Medical Robotics

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Classification of surgical systems

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We record that human-robot cohoperation is a centarl topic in medical robotics

Outline

- human-robot cooperation is a central topic in medical robotics
- the design of medical robots poses technological challenges in sensing, actuation, interfaces, modality of control
- the adopted technical paradigms differ by degree of autonomy, type of provided support, type of access
- in this group of slides we mention four among the many ways used in the literature to classify surgical robots
  - examples of systems for each class are provided
- to conclude we recall how surgical robots are categorized in this course

Classification I
(J. Troccaz, 2001)

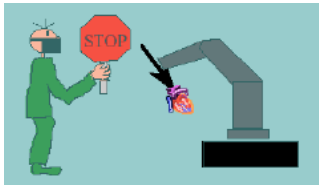
French researcher which has also invented several medical devices. He focuses on the degree of autonomy of system

- passive systems

  It is the surgeon that control the whole procedure. This passive systems are used to support the surgical gesture by providing info to the surgeon.

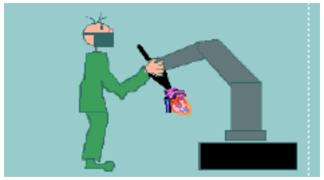
  - provide information to the surgeon

- active systems: perform the procedure under human supervision



The robot manipulator is executing some procedure on the art and the human operator has the ability to stop the procedure.

- interactive systems: provide physical guide to the surgeon
  - semi-active devices
  - synergistic devices



- teleoperated systems

The human operator manipulates a robot. It is itself the manipulator of the robot.

This type of robot is used to provide info to the surgeon.

passive system example

Viewing Wand
(ISG Technologies)

It is used in neurosurgery

- articulated arm with manually guided probe
- the probe position w.r.t. to the skull is used for registration and navigation

The probe is guided by the surgeon hand to touch some specific points on the patient's body. It is a passive system and articulated passive arm is used for registration of the surgical plan which is based on preoperative images and this surgical plan is then transferred to the refernce frame (of the bed). So if you know where this point is with respect to the base frame of this articulated arm, and you know the position of the articulated arm with respect to the bed. Every operation position is registered in coordinates

advantages

- stability of positioning if the arm is equipped with brakes
- no need of a free line-of-sight

For ex. if there is a surgical tool mounted on this passive system, once the tool is in position and the surgeon put the surgical tool in the desired position, then the arm can be locked in that configuration and the surgical tool inserted easily.

for ex. for optical system it needs.

drawbacks

- cumbersome (ingombrante)
- constraints surgeon’s movements
- limited use

We can find examples of these in orthopedics

active systems

mainly indicated for

- machining of rigid surfaces

  It is very similar to industral task
  - ROBODOC, CASPAR

    It is smilar to ROBODOC an dit is used for knee replacement
- carry/hold heavy tools
  - Cyberknife

    It is used to manipulate particle accelerator like radiative therapy
- force controlled actions
  - TMS Robot, MELODY, Hippocrate, SCALPP

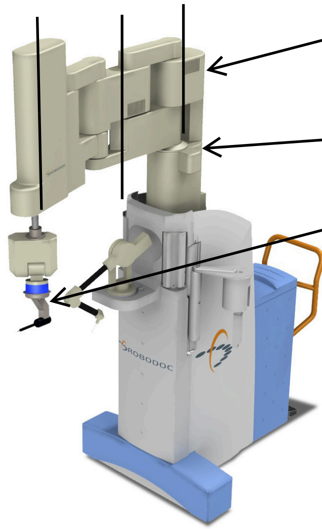
    it is a robot used for transcranial magnetic stimulation, which is a tecnique used to stimulate deep area in the brain to treat some disorders like epilepsy
- intra-body tasks
  - active endoscopic pills

    problems of active locomotion
- moving targets
  - Cyberknife + real-time patient tracking

It is one of the rare examples of active system and it is used in knee and hip(anca) replacement.

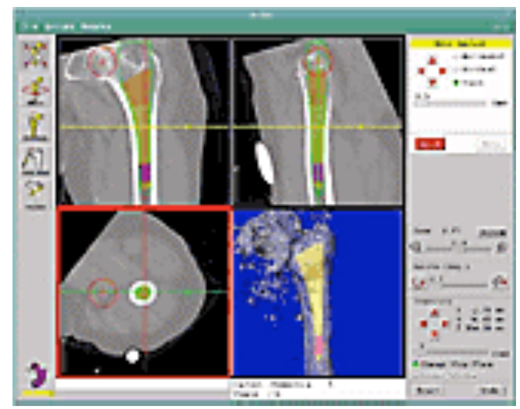
active sytems examples: ROBODOC

3 joints with parallel axes and it has in addition 2 dof



- SCARA with a 2dof wrist
- 6D force/torque sensor on the wrist
- Orthodoc: planning system

This tool can be used to drill(trapanare) bones or to cut bones on specific direction. So there are forces exchange at the tool level. This interaction force needs to be kept within specified bounce and so on. Sensors are necessary to control the interaction.

