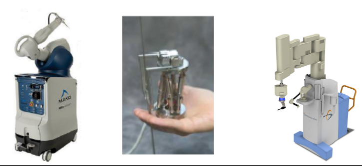
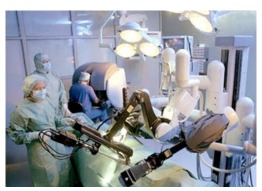
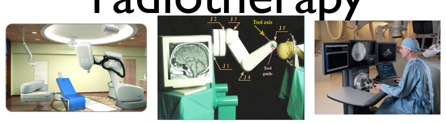
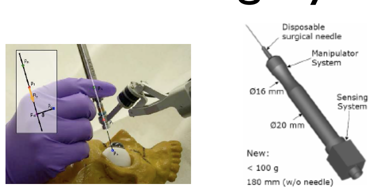
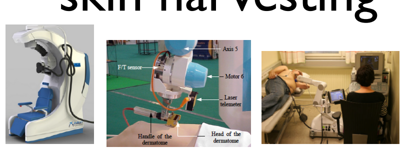
Medical Robotics

Marilena Vendittelli

Kinematic Design of Medical Robots

SAPIENZA
UNIVERSITÀ DI ROMA

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, intervent. radiology, radiotherapy 	constrained targeting	conventional + front-end with dedicated architecture 5 or 6 dof	teleoperation (semi)-autonomous	MR/CT compatible (pneumatic, 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-echo, TMS, skin harvesting 	surface tracking	conventional + dedicated wrist architecture	autonomous teleoperation	conventional vel: mm/s force: few N

general specifications (by the row)

- required degrees of freedom

- workspace and type of motions

  ➡robot kinematic architecture

- control modality

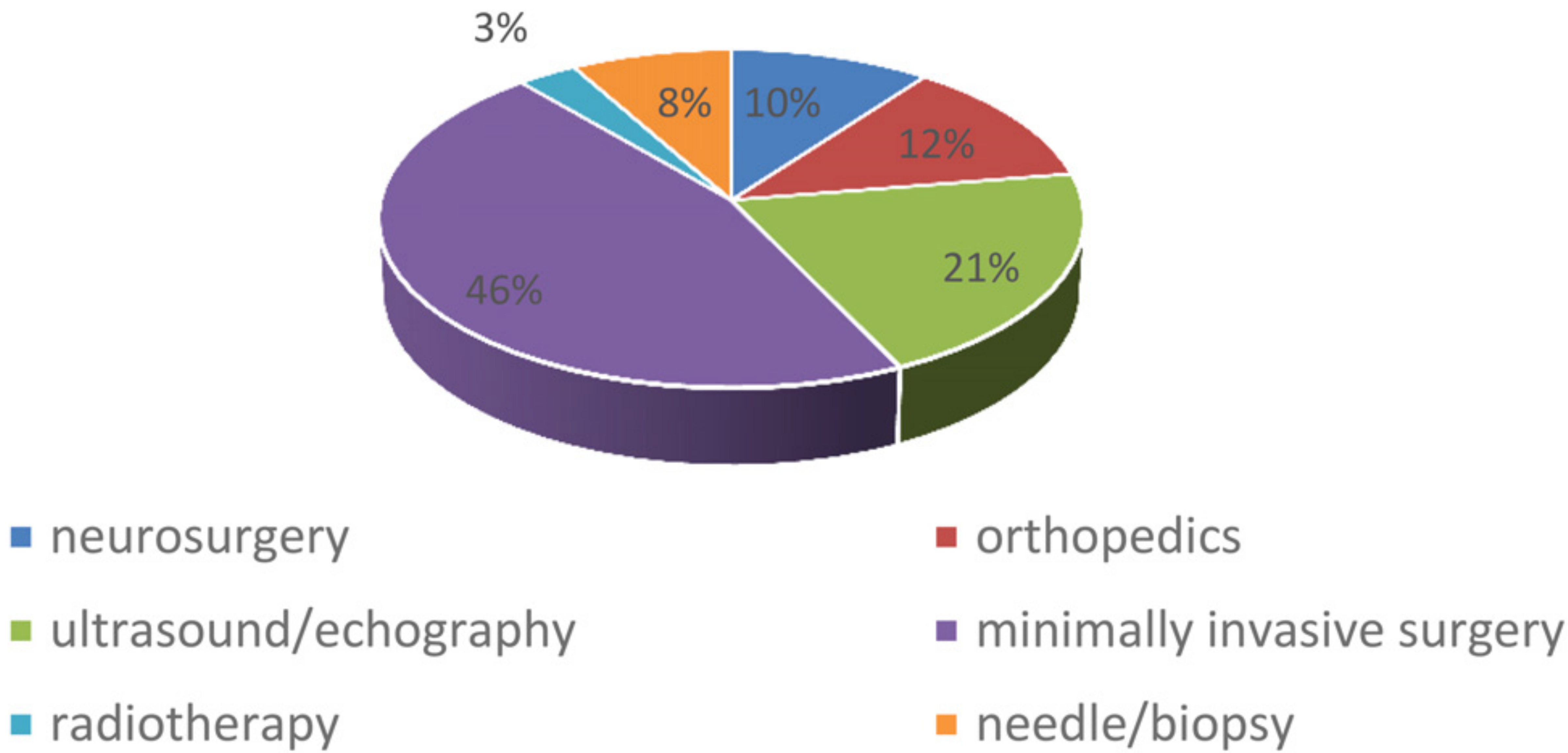
- required velocities and accelerations

- required forces and torques

  ➡sensors and actuators

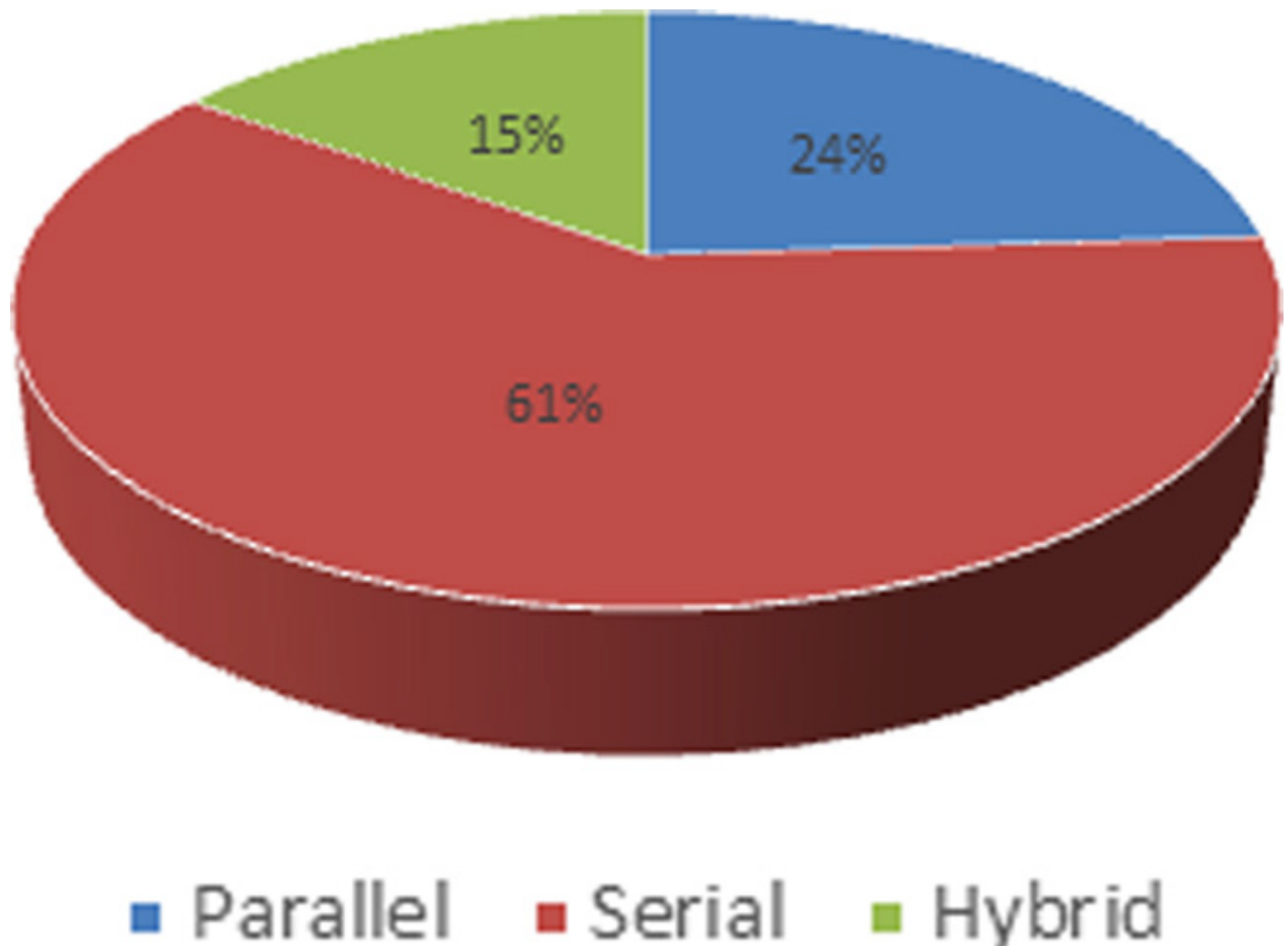
distribution of the domains of use (1)

