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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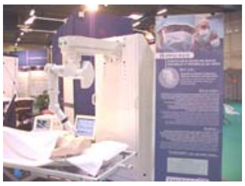
- Echographic monitoring (Hippocrate, [Pierrot 99])

• A robot manipulating ultrasonic probes used for cardio-vascular desease 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])

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- Minimally invasive surgery [Krupa 02], [Ortmaïer 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

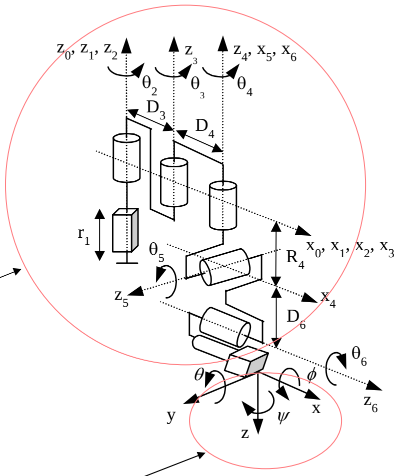
- Haptic devices [Hannaford 99], [Shimachi 03], [Duchemin 05]

• Force sensing for contact rendering, palpation, feeling or estimating mechanical properties of tissue, …

Contents

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

Geometric modeling



Joint space

Operational space
where the end-effector motion and forces are specified, task description

Equations of motion

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

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

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

$\mathbf{A}(\mathbf{q}) \in \mathbb{R}^{n*n}$: 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

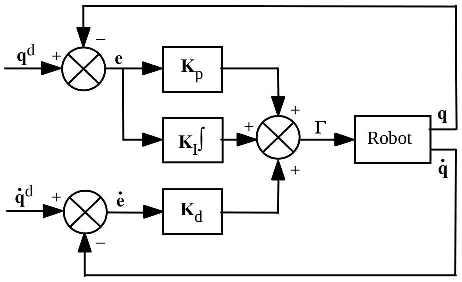
$\mathbf{F}_V \in \mathbb{R}^n$: Vector of viscous friction

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

PID control in the joint space [Khalil 02]

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

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



⌧ More conventional : « cascade structure » including inner loop (velocity) and outer loop (position)
- easier tuning,
- « robustness »

PID control in the joint space

- 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

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PID control in the joint space

- 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:

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

PID control in the joint space

⌧ 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 ⇒ 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

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

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

⌧ 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 to small in order to avoid oscillations that could be caused by Coulomb frictions

⌧ The predictive action $\mathbf{K}_d\dot{\mathbf{q}}^d$ reduces significantly the tracking errors

Joint space vs task space

- 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

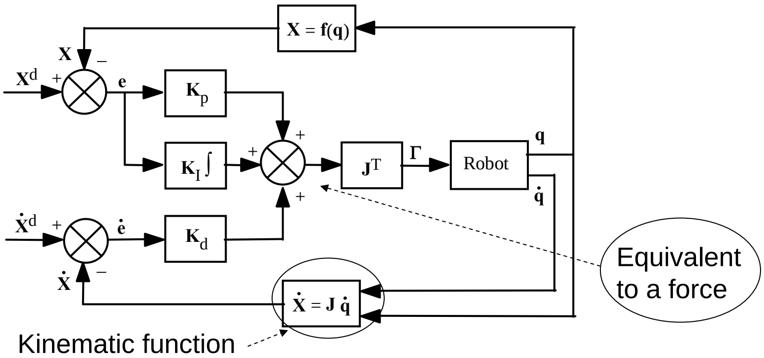
- Objective:
  - the possibility of acting directly on operational space variables → compensating for any uncertainty of the structure: backlash, elasticity, friction, coupling, …
  - very often only a potential advantage, since measurement of operational space variables is not performed directly
- Two 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

- The control is given by:

$$\Gamma = \boxed{\mathbf{J}}^{T}[\mathbf{K}_{p}(\mathbf{X}^{d}-\mathbf{X})+\mathbf{K}_{d}(\dot{\mathbf{X}}^{d}-\dot{\mathbf{X}})+\mathbf{K}_{I}\int_{t_0}^{t}(\mathbf{X}^{d}-\mathbf{X})dt]$$

