



Aalto University
School of Electrical
Engineering

ELEC-E8126: Robotic Manipulation Control in contact

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10.2.2020

Learning goals

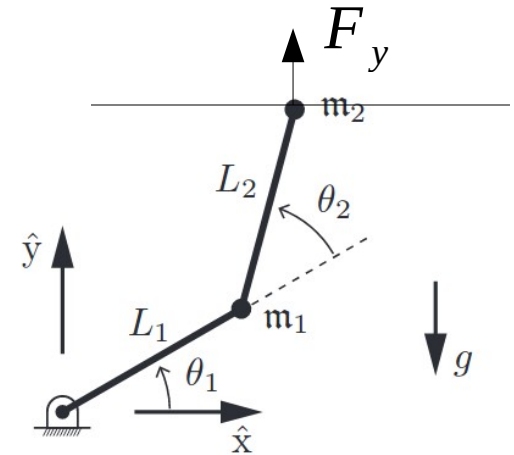
- Understand basic approaches of force and impedance control.
- Understand how control can be partitioned with multiple objectives.

Contact

- Contact requires control of interaction forces.
- Approaches:
 - Control interaction forces to desired values → force control
 - Control interaction behavior → impedance control

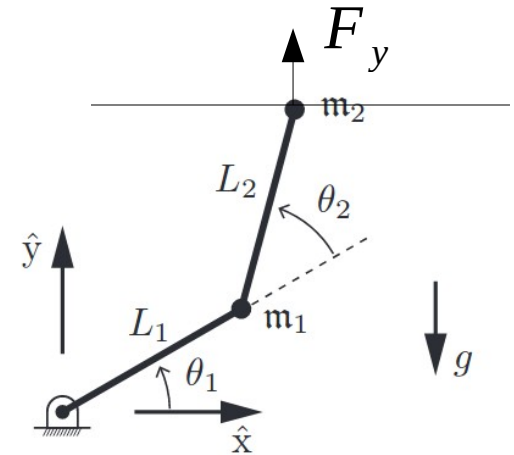
Force control

- Try to achieve vertical contact force F_{yd}
- Propose a feedforward controller!



Force control

- Try to achieve vertical contact force F_{yd}



- Propose a feedforward controller!

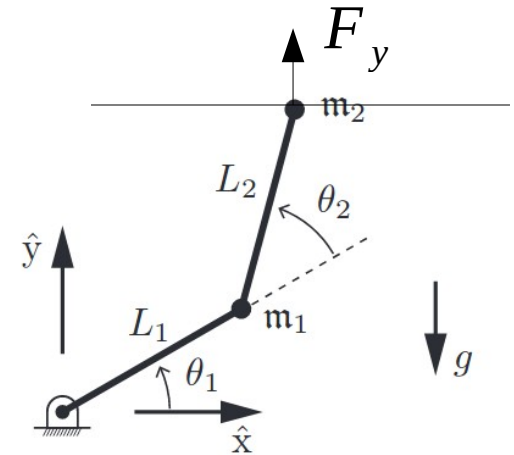
$$\boldsymbol{\tau} = \mathbf{J}_y^T(\boldsymbol{\theta}) F_{yd} + \hat{\mathbf{h}}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})$$

What's this?
What is its meaning?

Dynamics (gravity)
compensation

Force control

- Try to achieve vertical contact force F_{yd}



- Propose a feedforward controller!

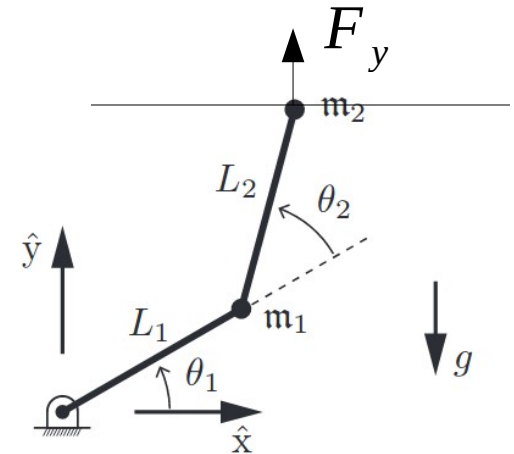
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What's this?
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Force control

- Try to achieve vertical contact force F_{yd}
- Now assume force can be measured, giving error $F_{ye} = F_y - F_{yd}$



