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Motion Control and Interaction Control in Medical Robotics

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Introduction

Examples in medical fields as soon as the system is active to provide safety, tactile capabilities, contact constraints or man/machine interface (MMI) functions:

☒ Safety monitoring, tactile search and MMI in total hip replacement with ROBODOC [Taylor 92] or in total knee arthroplasty [Davies 95] [Denis 03]

- Force feedback to implement « guarded move » strategies for finding the point of contact or the locator pins in a surgical setting [Taylor 92]
- MMI which allows the surgeon to guide the robot by leading its tool to the desired position through zero force control [Taylor 92] e.g registration or digitizing of organ surfaces [Denis 03]



Introduction

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☒ Echographic monitoring (Hippocrate, [Pierrot 99])

- A robot manipulating ultrasonic probes used for cardio-vascular disease prevention

→ to apply a given and programmable force on the patient's skin to guarantee good conduction of the US signal and reproducible deformation of the artery



☒ Reconstructive surgery with skin harvesting (SCALPP, [Dombre 03])



Introduction

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☒ Minimally invasive surgery [Krupa 02], [Ortmaier 03]

- Non damaging tissue manipulation requires accuracy, safety and force control

☒ Microsurgical manipulation [Kumar 00]

- Cooperative human/robot force control with hand-held tools for compliant tasks

☒ Haptic devices [Hannaford 99], [Shimachi 03], [Duchemin 05]

- Force sensing for contact rendering, palpation, feeling or estimating mechanical properties of tissue, ...



Contents

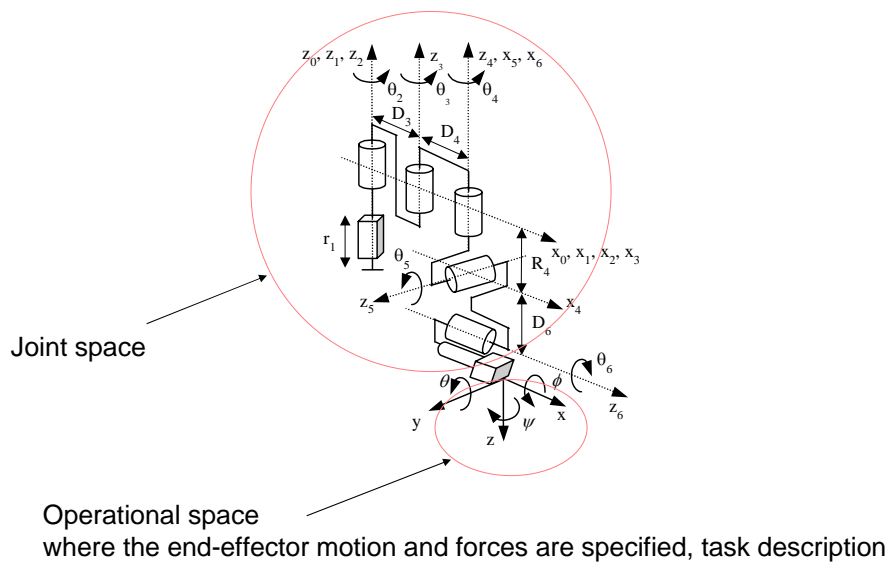
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- ⊠ Motion control
 - joint space control
 - operational space control (task specification)
- ⊠ Interaction control
 - indirect force control
 - direct force control



Geometric modeling

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Equations of motion

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$$\Gamma = \mathbf{A}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{Q}(\mathbf{q}) + \mathbf{diag}(\dot{\mathbf{q}})\mathbf{F}_v + \mathbf{diag}(\text{sign}(\dot{\mathbf{q}}))\mathbf{F}_c$$

$\Gamma \in \mathbb{R}^n$: Vector of joint torques

$\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}} \in \mathbb{R}^n$: Joint position, velocity and acceleration

$\mathbf{A}(\mathbf{q}) \in \mathbb{R}^{n \times n}$: Inertia matrix

$\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} \in \mathbb{R}^n$: Vector of Coriolis and centrifugal torques

$\mathbf{Q}(\mathbf{q}) \in \mathbb{R}^n$: Vector of gravity torques

$\mathbf{F}_v \in \mathbb{R}^n$: Vector of viscous friction

$\mathbf{F}_s \in \mathbb{R}^n$: Coulomb friction parameters

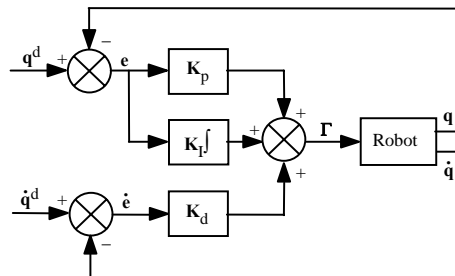


PID control in the joint space [Khalil 02]

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⊠ The control law is given (for most industrial robots) by a local decentralized PID control with constant gain:

$$\Gamma = \mathbf{K}_p(\mathbf{q}^d - \mathbf{q}) + \mathbf{K}_d(\dot{\mathbf{q}}^d - \dot{\mathbf{q}}) + \mathbf{K}_I \int_{t_0}^t (\mathbf{q}^d - \mathbf{q}) dt$$



⊠ More conventional : « cascade structure » including inner loop (velocity) and outer loop (position)

- easier tuning,
- « robustness »



PID control in the joint space

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⊗ Advantages:

- simplicity of implementation
- low cost

⊗ Drawbacks:

- the dynamic performance of the robot varies according to its configuration
- when tracking high velocity trajectories or when using direct drive actuators → strong influence of the nonlinear coupling terms → poor dynamic accuracy



PID control in the joint space

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⊗ Computation of the gains by considering that each joint j is modeled by a linear second order differential equation:

$$\Gamma_j = a_j \ddot{q}_j + F_{vj} \dot{q}_j + \gamma_j$$

where: a_j : maximum magnitude of element of inertia matrix
 γ_j : disturbance torque

