Medical Robotics

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Control Modalities of Medical Robots I

Hands-On Systems

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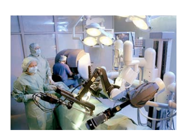
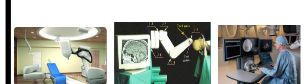
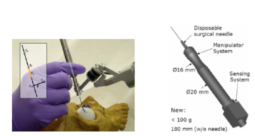
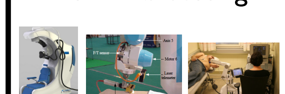
- differ in the way human input is mapped to motions of surgical instruments

peculiarity of medical robot is that they are related to the human

- can be combined in mixed control schemes
- the choice is affected by the function and, hence, by the domain of use

domain of use	function	kinematic architecture	control modality	sensors and actuators
orthopedics 	machining of rigid surface	**conventional** 5 (drill) or 6 (cut) dof	autonomous cooperative or “hands-on”	conventional vel: mm/s force: until 100N
MIS 	constrained manipulation	**RCM** 5 or 6 external + extra internal dof	teleoperation shared control	conventional vel: cm/sec (high acceleration in case of beating hearth surg)
neurosurgery, int. radiology, radiotherapy 	constrained targeting	**conventional + front-end with dedicated architecture**	teleoperation (semi)-autonomous	MR/CT compatible (pneumatic, ultrasonic) force: few N insertion (usually) manual
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

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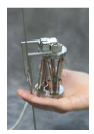
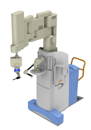
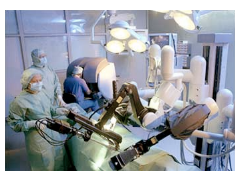
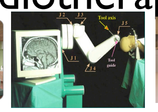
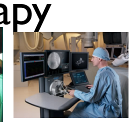
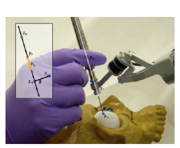
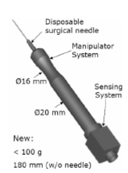
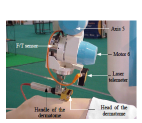
orthopedics   	machining of rigid surface	**conventional** 5 (drill) or 6 (cut) dof	autonomous cooperative or “hands-on”	conventional vel: mm/s force: until 100N
MIS 	constrained manipulation	**RCM** 5 or 6 external + extra internal dof	teleoperation shared control the robot is in direct contact with the user	conventional vel: cm/sec (high acceleration in case of beating hearth surg) force: few N
neurosurgery, int. radiology, radiotherapy   	constrained targeting	**conventional + front-end with dedicated architecture**	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

cooperative or "hands-on" systems

we will see the orthopedic surgery(cutter)

- both the robot and the surgeon interact directly with a surgical instrument

- a force sensor detects the direction toward which the surgeon wishes to move the tool and the controller makes the robot move to comply

  the surgeon guides and the robot follows but the forces can be scaled

control modality that is quite popular because the surgeon keep the control of the surgical tool and he execute the task

- surgeons find this form of control very convenient and natural for surgical tasks

other type of control

- combines the precision, strength, and tremor-free motion of robotic devices with some of the immediacy of freehand surgical manipulation

  some gesture are more difficult to plan and to be executed in authomatic way.

- less expensive than telesurgical systems (less hardware) and easier to introduce into existing surgical settings

- force scaling is allowed but position scaling is inherently not permitted

- incompatible with any degree of remoteness between the surgeon and the surgical tool $\rightarrow$ not suited for instruments with distal dexterity

- examples: orthopedic surgery, microsurgery

cooperative systems peculiarities

- typically non-backdrivable and velocity-controlled actuators (admittance type systems)

- the velocity is typically controlled with a high-bandwidth servo controller to be proportional to the operator-applied force $\rightarrow$ force-to-motion scaling

- linear admittance-type device control is generally modeled as

$$V(s) = Y(s)F(s) \qquad (*)$$

- with $F(s)$: measured command force externally applied by the surgeon; $Y(s)$: device admittance; $V(s)$: device desired velocity

- the selection of $Y(s)$ determines the responsiveness of the system to human inputs, allowing significant scaling between human-applied force and robot velocity, which improves accuracy

cooperative systems peculiarities (cont'd)

- non-backdrivability and natural stiffness of the robot are assumed to be sufficient to reject applied external forces from the operator and the environment not used by the controller

- smoothness can be enhanced by thresholding and filtering the measured command force and by reducing unintentional motions and tremor

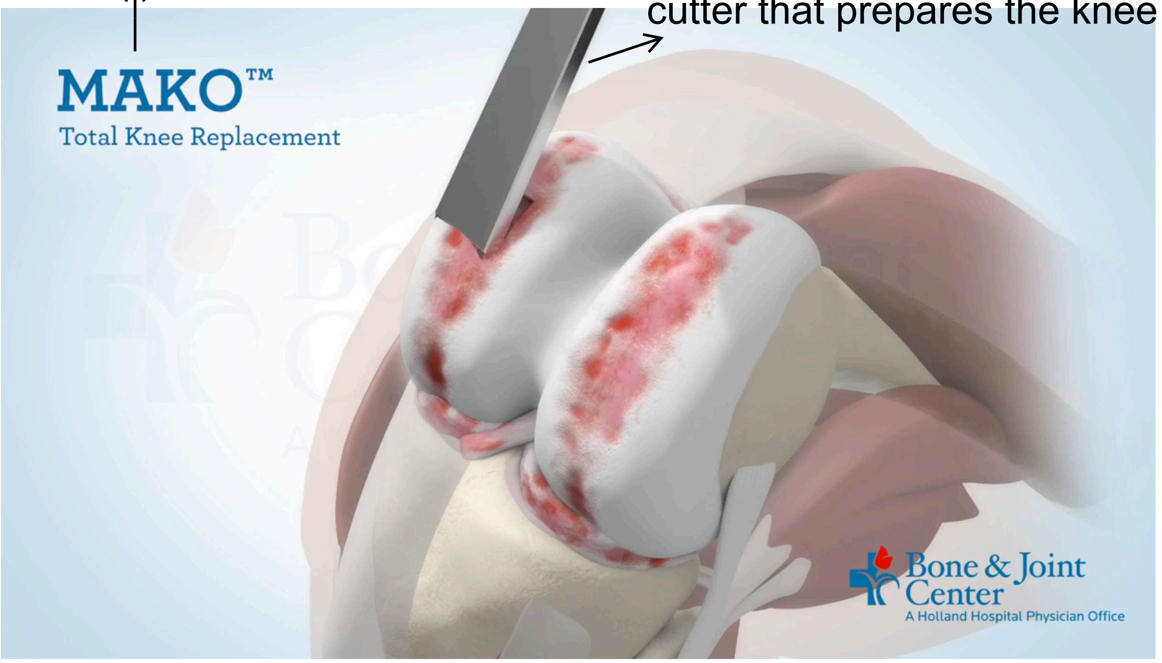
- the admittance value is limited by stability considerations