(~ 100 medical robots considered)

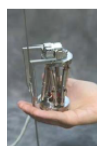
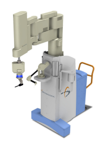
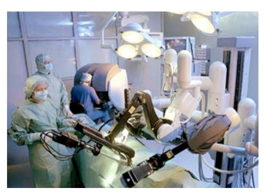
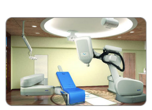
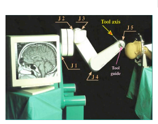
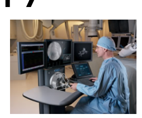
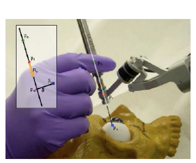
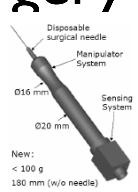
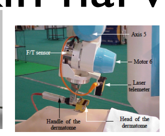
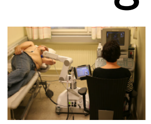


distribution of kinematic structure (1)

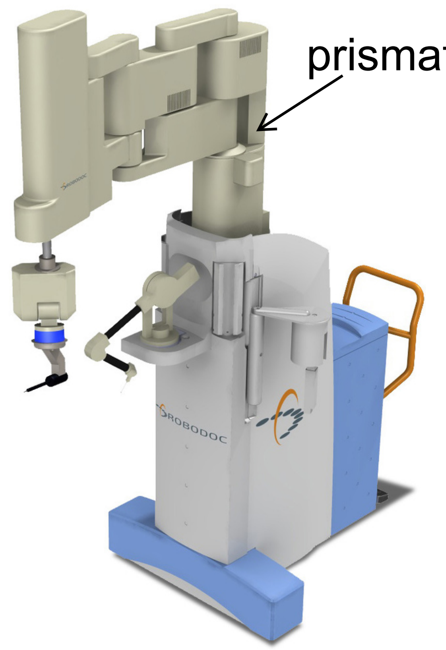
kind of kinematic architecture



both parallel and serial

domain of use	function	kinematic architecture	control modality	sensors and actuators
orthopedics   	machining of rigid surface	conventional serial or parallel + possible dedicated wrist with 5 (drill) or 6 (cut) dof	autonomous cooperative or "hands-on"	conventional vel: mm/s force: until 100N
MIS 	constrained manipulation	RCM passive joints 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, intervent. radiology, radiotherapy   	constrained targeting	conventional + front-end with dedicated architecture 5 or 6 dof	teleoperation (semi)-autonomous	MR/CT compatible (pneumatic, ultrasonic) force: few N insertion (usually) manual (undetermined in case of neurosurgery)
microsurgery  	micromanipulation	dedicated kinematic architecture, possible RCM	shared/ cooperative teleoperation	piezo, ultrasonic actuators force: few mN vel: 0.70m/s (manual procedure)
tele-echo, TMS, skin harvesting   	surface tracking	conventional + dedicated wrist architecture possible RCM	autonomous teleoperation	conventional vel: mm/s force: few N

two important kinematic types



prismatic joint here

It is composed by a planar arm with 3 joints

- SCARA manipulator plus two final dof
- hip and knee surgery
- autonomous (active)

ROBODOC

Curexo Technology Corporation

It is used in the orthopedics domain

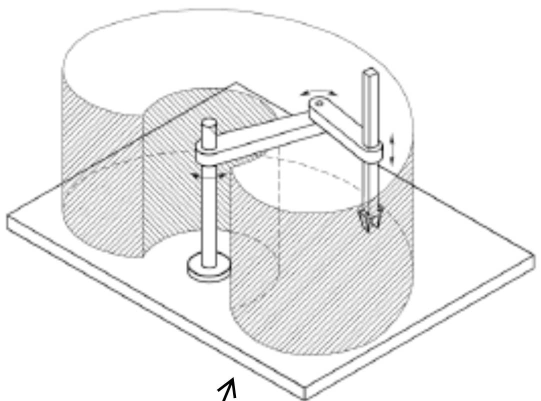
- anthropomorphic manipulator plus three final dof
- knee surgery
- interactive ("hands-on")

MAKO (based on Acrobot)

stryker company

There is always a cooperation between the robot and the surgeon. the role of robot is to constrain the motion of the surgeon we compare the two architectures with respect to the surgical tasks.

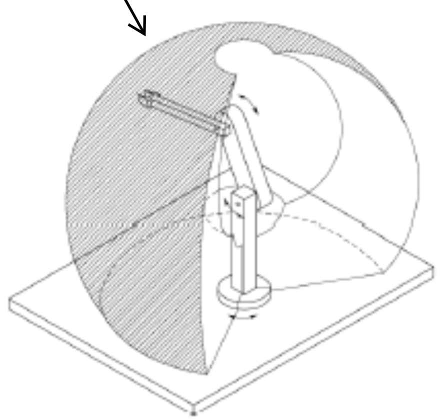
SCARA vs anthropomorphic

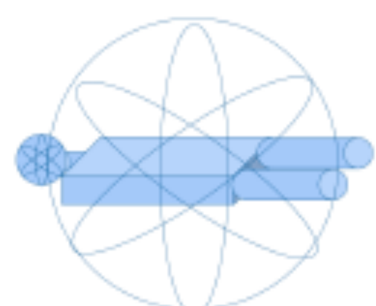


SCARA

- workspace fits well the intervention volume
- inverse kinematics in closed form
- in case of fault, can not collapse on the patient under gravity

workspace





anthropomorphic

less effective than the SCARA

- part of the workspace is not used
- inverse kinematics in closed form

DISADVANTAGE

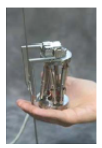
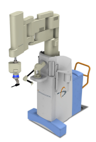
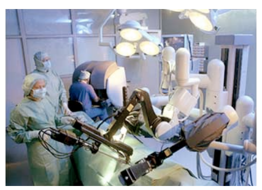
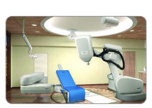
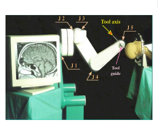
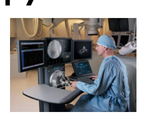
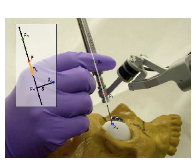
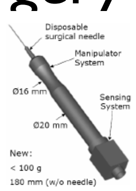
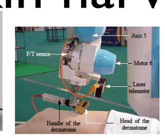
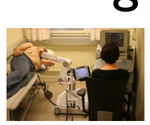
- needs brakes to prevent the robot from collapsing when the power is off

The singularity of the first three dof can be characterized in the workspace, and so by planning in an appropriate way the trajectory of the EE in particular the center of the wrist, it's possible to avoid singularities.

- structure singularities can be characterized in the workspace and avoided by appropriately planning the end-effector trajectory

If I plan the trajectory inside the my workspace, I can avoid this singularities

- spherical wrist singularities can be encountered anywhere inside the manipulator reachable workspace

domain of use	function	kinematic architecture	control modality	sensors and actuators
orthopedics   	machining of rigid surface	conventional serial or parallel + possible dedicated wrist 5 (drill) or 6 (cut) dof	autonomous cooperative or "hands-on"	conventional vel: mm/s force: until 100N
MIS 	constrained manipulation	RCM passive joints 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, intervent. radiology, radiotherapy   	constrained targeting	conventional + front-end with dedicated architecture 5 or 6 dof	teleoperation (semi)-autonomous	MR/CT compatible (pneumatic, ultrasonic) force: few N insertion (usually) manual (undetermined in case of neurosurgery)
microsurgery  	micromanipulation	dedicated kinematic architecture, possible RCM	shared/ cooperative teleoperation	piezo, ultrasonic actuators force: few mN vel: 0.70m/s (manual procedure)
tele-echo, TMS, skin harvesting   	surface tracking	conventional + dedicated wrist architecture possible RCM	autonomous teleoperation	conventional vel: mm/s force: few N

