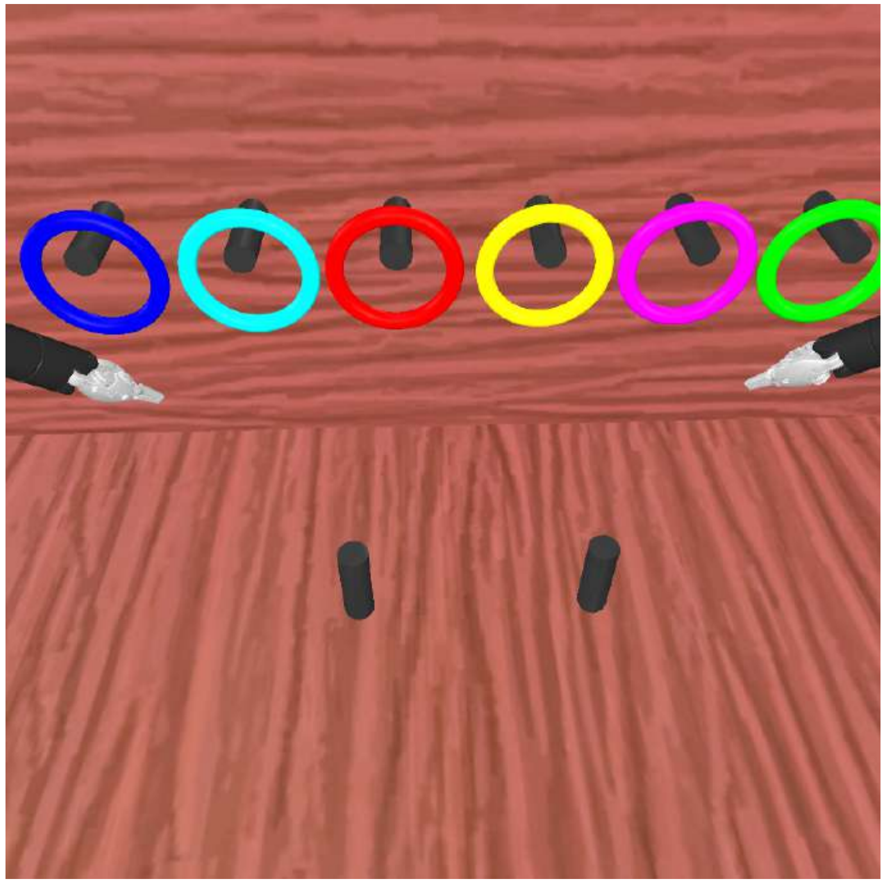
- engineers may need to train themselves to develop and test novel control strategies
- contacts and interactions among objects have been simulated by creating respondable and simplified dynamic entities through the embedded V-REP functions
- a proximity sensor between the needle driver pads is used to simulate objects grasping