Assuming $\gamma_j = 0$, the closed loop transfer function is given by:

$$\frac{q_j(s)}{q_j^d(s)} = \frac{K_{dj}s^2 + K_{pj}s + K_{lj}}{a_j s^3 + (K_{dj} + F_{vj})s^2 + K_{pj}s + K_{lj}}$$



PID control in the joint space

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- ⊗ Characteristic equation:

$$\Delta(s) = a_j s^3 + (K_{dj} + F_{vj})s^2 + K_{pj}s + K_{ij}$$

- ⊗ Common solution in robotics:

adjust the gains in order to obtain a negative real triple pole \ominus
fastest possible response without overshoot

$$\Delta(s) = a_j (s + \omega_j)^3$$

Bandwidth adapted through ω_j

- ⊗ Computed gains:

$$K_{pj} = 3a_j \omega_j^2$$

$$K_{dj} + F_{vj} = 3a_j \omega_j$$

$$K_{ij} = a_j \omega_j^3$$



Practical aspects

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- ⊗ High gains decrease the tracking error (but bring the system near the instability domain) \ominus Trade-off for the chosen frequency with respect to the structural resonance frequency:

$$\omega_j < \omega_{ij} / 2$$

- ⊗ In the absence of integral action, a static error due to gravity may affect the final position

- ⊗ Practically it can be deactivated when:

- The position error is very large, since the P action is sufficient
- The position error becomes too small in order to avoid oscillations that could be caused by Coulomb frictions

- ⊗ The predictive action $K_d \dot{q}^d$ reduces significantly the tracking errors



Joint space vs task space

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- ⊗ Joint space control scheme does not influence operational space variables (open loop)
 - Backlash, elasticity, friction, coupling ... cause a loss of accuracy
- ⊗ Task specification carried out in the operational space
- ⊗ Control action carried out in the joint space



PID control in the task space

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- ⊗ Objective:
 - the possibility of acting directly on operational space variables → compensating for any uncertainty of the structure: backlash, elasticity, friction, coupling, ...
 - very often only a potential advantage, since measurement of operational space variables is not performed directly
- ⊗ Two possible schemes:
 - specified trajectory in the task space → trajectory in the joint space → control in the joint space
 - control law directly designed in the task space



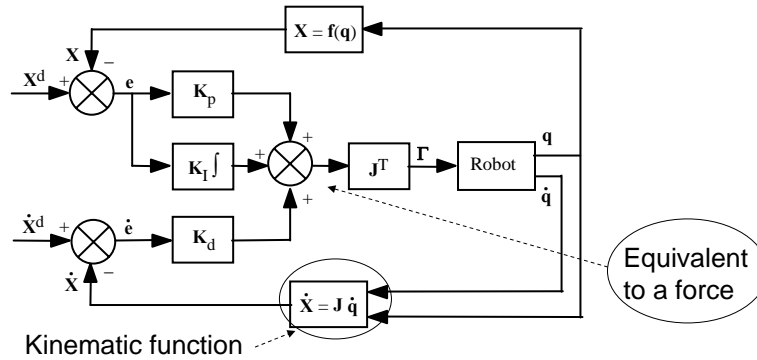
PID control in the task space

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⊗ The control is given by:

$$\Gamma = \mathbf{J}^T [\mathbf{K}_p (\mathbf{X}^d - \mathbf{X}) + \mathbf{K}_d (\dot{\mathbf{X}}^d - \dot{\mathbf{X}}) + \mathbf{K}_I \int_{t_0}^t (\mathbf{X}^d - \mathbf{X}) dt]$$

Transform the task space error into the joint space



⊗ Extra cost for adding sensor in the operational space



Linearizing and decoupling control

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Task requirements:

- ⊗ Fast motion
- ⊗ High dynamic accuracy

Need:

- ⊗ Improve performance of the control by taking into account the dynamic interaction effects between joints

Basic solution:

- ⊗ Linearizing and decoupling control based on canceling the nonlinearities in the robot dynamics → *Inverse dynamics control*



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Inverse dynamics control

- Dynamic model of an n -joint manipulator:

$$\Gamma = \mathbf{A}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{H}(\mathbf{q}, \dot{\mathbf{q}})$$

- If we define the control law with \mathbf{w} the new input control vector:

$$\Gamma = \hat{\mathbf{A}}(\mathbf{q})\mathbf{w} + \hat{\mathbf{H}}(\mathbf{q}, \dot{\mathbf{q}})$$

- Assuming perfect modeling ($\hat{\mathbf{A}} = \mathbf{A}$, $\hat{\mathbf{H}} = \mathbf{H}$) and absence of disturbances:

$$\ddot{\mathbf{q}} = \mathbf{w}$$

- The problem is reduced to the linear control of n decoupled double-integrators

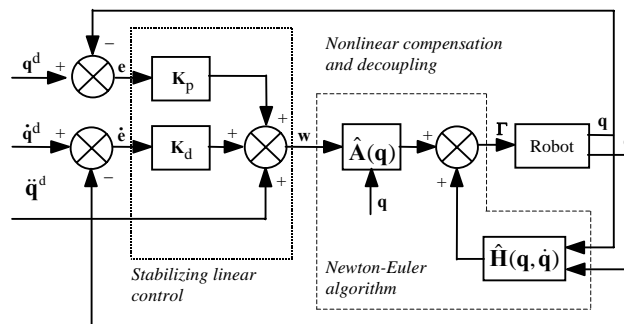


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Inverse dynamics control in the joint space

- By defining \mathbf{w} :

$$\mathbf{w} = \ddot{\mathbf{q}}^d + \mathbf{K}_d(\dot{\mathbf{q}}^d - \dot{\mathbf{q}}) + \mathbf{K}_p(\mathbf{q}^d - \mathbf{q})$$





