TAMPERE UNIVERSITY OF TECHNOLOGY

Force control
interaction with environment

Reza Ghabcheloo

IHA 4506 Advanced Robotics

Reference

- Siciliano et al. Robotics: modeling, planning and control, Springer 2009- Chapter 9

Categories

- Direct force control: Hybrid force/position control
- Indirect force control: compliance control, impedance control
- Passive and Active compliance

Compliance control

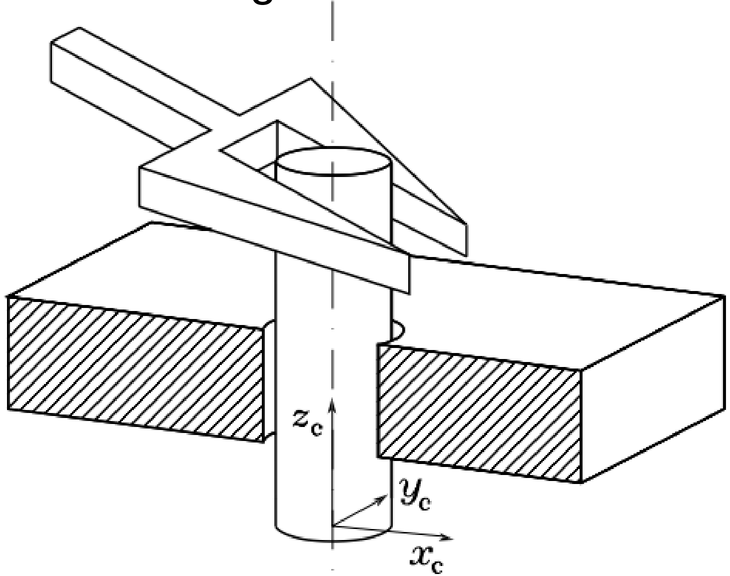
Compliance control, mobile robot

Why we need force control

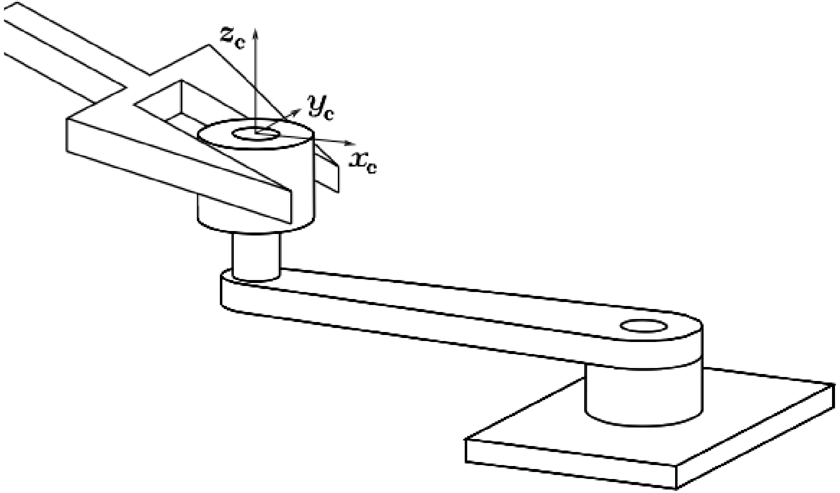
- Successful execution of an interaction task with the environment by using motion control could be obtained only if the task were accurately planned. This would, in turn, require an accurate model of both the robot manipulator (kinematics and dynamics) and the environment (geometry and mechanical features). Manipulator modelling can be achieved with enough precision, but a detailed description of the environment is difficult to obtain.