the training task is to place the object

pick & place



peg on board

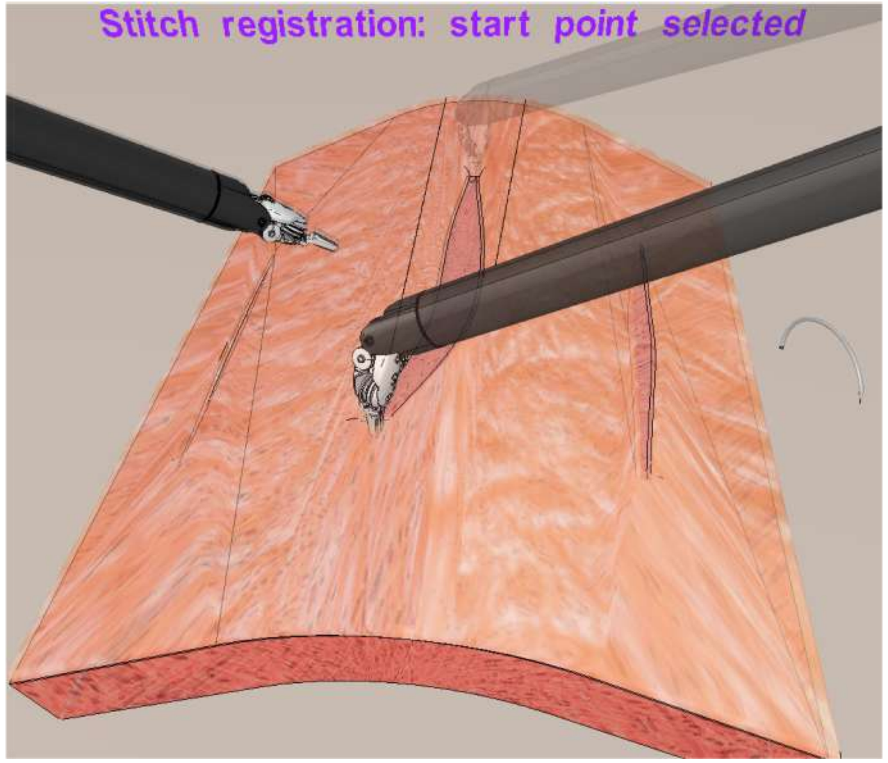


Example scenes: suturing

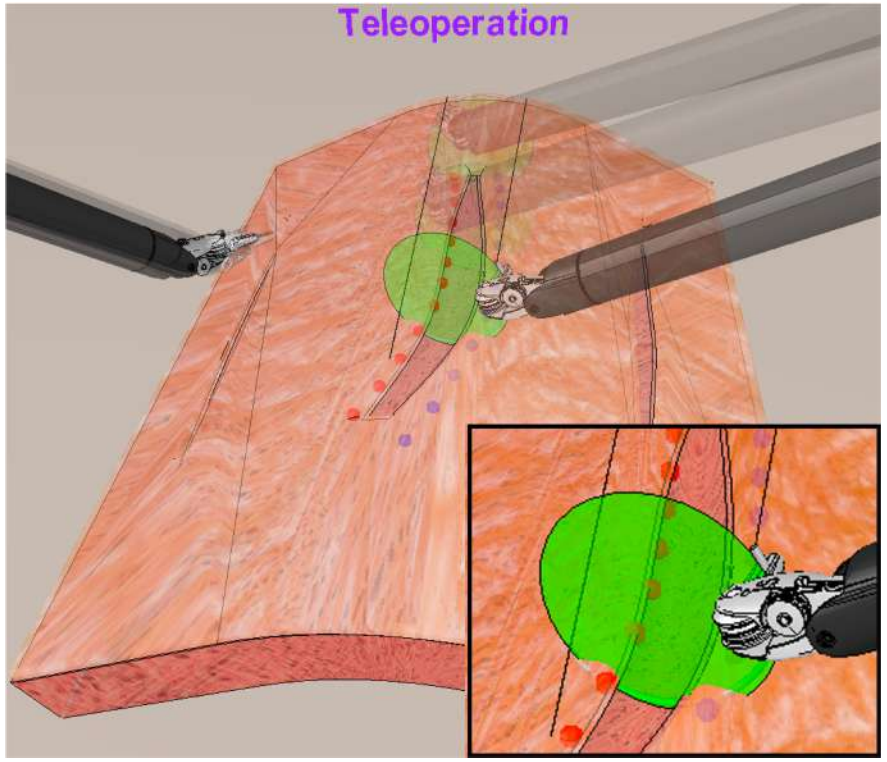
- a suturing phantom has been designed taking inspiration from real commercial phantoms
- banners and overlayed objects are included to give information through augmented reality

We add means to have more info and this is what the augmented reality does.