Transform the task space error into the joint space



Kinematic function

- Extra cost for adding sensor in the operational space

Linearizing and decoupling control

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*

Inverse dynamics control

- Dynamic model of an *n*-joint manipulator:

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

- If we define the control law with w the new input control vector:

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

- 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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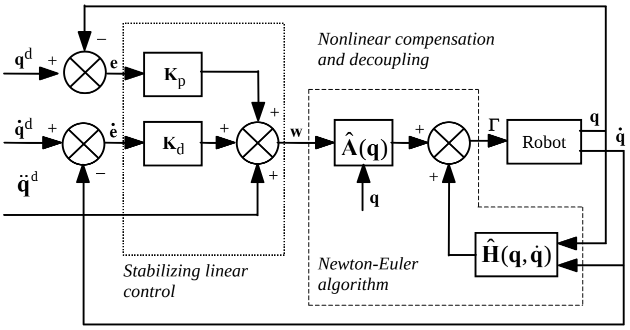
Inverse dynamics control in the joint space

- By defining w:

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



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Inverse dynamics control in the joint space

- ⌦ 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 :

$$\begin{cases} K_{pj} = \omega_j^2 \\ K_{dj} = 2\xi_j \omega_j \end{cases}$$

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

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

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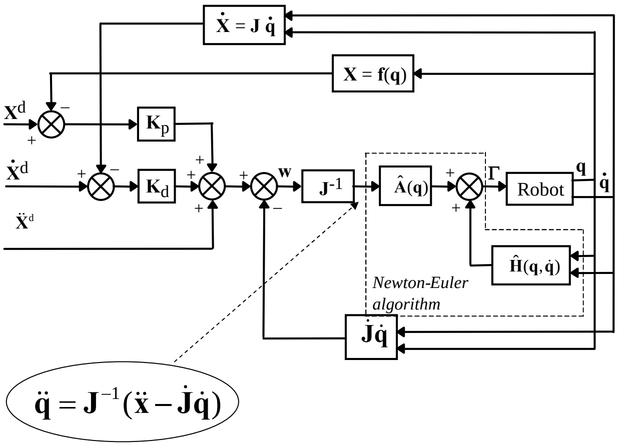
Inverse dynamics control in the task space



Conclusion

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], [Ortmaïer 03])
- Adaptive control ([Krupa 02], [Ortmaïer 03])
- Robust control (sliding mode,…)

Interaction control

- 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:

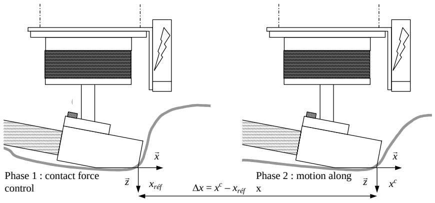
  - precise model of the mechanism
  - exact knowledge of the location and stiffness of the environment

Compliant motion in medical robotics

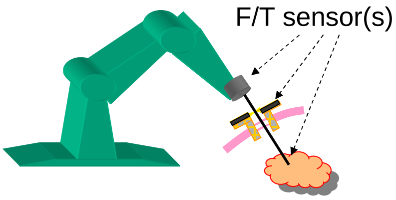
- Specificities in medical robotics:

  - 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

- 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

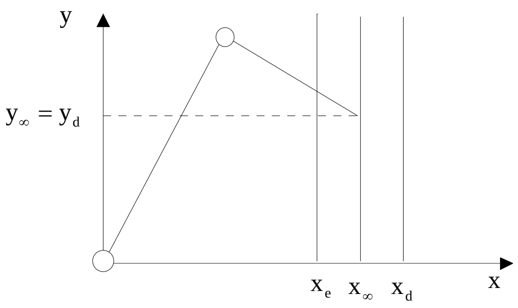
Interaction control strategies

Two categories:

- ⌧ Indirect force control ⇒ force control via motion control without explicit closure of a force feedback
  - Compliance control, impedance control
- ⌧ Direct force control ⇒ explicit force control to a desired value
  - Hybrid position/force control, external force control

