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ELEC-E8126: Robotic Manipulation Control in contact

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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
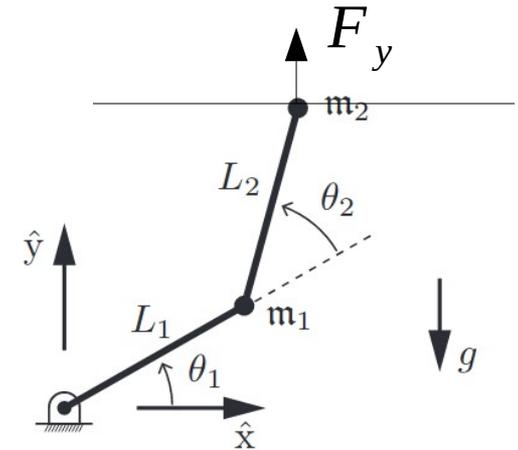 - Control interaction behavior → impedance control

Force control

- Try to achieve vertical contact force F_{yd}

- Propose a feedforward controller!
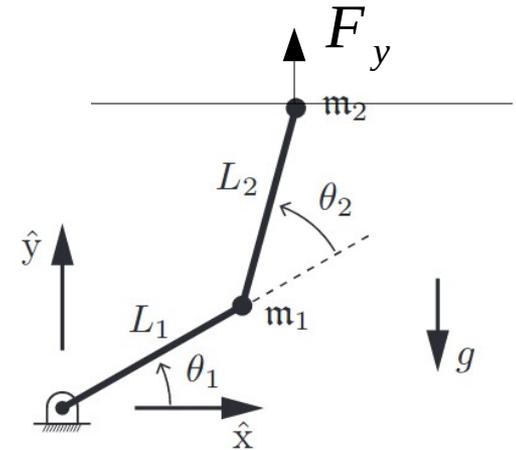
Force control

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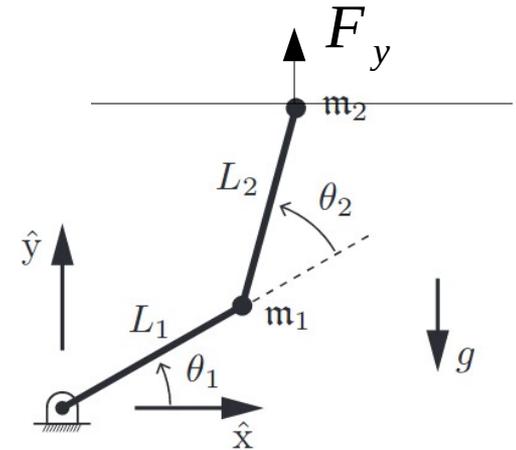
- Propose a feedforward controller!

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

What's this?
What is its meaning?

Dynamics (gravity)
compensation

Force control

- Try to achieve vertical contact force F_{yd}
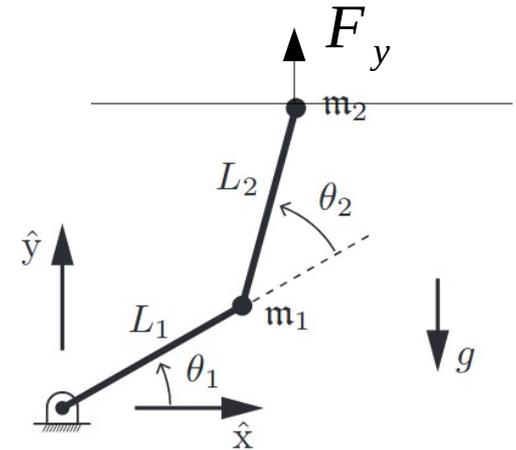

- Propose a feedforward controller!

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

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Remember we do not want force in horizontal direction!

Force control

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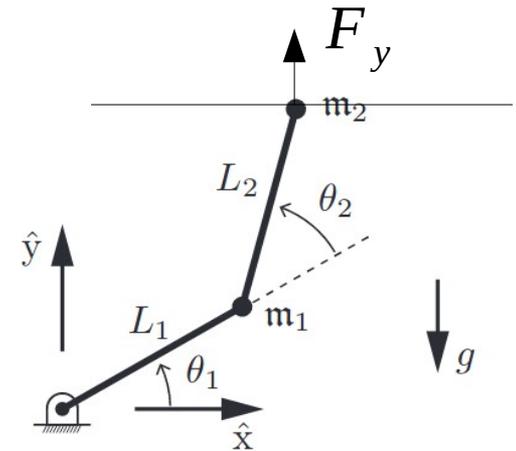- Now assume force can be measured, giving error $F_{ye} = F_y - F_{yd}$

- PI-controller with feedforward can then be constructed:

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

Dynamics compensation

What happens if there are disturbances?