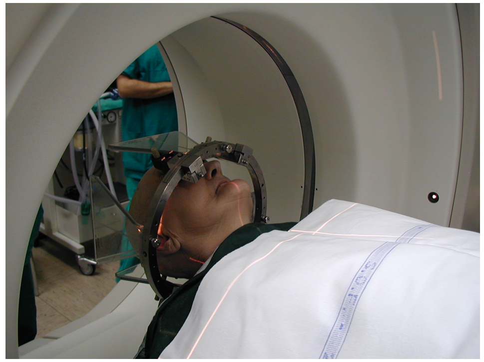


- planning with Orthodoc software
- pre-op to intra-op registration using implanted titanium pins that are visible in the CT scan
- intra-operative bone milling procedure using ROBODOC

Once the registration of the preoperative plan in the intraoperative phase is done, the plan is transferred to the robot and the robott executes the surgery

It's been an important evolution in neusurgery and radiotherapy.

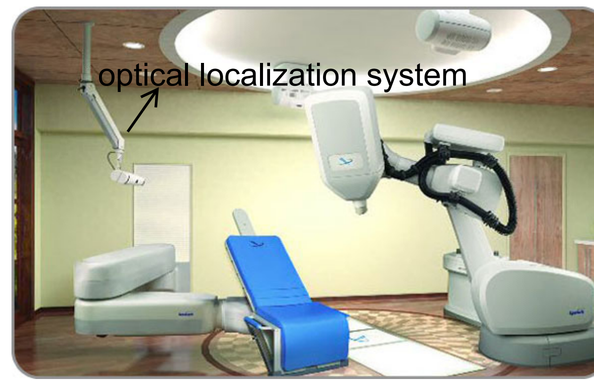
active sytems examples: Cyberknife



To registrate the preoperative images taken in this case by a CT scanner.

- registration frame for neurosurgery/radiotherapy

It was necessary to implement in a very impressive way our registration frame on the patient's scalp.



- frameless neurosurgery/radiotherapy
- patient motion compensation
- large workspace

Not always needed optical localization system

- 6 dof manipulator moving a 6MeV accelerator
- 1 eV = amount of kinetic energy gained by a single unbound electron when it accelerates through an electrostatic potential di
erence of one volt

The surgeon executes the procedure but surgical tool is shared between the robot and the surgeon. The robot constraints make sure that the surgeon suction(aspirazione) is within the limit that has been defined(not risk).

interactive systems

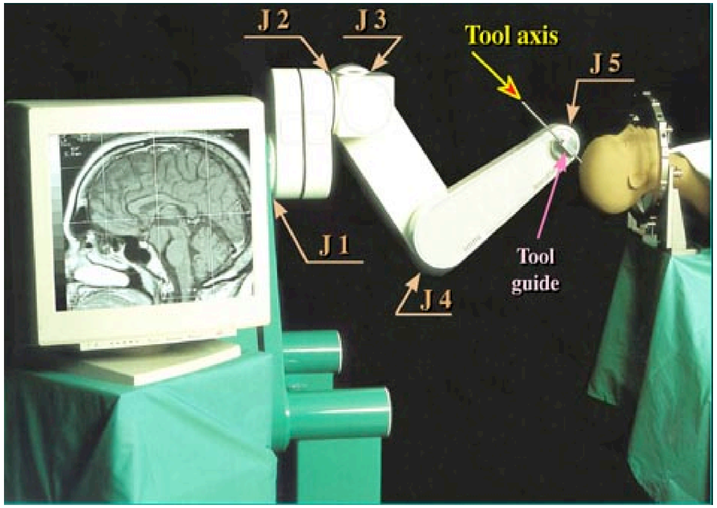
- principle: the robot constraints the surgeon's action

- possible approaches
  - semi-active: a mechanical constraint
  - synergistic: a programmable constraint

- advantages
  - human/machine cooperation (safety, psycological acceptance)
    Both for the surgeon and the patient
  - direct interpretation of haptic information

The constraint is mainly mechanical.

semi-active systems



NeuroMate

- pre-positioning: robot
- surgical action: surgeon
- simple tasks
  - linear motions (e.g., needle insertion)
  - planar motions (e.g., osteotomy)
  - conical motions (e.g., laparoscopy)