- admittance control can also be modified to provide haptic feedback and virtual fixtures

The “Hands-On” Acrobot (Active Constraints Robot)

previous company that commerces Acrobot

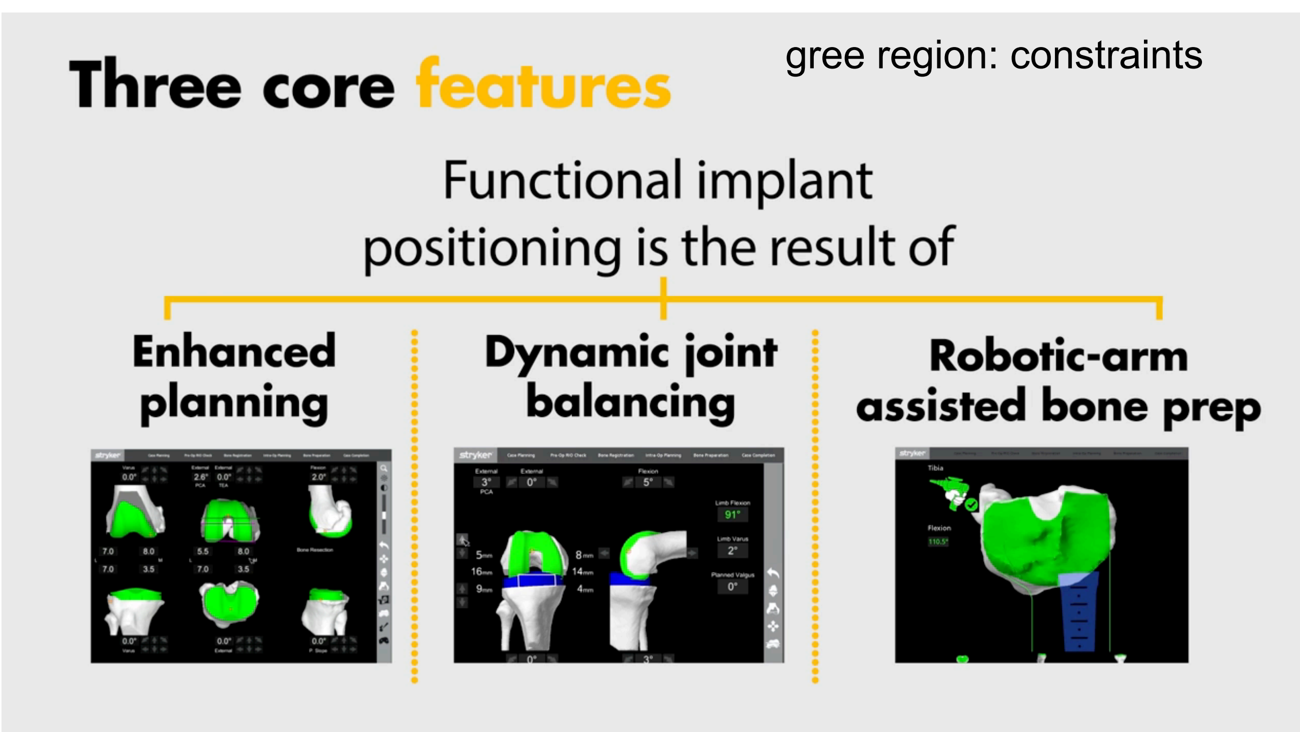
cutter that prepares the knee bones to the implant of the prosthesis component.