Inverse dynamics control in the joint space

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- ⊗ The closed loop system response is determined by the decoupled linear error equation:

$$\ddot{\mathbf{e}} + \mathbf{K}_d \dot{\mathbf{e}} + \mathbf{K}_p \mathbf{e} = \mathbf{0}$$

- ⊗ The gains are adjusted to provide the desired dynamics with a given damping coefficient ξ_j and a given control bandwidth fixed by a frequency ω_j :

$$\begin{cases} \mathbf{K}_{pj} = \omega_j^2 \\ \mathbf{K}_{dj} = 2\xi_j \omega_j \end{cases}$$

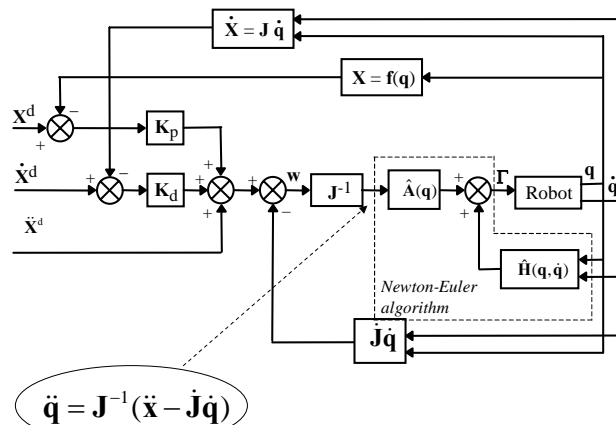
Generally $\xi_j = 1$ to obtain the fastest response without overshoot

- ⊗ Robustness and stability [Samson 87] (in presence of modeling errors)



Inverse dynamics control in the task space

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Conclusion

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In case of load variation, high velocity trajectory, low tracking error, imperfect knowledge for model uncertainty, these controllers are not sufficient ☹

- ⊗ Predictive control ([Ginhoux 03], [Ortmaier 03])
- ⊗ Adaptive control ([Krupa 02], [Ortmaier 03])
- ⊗ Robust control (sliding mode,...)



Interaction control

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- ⊗ Objective:

Achieve a task requiring contact and control of interaction between the robot end-effector and the environment.

- ⊗ First interaction controller based on motion control
- ⊗ Difficulties with purely position control systems ☹ requirements:
 - precise model of the mechanism
 - exact knowledge of the location and stiffness of the environment



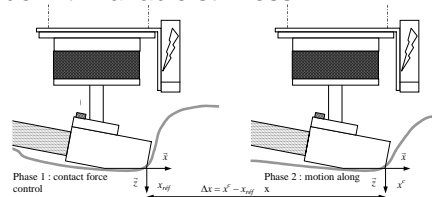
Compliant motion in medical robotics

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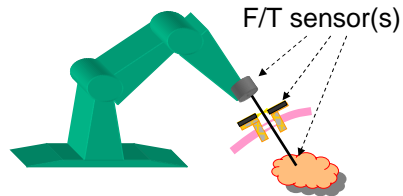
⊗ Specificities in medical robotics:

- interaction with patient (see examples below)
- interaction with surgeon (e.g. manually guiding the robot by grabbing the tool or telemanipulating with haptic feedback)
- soft deformable tissue with variable stiffness

⊗ Skin harvesting



⊗ Minimally invasive surgery



Interaction control

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⊗ Design a control scheme able to:

- control the robot position along the direction of the task space, the environment imposes natural force constraints
- control the robot force along the direction of the task space, the environment imposes natural position constraints



Interaction control strategies

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Two categories:

⊠ Indirect force control \rightarrow force control via motion control without explicit closure of a force feedback

- Compliance control, impedance control

⊠ Direct force control \rightarrow explicit force control to a desired value

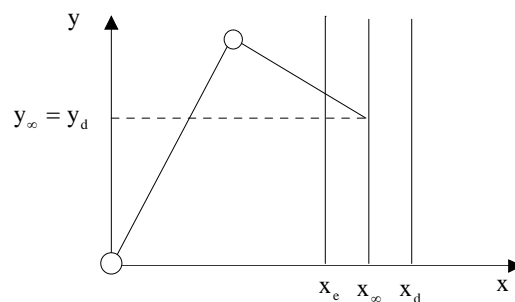
- Hybrid position/force control, external force control



Compliance control [Siciliano 00]

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⊠ Two-link planar arm in contact with an elastically compliant plane (stiffness = k_e)



x_∞ end-effector equilibrium position

x_e undeformed position

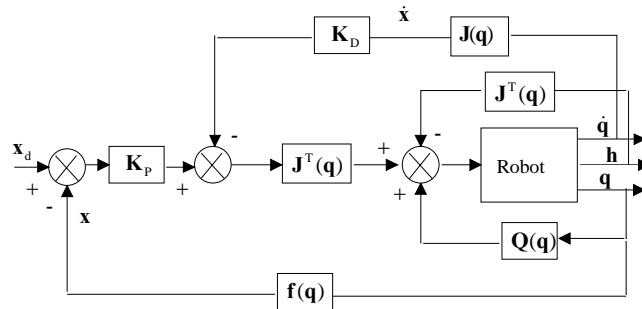
x_d desired position



Compliance control

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⊗ Compliance control with operational space PD control and gravity compensation ($\mathbf{x}_d = \text{cte}$, $\dot{\mathbf{x}}_d = \mathbf{0}$)



Robot dynamic model: $\mathbf{A}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{Q}(\mathbf{q}) = \mathbf{w} - \mathbf{J}(\mathbf{q})^T \mathbf{h}$