The robot is used for positioning the tool. So according to the preoperative plan, the robot positions the probe, which mens that the probe tip and the orientation are desidered as planned in the open preoperative phase. The robot can do this in a very accurate way, but then the surgical action is executed by the surgeon

synergistic systems

- generalization of semi-active systems

- programmable guides

The programming can be obtain through several technologies

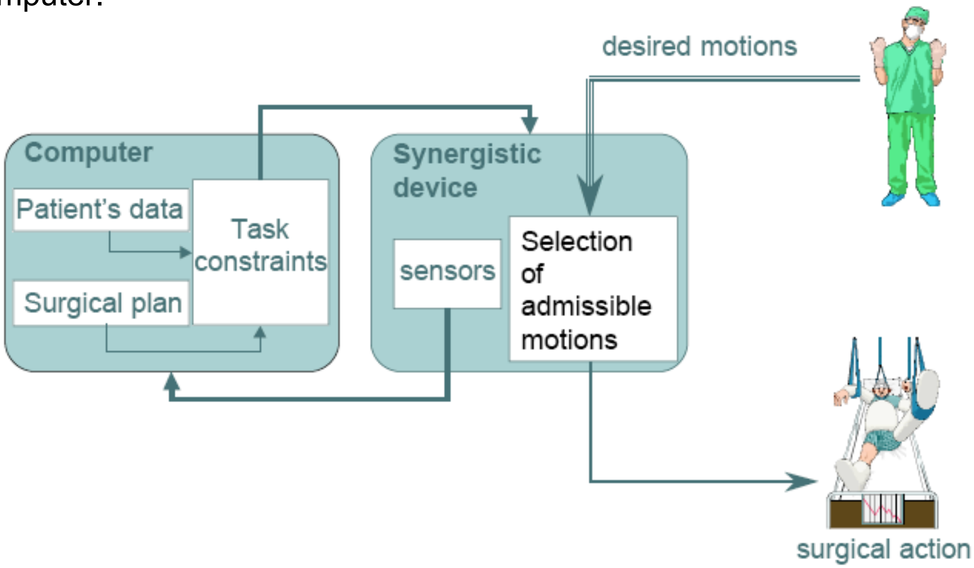
- different technologies
  - programmable brakes (Taylor, P-TER, IMCAS)
  - “nonholonomic coupling” of dofs (Cobot)
  - windows of admissible velocities (PADyC)
  - active Constraint ROBOT (Acrobot)

It's a robot that was designed and built for pericardical puncture. It must be said that the robot is no longer in use(mainly research prototype).

PADyC (Passive Arm with Dynamic Constraints)

The idea is that in the preoperative phace, patient's data are acquired. This means CT scan or magnetic resonance or other give info about the patient. So a surgical plan is made, based on the patient data and the constraints are defined. The constraint of the robot are translated into constraints for the surgeon. If the robot is constrained in its motion, it means that the surgeon will not able to move the surgical tool toward forbidden direction. We have not only the task acting in control of the new synergistic device, but als the action of the surgeon that guides manually the tool. The motion of the joints is measured by sensors that provide feedback to the computer.

PADyC (TIMC Grenoble): pericardial puncture robot



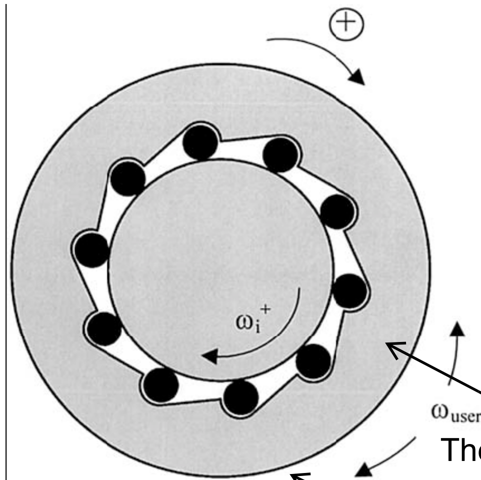
How is this selection of admissible motions obtained? Through a combination of motor control and some mechanical devices.

freewheels

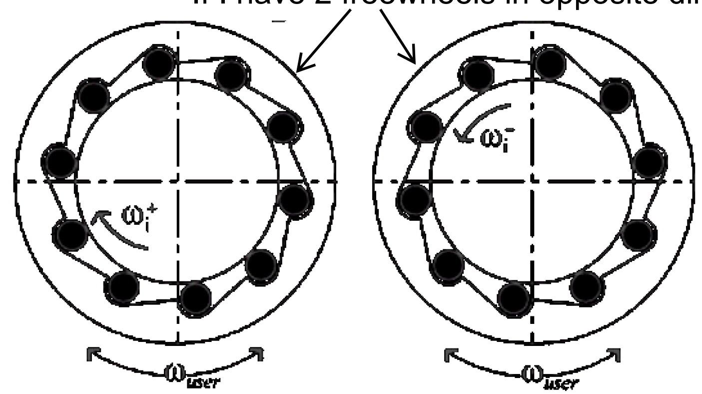
Joints are made by the decoupling of two freeWheels, which are mounted in the opposite direction.