Compliance control [Siciliano 00]

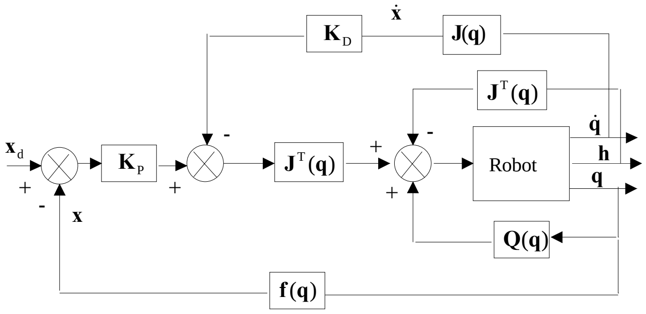
- ⌧ Two-link planar arm in contact with an elastically compliant plane (stiffness = k_e)



x_∞	end-effector equilibrium position
x_e	undeformed position
x_d	desired position

Compliance control

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

Compliance control

At the equilibrium: $\dot{x} = 0$ and $K_P\tilde{x} = h$

Assuming that: $h = K_e(x - x_e)$

$K_e = \text{diag}\{k_x, 0\}$ $K_P = \text{diag}\{k_{Px}, k_{Py}\}$ (frictionless)

Let $p_d = \begin{bmatrix} x_d & y_d \end{bmatrix}^T$ be the desired tip position

Equilibrium equation for position:

$$p_\infty = \begin{bmatrix} \dfrac{k_{Px}x_d + k_x x_e}{k_{Px} + k_x} \\ y_d \end{bmatrix}$$

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

Compliance control

Equilibrium equation for force:

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

- ⌧ Difference between xd and xe
- ⌧ Equivalent stiffness coefficient (parallel composition)

⇒ Arm stiffness and environment stiffness influence the resulting equilibrium configuration

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Compliance control

⌧ $k_{Px}/k_x \gg 1$ ⇒ $x_\infty \approx x_d \quad f_{x\infty} \approx k_x\left(x_d - x_e\right)$

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

⌧ $k_{Px}/k_x \ll 1$ ⇒ $x_\infty \approx x_e \quad f_{x\infty} \approx k_{Px}\left(x_d - x_e\right)$

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

Impedance control [Hogan 85]

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

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

$\mathbf{B}$: the desired damping matrix

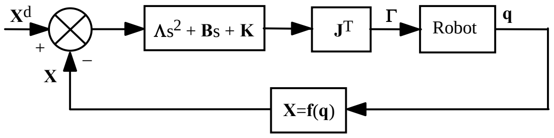
$\mathbf{K}$: the desired stiffness matrix

Impedance control

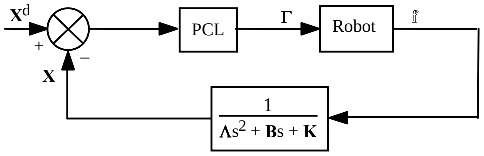
$\boldsymbol{\Lambda}$	High values in the directions where a contact is expected in order to limit the dynamics
$\mathbf{B}$	High values where it is necessary to dissipate the kinetic energy and damp the response
$\mathbf{K}$	The stiffness affects the accuracy of the position control

Two families of impedance control

- Impedance control scheme without force feedback



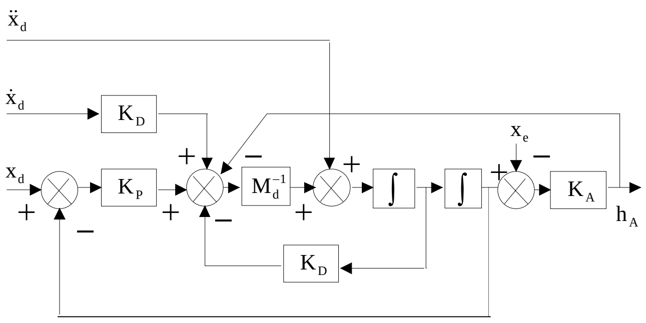
- Impedance control scheme with force feedback