Constraint motion

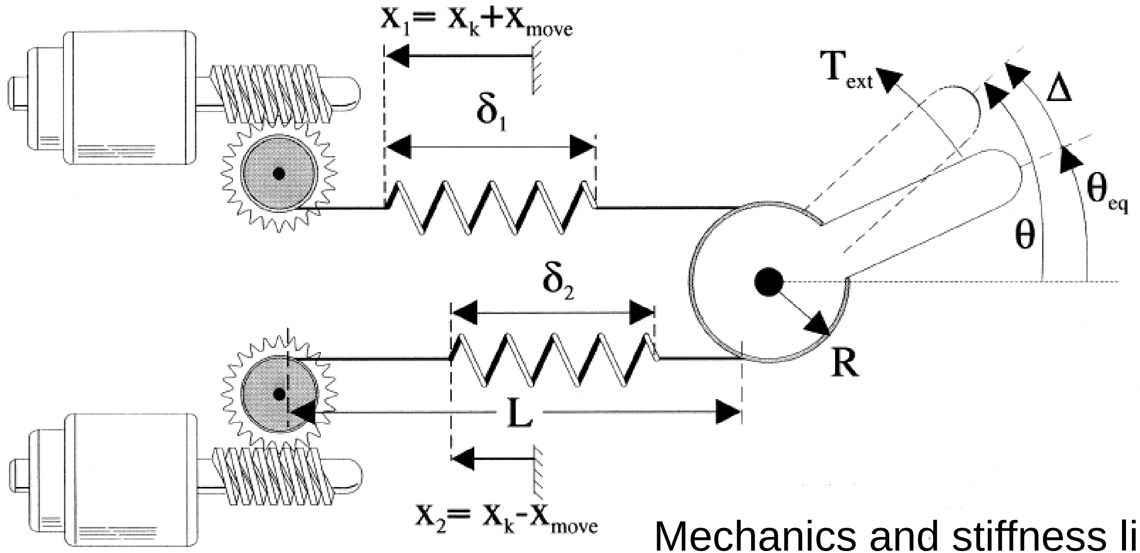
Peg-in-hole



Turning a crank



Variable stiffness actuators



Mechanics and stiffness limitations of a variable stiffness actuator for use in prosthetic limbs
C.E.English, D.Russell

PD + gravity compensation in task space

- $u = g(q) + J_A^T(K_P\tilde{x} - K_D J_A \dot{q})$ $\qquad \tilde{x} = x_d - x$

$$\boldsymbol{B}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{F}\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{u} - \boldsymbol{J}^T(\boldsymbol{q})\boldsymbol{h}_e$$

- At equilibrium

$$\boldsymbol{J}_A^T(\boldsymbol{q})\boldsymbol{K}_P\widetilde{\boldsymbol{x}} = \boldsymbol{J}^T(\boldsymbol{q})\boldsymbol{h}_e \rightarrow \widetilde{\boldsymbol{x}} = \boldsymbol{K}_P^{-1}\boldsymbol{T}_A^T(\boldsymbol{x}_e)\boldsymbol{h}_e = \boldsymbol{K}_P^{-1}\boldsymbol{h}_A$$