They present an internal part which is moved by a motor

Clockwise velocity is considered as positive



If I have 2 freewheels in opposite direction



The extarnal part(metallic ring) rotates on the axis of the model. This part is connected to the internal by means of small spheres

- one joint: two freewheels mounted in the opposite direction and actuated by two independent motors

F1: $\omega_i^- = 0 \wedge \omega_i^+ \neq 0$ only ω_{user}^+

F2: $\omega_i^- \neq 0 \wedge \omega_i^+ = 0$ only ω_{user}^-

F3: $\omega_i^- \neq 0 \wedge \omega_i^+ \neq 0$ both directions

F4: $\omega_i^- = 0 \wedge \omega_i^+ = 0$ none

If the internal circle moves in the clockwise direction and the surgeon moves the external in the opposite direction, then the motion is free. If it moves the external part clockwise direction, what happens depends on the relative speed between the internal and the external part. If the external part has lower speed with respect to the internal, then the motion is free. If the speed is the same, then the user can move freely the external part. If the external is faster, them the motion is blocked. This for only one freewheels

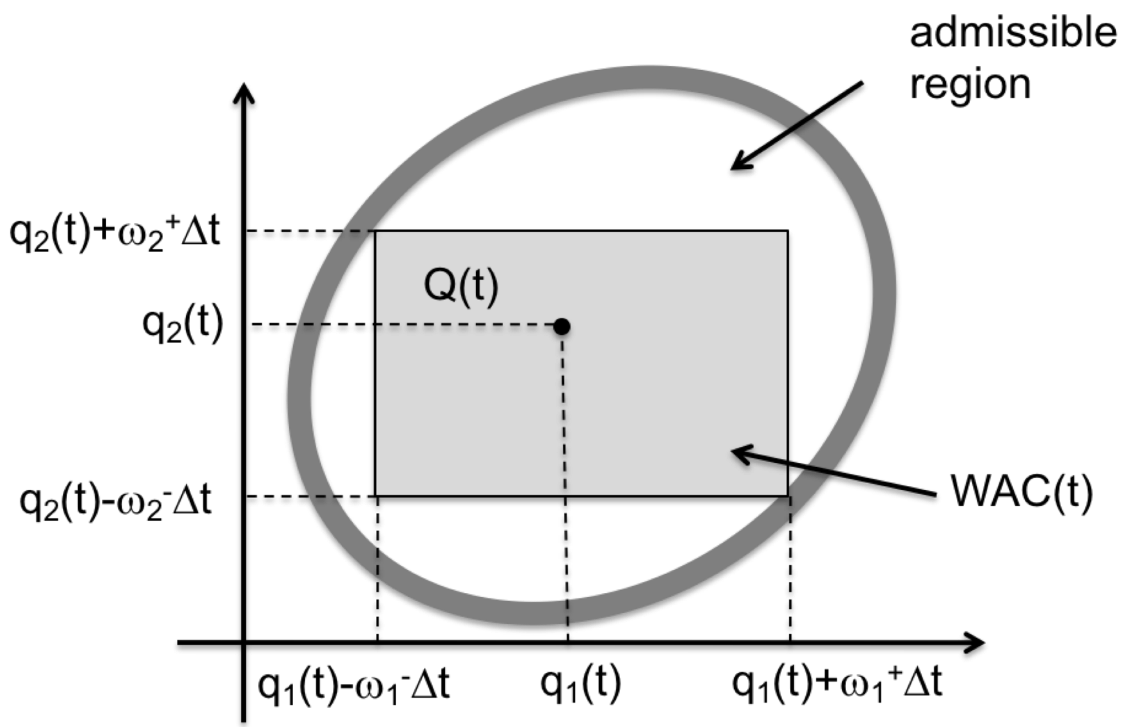
- ω_i^- and ω_i^+ controlled by the computer, ω_{user} controlled by the user
- motion authorized for $\omega_i^- \leq \omega_i \leq \omega_i^+$

Here we summarize what are motion modes.

PADyC: task constraints

- free mode: no constraint, the system computes and memorizes the position of the surgical tool
- position mode: PADyC helps the user to move the tool towards a predefined position and orientation (e.g., bone fragment or a prosthesis component)
- region mode: the tool is free to move in a given region of space, but cannot escape from that region (e.g., tumor resection or cavity preparation for prosthesis placement, avoidance of critical areas)
  - keep inside
  - keep outside
- trajectory mode: constrains the motion to follow a predefined trajectory with a given accuracy (e.g., biopsy trajectory)
- specialized modes
  - linear motions
  - planar motions
  - conical motions