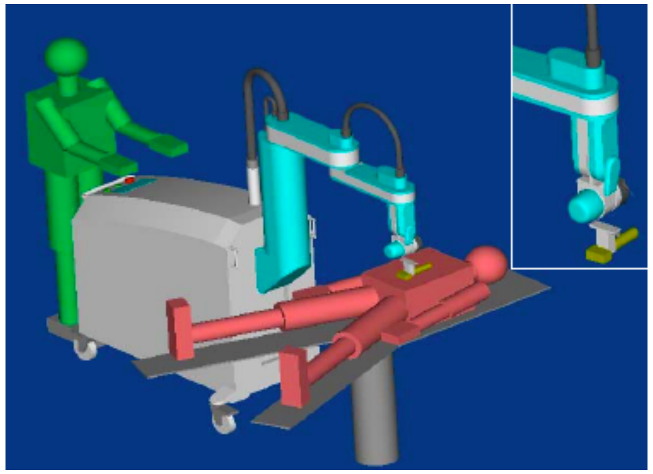
ex. of dedicated wrist

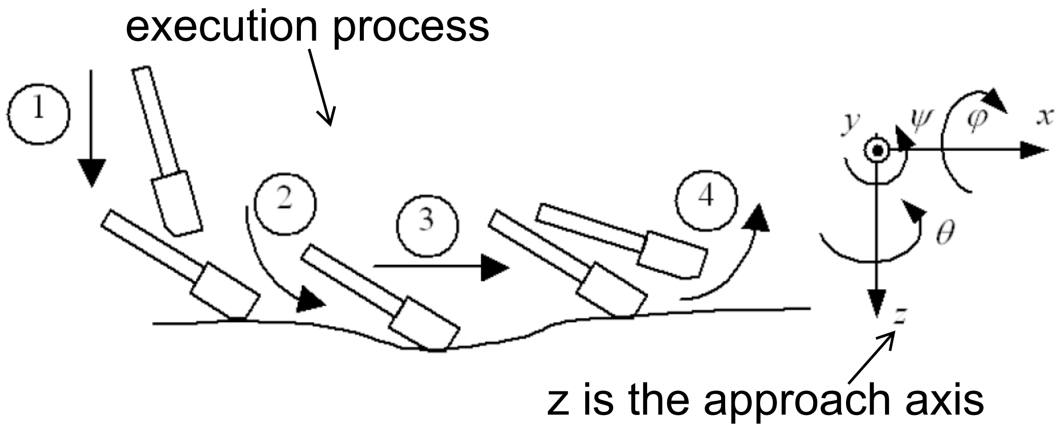
example

the robot is used to take samples of the skin, collected from some parts of the body

the SCALPP project

(**S**ystème de **C**oupe **A**utomatisé pour **L**e **P**rélèvement de **P**eau)



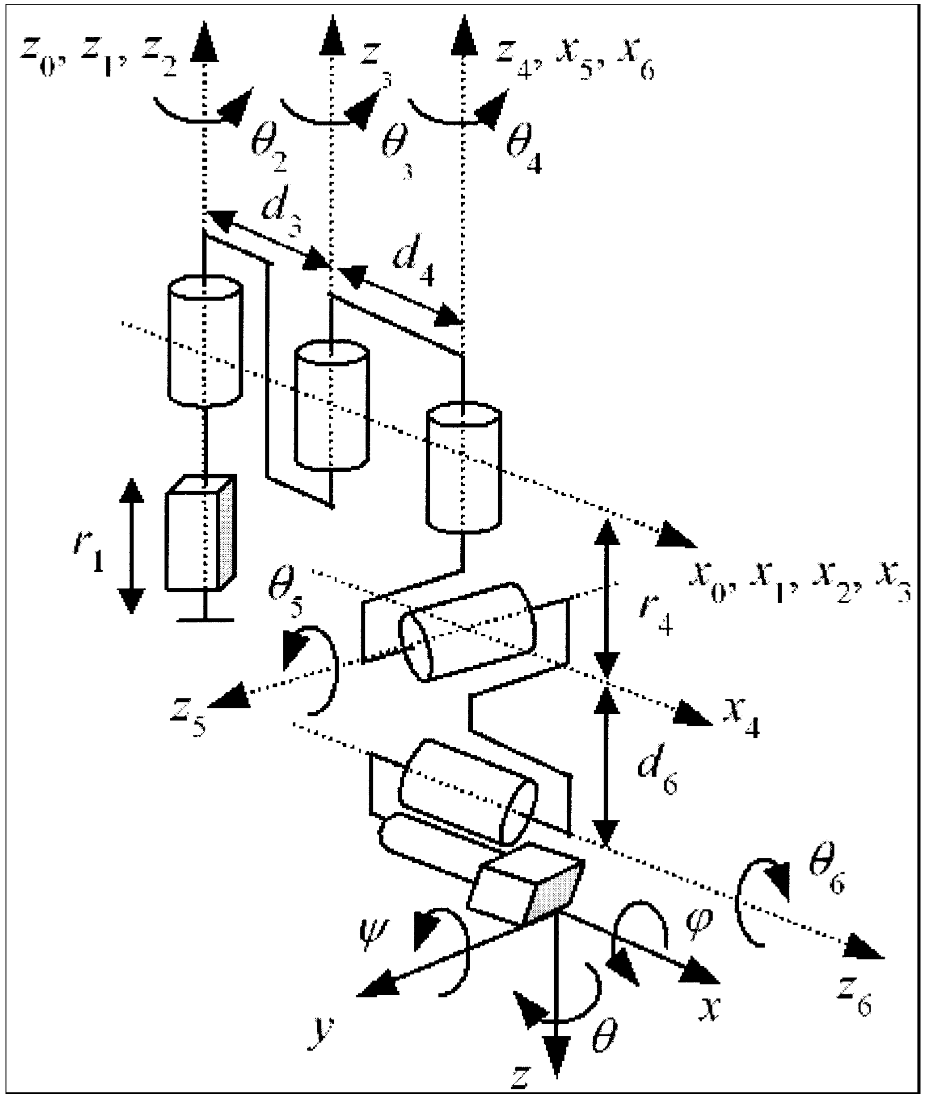


The architecture is that of a SCARA, on the wrist is mounted a tool which is called DERMATOME. There is a blade that cuts the superficial part of the skin and take a sample of the skin to be used.

design constraints

- for asepsis considerations, non-medical equipment can not be closer than 400 mm to the operating table
- the length of a zone to harvest may vary from a few millimeters to 400 mm (which corresponds to the length of a thigh); the orientation change of the dermatome may be up to 90^0 about the y axis (skull harvesting), and a few degrees about the z axis
- the robot might be set up on either side of the OT $\Rightarrow$ symmetrical joint limits
- good accessibility to the dermatome handle is needed
- motion free from singularities and joint limits

The first four dof are like the SCARA. In the last 3 dof the robot is characteristics with respect to the surgical task. But the last 2 are designed in such a way to keep wrist singularities of the useful workspace.

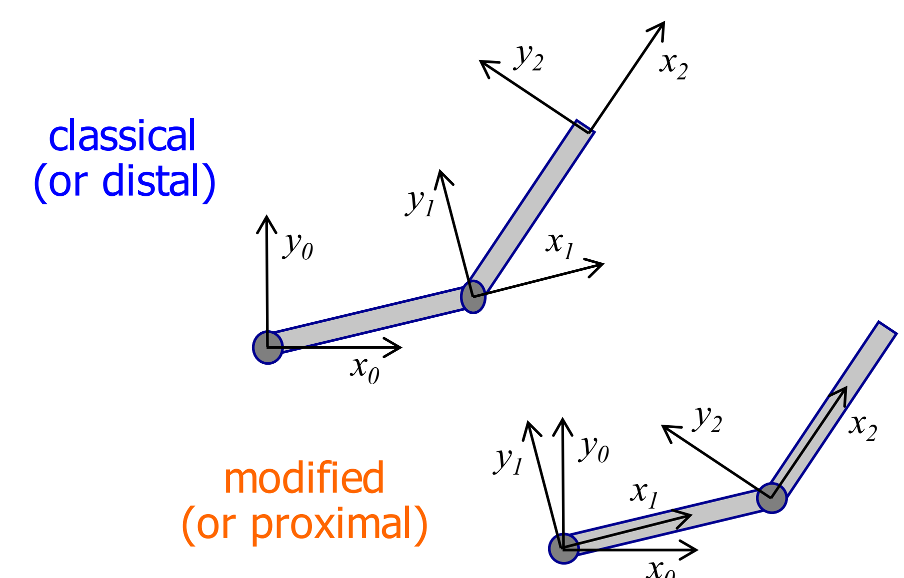


- SCARA manipulator plus two final dof $\Rightarrow$ 6 dof
- non-spherical wrist $\Rightarrow$ no singularities within the reachable workspace
- one classical singularity at the elbow
- autonomous (active)

i	α_i	a_i	q_i	d_i
1	0	0	r_1	0
2	0	0	θ_2	0
3	0	d_3	θ_3	0
4	0	d_4	θ_4	r_4
5	$\frac{\pi}{2}$	0	$\theta_5 + \frac{\pi}{2}$	0
6	$\frac{\pi}{2}$	d_6	θ_6	0

(modified) Denavit-Hartenberg parameters

- a modified version used in J. Craig's book "Introduction to Robotics", 1986
  - has z_i axis on joint i
  - a_{i-1} & α_{i-1} = distance & twist angle from z_{i-1} to z_i, measured along & about x_{i-1}
  - d_i & θ_i = distance & angle from x_{i-1} to x_i, measured along & about z_i
  - source of much confusion... if you are not aware of it (or don't mention it!)
  - convenient with link flexibility: a rigid frame at the base, another at the tip...



direct kinematics

$$
{}^0T_6 = \begin{bmatrix} -c_{234}s_5c_6 + s_{234}s_6 & c_{234}s_5s_6 + s_{234}c_6 & c_{234}c_5 & d_4c_{23} + d_3c_2 - d_6c_{234}s_5 \\ -c_{234}s_6 - s_{234}s_5c_6 & -c_{234}c_6 + s_{234}s_5s_6 & s_{234}c_5 & d_4s_{23} + d_3s_2 - d_6s_{234}s_5 \\ c_5c_6 & -c_5s_6 & s_5 & r_1 + r_4 + d_6c_5 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