→ System behaves like a spring w/ stiffness K_P^{-1}

Compliance

- $h_A = K_P \tilde{x}$ with stiffness matrix K_P

This behaviour is called *active compliance*

vs

Passive compliance: mechanical system elasticity

Note: K_P has both translational and rotational stiffness

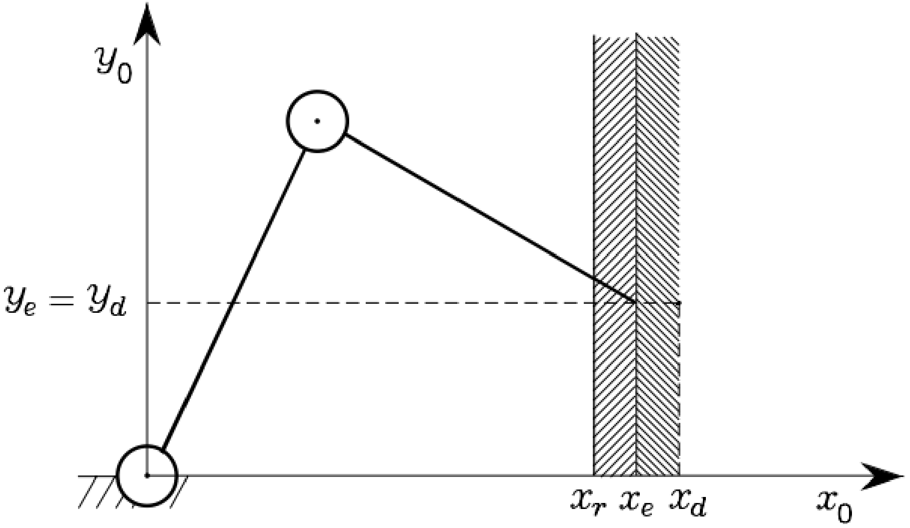
Important frames

- r environment
- e end-effector
- d desired

$$h_e = K_P \mathrm{d}x_{e,d}$$

$$h_e = K \mathrm{d}x_{r,e}$$

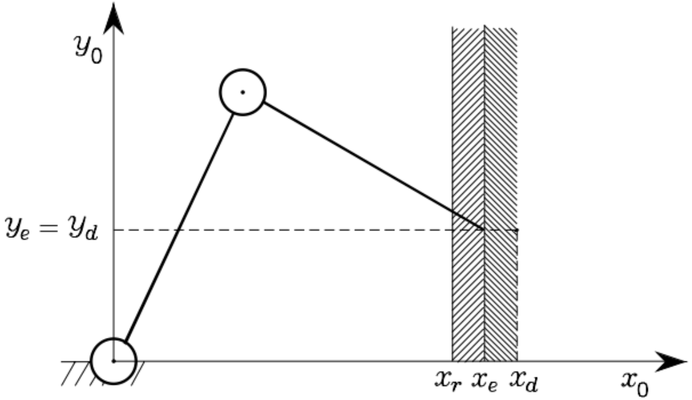
K environment stiffness



Compliant environment

$$h_e = K_P \mathrm{d}x_{e,d}$$

$$h_e = K \mathrm{d}x_{r,e}$$



$$\mathrm{d}x_{e,d} = K_P^{-1}(I_6 + K K_P^{-1})^{-1} K \mathrm{d}x_{r,d}$$

Special cases: either the robot (passive+active) or the environment stiffness is dominant

Example

- Check out example 9.1. page 371

Compliance control/summary

- Objective is to make the robot behave like a spring against external forces

$$K_P \tilde{x} = h_A$$

Compliance is characterized by K_P

Note: compliance can be programmed into the system by seting a desired K_P in motion controllers

Impedance control

- Objective is to make the system behave spring-mass-damper

$$M_d\ddot{\tilde{x}} + K_D\dot{\tilde{x}} + K_P\tilde{x} = h_A$$

Characterized by M_d, K_D, K_P

Impedance control *without* force measurement

$$u = B(q)y + n(q, \dot{q})$$

$$y = J_A^{-1}(q)M_d^{-1}\left(M_d\ddot{x}_d + K_D\dot{\tilde{x}} + K_P\tilde{x} - M_d\dot{J}_A(q,\dot{q})\dot{q}\right)$$

$$M_d\ddot{\tilde{x}} + K_D\dot{\tilde{x}} + K_P\tilde{x} = M_dB_A^{-1}(q)h_A$$

$$B_A(q) = J_A^{-T}(q)B(q)J_A^{-1}(q)$$

- To make the relationship linear, we need to measure the contact force

Impedance control *with* force measurement

$$\boldsymbol{u} = \boldsymbol{B}(\boldsymbol{q})\boldsymbol{y} + \boldsymbol{n}(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \boldsymbol{J}^T(\boldsymbol{q})\boldsymbol{h}_e$$

$$\boldsymbol{y} = \boldsymbol{J}_A^{-1}(\boldsymbol{q})\boldsymbol{M}_d^{-1}\left(\boldsymbol{M}_d\ddot{\boldsymbol{x}}_d + \boldsymbol{K}_D\dot{\widetilde{\boldsymbol{x}}} + \boldsymbol{K}_P\widetilde{\boldsymbol{x}} - \boldsymbol{M}_d\dot{\boldsymbol{J}}_A(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} - \boldsymbol{h}_A\right)$$

$$\boldsymbol{M}_d\ddot{\widetilde{\boldsymbol{x}}} + \boldsymbol{K}_D\dot{\widetilde{\boldsymbol{x}}} + \boldsymbol{K}_P\widetilde{\boldsymbol{x}} = \boldsymbol{h}_A$$