PADyC: window of admissible configurations



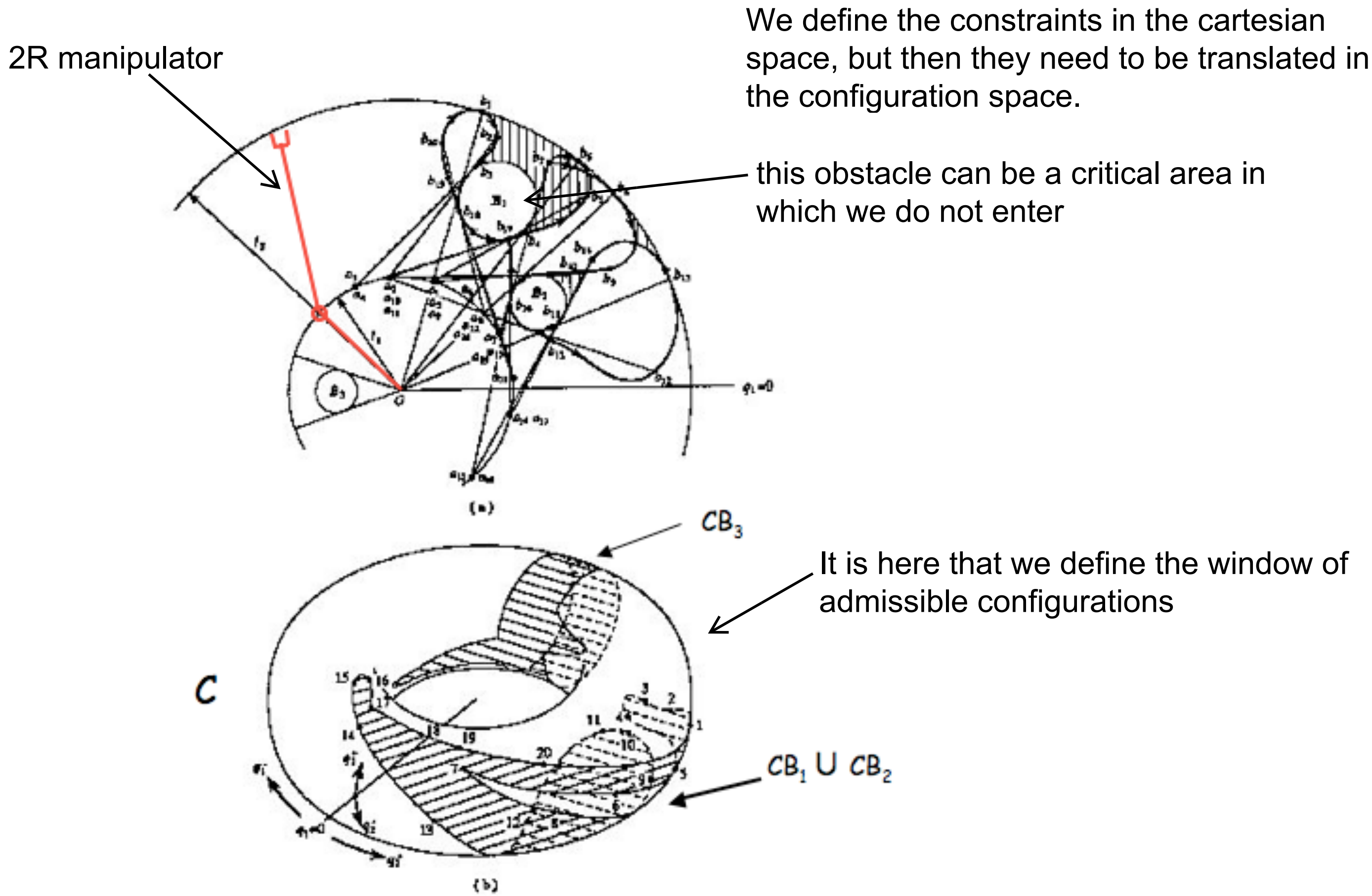
planar

example: 2R manipulator, region mode

- given the robot configuration Q(t), the velocity constraints must be such that the configuration Q(t+Δt) is contained in the admissible region

The constraints are defined because we are controlling the robot at the joint level. It is necessary to express the constraint in the joint space.