The manipulator has no singularities inside the useful workspace

singularities

$$
\det {}^6J_6 = d_3d_4 \sin\theta_3 \cos\theta_5
$$

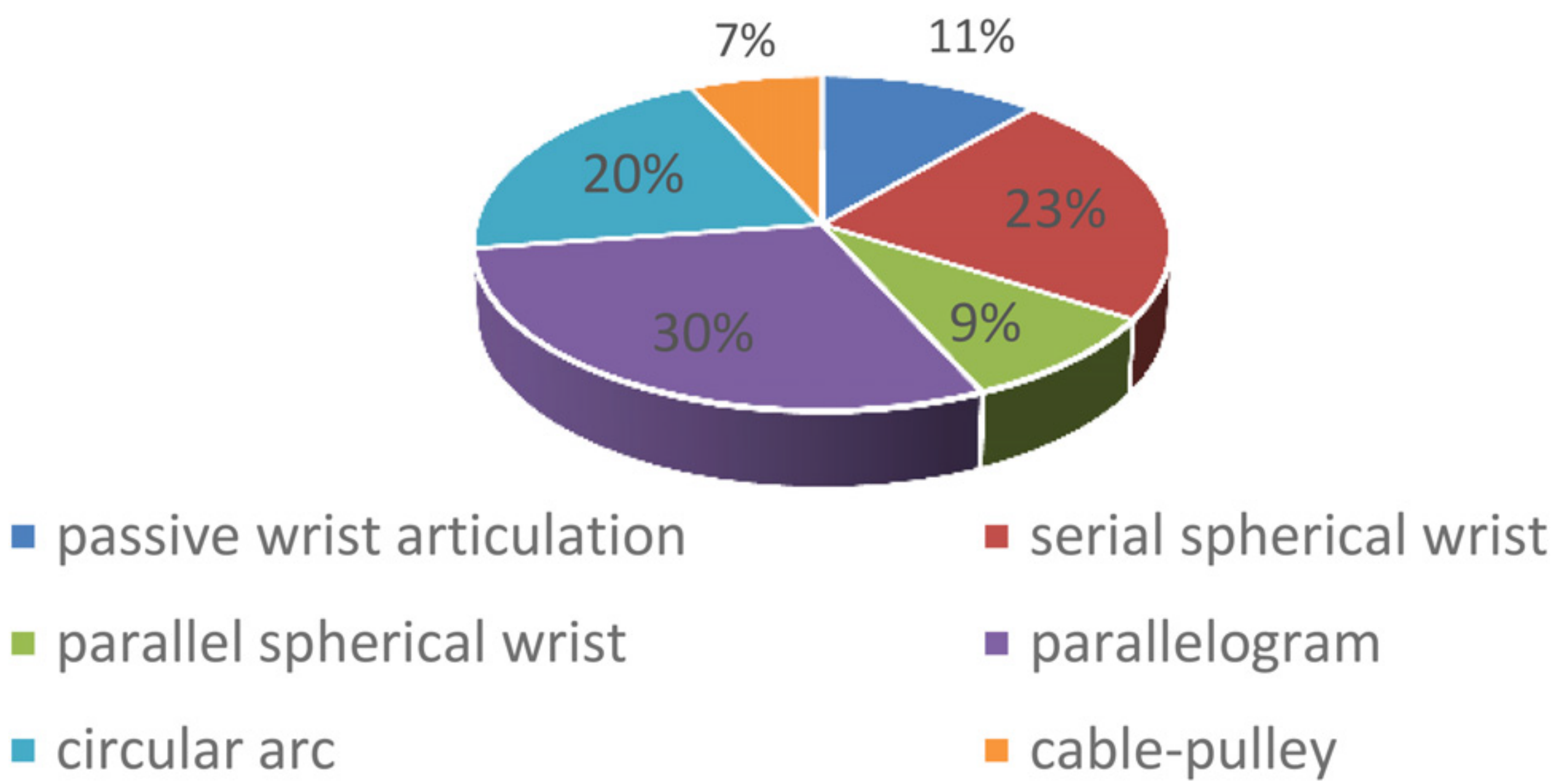
- θ_3: typical SCARA elbow singularity
- θ_5: not compatible with the task

inverse kinematics

given the end-effector pose ${}^0T_E = \begin{bmatrix} \mathrm{s} & \mathrm{n} & \mathrm{a} & \mathrm{p} \\ 0 & 0 & 0 & 1 \end{bmatrix}$

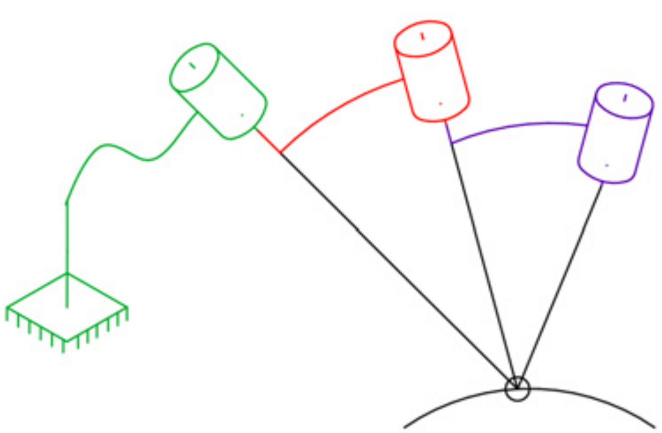
1. from the third row of ${}^0T_6$ one determines θ_5, θ_6, r_1 as a function of s_z, n_z, a_z, p_z and obtaines the matrices ${}^4T_5$ e ${}^5T_6$
2. the equation ${}^0T_1\,{}^1T_2\,{}^2T_3\,{}^3T_4 ={}^0 T_E\,{}^ET_6\,{}^6T_5\,{}^5T_4$ describes the direct kinematics of a SCARA with 4 dof (the rhs is a function of θ_5 and θ_6 only)
3. due to the joint limits one of the solutions for θ_5 is not valid so that only two solutions are possible: "elbow right" and "elbow left" (choice left to the surgeon)

other “wrist” architectures in medical robots (1)

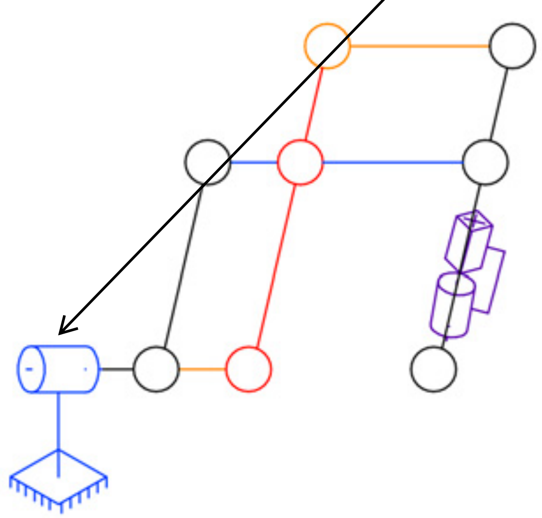


rotates arround the first revolute joint

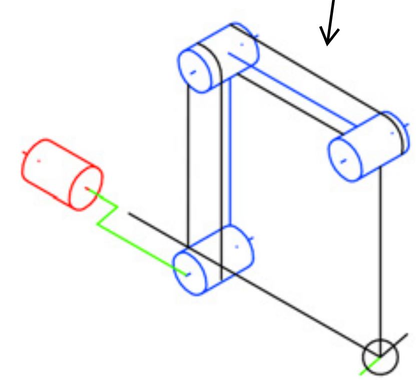
analogue to the parallelogram but
here we have cable to transmit motion



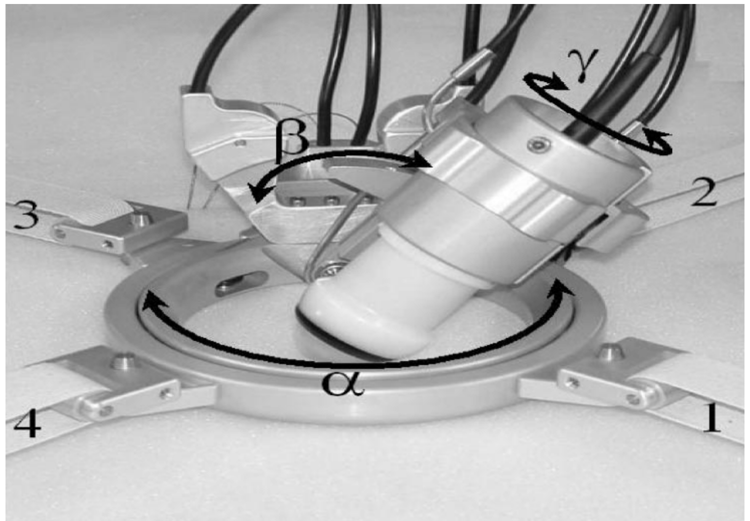
serial



parallelogram



cable-pulley



circular arc

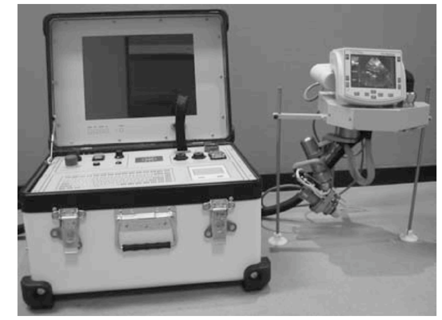
used especially for telegraohy

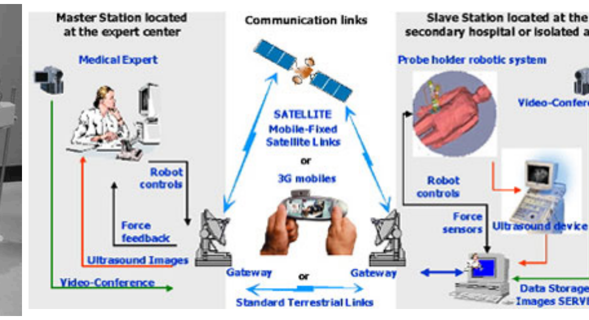
The doctor is very far from the patient so we are talking about real teleoperation.