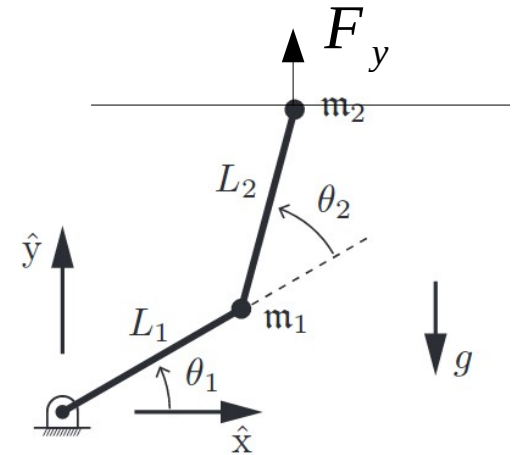
- PI-controller with feedforward can then be constructed:

$$\boldsymbol{\tau} = J_y^T(\boldsymbol{\theta}) \left(F_{yd} + K_{fp} F_{ye} + K_{fi} \int F_{ye} \right) + \hat{\mathbf{h}}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})$$

Dynamics
compensation

Recap: Position control

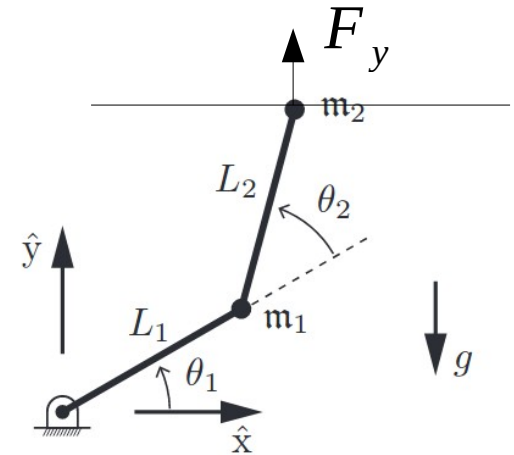
- Propose a position controller to remain in horizontal position x_d



Recap: Position control

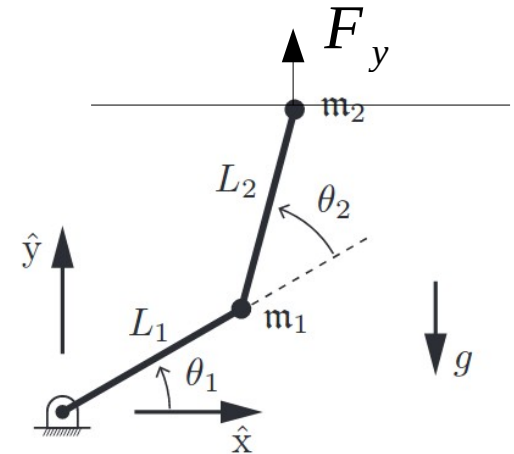
- Propose a position controller to remain in horizontal position x_d
- Computed torque controller:

$$\tau = J_{\hat{x}}^T(\theta) \left(M_C(\theta) \left(\ddot{x}_d + K_p x_e + K_i \int x_e + K_d \dot{x}_e \right) \right) + \hat{h}(\theta, \dot{\theta})$$



Recap: Position control

- Propose a position controller to remain in horizontal position x_d
- Computed torque controller:



$$\boldsymbol{\tau} = J_{\hat{x}}^T(\boldsymbol{\theta}) \left(M_C(\boldsymbol{\theta}) \left(\ddot{x}_d + K_p x_e + K_i \int x_e + K_d \dot{x}_e \right) \right) + \hat{\mathbf{h}}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})$$

How to combine with force controller?

$$\boldsymbol{\tau} = J_y^T(\boldsymbol{\theta}) \left(F_{yd} + K_{fp} F_{ye} + K_{fi} \int F_{ye} \right) + \hat{\mathbf{h}}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})$$

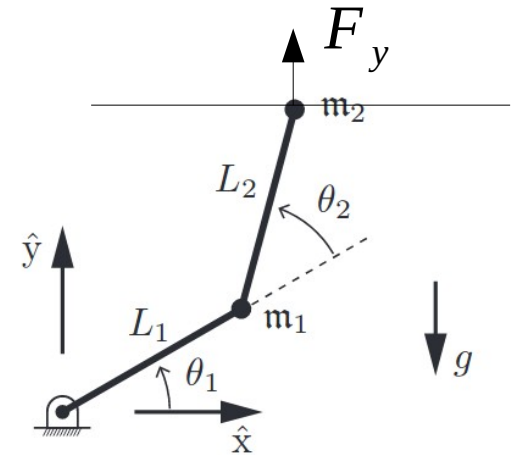
Hybrid control (example)