problem: mapping the task constraints to configuration constraints in real time

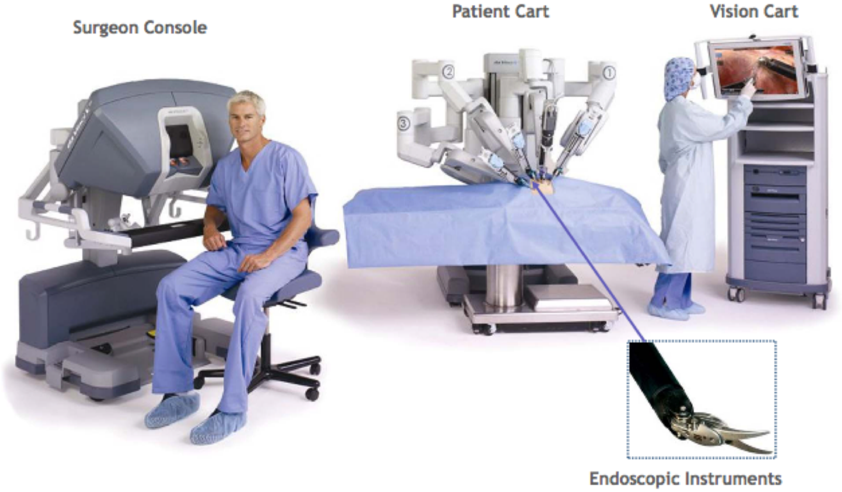


a $WAC_j(t)$ needs to be computed for k control points on the surgical tool

$$WAC(t) = \cap_{j=1}^{k} WAC_j(t)$$

teleoperated systems

- da Vinci

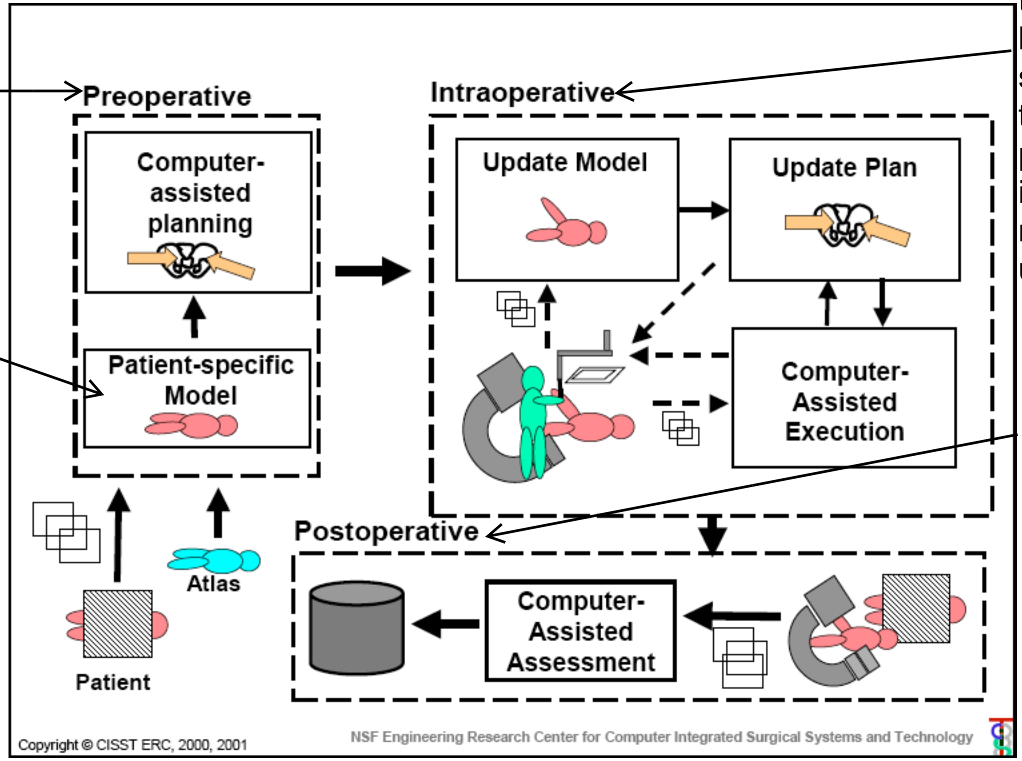


- Zeus

He is one of the father of medical robotics

Classification 2 (R. H. Taylor, 2003)

In the preoperative phase computer assists in planning the surgery based on a model that uses data from the patient, but also general anatomical data, so all the data that are useful to built a specific model are included here.



the surgery can be executed by cooperating robot-surgeon. Now we need to translate the plan from the preopetive to the intraoperative ohase. The model and plan can be update.

We have technological tools that help in following up with the surgery. The patient is monitoredd through images or other kind of exams. The info are stored and classified

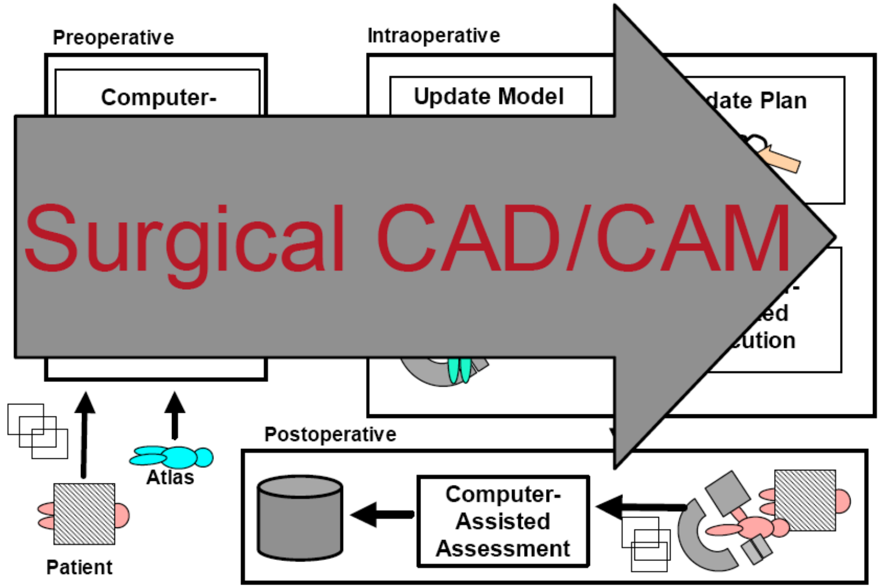
Computed Integrated Surgery (CIS)