``hands-on'' robotic system for bone machining in knee replacement surgery

We need to define geometrics constraints such as boundary

gree region: constraints



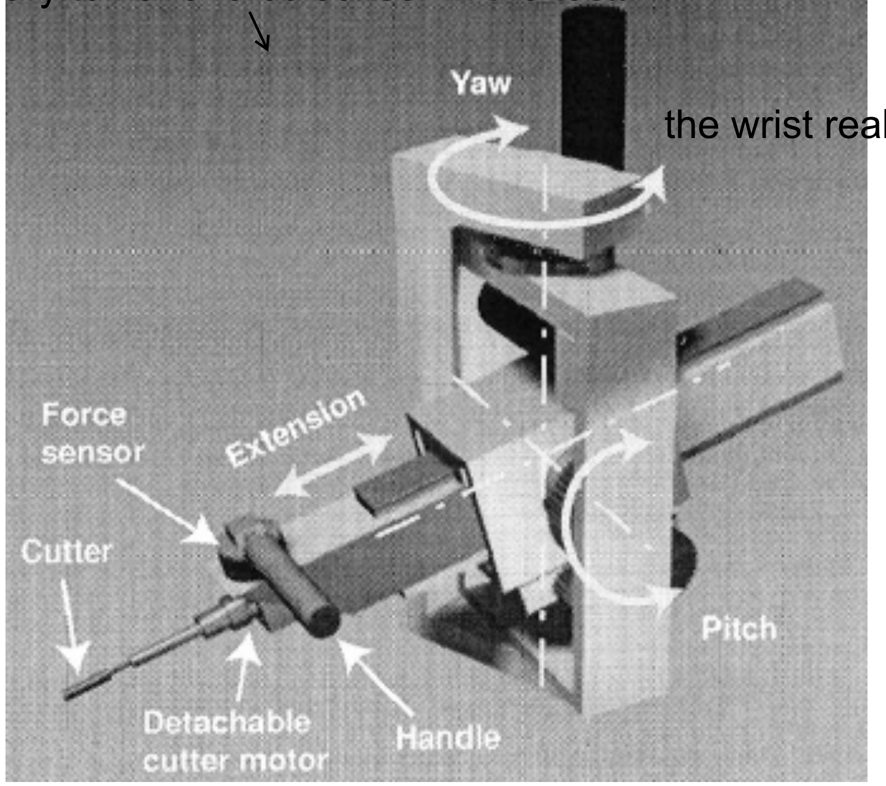
pre-operative phase

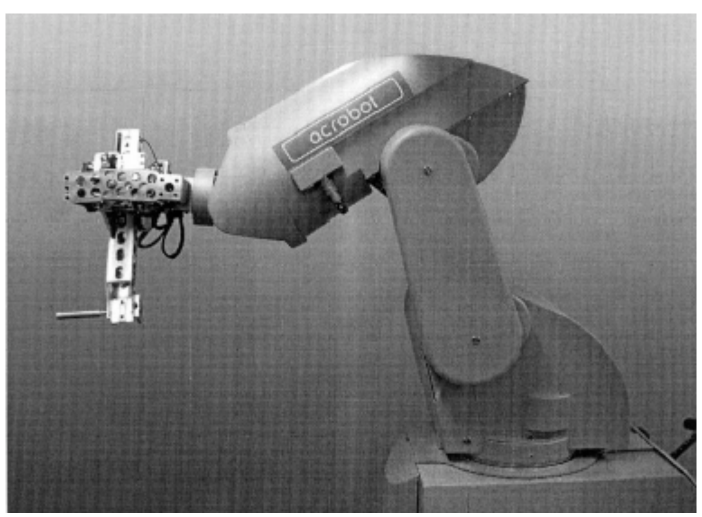
- CT scan of the knee
- 3D model of the knee
- personalized size and position of the prosthesis
- generation of the constraints for the motion of the surgical tool

It is designed in such a way that the impedences along the axes are very low. If the surgical tool is not in contact with the bones(not cutting or trilling the bone) then the impedence is very low. The surgeon should no perceives any nertia. If the tol is in contact with the bone interaction foces are clearly transmitted to the surgeon. It's not necessary to have force sensor in the tool.

original system description

orthopedic cutter





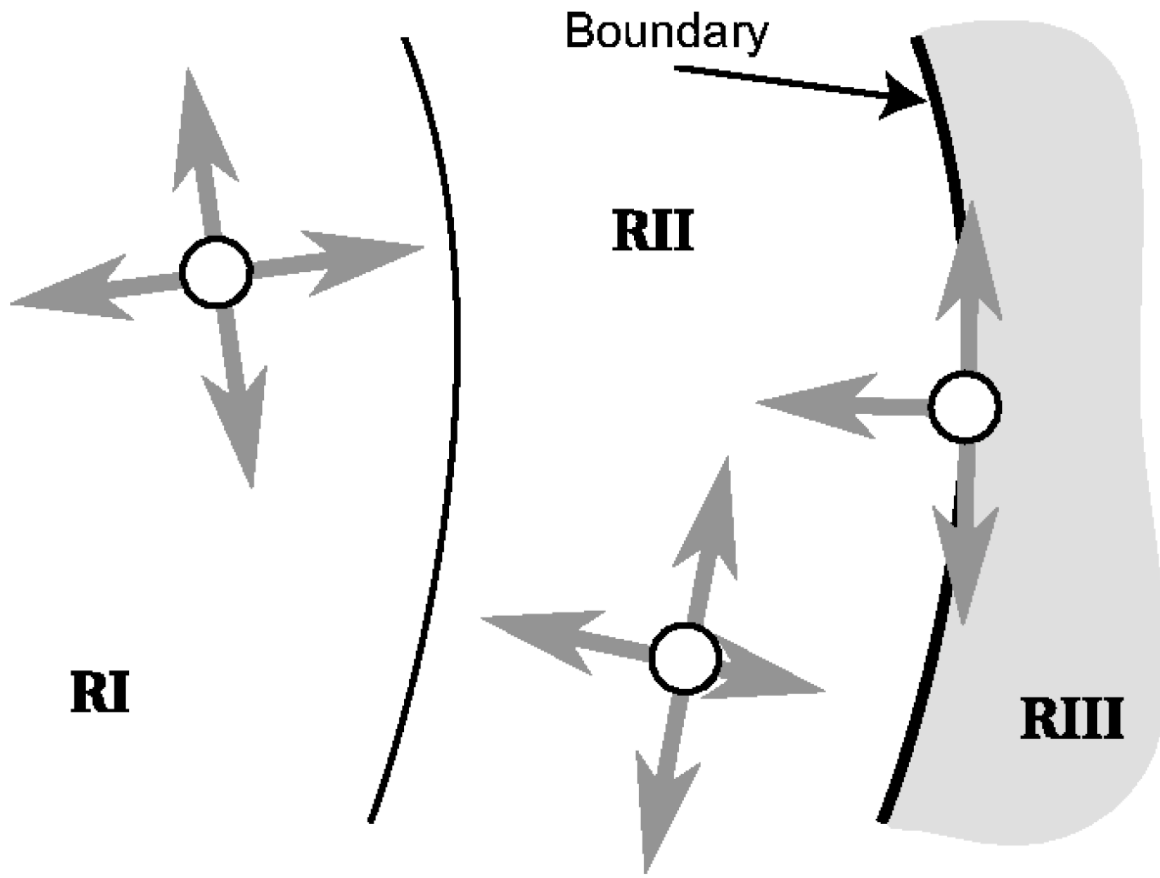
- spherical manipulator with three orthogonal axes of motion: yaw, pitch (within $[-30^o, 30^o]$), and extension (within 30–50 cm)

the wrist realizes spherical manipulation through roll, pitch yaw angles

- kinematic design: mechanical impedance of the axes is low and similar for all axes allowing the robot to be moved by the surgeon with low force; force generated during hard bone cutting can be detected without the need for force sensors in the robot cutter
- the surgeon moves the robot by pushing the handle near the tip of the robot
- the handle incorporates a six-axes force sensor, which measures the guiding forces and torques
- a high-speed orthopaedic cutter motor (removable for autoclave sterilization) is mounted at the tip
- the Acrobot is placed on a six-axes gross positioning device to increase its small working envelope

when the surgeon try to guide the surgical tool outside the safety region, then the robot becomes more difficult to move the surgical tools.