example: the Otelo robot

mObile Tele-Ecography using an ultra-Light rObot

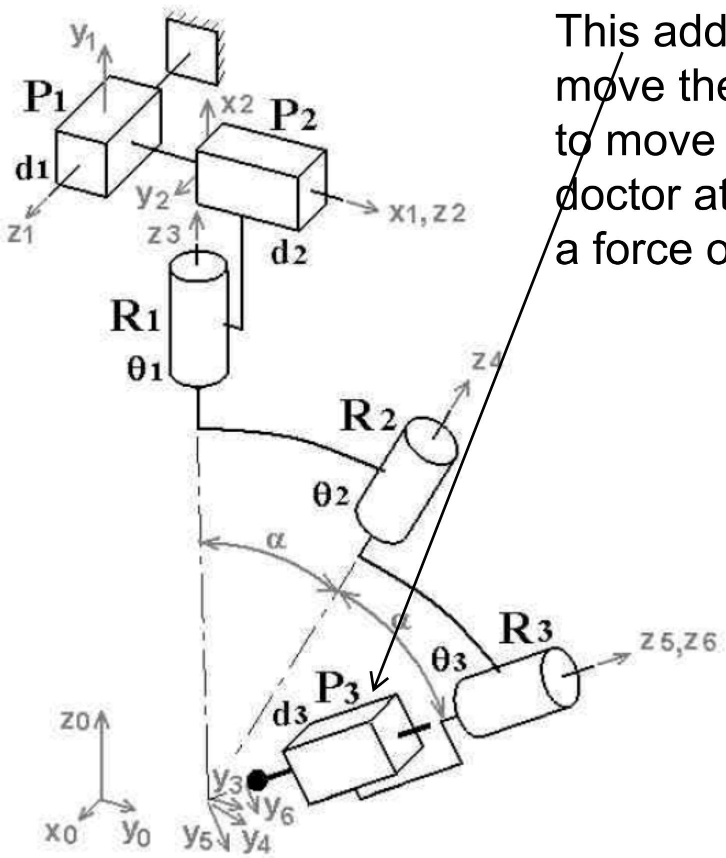
It's not surgery. The control of the probe is shared between the doctor and the manipulator, for ex. if there is a big delay, the local control completes the motion



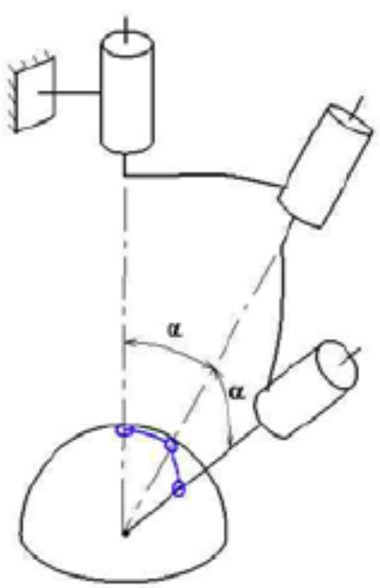


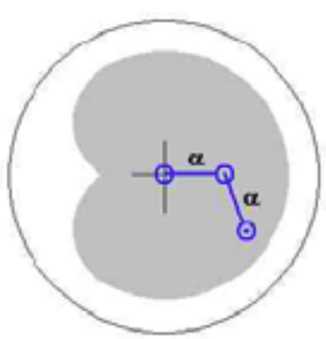
the Otelo robot

(m**O**bile **T**ele-**E**cography using an ultra-**L**ight r**O**bot)



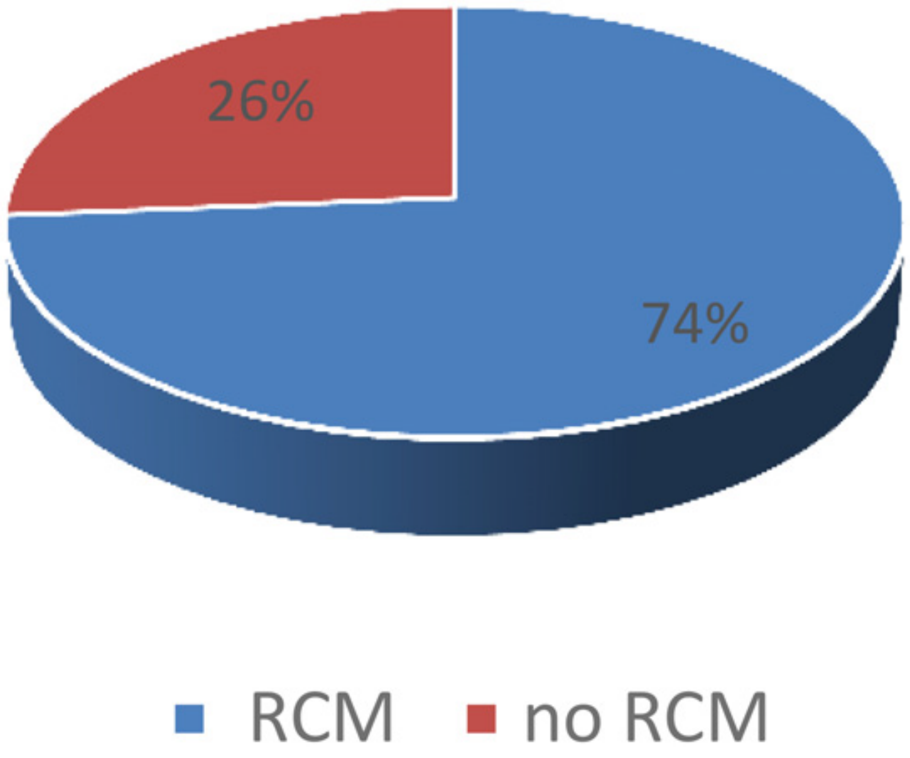
This additional prismatic joint is used to move the probe towards the patient and to move away from the patient when the doctor at the remote side stops applyng a force on the echographic probe



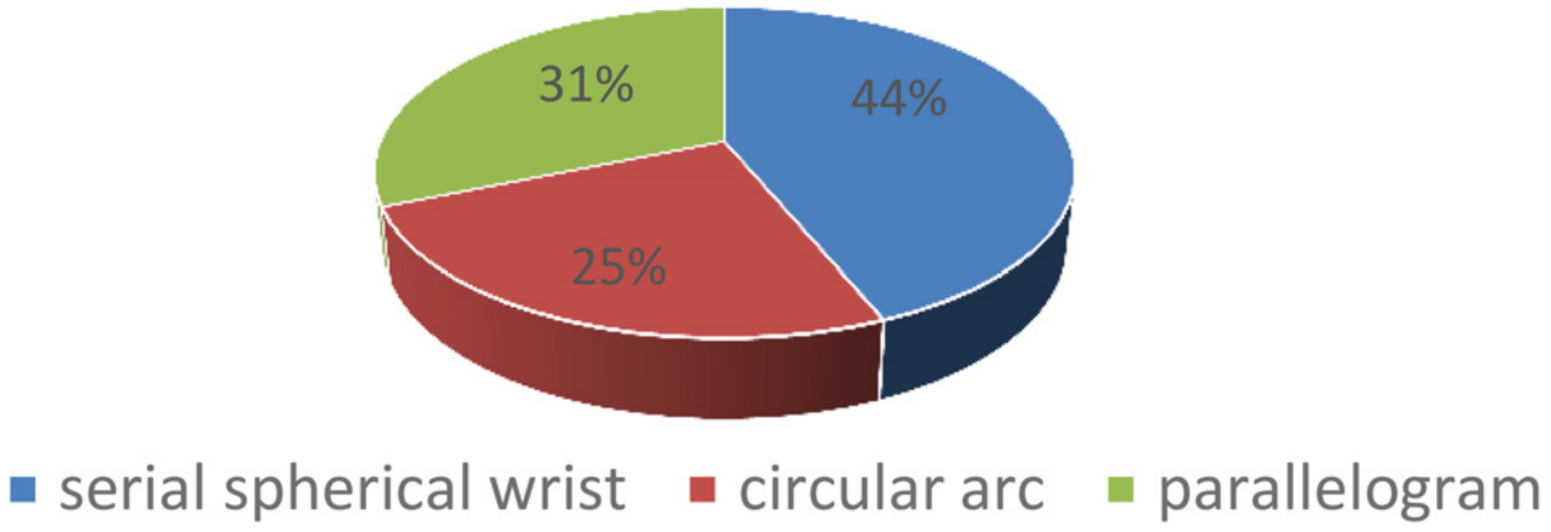


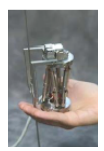
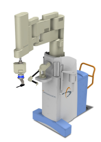
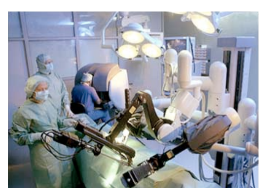
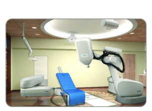
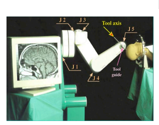
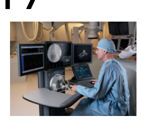
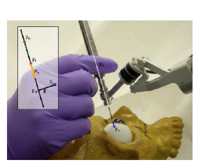
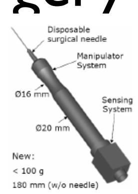
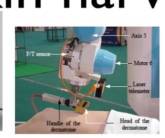
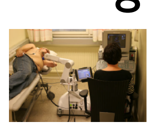
- 6 dof: PPRRRP
- closed form inverse kinematics
- R_1, R_2, R_3 form a spherical wrist
- one of the singularities corresponds to the vertical pose of the probe
- paths going through the singular configuration are approximately followed
- a second singularity is on the frontier of the workspace and is avoided using mechanical or software joint limits
- if $\alpha > \pi/4$ there exists an additional singularity corresponding to z_6 parallel to the plane formed by z_1 and z_2