- surgical robotic systems are first part of CIS and then medical robots
- hence, they can be classified according to their role in CIS systems

surgical robot can be classified according to their role in the compputer integrated search.

surgical CAD/CAM

FROM LEFT TO RIGHT



- patient modeling
- planning Moving from the preoperative to the intraoperative phase
- registration
- execution
- follow-up

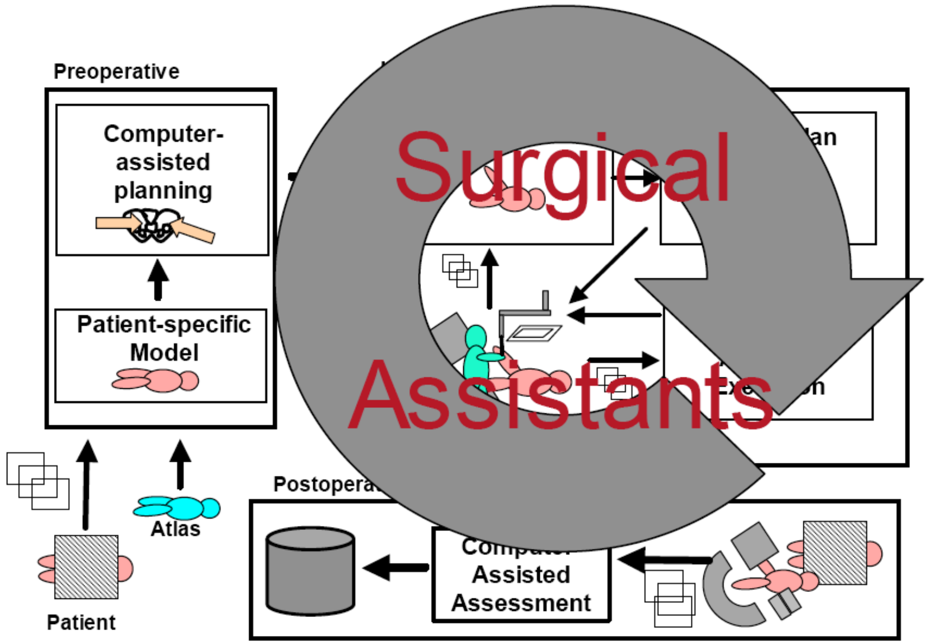
CAD/CAM examples

- robot assisted execution
  - orthopedic prosthesis implant (ROBODOC)
  - percutaneous therapy (NeuroMate)

- execution assisted by navigation systems
  - that uses info from different sources
  - therapy delivery with the aid of multi-modal images (Cyberknife)
  - augmented reality (images overlay)

if we move into itraoperative phase

surgical assistants



- surgical extenders
  - improve or extend surgeon's abilities in manipulating surgical tools (e.g., tremor cancellation)
- auxiliary surgical supports
  - work side-by-side with the surgeon (e.g., endoscope holding or retraction)

surgical assistants examples

- surgical extenders
  - teleoperated systems (Zeus, daVinci)
  - microsurgical systems (teleoperated or not, possibly without manipulators)
    smart tools for tremor cancellation
  - cooperative/synergistic systems

- auxiliary surgical supports
  - endoscopes, ecographic probes, …, controlled by the surgeon through various interfaces (AESOP)
  - systems for intraluminal appilcations (active catheters, capsules)

Classification 3 (L. Joskowicz, 2005)

focus on **support** systems

they can be just rigid objects like individual templates. for ex. device systems for intraoperative imaging system, for navigation or robotics that is floor/bed mounted or patient mounted

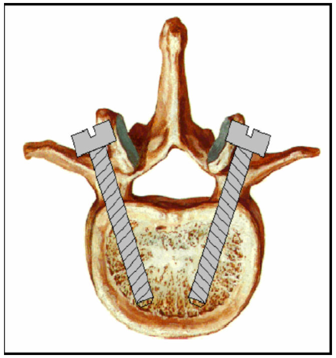
- passive mechanisms
  - adjustable frame/arm/support
  - individual templates
- intraoperative imaging
- navigation
- robotics
  - floor/bed mounted
  - patient mounted