Control law: $\mathbf{w} = \mathbf{J}^T(\mathbf{q})[\mathbf{K}_p \tilde{\mathbf{x}} - \mathbf{K}_D \dot{\tilde{\mathbf{x}}}] + \mathbf{Q}(\mathbf{q})$



Compliance control

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At the equilibrium: $\dot{\mathbf{x}} = 0$ and $\mathbf{K}_p \tilde{\mathbf{x}} = \mathbf{h}$

Assuming that: $\mathbf{h} = \mathbf{K}_e (\mathbf{x} - \mathbf{x}_e)$

$\mathbf{K}_e = \text{diag}\{k_x, 0\}$ $\mathbf{K}_p = \text{diag}\{k_{px}, k_{py}\}$ (frictionless)

Let $\mathbf{p}_d = [x_d \quad y_d]^T$ be the desired tip position

Equilibrium equation for position:

$$\mathbf{p}_\infty = \begin{bmatrix} \frac{k_{px} x_d + k_x x_e}{k_{px} + k_x} \\ y_d \end{bmatrix}$$

The elastic plane imposes that the arm moves as far as it reaches the coordinate



Compliance control

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Equilibrium equation for force:

$$f_{\infty} = \begin{bmatrix} \frac{k_{Px} k_x}{k_{Px} + k_x} (x_d - x_e) \\ 0 \end{bmatrix}$$

⊠ Difference between x_d and x_e

⊠ Equivalent stiffness coefficient (parallel composition)

⦿ Arm stiffness and environment stiffness influence the resulting equilibrium configuration



Compliance control

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⊠ $k_{Px}/k_x \gg 1$ ⦿ $x_{\infty} \approx x_d$ $f_{x_{\infty}} \approx k_x (x_d - x_e)$

⦿ The plane complies almost up to x_d and the elastic force is mainly imposed by the environment (passive compliance)

⊠ $k_{Px}/k_x \ll 1$ ⦿ $x_{\infty} \approx x_e$ $f_{x_{\infty}} \approx k_{Px} (x_d - x_e)$

⦿ The environment prevails over the arm. The elastic force is mainly generated by the arm (active compliance)



Impedance control [Hogan 85]

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- ⊗ Basic idea: assigned a prescribed dynamic behaviour while its effector is interacting with environment
- ⊗ Performances specified by a generalized dynamic impedance representing a mass-spring-damper system
- ⊗ End-effector velocity or position and applied force are related by a mechanical impedance:

$$\mathbf{F}(s) = \mathbf{Z}(s)\dot{\mathbf{X}}(s) \quad \text{or} \quad \mathbf{F}(s) = s\mathbf{Z}(s)\mathbf{X}(s)$$

where: $s\mathbf{Z}(s) = \mathbf{\Lambda}s^2 + \mathbf{B}s + \mathbf{K}$

$\mathbf{\Lambda}$: the desired inertia matrix

\mathbf{B} : the desired damping matrix

\mathbf{K} : the desired stiffness matrix



Impedance control

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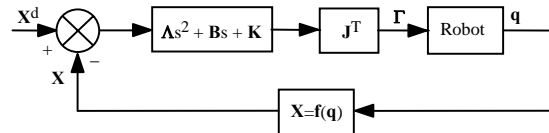
- $\mathbf{\Lambda}$ ⊗ High values in the directions where a contact is expected in order to limit the dynamics
- \mathbf{B} ⊗ High values where it is necessary to dissipate the kinetic energy and damp the response
- \mathbf{K} ⊗ The stiffness affects the accuracy of the position control



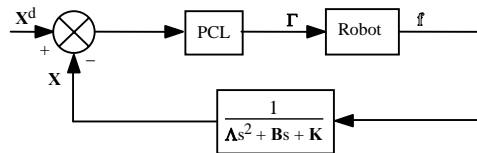
Two families of impedance control

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- ⊗ Impedance control scheme without force feedback



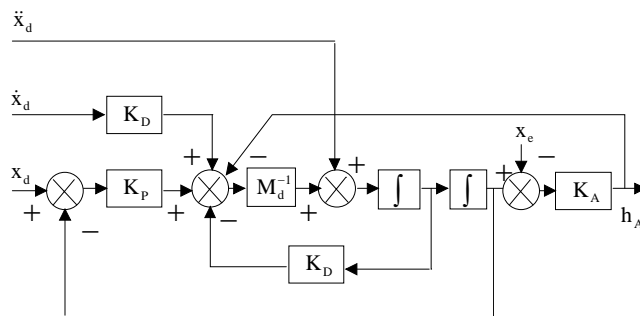
- ⊗ Impedance control scheme with force feedback