breakdown for echographic robots

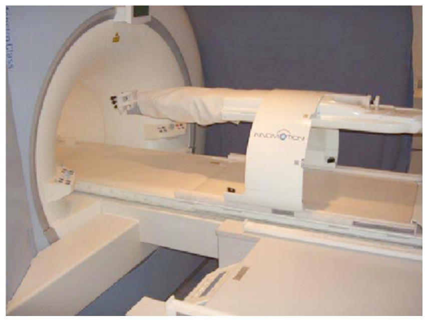


RCM is required also by surgical gestures in other domains!

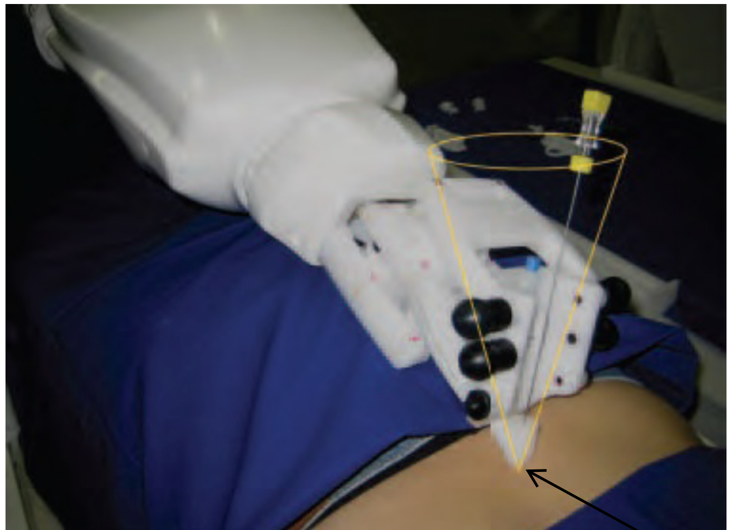


domain of use	function	kinematic architecture	control modality	sensors and actuators
orthopedics   	machining of rigid surface	conventional serial or parallel + possible dedicated wrist 5 (drill) or 6 (cut) dof	autonomous cooperative or “hands-on”	conventional vel: mm/s force: until 100N
MIS 	constrained manipulation	RCM passive joints 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, intervent. radiology, radiotherapy   	constrained targeting	conventional + front-end with dedicated architecture 5 or 6 dof	teleoperation (semi)-autonomous	MR/CT compatible (pneumatic, ultrasonic) force: few N insertion (usually) manual (undetermined in case of neurosurgery)
microsurgery  	micromanipulation	dedicated kinematic architecture, possible RCM	shared/ cooperative teleoperation	piezo, ultrasonic actuators force: few mN vel: 0.70m/s (manual procedure)
tele-echo, TMS, skin harvesting   	surface tracking	conventional + dedicated wrist architecture possible RCM	autonomous teleoperation	conventional vel: mm/s force: few N

kinematic design and required degrees of freedom



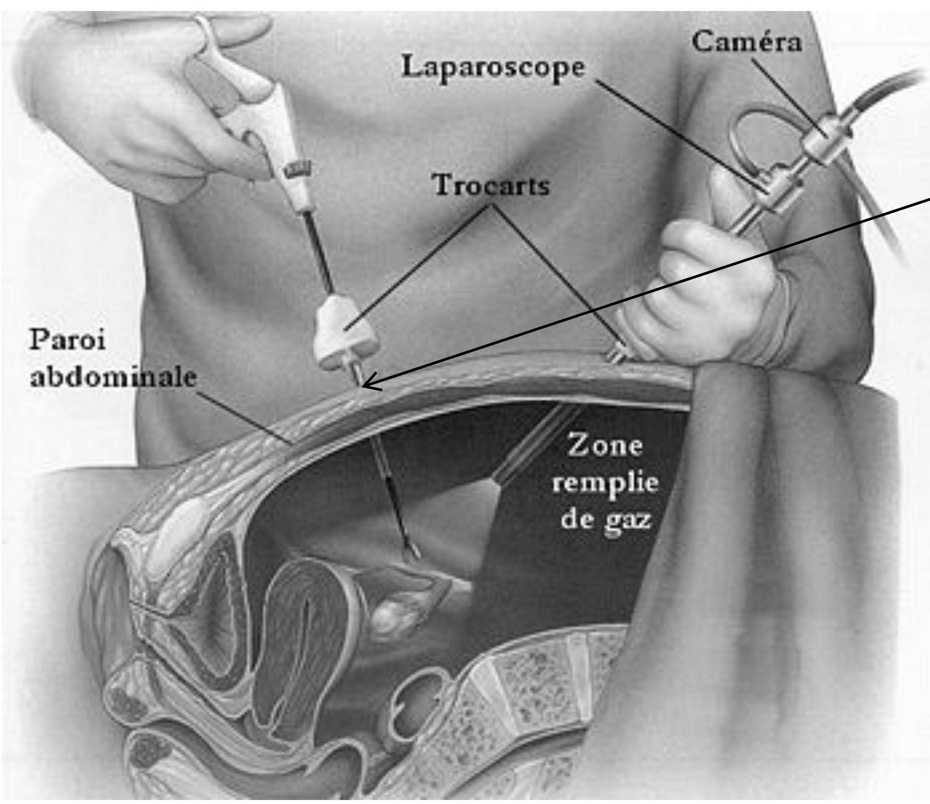
INNOMOTION



needle positioning and orientation in interventional radiology

- 3 translation to determine the entry point
- 2 rotations about this point to reorient tools

point which is fixed in the space and all the rotations happen arround this point



the entry point is where we need to place the remote center of motion

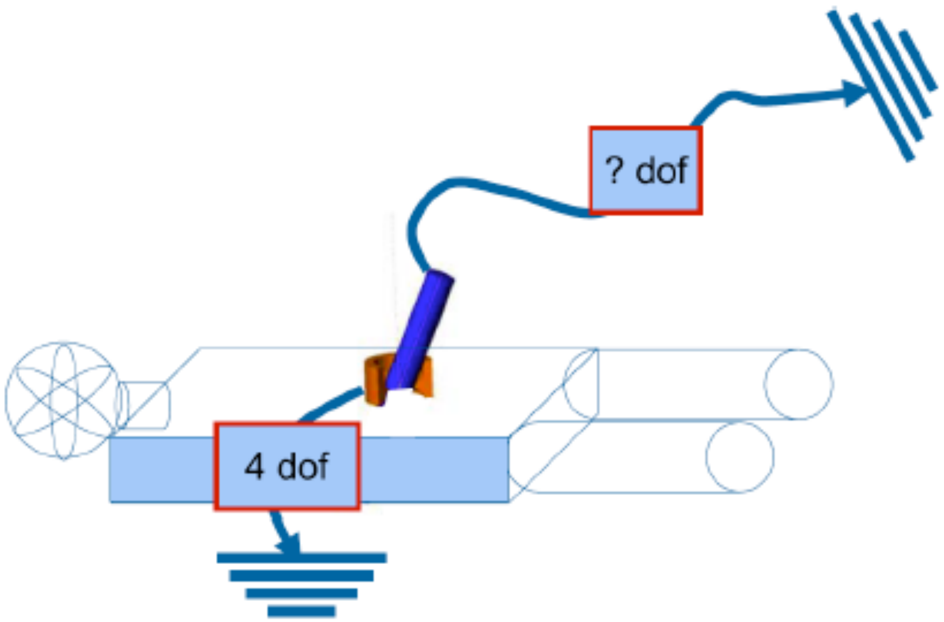
laparscopic surgery

- how many interna/externale DOFs?