- Hybrid just combination of the two

$$\boldsymbol{\tau} = J_x^T(\boldsymbol{\theta}) \left(M_C(\boldsymbol{\theta}) \left(\ddot{\mathbf{x}}_d + K_p \mathbf{x}_e + K_i \int \mathbf{x}_e + K_d \dot{\mathbf{x}}_e \right) \right) + J_y^T(\boldsymbol{\theta}) \left(F_{yd} + K_{fp} F_{ye} + K_{fi} \int F_{ye} \right) + \hat{\mathbf{h}}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})$$

- Note: $J = \begin{bmatrix} J_x \\ J_y \end{bmatrix}$

- Can we write this now somehow in form $\boldsymbol{\tau} = J^T(\dots)$?



Hybrid control (example)

$$\begin{aligned}\boldsymbol{\tau} = & J_x^T(\boldsymbol{\theta}) \left(M_C(\boldsymbol{\theta}) \left(\ddot{x}_d + K_p x_e + K_i \int x_e + K_d \dot{x}_e \right) \right) \\ & + J_y^T(\boldsymbol{\theta}) \left(F_{yd} + K_{fp} F_{ye} + K_{fi} \int F_{ye} \right) + \hat{\mathbf{h}}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})\end{aligned}$$

$$\begin{aligned}\boldsymbol{\tau} = & J^T(\boldsymbol{\theta}) \\ & \left(\begin{bmatrix} 1 \\ 0 \end{bmatrix} M_C(\boldsymbol{\theta}) \left(\ddot{x}_d + K_p x_e + K_i \int x_e + K_d \dot{x}_e \right) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \left(F_{yd} + K_{fp} F_{ye} + K_{fi} \int F_{ye} \right) \right) \\ & + \hat{\mathbf{h}}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})\end{aligned}$$

$$\boldsymbol{\tau} = \mathbf{J}^T(\boldsymbol{\theta})$$

$$\begin{pmatrix} 1 \\ 0 \end{pmatrix} M_C(\boldsymbol{\theta}) \left(\ddot{x}_d + K_p x_e + K_i \int x_e + K_d \dot{x}_e \right) + \begin{pmatrix} 0 \\ 1 \end{pmatrix} \left(F_{yd} + K_{fp} F_{ye} + K_{fi} \int F_{ye} \right) + \hat{\mathbf{h}}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})$$

Orthogonal directions where controllers act

$$\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} M_C(\boldsymbol{\theta}) \left(\ddot{x}_d + K_p x_e + K_i \int x_e + K_d \dot{x}_e \right) + \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \left(F_d + K_{fp} F_{ye} + K_{fi} \int F_{ye} \right) + \hat{\mathbf{h}}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})$$

$$\mathbf{x} = \begin{bmatrix} x \\ y \end{bmatrix}$$

$$\mathbf{F} = \begin{bmatrix} F_x \\ F_y \end{bmatrix}$$

Hybrid control

- General formulation

$$\begin{aligned} \tau = J_b^T(\theta) & \left(\underbrace{P(\theta) \left(\tilde{\Lambda}(\theta) \left(\frac{d}{dt}([\text{Ad}_{X^{-1}X_d}]\mathcal{V}_d) + K_p X_e + K_i \int X_e(t)dt + K_d \mathcal{V}_e \right) \right)}_{\text{motion control}} \right. \\ & + \underbrace{(I - P(\theta)) \left(\mathcal{F}_d + K_{fip} \mathcal{F}_e + K_{fi} \int \mathcal{F}_e(t)dt \right)}_{\text{force control}} \\ & \left. + \underbrace{\tilde{\eta}(\theta, \mathcal{V}_b)}_{\text{Coriolis and gravity}} \right). \end{aligned} \quad (11.61)$$

Simultaneous tasks

Some alternative formulations

- Torque control, two Cartesian space controllers

$$\boldsymbol{\tau} = J^T(\boldsymbol{\theta}) \left(P C_1(\boldsymbol{\theta}) + (I - P) C_2(\boldsymbol{\theta}) \right) \quad (+dyn)$$