control



The robot is free to move in the task space. In R1 the robot is free to move in all the direction under the action of the surgeon. On the boundary we have the safetyregion. The gray region is consider unsafed, cutter should not remove material in this region.

idea: gradually increase the robot stiffness when approaching a boundary defined in the intervention planning phase

- the robot is free to move inside the safe region (RI) due to the low mechanical impedance of the robot
- at the boundary of the safe region, the robot becomes very stiff, thus preventing further motion over the boundary (RIII)
- the portion of the guiding force normal to the boundary is directly compensated, which substantially reduces the over-boundary error (this error is inevitable due to the limited motor power)
- to avoid instabilities at the boundary, the stiffness increases gradually over a small region (with width D_1) close to the boundary (RII)
- only the stiffness in a direction toward the boundary is adjusted, to allow motion along or away from the boundary with a very low guiding force

control (cont'd)

feedback term proportional to the error between the desired joint position and the actual

feedback term proportional to the error between the desired joint velocity and the current

compensation term that compensates the forces applied by the surgeon as seen at the joint level

- two control loops: an inner joint position/velocity control loop (2 ms) with friction, gravity and surgeon's guiding force compensation:

these 2 terms compensate friction and gravity

viscous friction is proportional also to the velocity

$$\tau = K_P(\Theta_d - \Theta) + K_D(\dot{\Theta}_d - \dot{\Theta}) + \tau_C + f^*(\Theta, \dot{\Theta}) + g^*(\Theta)$$

τ torque output from the controller to the robot motors, K_P, K_D proportional/derivative gains, Θ_d, $\dot{\Theta}_d$ (Θ, $\dot{\Theta}$) desired (measured) joint position and velocity, τ_C compensation of the surgeon's guiding force F_G, $f^*(\Theta, \dot{\Theta})$, $g^*(\Theta)$ respectively friction and gravity compensation

- the outer control loop is slower (10-15 ms) and implements the idea of active constraint
  - cartesian control

    the E-E is the cutter
  - provides the gains of the inner loop K_P and K_D, the desired position and velocity (in operative space) X_d, $\dot{X}_d$ ($\Rightarrow \Theta_d$, $\dot{\Theta}_d$ are obtained by kinematic inversion) and the amount of force compensation F_C ($\Rightarrow \tau_C = J^T F_C$, quasi-static operational conditions)
- the controller parameters are adapted on the basis of the end-effector position X and of the force F_G
- determined the point on the boundary X_{np} closest to X, define

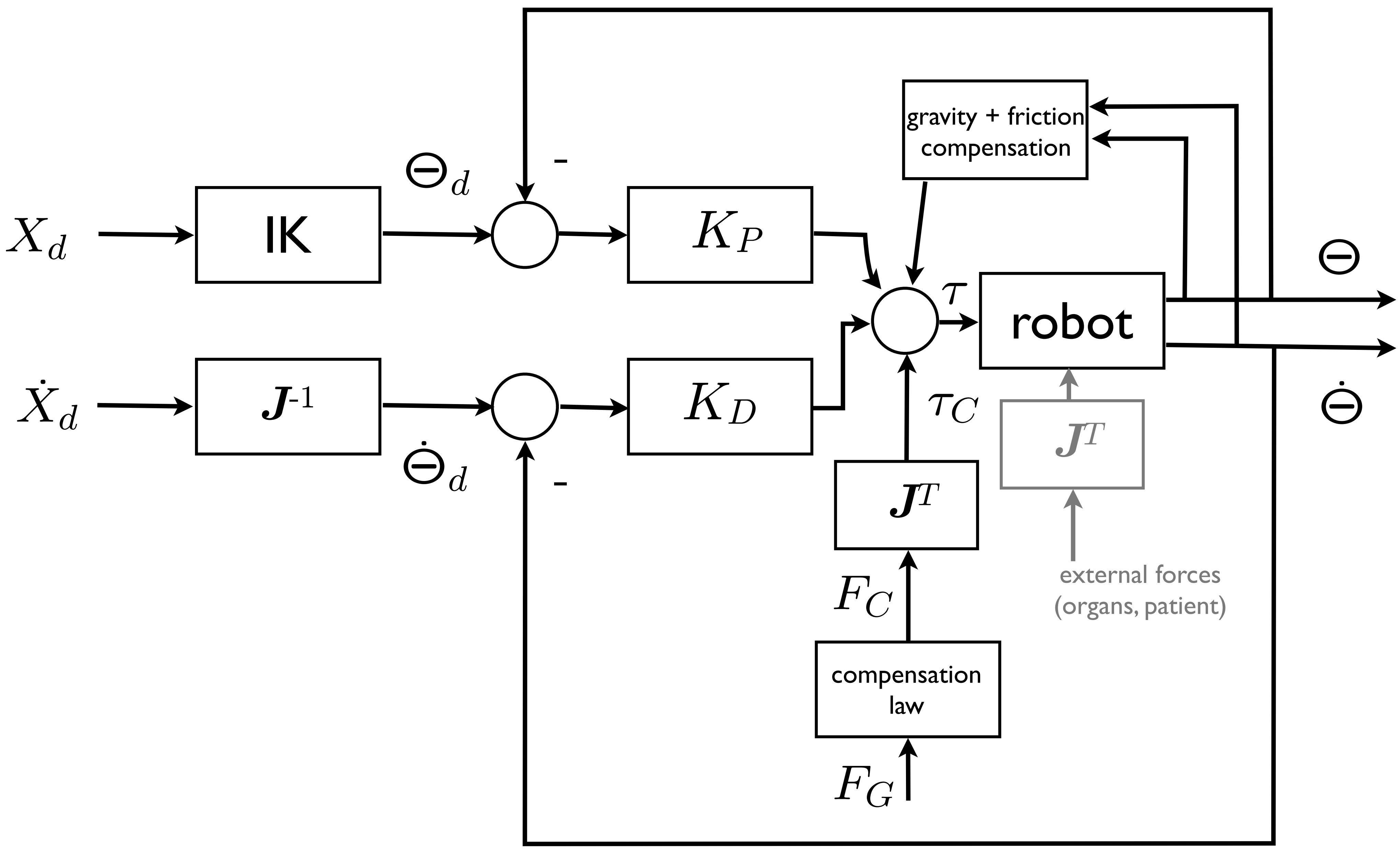
distance of the current position of the tool from the boundaries $\longrightarrow$ $d = ||X - X_{np}|| = (X - X_{np}) \cdot N_{np}$