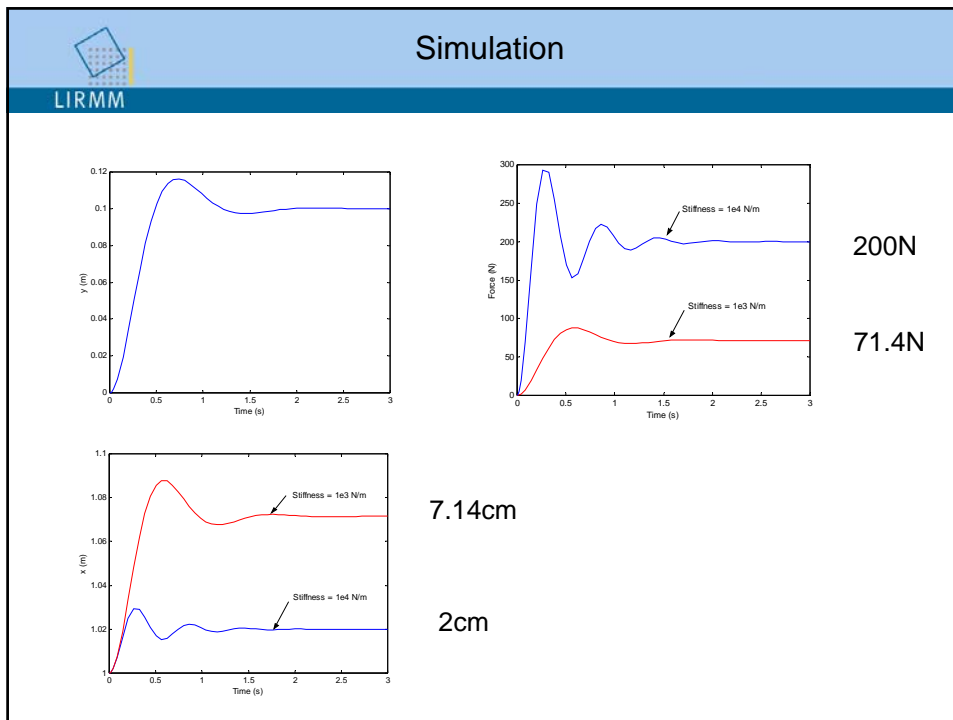


Simulation [Siciliano 00]

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- ⊗ Manipulator in contact with an elastic environment under impedance control
- ⊗ Inverse dynamics control in the operational space and contact force measurement





Remarks

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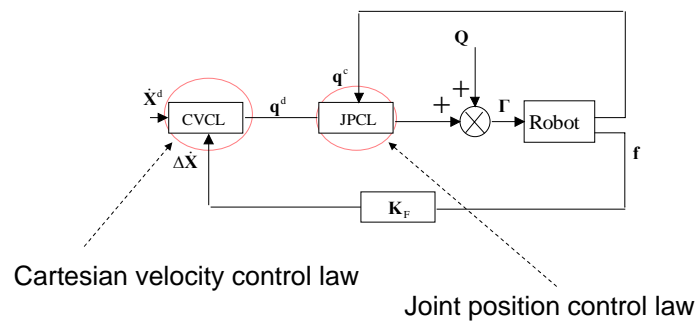
- ⊗ Impossible to prescribe (and to control accurately) a desired wrench
- ⊗ Mechanical devices interposed between the end-effector and the environment ☹ Low versatility



Damping control

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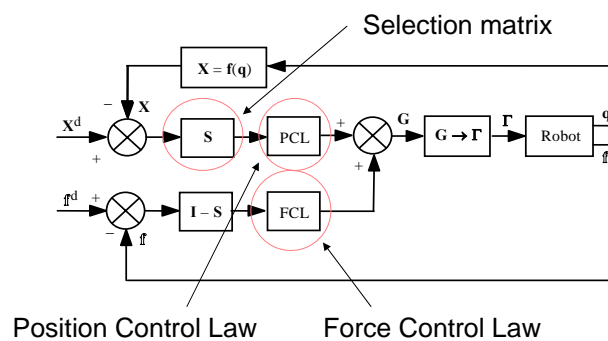
- ⊗ In [Taylor 92], the reference velocity is derived from the force error
- ⊗ In [Davies 95], the reference velocity is derived from the guiding surgeon force



Hybrid position / force control [Raibert 81]

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- ⊗ Principle of the hybrid position / force control:



- ⊗ Direction constrained in position \cup force controlled
- ⊗ Direction constrained in force (null force) \cup position controlled



Notes

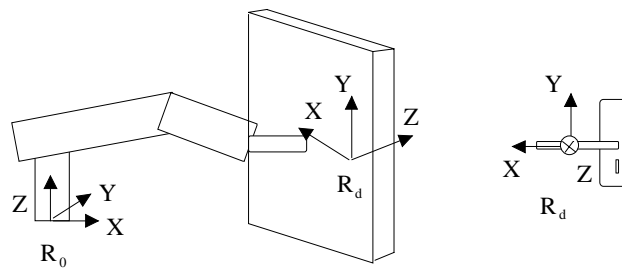
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- ⊗ Incoherence with respect to the Mason description [Mason 81]
 - force/position duality [Raibert 81]
 - force/velocity duality [Mason 81] ⇨ the task can be better described in terms of velocity and force
- ⊗ No robust behaviour in free space along a direction which is controlled in force but not constrained



Force / velocity duality

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- ⊗ Open a door ⇨ two tasks 1) turn the handle and 2) pull the door
 - 1) Velocity can be controlled along Y
 - 2) Velocity can be controlled along Y and Z



Force / velocity duality

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- ⊗ The task is described in term of velocity setpoint expressed in the operational space frame
- ⊗ The motion direction depends on the current position of the task frame
- ⊗ In case of disturbances, the motion can always be executed without constraint ⊕ the trajectory is automatically adapted



Zero force setpoint

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To guide the robot by grabbing the end-effector, we may have to control the force along non constrained directions with a desired force of 0

- ⊗ Assume that the robot is subject to a disturbance

- case 1:

the disturbance is applied below the force sensor ⊕ the force control is active

- case 2:

the disturbance is applied before the force sensor ⊕ in free space, the robot is not controlled since the disturbance is not observed (and no position control)

- ⊗ Necessity to use additional sensors



Some examples of hybrid control scheme

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⊗ Strategy with on-line stiffness estimation and controller parameters tuning [Ortmaier 03]

- In beating heart surgery, they compensate the heart motion by exerting a constant force to the organ

⊗ Control « towards zero » the lateral forces applied to the constrained degrees of freedom (trocar) during laparoscopic manipulation [Krupa 02]



Hybrid external force control [De Schutter 88] [Perdereau 91]

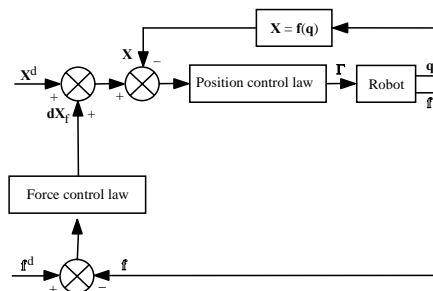
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⊗ It is composed of two embedded control loops:

- Outer loop control force

The output of the outer loop is transformed into a desired position input for the inner loop

- Inner loop control position



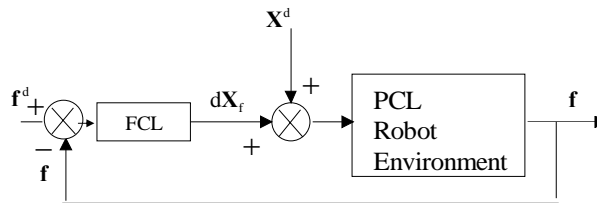


Properties

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⊗ Force control loop is hierarchically superior with respect to position

- Let's consider a step on the desired position
- Control theory: a disturbance is rejected if there is an integrator before the disturbance



- A static error due to the desired position is cancelled



Properties

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⊗ Inner position loop control is always active:

- less stability problem when switching between position control and force control
- if a disturbance is applied to the robot before the force sensor and if the robot is not in contact with the environment:
 - ⌚ the disturbance is not detected by the force sensor
 - ⌚ but it is compensated by the position loop
- if the force is applied after the force sensor, this is equivalent to a contact with the environment
 - ⌚ the robot is moving along the direction of the applied force to compensate it



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Properties

- ⊗ Easily implementable with decentralized industrial controllers (PID) due to the cascade structure of the scheme [Dégoulange 93]
- ⊗ Except the IGM and DGM, few on line computations are required
- ⊗ Cascade structure easily tuned by starting with the inner position loop



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Example : SCALPP Project (1999-2003)

- ⊗ Robotized skin harvesting in reconstructive surgery with external position / force control [Dombre 03]

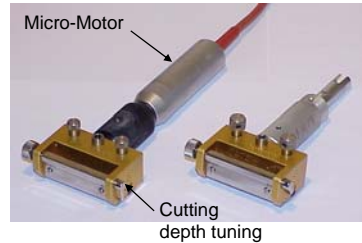




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Skin Harvesting: Medical Task Analysis (1)

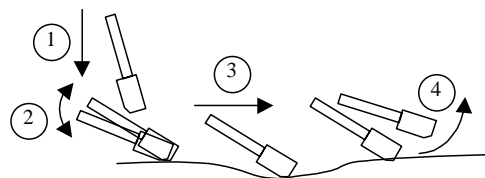
- ⊗ Grafting in reconstructive surgery: severely burnt, maxilla-facial, orthopaedic...
- ⊗ Two steps:
 - skin harvesting
 - grafting of the harvested skin strip onto a burnt location
- ⊗ Constraints on the skin strip to reduce scars:
 - thickness regularity
 - width regularity
 - no hole
- ⊗ ... depends on:
 - harvested location (thighs, head, back...)
 - surgeon skill
 - stability of the force and moment applied



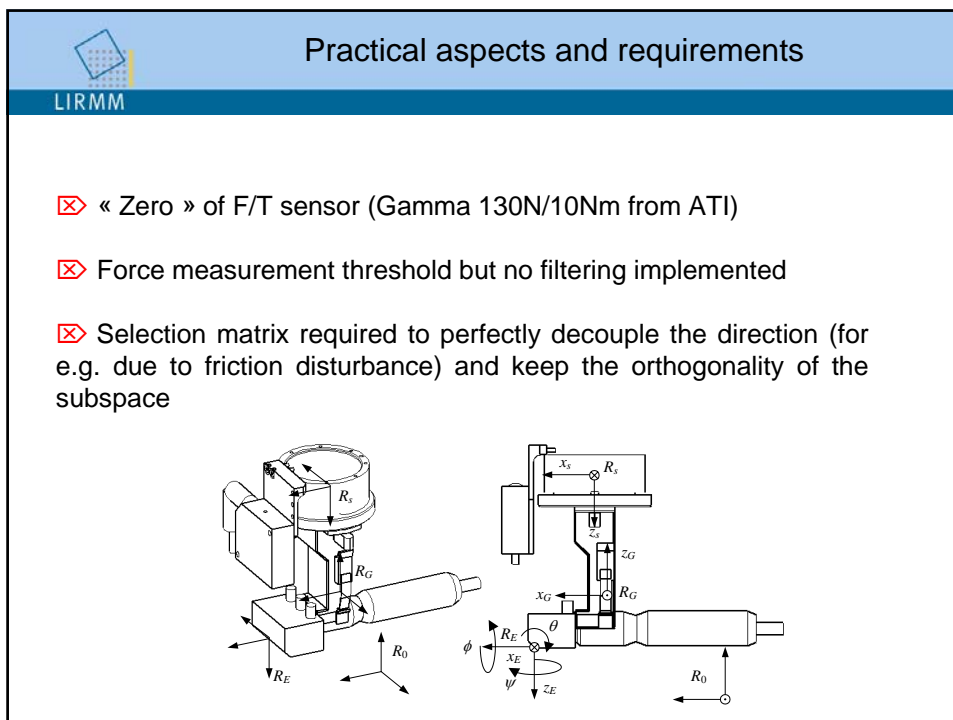
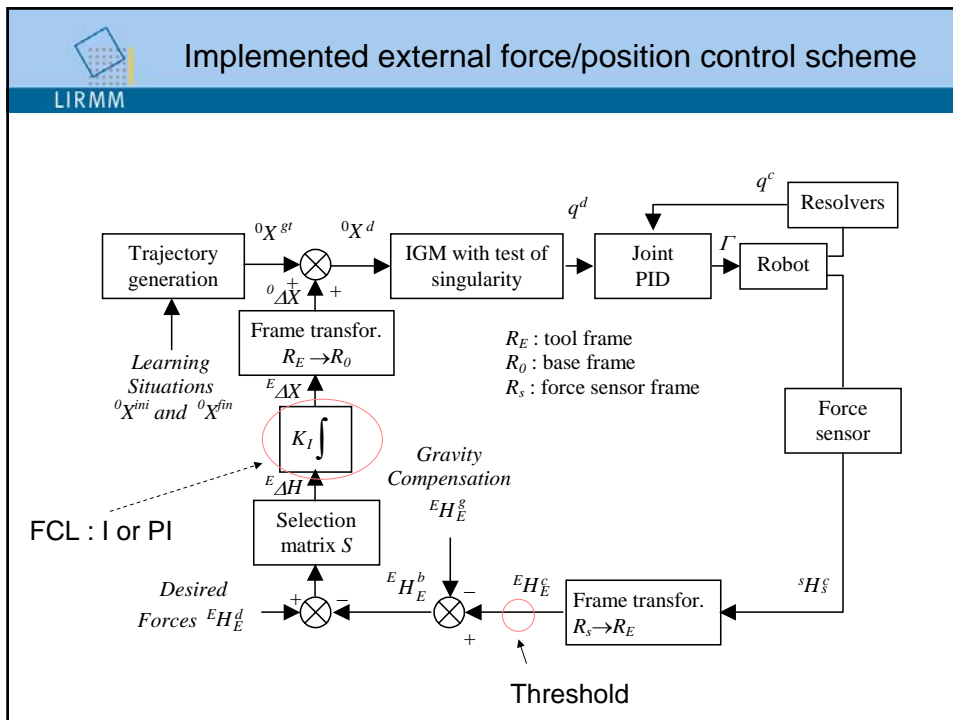
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Skin Harvesting: Robotic Approach