- Velocity control

$$\dot{\boldsymbol{\theta}} = J_1^+ \dot{\mathbf{x}}_1 + N_1 \left(J_2^+ \dot{\mathbf{x}}_2 + N_2(\dots) \right)$$

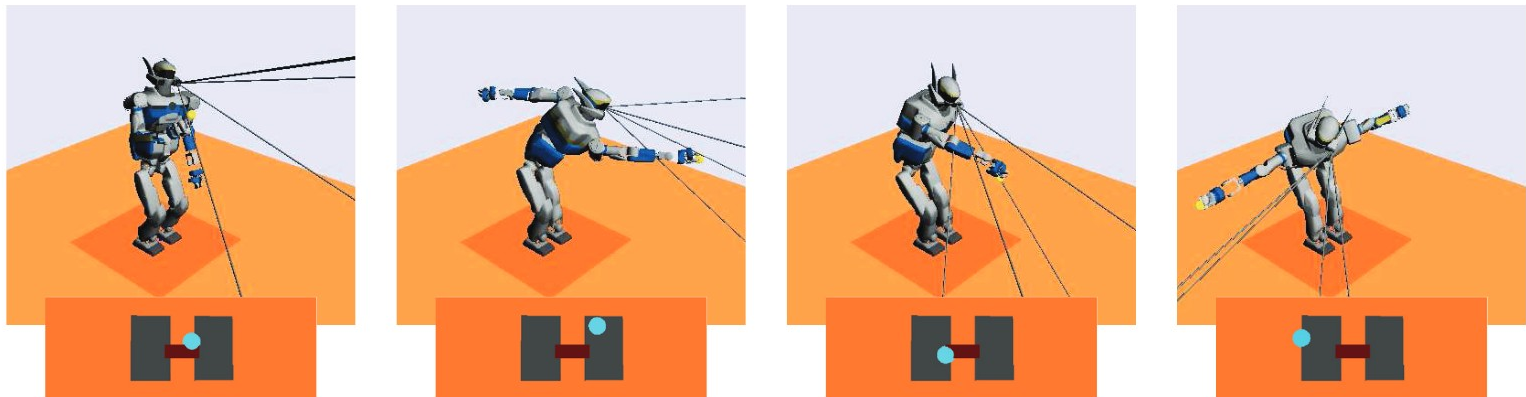
Jacobian of 1st task

Null space of 1st task

$$N_i = I - J_i^+ J_i$$

Task formalism for control

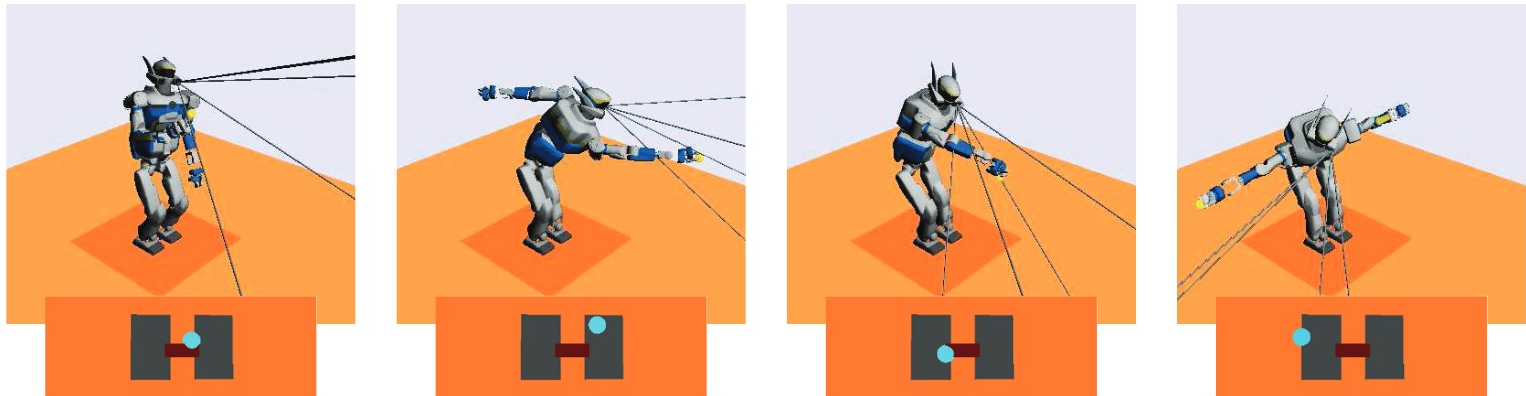
- Stack of tasks (e.g. Mansard 2009) provides hierarchical approach of execution of multiple simultaneous tasks.
- Tasks prioritized.
- Example: simultaneous balancing, reaching, field of view



Escande et al., IJRR 2014

Task formalism for control

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Back to in-contact control!