Recap: Position control

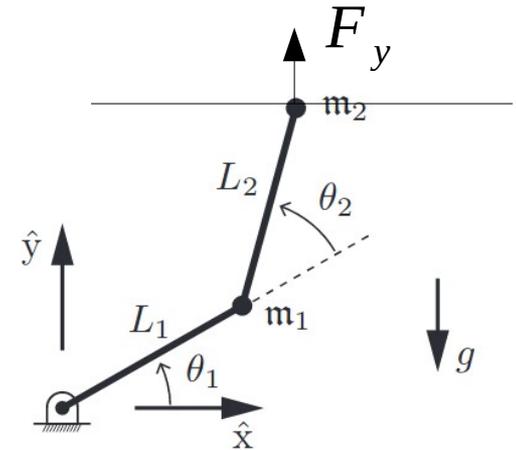- Propose a position controller to remain in horizontal position x_d

Recap: Position control

- Propose a position controller to remain in horizontal position x_d

- Computed torque controller:

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

Recap: Position control

- Propose a position controller to remain in horizontal position x_d

- Computed torque controller:
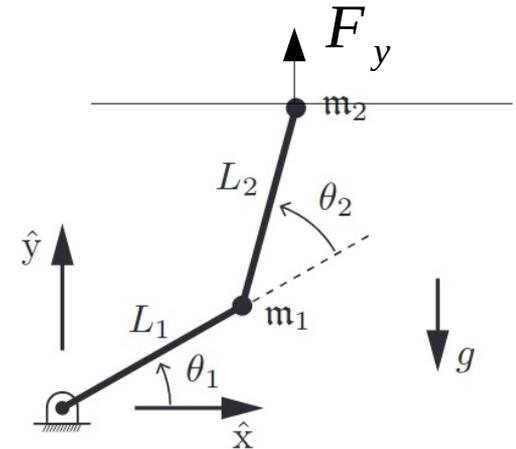
$$\boldsymbol{\tau} = J_x^T(\boldsymbol{\theta}) \Big(M_C(\theta) \Big(\ddot{x}_d + K_p x_e + K_i \int x_e + K_d \dot{x}_e \Big) \Big) + \hat{\boldsymbol{h}}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})$$

How to combine with force controller?

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

Hybrid control (example)

- Hybrid just combination of the two

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

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

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

Hybrid control (example)

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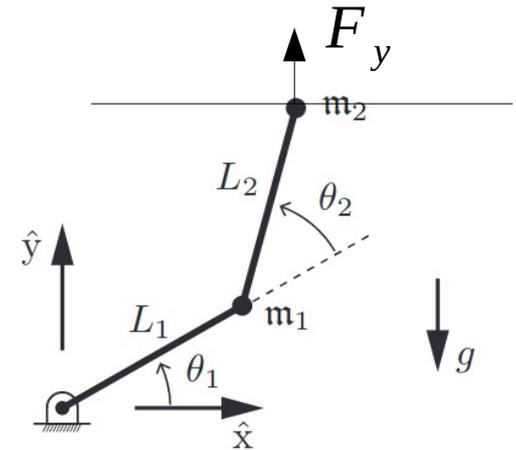
$$\boldsymbol{\tau} = J^T(\boldsymbol{\theta})$$
$$\left(\begin{bmatrix} 1 \\ 0 \end{bmatrix} M_C(\theta)\left(\ddot{x}_d + K_p x_e + K_i \int x_e + K_d \dot{x}_e\right) + \begin{bmatrix} 0 \\ 1 \end{bmatrix}\left(F_{yd} + K_{fp} F_{ye} + K_{fi} \int F_{ye}\right)\right)$$
$$+ \hat{\boldsymbol{h}}(\boldsymbol{\theta},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

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

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

$$+ \hat{\boldsymbol{h}}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})$$