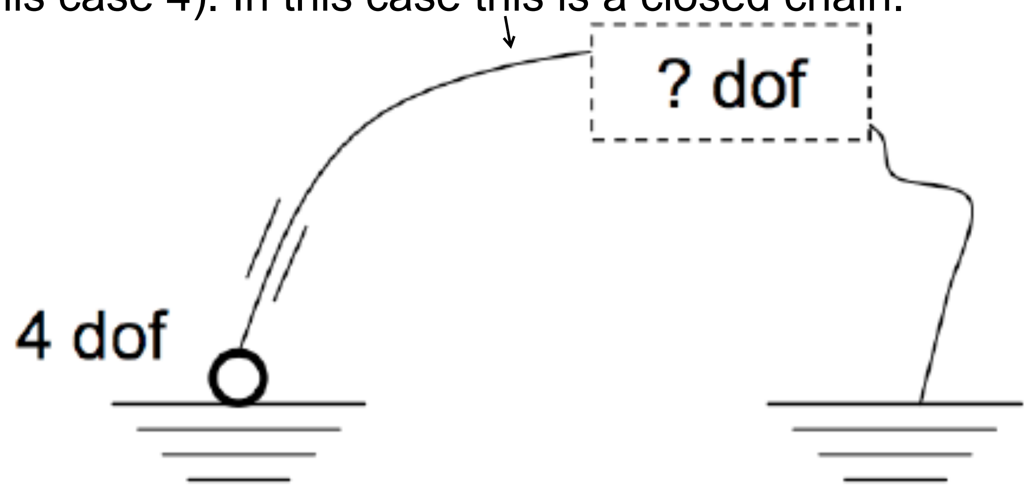
SEE SLIDE 4 OF 04_RCM

kinematic design and required degrees of freedom

At the enter point we have a two dimensional constraint because when you enter the surface you can rotate around the point or transate through the point.



consists of modelling this this manipulator as a serial linkage. At entry point we put a joint with a number of dof that correspond to the desired internal mobility(in this case 4). In this case this is a closed chain.



- in MIS surgery translation is constrained in two directions because the tool axis always passes through one fixed point ($\Rightarrow$ 4 internal dof)
- how many dof are necessary to satisfy the constraint and obtain the desired degrees of mobility for the tool?
- Grubler's formula:

$$m = \sum_{i=1}^{n} d_i - 6(n + 1 - l)$$

m: ee degrees of mobility (dof of the linkage);

d_i: dof of the i-th joint;

n: number of joints;

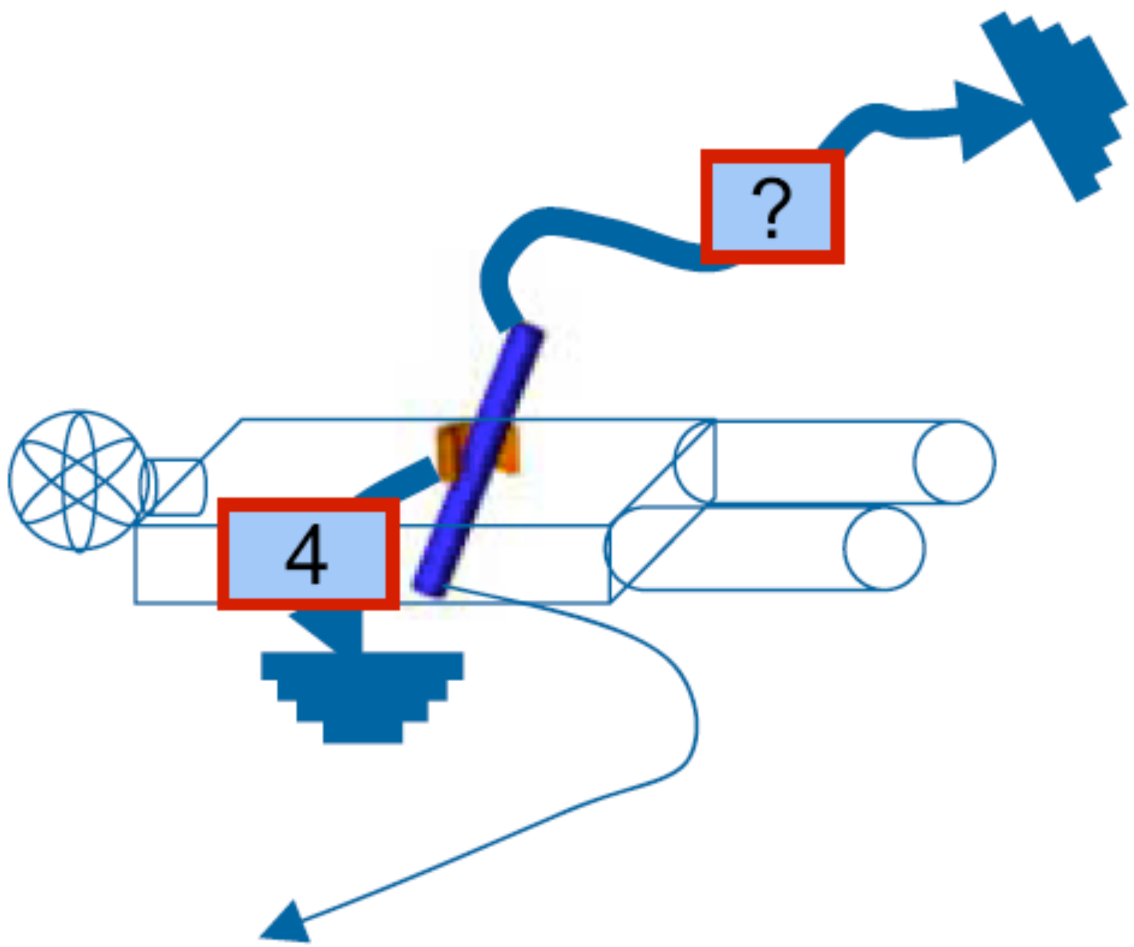
l: number of rigid bodies including the base;

including the base

- in a loop: $n = l \Rightarrow m$ = total dofs - 6

required degrees of freedom: examples

m:degree of mobility



- $m = 3$

$$3 = 4 + x - 6 \Rightarrow x = 5$$

- $m = 4$

$$4 = 4 + x - 6 \Rightarrow x = 6$$

- $m = \{3, 4\}$

m depends on the task of the robot.

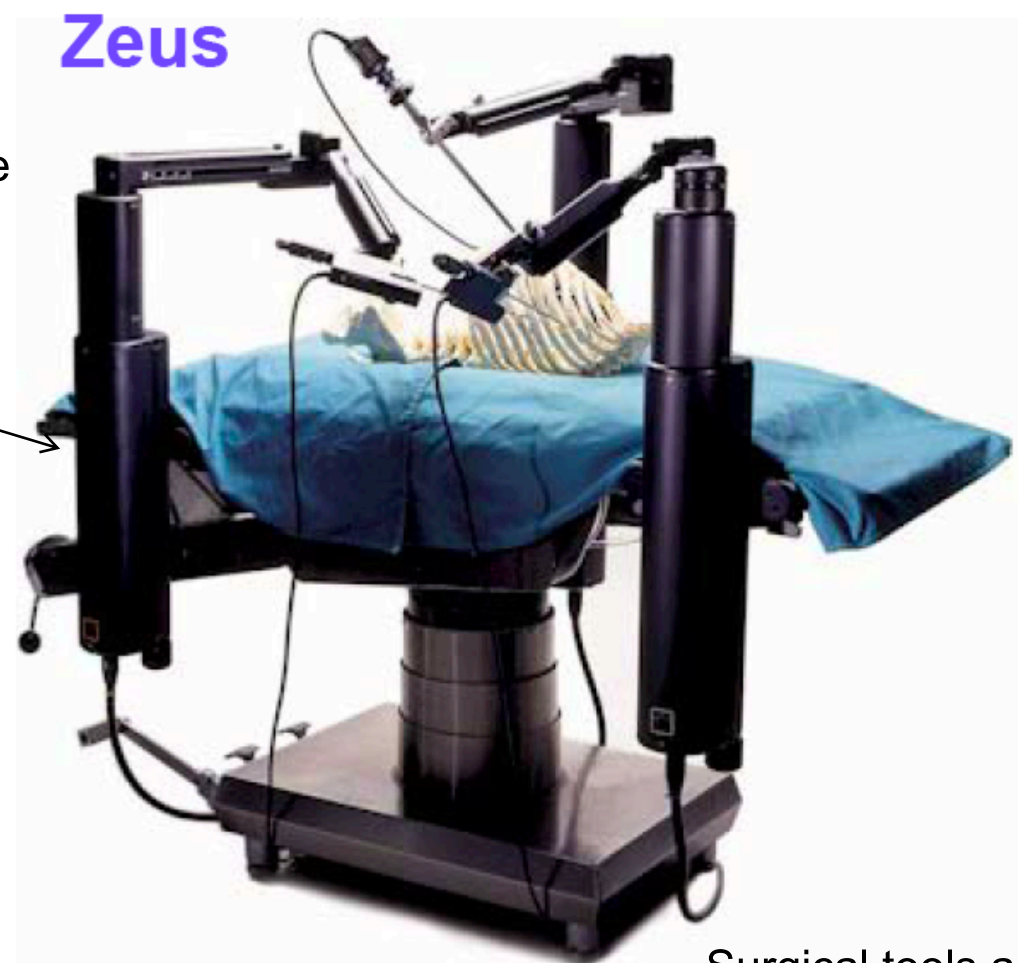
how constraints can be satisfied by kinematic design

passive joints (passive redundant kinematics)

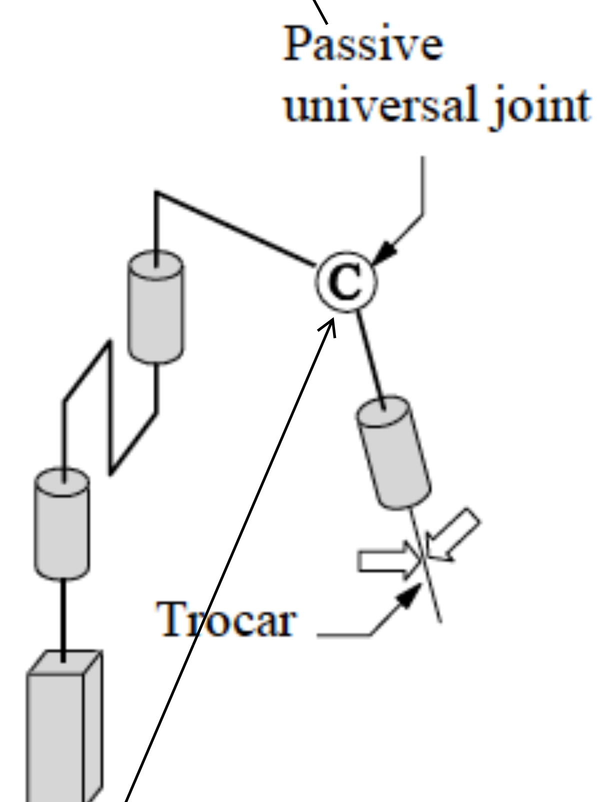
In zeus the contraint is obtained through the use of a passive joint. So we have a redundant kinematics and 2 passive joints.