N_{np}: normal to the boundary at X_{np}

control (cont'd)

friction depends on the position and velocity, but depends on tthe nature of the friction

inner pos/vel control loop, 2 ms (550Hz)



outer control loop implementing the active constraints
10-15 ms (100Hz)

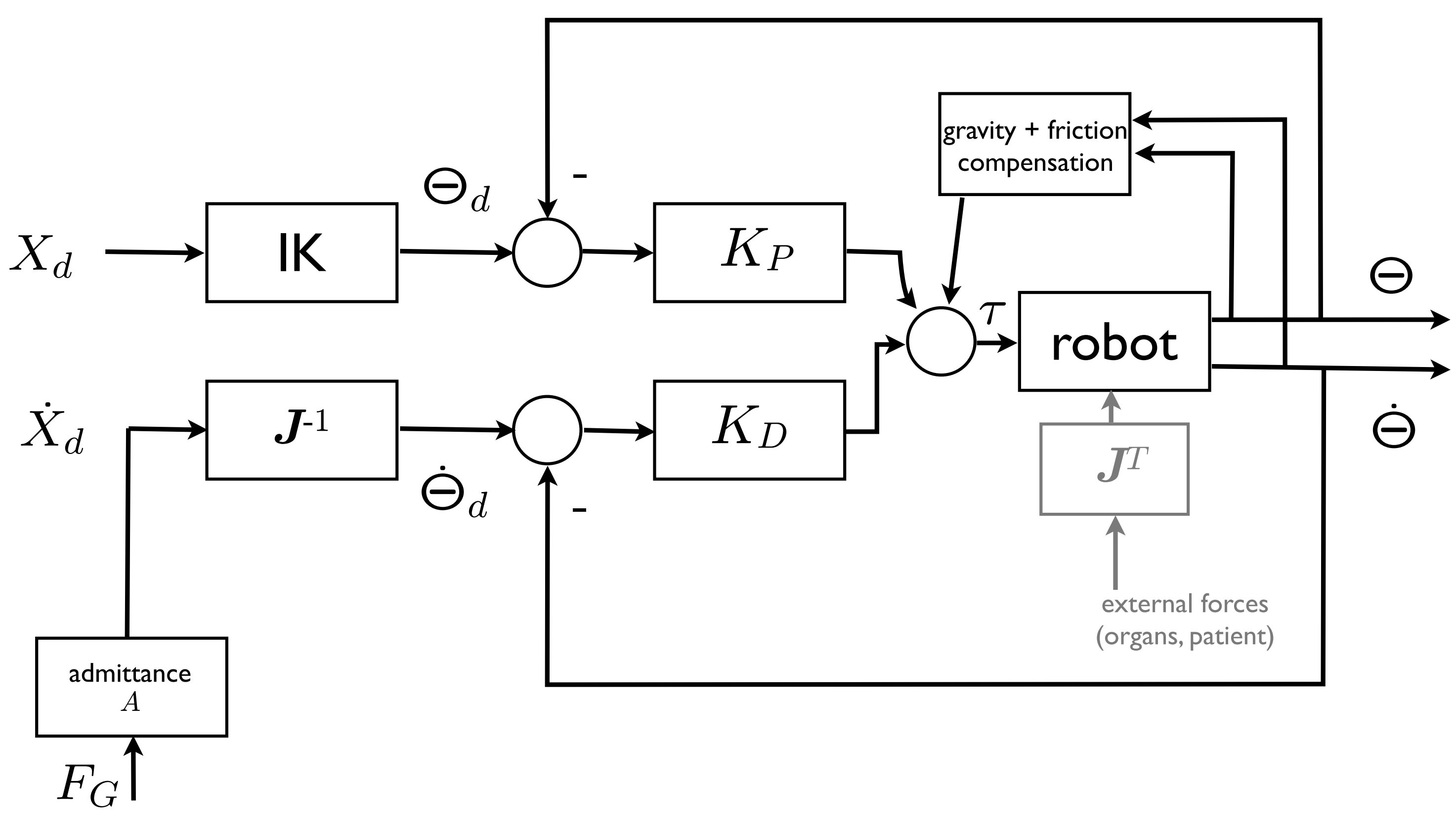
control (cont'd)