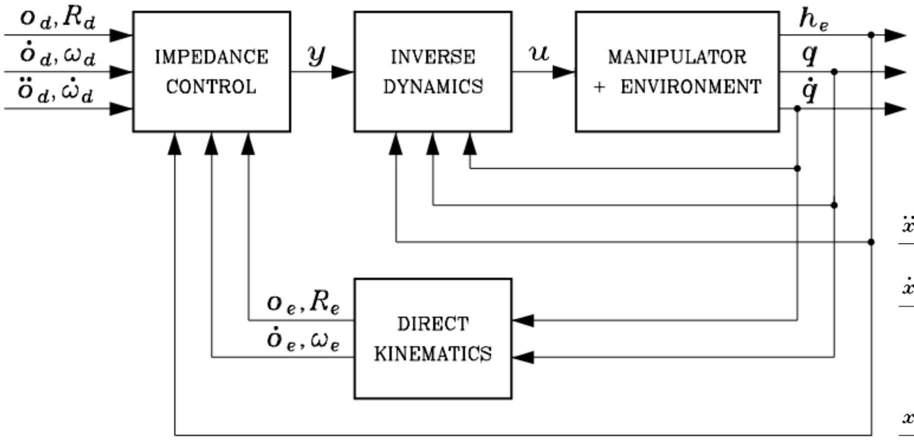
Without force meas.

$$\boldsymbol{u} = \boldsymbol{B}(\boldsymbol{q})\boldsymbol{y} + \boldsymbol{n}(\boldsymbol{q}, \dot{\boldsymbol{q}})$$

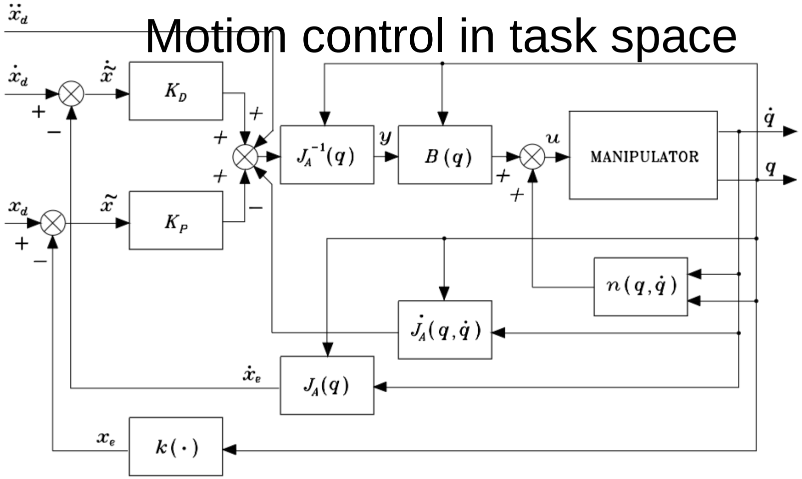
$$\boldsymbol{y} = \boldsymbol{J}_A^{-1}(\boldsymbol{q})\boldsymbol{M}_d^{-1}\left(\boldsymbol{M}_d\ddot{\boldsymbol{x}}_d + \boldsymbol{K}_D\dot{\widetilde{\boldsymbol{x}}} + \boldsymbol{K}_P\widetilde{\boldsymbol{x}} - \boldsymbol{M}_d\dot{\boldsymbol{J}}_A(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}}\right)$$

$$\boldsymbol{M}_d\ddot{\widetilde{\boldsymbol{x}}} + \boldsymbol{K}_D\dot{\widetilde{\boldsymbol{x}}} + \boldsymbol{K}_P\widetilde{\boldsymbol{x}} = \boldsymbol{M}_d\boldsymbol{B}_A^{-1}(\boldsymbol{q})\boldsymbol{h}_A$$