Wound registration



Stitch planning and execution

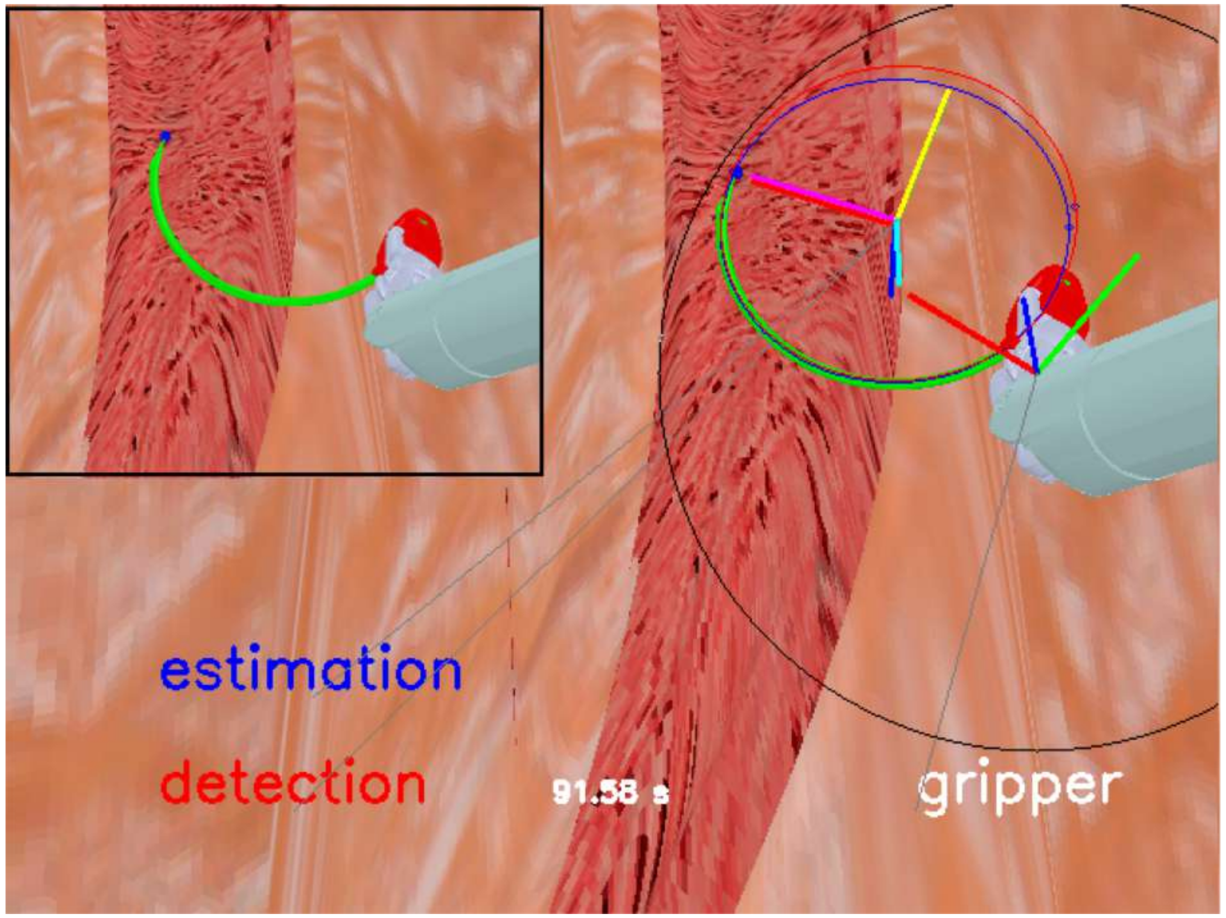


[2] G.A. Fontanelli, G. Z.Yang , B. Siciliano, "A comparison of assistive methods for suturing in MIRS" IROS 2018

Example scenes: needle tracking

- using the simulated stereo-cameras to track a suturing needle
- both the visual information and the PSM arm kinematic information are provided by V-REP