Orthogonal directions where controllers act

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

$$\left(\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} M_C(\boldsymbol{\theta}) \left(\ddot{\boldsymbol{x}}_{\boldsymbol{d}} + K_p \boldsymbol{x}_{\boldsymbol{e}} + K_i \int \boldsymbol{x}_{\boldsymbol{e}} + K_d \dot{\boldsymbol{x}}_{\boldsymbol{e}} \right) + \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \left(\boldsymbol{F}_{\boldsymbol{d}} + K_{fp} \boldsymbol{F}_{\boldsymbol{ye}} + K_{fi} \int \boldsymbol{F}_{\boldsymbol{ye}} \right) \right)$$

$$+ \hat{\boldsymbol{h}}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})$$

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

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

Hybrid control

- General formulation

$$\tau = J_b^{\mathrm{T}}(\theta)\left(\boxed{P(\theta)}\left(\tilde{\Lambda}(\theta)\left(\frac{d}{dt}([\mathrm{Ad}_{X^{-1}X_d}]\mathcal{V}_d) + K_p X_e + K_i \int X_e(\mathrm{t})dt + K_d\mathcal{V}_e\right)\right)\right.$$

$$\underbrace{\phantom{J_b^{\mathrm{T}}(\theta)\left(P(\theta)\left(\tilde{\Lambda}(\theta)\left(\frac{d}{dt}([\mathrm{Ad}_{X^{-1}X_d}]\mathcal{V}_d)\right.\right.\right.}}_{\text{motion control}}$$

$$+ \boxed{(I - P(\theta))}\left(\mathcal{F}_d + K_{fp}\mathcal{F}_e + K_{fi}\int \mathcal{F}_e(\mathrm{t})dt\right)$$

$$\underbrace{\phantom{+(I-P(\theta))\left(\mathcal{F}_d + K_{fp}\mathcal{F}_e\right)}}_{\text{force control}}$$

$$\left.+ \underbrace{\tilde{\eta}(\theta, \mathcal{V}_b)}_{\text{Coriolis and gravity}}\right). \tag{11.61}$$

Simultaneous tasks
Some alternative formulations

- Torque control, two Cartesian space controllers

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

- Velocity control

$$\dot{\boldsymbol{\theta}} = J_1^+\,\dot{\boldsymbol{x}}_1 + N_1\left(J_2^+\,\dot{\boldsymbol{x}}_2 + N_2(\dots)\right)$$
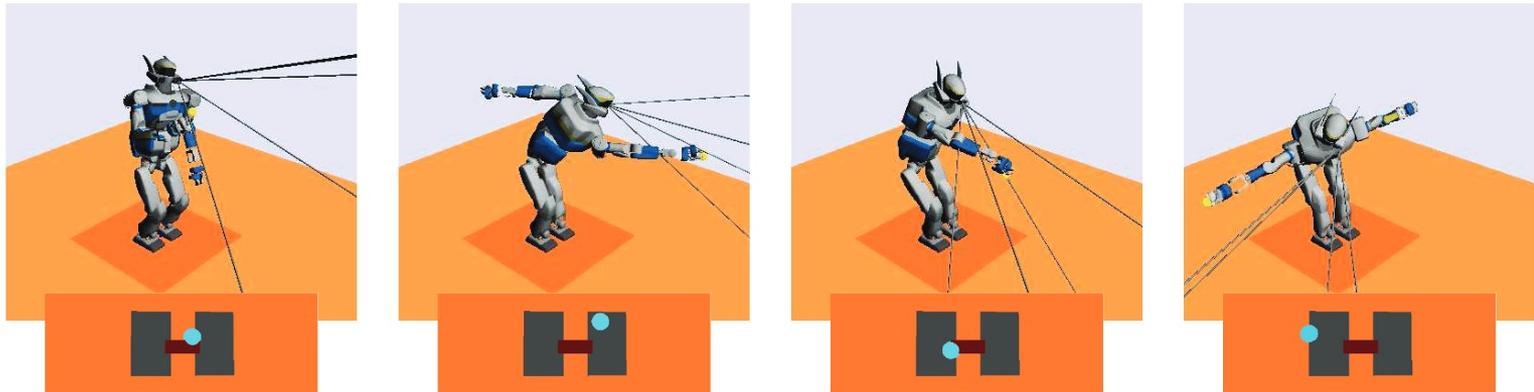
Jacobian of 1st task