Making robot compliant to external forces

- Instead of particular contact force, make robot mimic desired impedance characteristics (mass, spring, damper) when responding to external forces.
 - Robot acts as a virtual tool, e.g. with interacting human.
- Two approaches:
 - Sense robot (endpoint) motion and command torques
→ impedance control
 - Sense interaction forces and command positions
→ admittance control

Impedance control

Measure position difference!

- Desired behavior: mass-spring-damper with respect to a reference trajectory

$$F_{ext} = M \ddot{x}_e + B \dot{x}_e + K x_e$$

- Ideal control law

$$\tau = J^T(\theta) \left(\underbrace{M_C(\mathbf{x}) \ddot{\mathbf{x}} + \mathbf{h}_C(\mathbf{x}, \dot{\mathbf{x}})}_{\text{dynamics compensation}} - \underbrace{(M \ddot{x}_e + B \dot{x}_e + K x_e)}_{\text{desired behavior}} \right)$$

Negate true dynamics

Replace with desired dynamics

Impedance control in practice

- Typical control law

$$\boldsymbol{\tau} = \mathbf{J}^T(\boldsymbol{\theta}) \left(-\mathbf{K}(\mathbf{x} - \mathbf{x}_d) - \mathbf{B}(\dot{\mathbf{x}} - \dot{\mathbf{x}}_d) \right) + \mathbf{h}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})$$

May contain only gravity

What's the inertia that's felt?



Compare to ideal

$$\boldsymbol{\tau} = \mathbf{J}^T(\boldsymbol{\theta}) \left(\mathbf{M}_C(\mathbf{x}) \ddot{\mathbf{x}} + \mathbf{h}_C(\mathbf{x}, \dot{\mathbf{x}}) - \left(\mathbf{M} \ddot{\mathbf{x}}_e + \mathbf{B} \dot{\mathbf{x}}_e + \mathbf{K} \mathbf{x}_e \right) \right)$$

difficult to
measure

Admittance control

- Measure external force F_{ext} , respond according to desired impedance behavior

$$F_{ext} = M \ddot{x} + B \dot{x} + K x$$

- Desired acceleration then

$$\ddot{x}_d = M^{-1} (F_{ext} - K x - B \dot{x})$$

- Desired accelerations in joint space

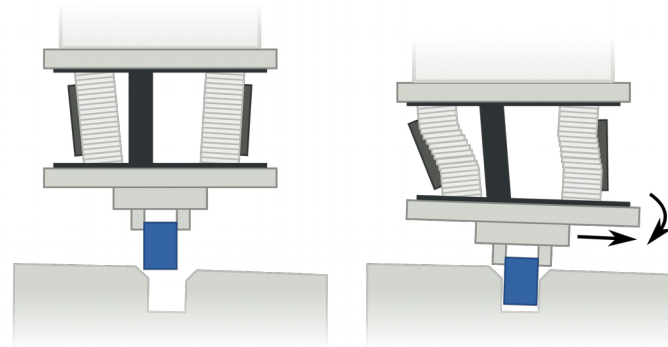
$$\ddot{\theta}_d = J^+ (\theta) (\ddot{x}_d - \dot{J} (\theta) \dot{\theta})$$

Actuator effects

- Actuators do not produce torque exactly and may have significant internal dynamics.
 - Gearing introduces backlash.
 - Strain gauges may be used to close loop in torque.
- Passive compliance can be included in actuator.

Also variable impedance possible.

Torsional spring of series elastic actuator



Remote center of compliance device

Summary

- Force control is used when desired forces can be specified.
- Impedance control typical for physically interacting with humans.

Next time: Grasping and statics

- Readings:
 - Lynch & Park, Chapter 12.-12.1.3