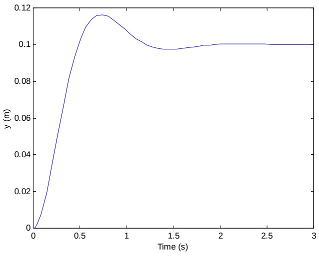
Simulation [Siciliano 00]

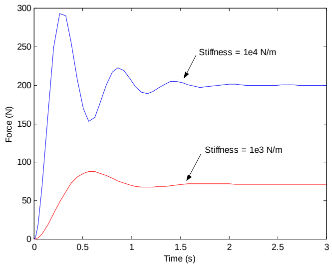
- Manipulator in contact with an elastic environment under impedance control

- Inverse dynamics control in the operational space and contact force measurement



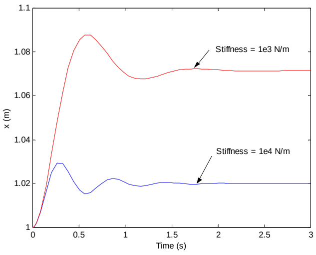
Simulation





200N

71.4N



7.14cm

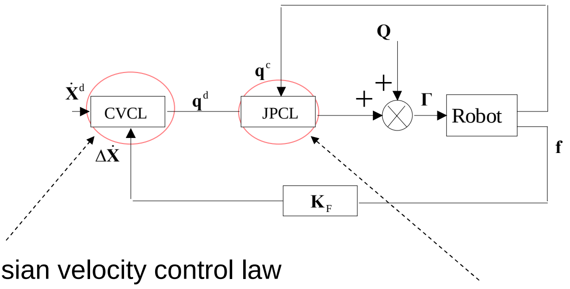
2cm

Remarks

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

Damping control

- 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



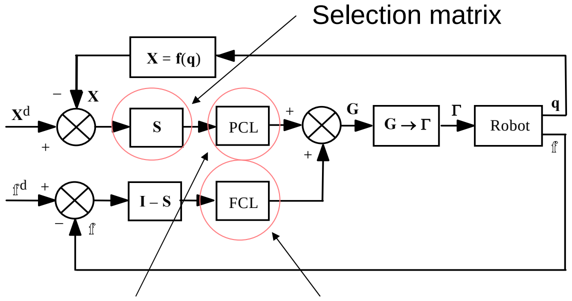
Cartesian velocity control law

Joint position control law

Hybrid position / force control [Raibert 81]

- Principle of the hybrid position / force control:

Selection matrix



Position Control Law

Force Control Law

- Direction constrained in position ⇔ force controlled
- Direction constrained in force (null force) ⇔ position controlled

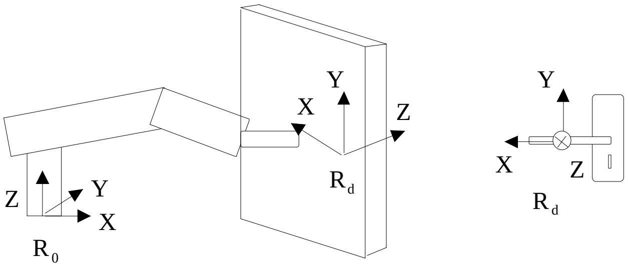
Notes

⌦ 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



⌦ 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

⌧ 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

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Zero force setpoint

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

⌧ Strategy with on-line stiffness estimation and controller parameters tuning [Ortmaïer 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]

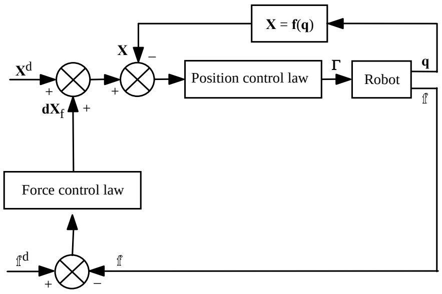
Hybrid external force control [De Schutter 88] [Perdereau 91]