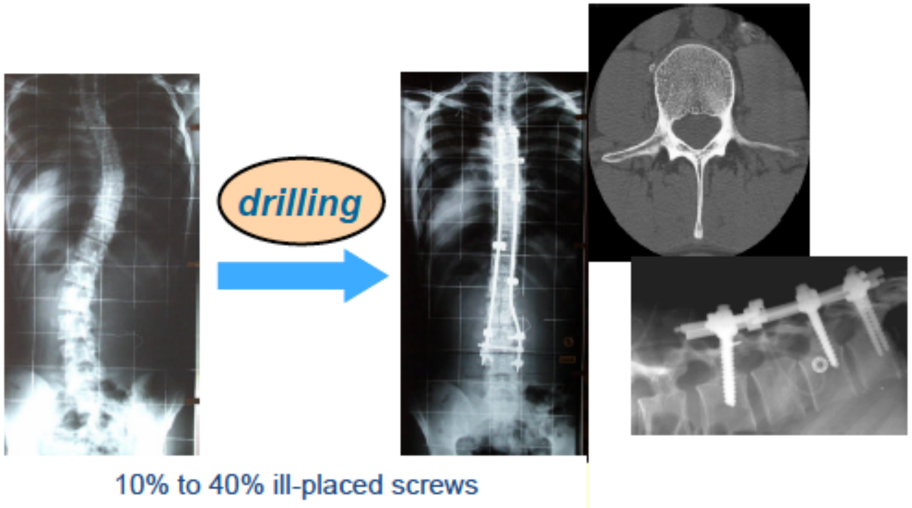
example

That consists in inserting screw on the vertebra. These screws arethen used to have fixed roads and plates all along the spine to treat some disorder ot fracture

- spine surgery: pedicle screw insertion

- recommended use
  - vertebra fracture
  - degenerative diseas
  - spine tumor
  - scoliosis



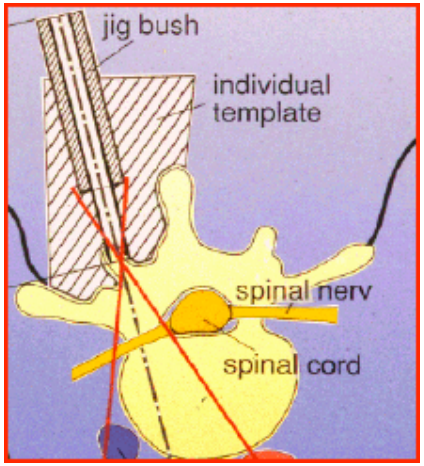


It is necessary to drill the vertebra, insert the screw and then affix roads and plates to keep the spine straight(la colonna dritta). This is a very critical operation.

example (cont'd)

The most popular way to do this is to use individual templates which are passive devices. It's a rigid object which is machine prepared based on patient images (on anatomy of the patient). There is a rigid guide and the screw is inserted with the help of this guide.

- individual template (passive device)



- advantages
  - inexpensive
  - rigid mechanical support
  - customized
- drawbacks
  - requires manufacturing
  - no intraoperative changes
  - limited use: anatomy-dependent

for each patient there is a specific template

- patient mounted robots

MARS –Mazor Surgical Technologies, Israel

It is mountend on the patient spine.

He considers the type of interaction of the system

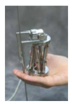
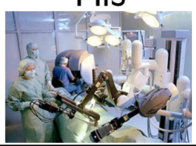
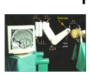
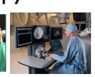
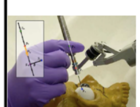
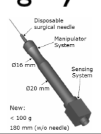
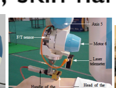
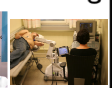
Classification 4 (P. Dario, 2004)

Refers to the way in which the devices access the human body

		Type of Access		
		Traditional Access	Minimally Invasive Access	Endocavitary/ endoluminal access
Type of Interaction	Autonomous systems	Systems that execute a planned program or automatically define their path		
	Interactive systems	Semi-active systems (decoupled DOF) and synergistic systems (shared DOF)		
	Teleoperated systems	Master-slave systems and systems with direct drive/control		
	Passive systems	Systems with no actuation (not really robotics)		

		Type of Access		
		Traditional Access	Minimally Invasive Access	Endocavitary/ endoluminal access
Type of Interaction	Autonomous systems	ROBODOC CASPAR	Stereotaxis Inc	MUSYC/EMIL
	Interactive systems	Eye scalpel RinC	AESOP MIAS	Active Catheters
	Teleoperated systems	Mammotome PAKY	da Vinci ZEUS	MiNOSC
	Passive systems	PinPoint	HALS (not robotic)	Given Imaging (not robotic)

Classification vs function

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**

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