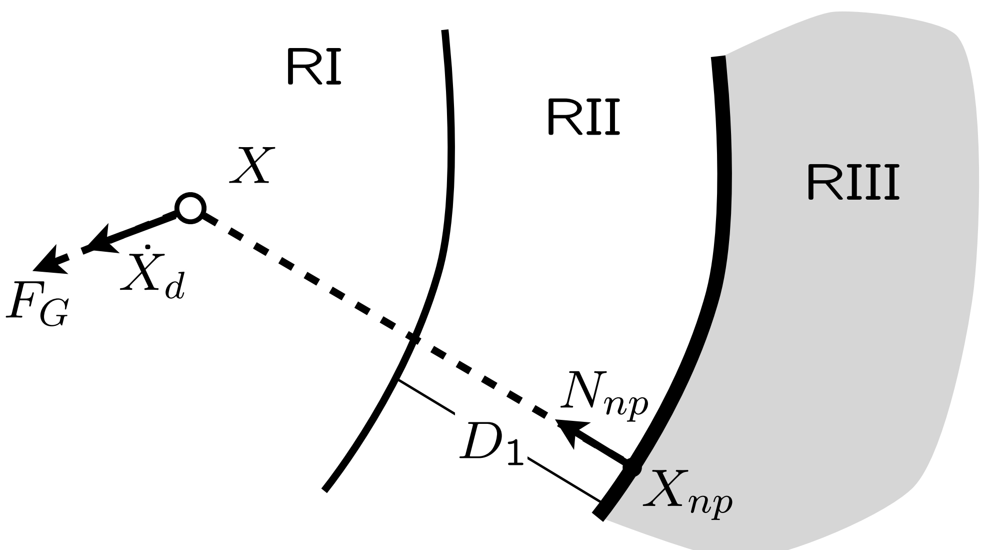
RI $(d > D_1)$

They are small because the referent position of the surgical tool is its current position.

- the PD gains are small to allow the surgeon to feel the cutting forces
- $X_d = X$ Currently the surgical tool is in position X. In this case the error is zero because the desided position is equal to the current
- $\dot{X}_d = AF_G$ admittance is the same in all directions
- $F_C = 0$ the surgeon's guiding force is not compensated in this region

because we don't want to compensate all the surgeon forces





Distance of the surgical tool position of the boundary is less then a given constant D1, the here when the surgeon enter this region then the robot control starts to act on the maniulator to provide a feedback

control (cont'd)

RII $(D_1 \geq d > 0)$ between the safety and unsafety region

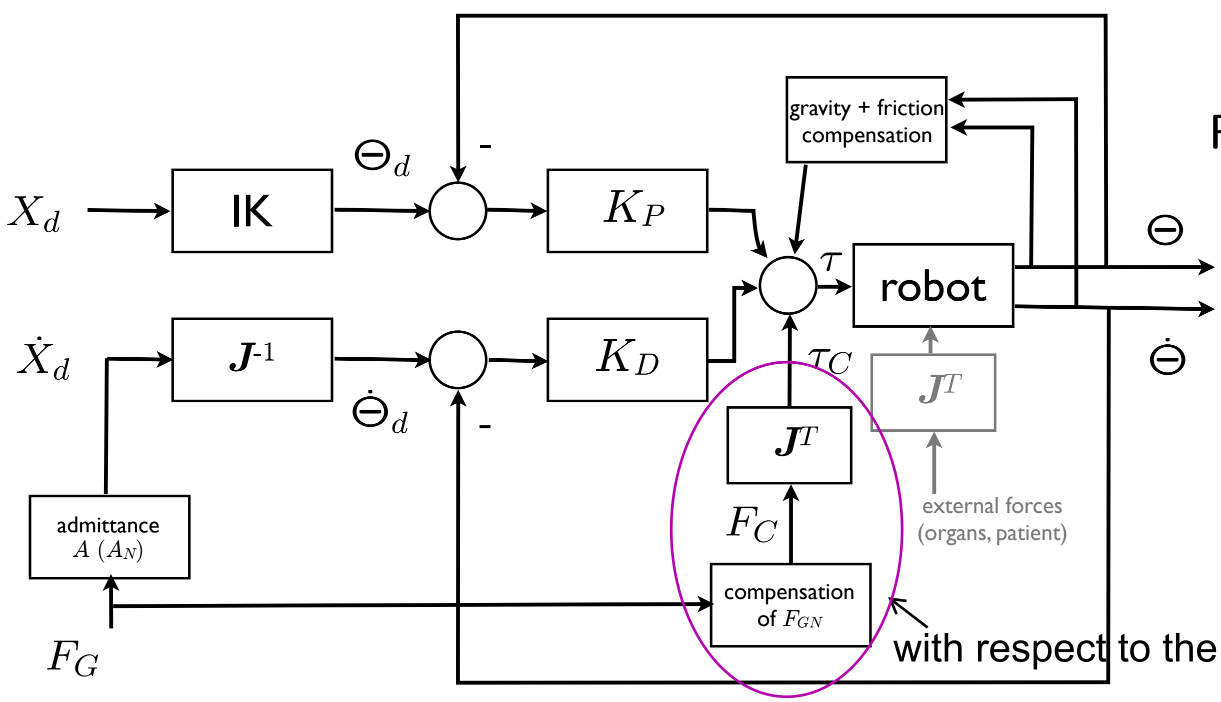
- the control gains increase as the distance to the boundary d decreases
- if $F_G \cdot N_{np} \geq 0 \Rightarrow X_d$, $\dot{X}_d$ and F_C as in RI
- otherwise F_G is decomposed into a normal and a tangential component