⌧ 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

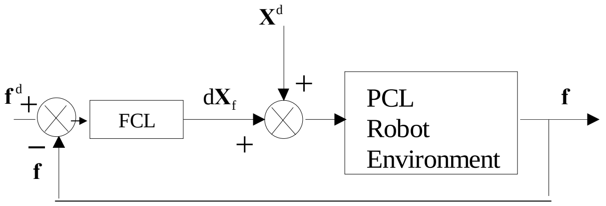


Properties

- 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

- 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

Properties

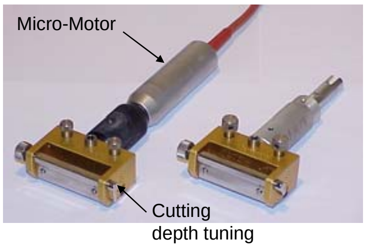
- Easily implementable with decentralized industrial controllers (PID) due to the cascade structure of the scheme [Dégoulange 93]
- Except the IGM and DGM, few on line computations are required
- Cascade structure easily tuned by starting with the inner position loop

Example : SCALPP Project (1999-2003)

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

Skin Harvesting: Medical Task Analysis (1)

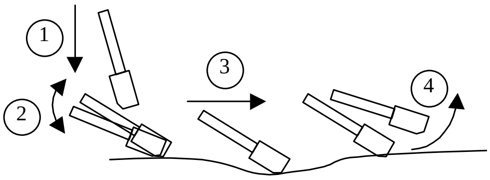
- Grafting in reconstructive surgery: severely burnt, maxilla-facial, orthopaedic...
- Two steps:
  - skin harvesting
  - grafting of the harvested skin strip onto a burnt location



- 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

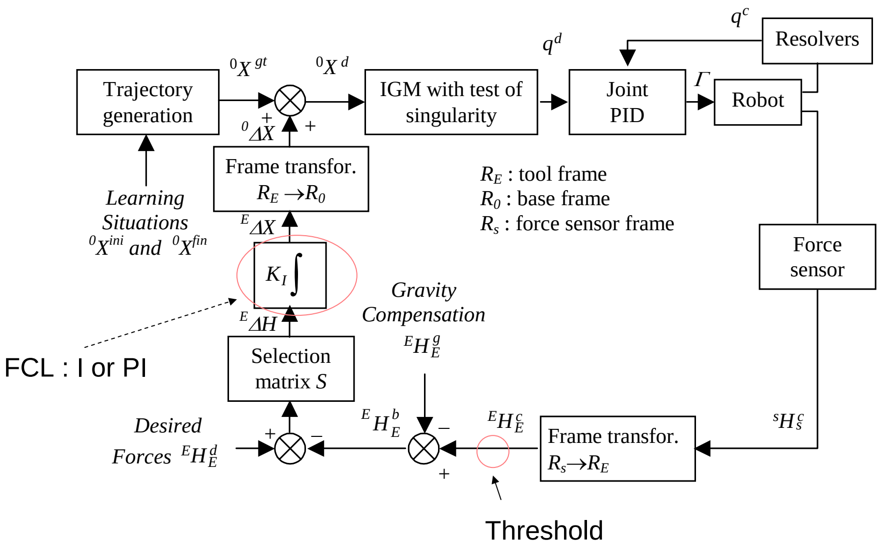
Skin Harvesting: Robotic Approach

- 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

Implemented external force/position control scheme



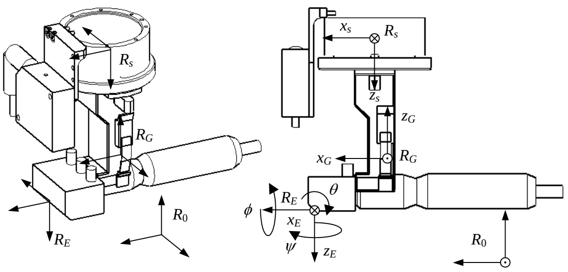
R_E : tool frame
R_0 : base frame
R_s : force sensor frame

FCL : I or PI

Threshold

Practical aspects and requirements

- ☒ « Zero » of F/T sensor (Gamma 130N/10Nm from ATI)
- ☒ Force measurement threshold but no filtering implemented
- ☒ Selection matrix required to perfectly decouple the direction (for e.g. due to friction disturbance) and keep the orthogonality of the subspace