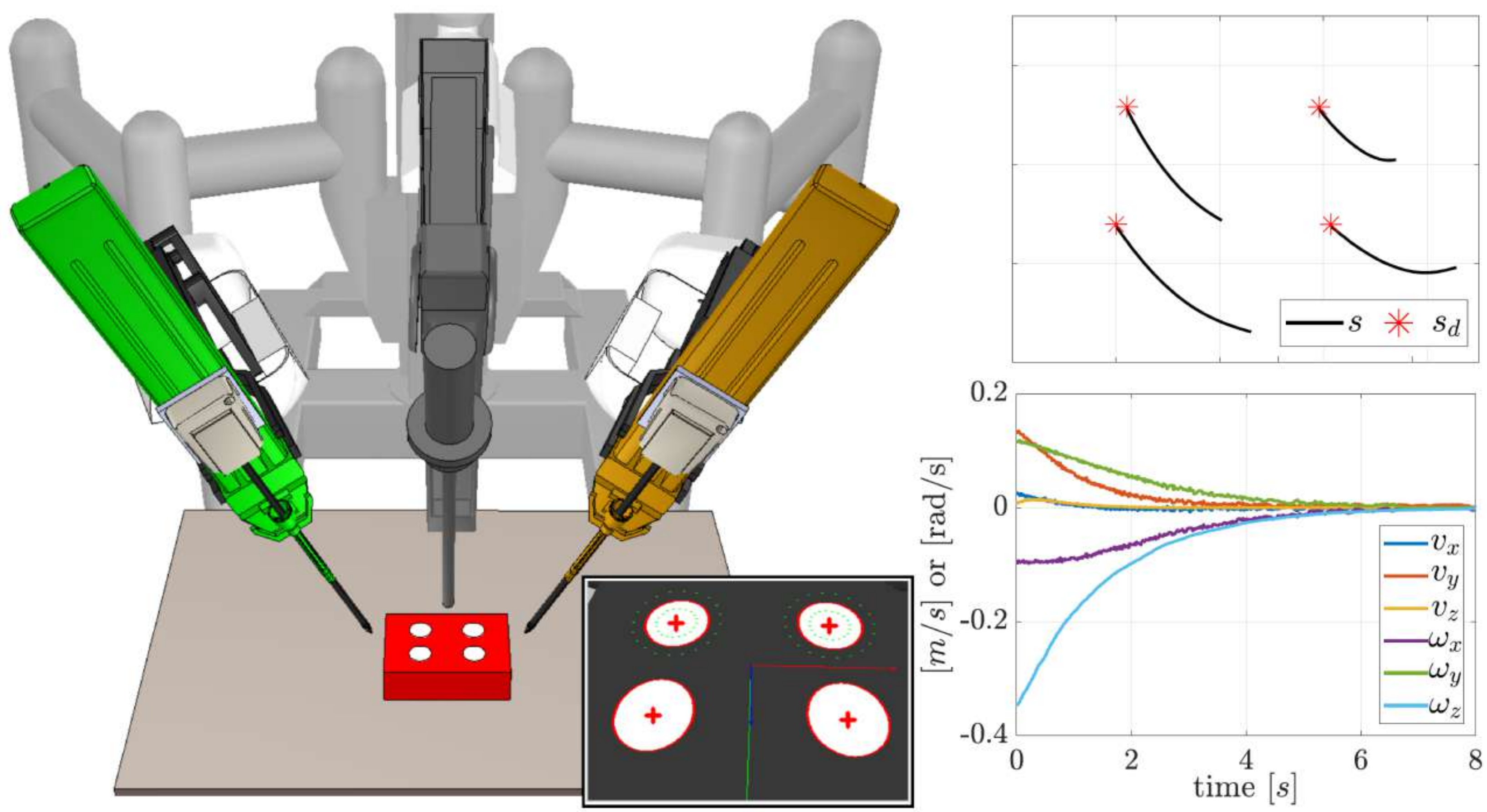
Needle visual segmentation and tracking



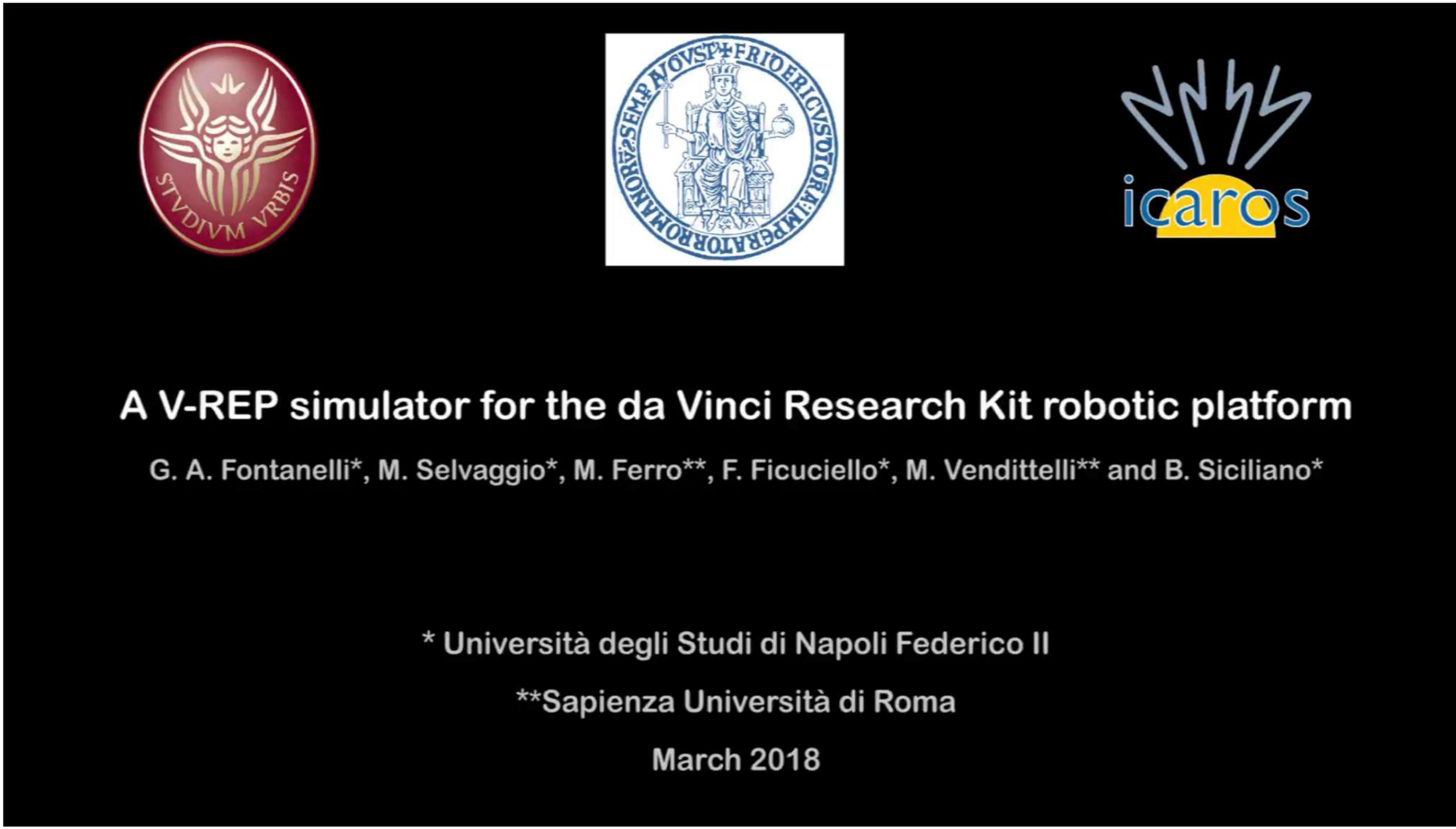
[3] M. Ferro, G. A. Fontanelli, F. Ficuciello, B. Siciliano, M. Vendittelli, "Vision-based suturing needle tracking with Extended Kalman Filter" CRAS 2017

Example scenes: visual servoing

- autonomously regulating the pose of the ECM to track a desided object
- simulated images are streamed through customary ROS topics and are then processed to extract the needed visual features
- both the visual information and the PSM arm kinematic information are provided by V-REP



Overview



VIDEO

Extensions

https://youtu.be/TWvy70cxzZU

VIDEO