Impedance control



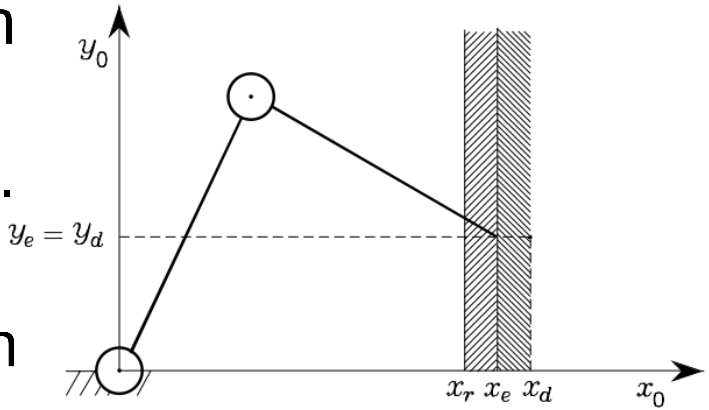
Motion control in task space



Check example 9.2. carefully
pp 374
Choosing good gains is not easy!

Motion composed of constraint and free motions

- Impedance control in the direction of free motion is equivalent to inverse dynamics position control.
- Problem is that good tracking (free space) needs high K_P, which may not be a desired value for constraint motion→ one solution is *admittance control*

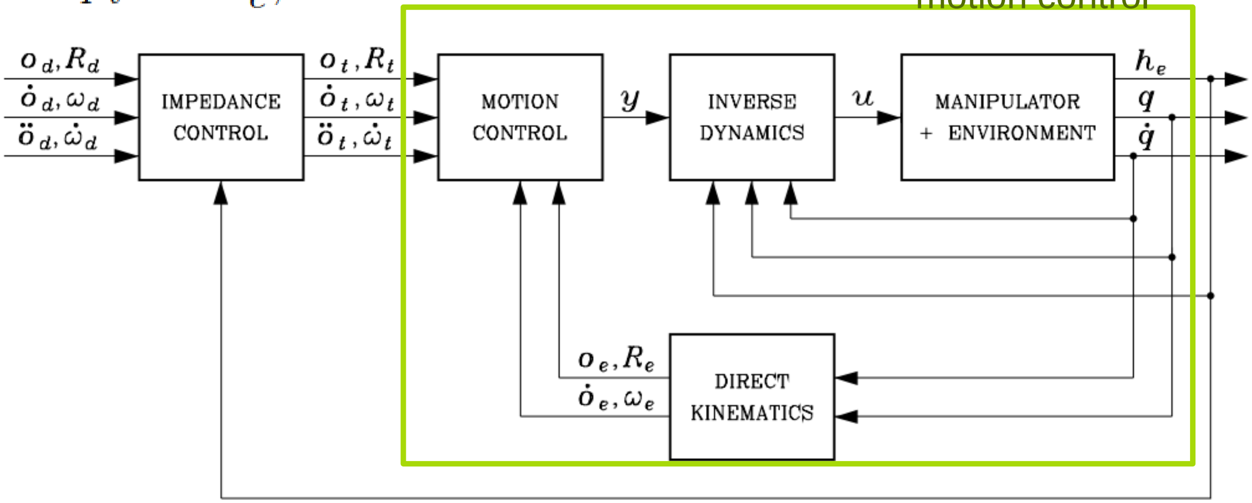


Admittance control

Concept of compliant frame t: $\tilde{z}$ operational space error between frames d and t

$$\boldsymbol{M}_t\ddot{\tilde{\boldsymbol{z}}} + \boldsymbol{K}_{Dt}\dot{\tilde{\boldsymbol{z}}} + \boldsymbol{K}_{Pt}\tilde{\boldsymbol{z}} = \boldsymbol{h}_e^d,$$

inverse dynamics
motion control



So far we had indirect force control

- Programed compliance or impedance behavior creates certain amount of force exerted to the environment
- Direct force control instead: reference inputs are desired forces

Force control

- Very similar to admittance control: the idea is to use the position or velocity motion control (e.g. based on inverse dynamic) at the inner loop and build the force control around it in the outer-loop

Force control
(only positions)

- x_F is then reference to position motion control. or
- v_F is then reference to velocity motion control.
- F is in fact the compliance frame.

$$x_F = C_F(f_d - f_e)$$
$$C_F = K_F + K_I \int (.) d\xi$$

$$v_F = C_F(f_d - f_e)$$
$$C_F = K_F K_P$$