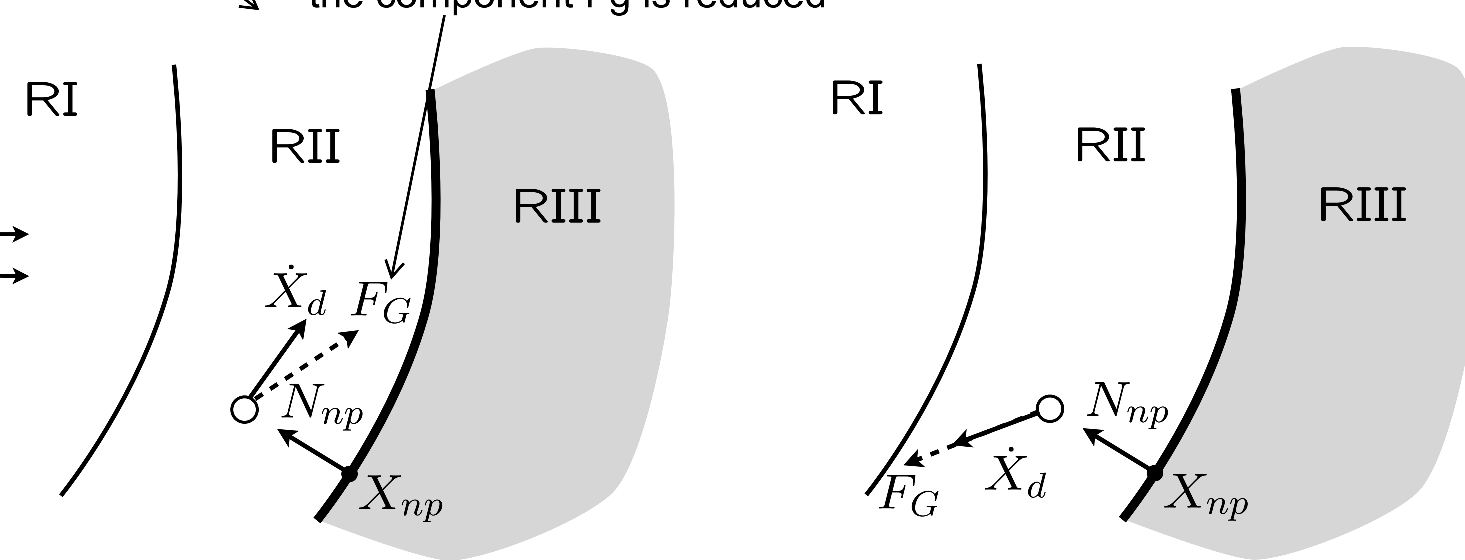
$$F_{GN} = (F_G \cdot N_{np})N_{np} \qquad F_{GT} = F_G - F_{GN}$$

$$\Rightarrow \dot{X}_d = AF_{GT} + A_N F_{GN}, \; A_N = \frac{d}{D_1}A$$

- F_G is compensated in a region with width $D_2 < D_1$
- if $d > D_2 \Rightarrow F_C = 0$, otherwise $F_C = -\frac{D_2 - d}{D_2}F_{GN}$

the component Fg is reduced





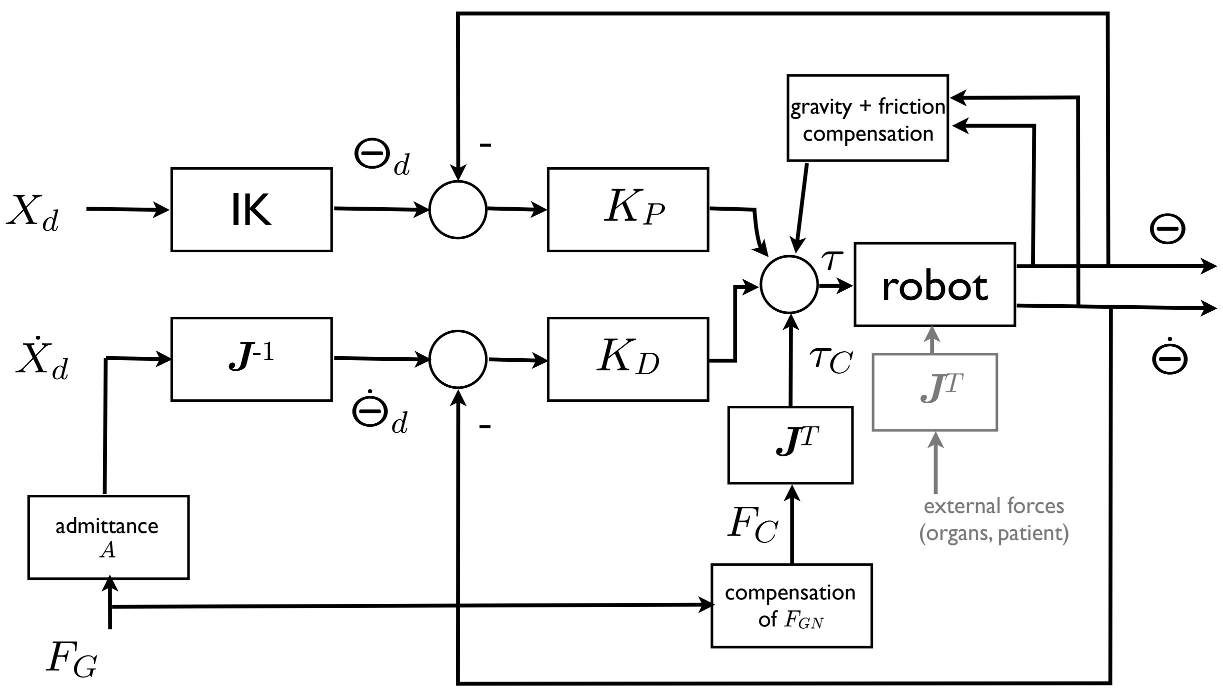
with respect to the prevoius slides we have a branch