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

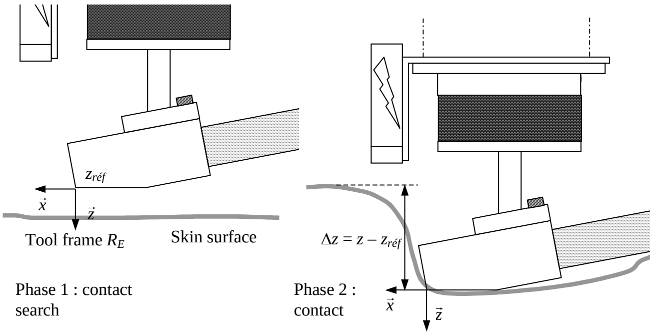
Zero force control in free space

- Video with an integrator controller

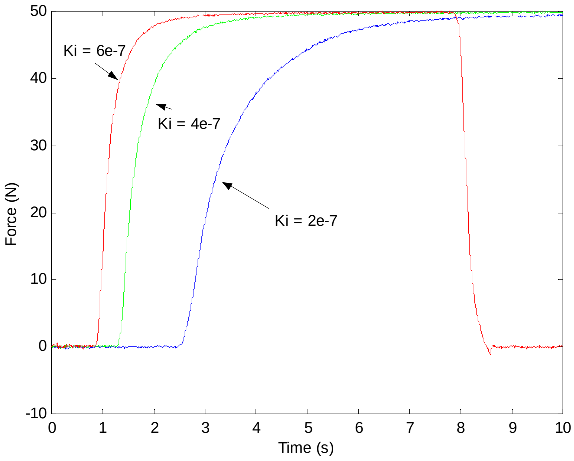
• position ramp while the force is applied
• « memory of motion »: the current position is maintained if the force stops

Implemented external force/position control scheme

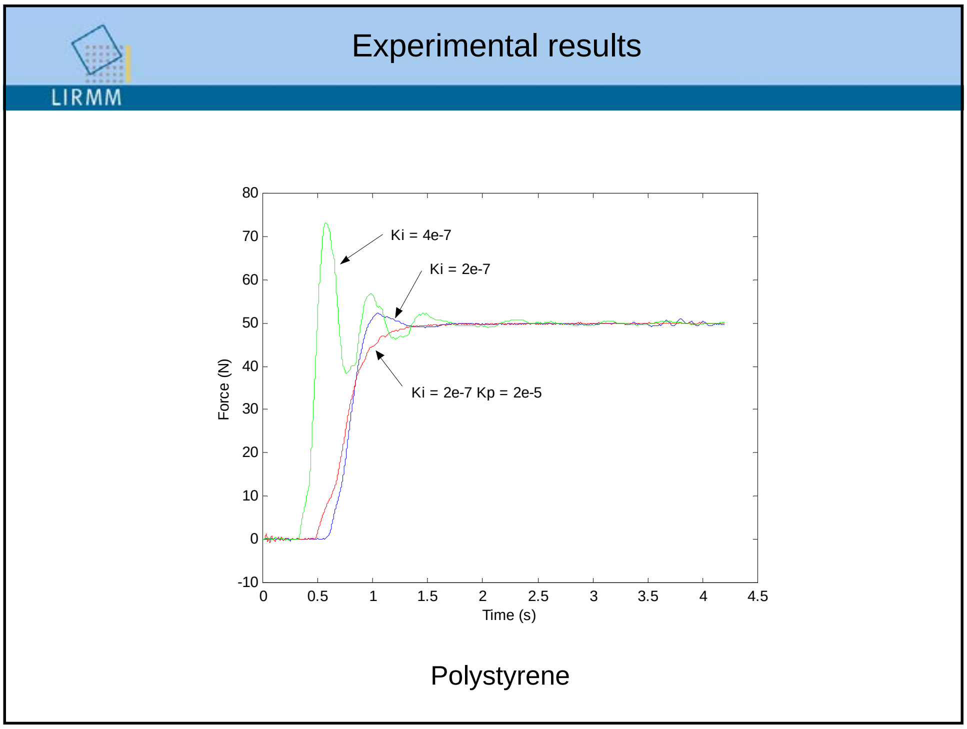
- I or PI for the force control loop ?
- Experimental procedure:



Experimental results

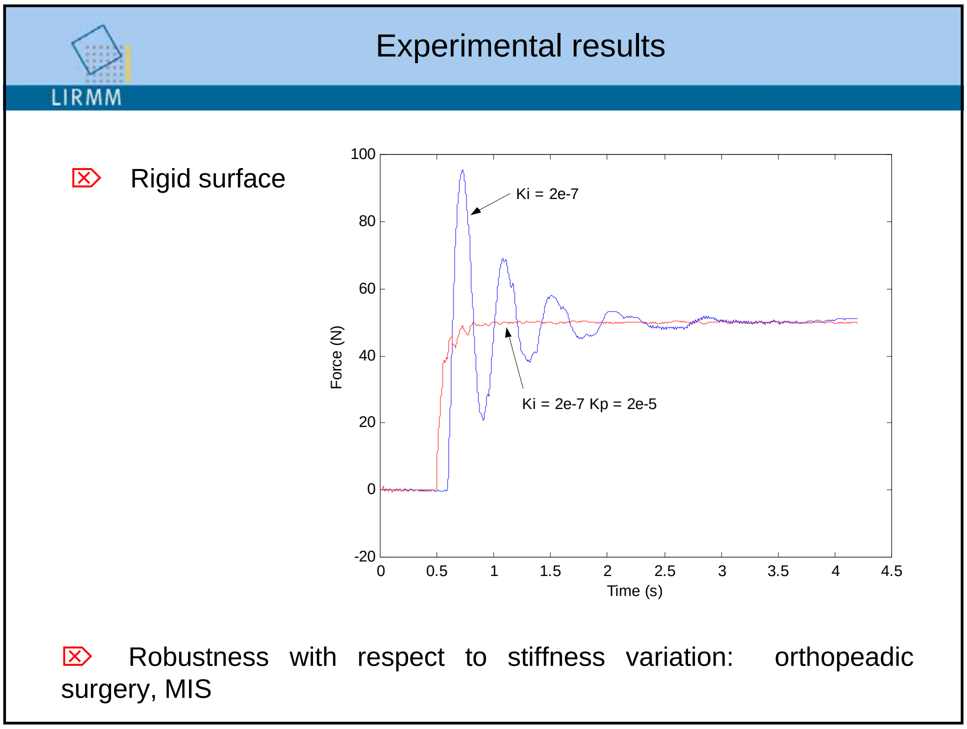


Soft surface



Experimental results

Polystyrene



Experimental results

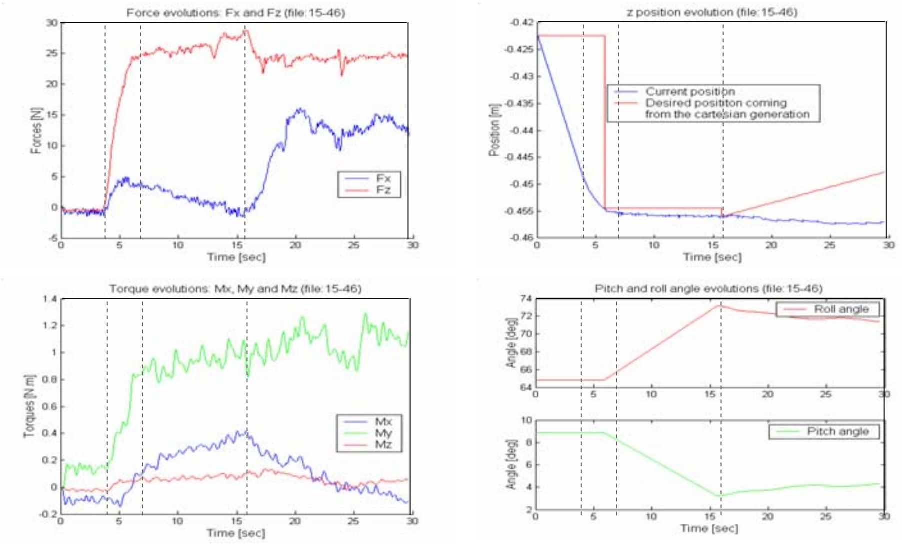
- Rigid surface

- Robustness with respect to stiffness variation: orthopeadic surgery, MIS

Video: skin harvesting on PhD student thigh

Video: clinical experiments on pig

Experimental Results



Experimental Results

Skin Modeling / Soft tissue mechanical properties identification

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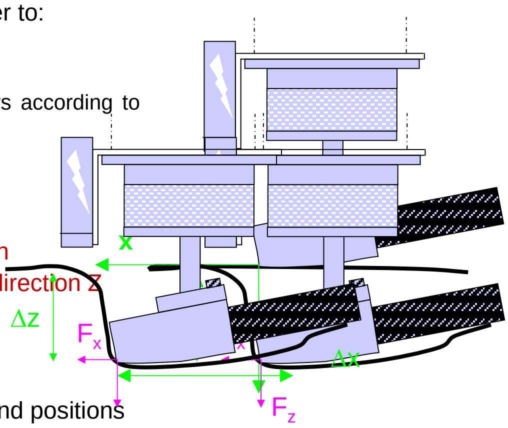
- Objectives: design of a physical parameter based model of deformable tissue of the skin (and the soft tissues underneath) reflecting its mechanical properties in order to:
  - improve tactile information
  - tune the control law parameters according to the patient
- Protocol: 3 phases
  - Approach xith contact search
  - Contact with desired force: direction Z
  - Motion: direction X