- ⊗ Skin harvesting is a difficult gesture which requires high accuracy and high efforts to the surgeon
- ⊗ It requires a long training process and a regular practice
- ⊗ The surgeon action may be divided into four steps:
 - 1) free motion until contact is reached,
 - 2) orientation step to make that the blade penetrates the skin;
 - 3) harvesting process: the blade plane is kept against the skin with a roughly constant contact force
 - 4) quick rotation to free the dermatome



→ Robotization with position/force control to help especially untrained surgeons





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Zero force control in free space

☒ Video with a proportional controller

- limited motion setpoint proportional to the applied force
- end-effector comes back as soon as the disturbance stops



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Zero force control in free space

☒ Video with an integrator controller

- position ramp while the force is applied
- « memory of motion »: the current position is maintained if the force stops



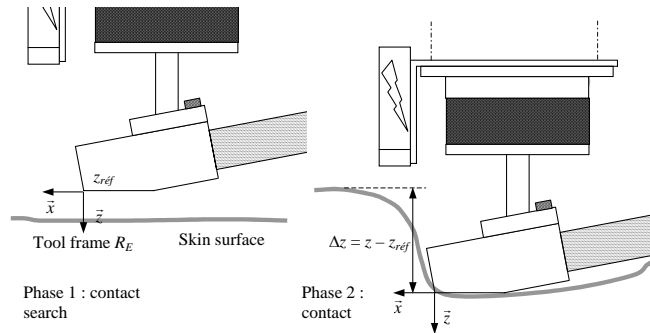


Implemented external force/position control scheme

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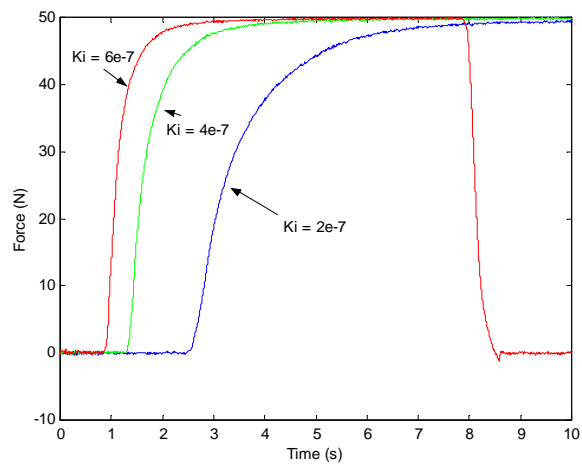
⊗ I or PI for the force control loop ?

⊗ Experimental procedure:



Experimental results

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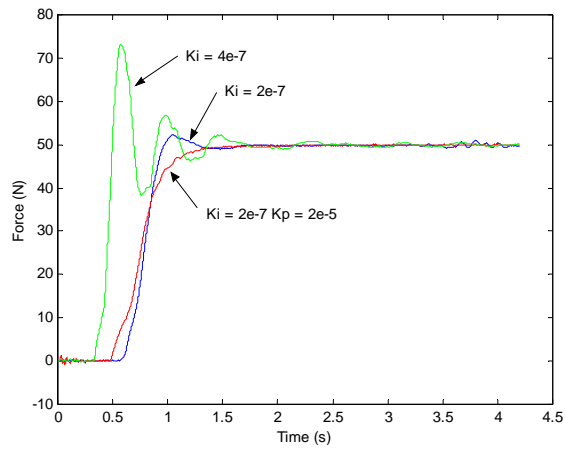


Soft surface



Experimental results

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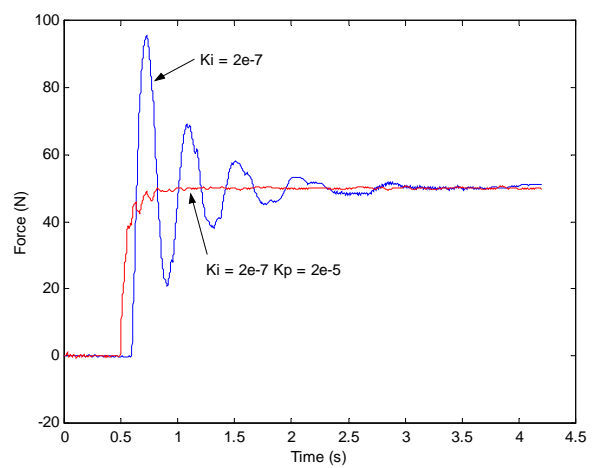
Polystyrene