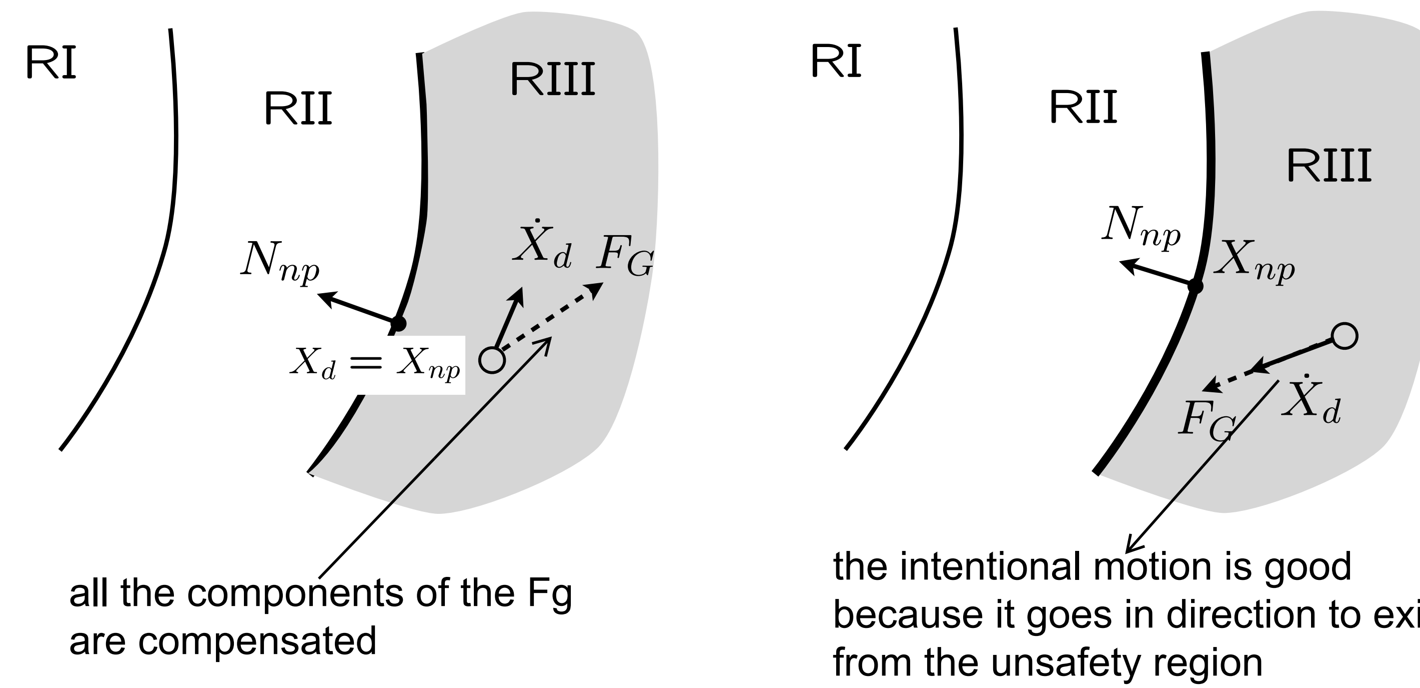
control (cont'd)

we want to attract the tool tip on the boundary

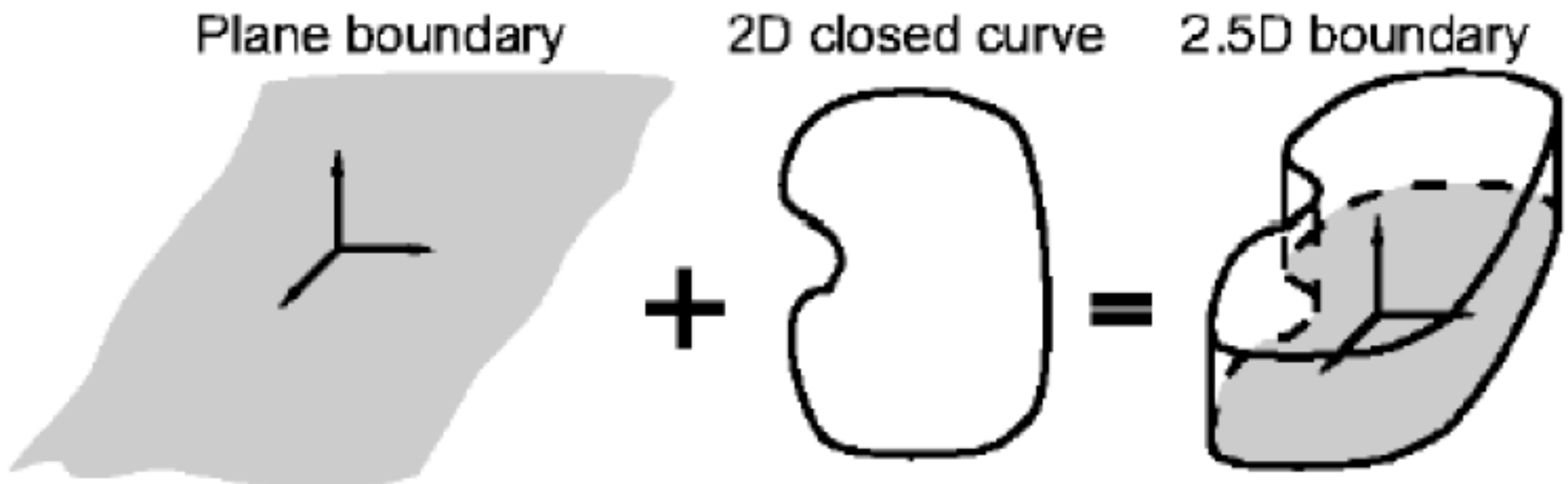
RIII $(d \leq 0)$

- the PD gains are high
- $X_d = X_{np}$
- if the direction of F_G points away from the boundary, $\dot{X}_d$ and F_C are set as in RI
- otherwise $\Rightarrow \dot{X}_d = AF_{GT}$, $F_C = -F_{GN}$





- the used prosthesis requires a number of flat planes to be cut; a "2.5D" constraint is defined: the plane part allows cutting a flat plane into the bone, the 2-D outline part provides protection for the surrounding tissue



- the two parts of the boundary are orthogonal $\Rightarrow X_d, \dot{X}_d, F_c$ can be computed separately for each part, following the above rules, and then combined before being passed on to the inner loop
- K_P and K_D are determined by the nearest point on the whole boundary

1999 the Acrobot Company was set up after 8 years of research at Imperial College London

2010 the Acrobot Company was acquired by the Stanmore Implants Worldwide Ltd (SIW)

2013 SIW sold the Acrobot system to the American company MAKO

Acrobot 2008

Acrobot 2016

stryker

References

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(2) G.D. Hager, A.M. Okamura, P. Kazanzides, L.L. Whitcomb, G. Fichtinger, R. H. Taylor, ``Surgical and interventional robotics: Part III," IEEE Robotics and Automation Magazine, vol. 15, no.~4, pp.~84--93, 2008