- Relationship between forces and positions



Skin Modeling

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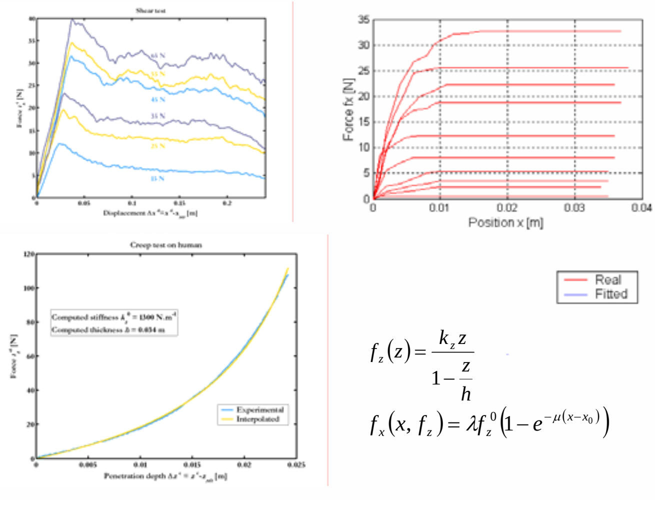


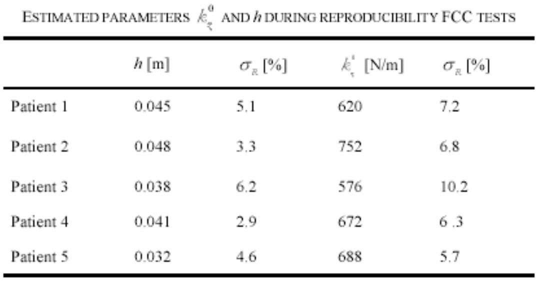
$$f_z(z) = \frac{k_z z}{1 - \frac{z}{h}}$$

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

In vivo experiments on human tissues

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

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



ESTIMATED PARAMETERS k_z^0 AND h DURING REPRODUCIBILITY FCC TESTS

	h [m]	σ_R [%]	k_z^0 [N/m]	σ_R [%]
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

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

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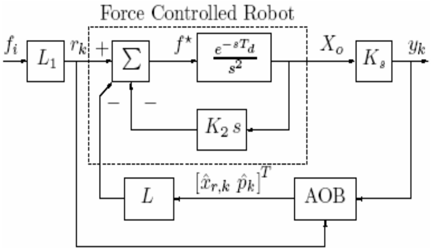
Towards robustness of force control

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



Compliant motion control with the AOB in the loop

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