Null space of 1st task

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

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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
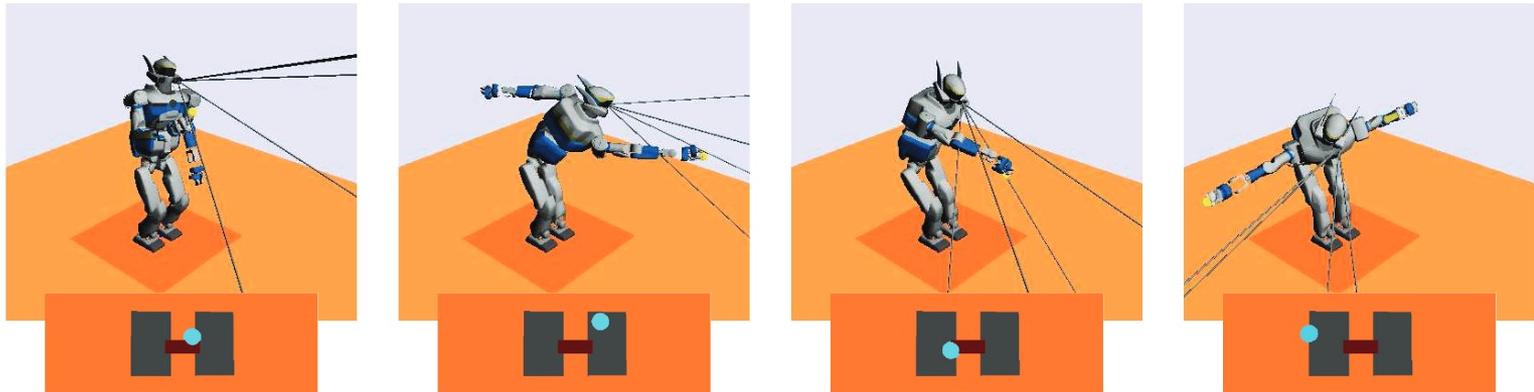
Task formalism for control

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Back to in-contact control!

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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
    $\rightarrow$ impedance control
  - Sense interaction forces and command positions
    $\rightarrow$ admittance control

Impedance control

- 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

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

Negate true dynamics

Replace with desired dynamics

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Impedance control in practice

- Typical control law

May contain only gravity

$$\boldsymbol{\tau} = J^T(\boldsymbol{\theta})\big(-K(\boldsymbol{x}-\boldsymbol{x_d}) - B(\dot{\boldsymbol{x}}-\dot{\boldsymbol{x_d}})\big) + \boldsymbol{h}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}})$$

What's the inertia that's felt?

Compare to ideal

$$\boldsymbol{\tau} = J^T(\boldsymbol{\theta})\big(M_C(\boldsymbol{x})\ddot{\boldsymbol{x}} + \boldsymbol{h_C}(\boldsymbol{x},\dot{\boldsymbol{x}}) - (M\ddot{\boldsymbol{x_e}} + B\dot{\boldsymbol{x_e}} + K\boldsymbol{x_e})\big)$$

difficult to measure

Admittance control

- Measure external force $\boldsymbol{F}_{ext}$, respond according to desired impedance behavior

$$\boldsymbol{F}_{ext} = M\,\ddot{\boldsymbol{x}} + B\,\dot{\boldsymbol{x}} + K\,\boldsymbol{x}$$

- Desired acceleration then

$$\ddot{\boldsymbol{x}}_d = M^{-1}\left(\boldsymbol{F}_{ext} - K\,\boldsymbol{x} - B\,\dot{\boldsymbol{x}}\right)$$

- Desired accelerations in joint space

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

$$\dot{\boldsymbol{x}} = J(\boldsymbol{\theta})\dot{\boldsymbol{\theta}}$$

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.

Also variable impedance possible.

- Passive compliance can be included in actuator.

Torsional spring of series elastic actuator
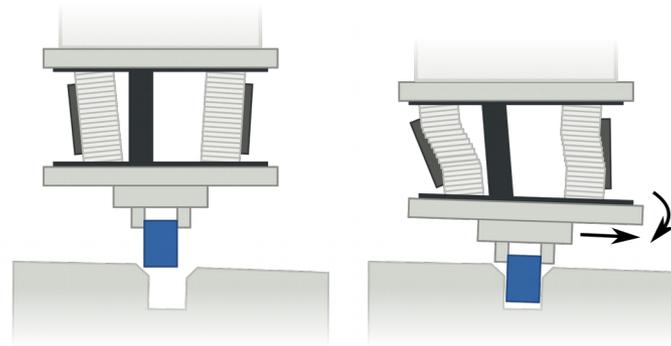
Remote center of compliance device

Why include passive compliance?
What are the effects?

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