There are then 4 rotational dof, the last 2 are in the wrist and are passive

Here we have a prismatic joint. The Whole structure can translate up and down thanks to this joint



Makes the motiion of YAW and PITCH



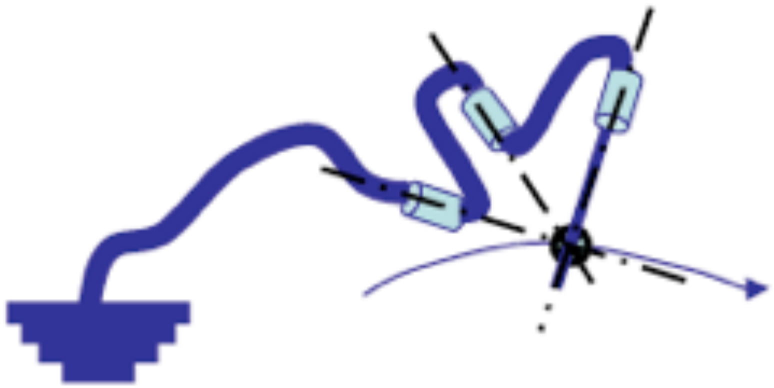
Surgical tools and the endoscope are introcuced in the body through the trocar. This constraints the motion of the surgical tool and induced a passive motion in this joint

- PRRRR with the first 3 joints actuated ($\rightarrow$ 3 degrees of mobility at the ee)
- the trocars force the passive joints to adapt mechanically

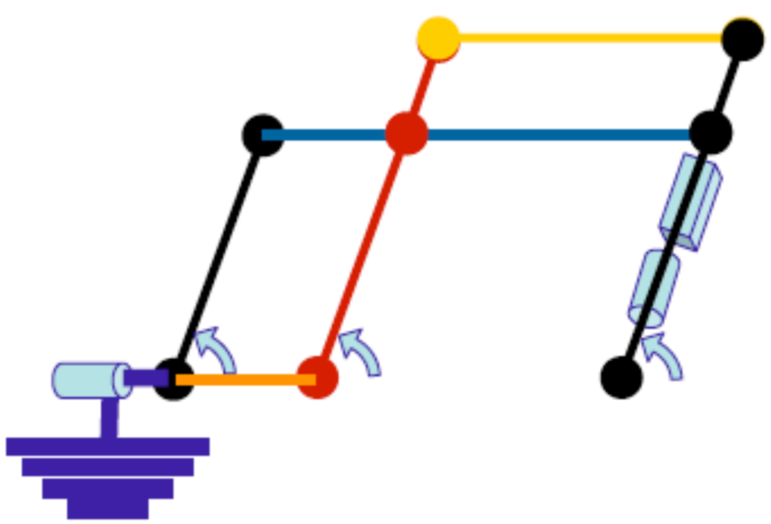
how constraints can be satisfied by kinematic design

mechanical RCM

design a device that always places the axis of the tool through the incision point; these devices produce a remote center of rotation (unencumbered by mechanisms) which can be placed at the incision point ($\Rightarrow$ the constraint is satisfied by construction)



- a spherical linkage (serial linkage of revolute joints with axes intersecting at a single point) requires complex parts



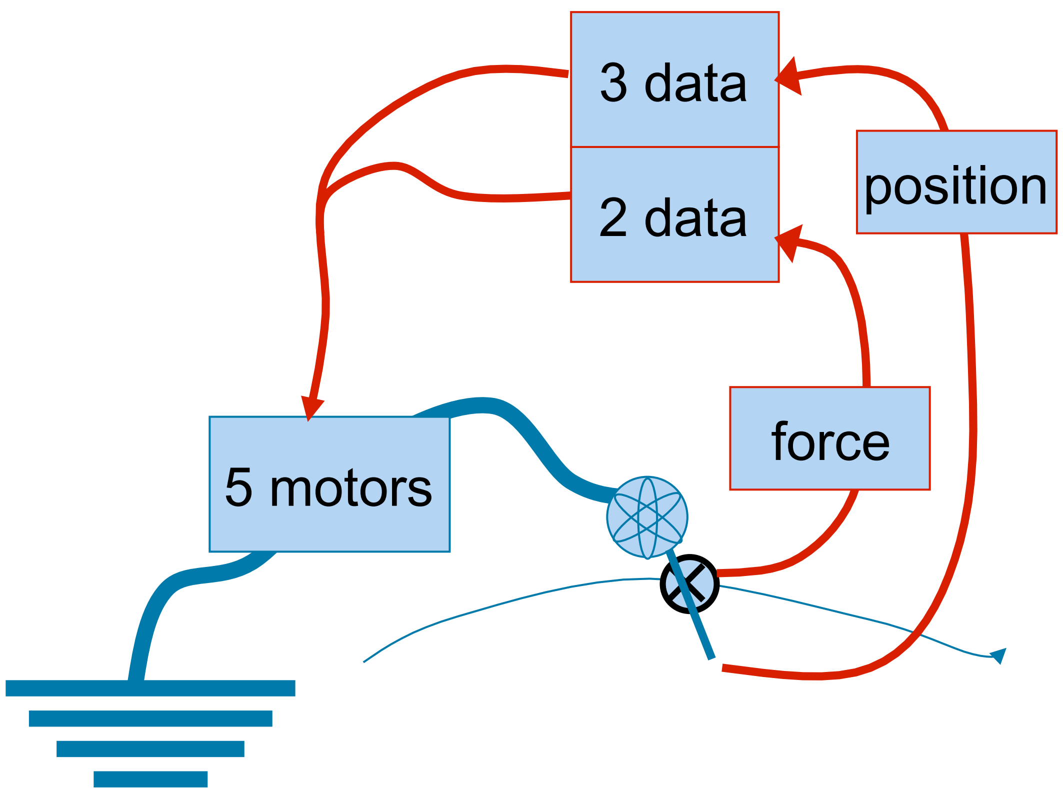
- a parallelogram can do the job as well

in this case the remote center of motion constrain is satisfied mechanically

how constraints can be satisfied by kinematic design

Another way to satisfied RCM constraint is by using feedback at the entry of the surgical ttool in the patient's body. This is obtained by control and the controller use not only the position but also the forces exchanged between the tool and the trocar with the human body at the entry point level.

force control



$m = 3 \Rightarrow 3 = 4 + x - 6 \Rightarrow x = 5$

2 dof controlled with force measurements

comparison of methods to satisfy MIS kinematic constraints

passive joints

- few motors
- forces can be high
  the trocar forces the passive joints to adapt mechanically
- no accurate positioning is needed
- safety is preferred to accuracy and rigidity Accuracy is not an issue because there is a human in the loop

mechanical RCM

- few motors and joints
- the trocar has no influence on the arm motion
- the arm must be precisely located (positioning device + procedure)

force control

- the trocar "forces" the passive joints to adapt using measures + control software
- a bit more complex
- may open the path to "multi-purpose" systems

kinematic control

- appropriate kinematic model of the RCM constraint + task
- easy to implement on position-controlled robots
- may open the path to "multi-purpose" systems

References

(1) L. Nouaille, M. A. Laribi, C. A. Nelson, S. Zeghloul, G. Poisson, "Review of Kinematics for Minimally Invasive Surgery and Tele-Echography Robots," Journal of Medical Devices, vol. 11, no. 4, 2017

(2) E. Dombre, G. Duchemin, P. Poignet, and F. Pierrot, "Dermarob: A Safe Robot for Reconstructive Surgery," IEEE Trans. on Robotics and Automation, vol. 19, no. 5, pp. 876-884, 2003

(3) C. Delgorge et al., "A Tele-Operated Mobile Ultrasound Scanner Using a Light-Weight Robot," IEEE Trans. on Information Technology in Biomedicine, vol. 9, no. 1, 2005

(4) "Parallel Robots," J.-P. Merlet, Kluer Academic Publishers, 2001

(5) Dombre, E. , Poignet, P. and Pierrot, F. (2013). Design of Medical Robots. In Medical Robotics, J. Troccaz (Ed.). doi:10.1002/9781118562147.ch5