Experimental results

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⊠ Rigid surface



⊠ Robustness with respect to stiffness variation: orthopaedic surgery, MIS



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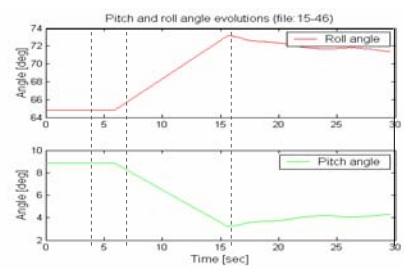
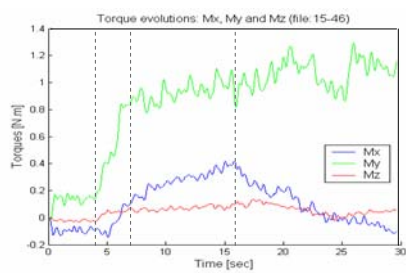
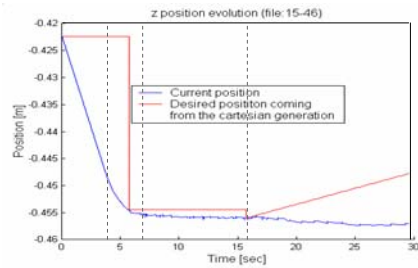
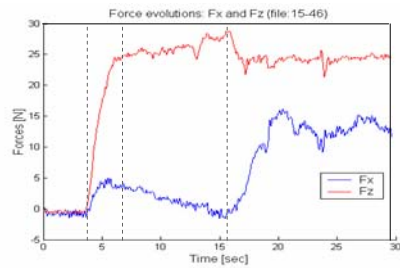
Video: skin harvesting on PhD student thigh



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Video: clinical experiments on pig







Skin Modeling / Soft tissue mechanical properties identification

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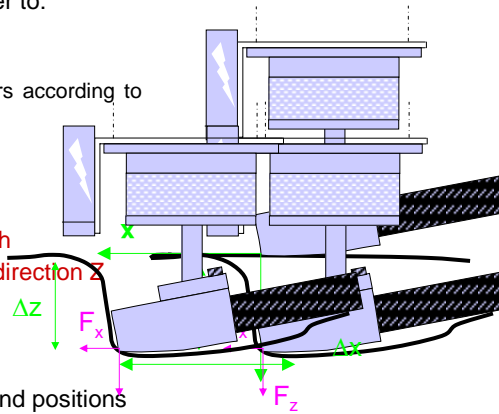
⊗ Objectives: design of a physical parameter based model of deformable tissue of the skin (and the soft tissues underneath) reflecting its mechanical properties in order to:

- improve tactile information
- tune the control law parameters according to the patient

⊗ Protocol: 3 phases

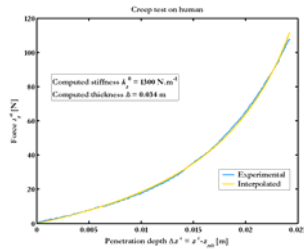
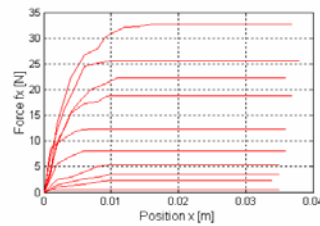
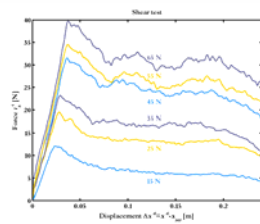
- Approach with contact search
- Contact with desired force: direction Z
- Motion: direction X

⊗ Relationship between forces and positions



Skin Modeling

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$$f_z(z) = \frac{k_z z}{1 - \frac{z}{h}}$$

$$f_x(x, f_z) = \lambda f_z^0 (1 - e^{-\mu(x-x_0)})$$



In vivo experiments on human tissues

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⊗ Example of estimated parameters during Force Control Compression (FCC) tests:

$$f_z(z) = k_z(z)z = \frac{k_z^0 z}{1 - \frac{z}{h}} \quad \text{with } z < h$$

ESTIMATED PARAMETERS k_z^0 AND h DURING REPRODUCIBILITY FCC TESTS

	h [m]	σ_z [%]	k_z^0 [N/m]	σ_z [%]
Patient 1	0.045	5.1	620	7.2
Patient 2	0.048	3.3	752	6.8
Patient 3	0.038	6.2	576	10.2
Patient 4	0.041	2.9	672	6.3
Patient 5	0.032	4.6	688	5.7



Conclusion

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Challenging issues:

- ⊗ Beating heart surgery (motion, friction compensation, ...)
- ⊗ Palpation, tactile information for haptic feedback
- ⊗ Small force / torque sensor for sterilizable and reusable instrument
- ⊗ Robustness wrt stiffness variation, transition between free and constrained space

...

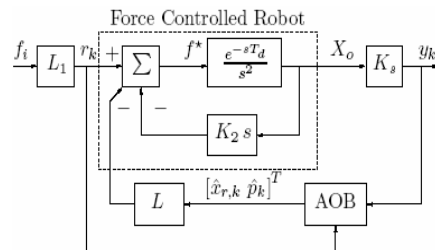
Thanks to G. DUCHEMIN and E. Dombre who contribute to these slides



Towards robustness of force control

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⊗ Compliant motion with force controlled robot, force active observer and on-line stiffness estimation [Cortesa0 02]



Compliant motion control with the AOB in the loop



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