8803 - Mobile Manipulation: Force Control

- Mike Stilman

- Robotics & Intelligent Machines @ GT
- Georgia Institute of Technology
- Atlanta, GA 30332-0760

- February 19, 2008

Force Control Strategies

- Logic Branching

- Continuous Force Control
  - Direct Feedback
  - Position/Velocity Feedback

- Position Control & Force Control
  - Impedance Control (Classic & Revised)
  - Hybrid Control

Logic Branching

Brief Description:

- Execute specified position/force commands
- Switch behavior on perceived input

Motivation:

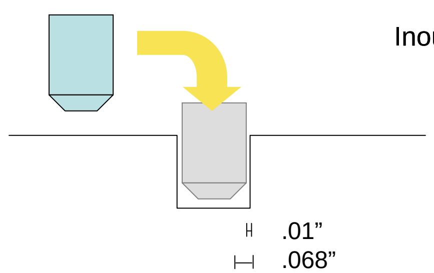
- Handle Uncertainty
- Achieve Very Low Tolerances

Ernst '61, Baber '73, Inoue '74

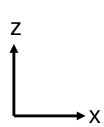
Peg In Hole

Case 1: Loose Fit

Inoue '74



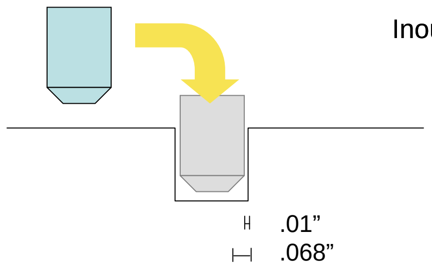
Suppose our positioning error is < .068"



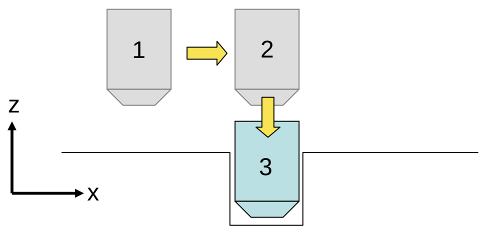
Peg In Hole

Case 1: Loose Fit

Inoue '74



Suppose our positioning error is < .068"

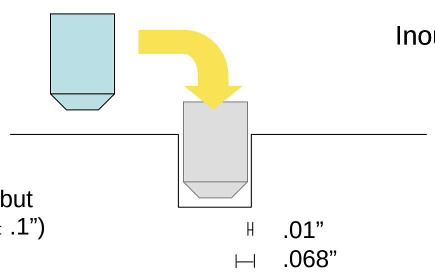


1) Position Control X
2) PUSH-INTO
   - Fz = Insert Force
   - Fx = 0

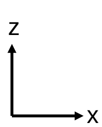
Peg In Hole

Case 2: Loose Fit
with Uncertainty

Inoue '74



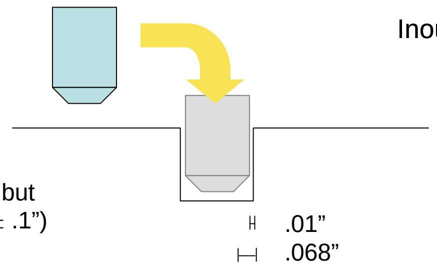
Our positioning error is < .068" but
Starting position is uncertain (± .1")



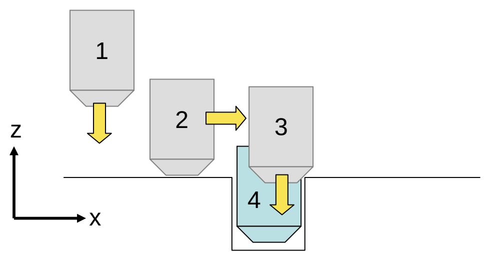
Peg In Hole

Case 2: Loose Fit
with Uncertainty

Inoue '74



Our positioning error is < .068" but
Starting position is uncertain (± .1")



1) $Z = Z - \Delta$ Until $Fz > 0$

2) DROP-INTO
   - $X = X + \Delta$
   - Fz = Small Contact Force
   - Fx = Small Sliding Force

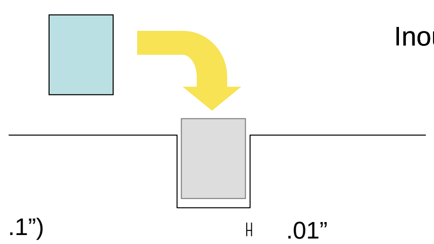
   Until Fx > Threshold

3) PUSH-INTO

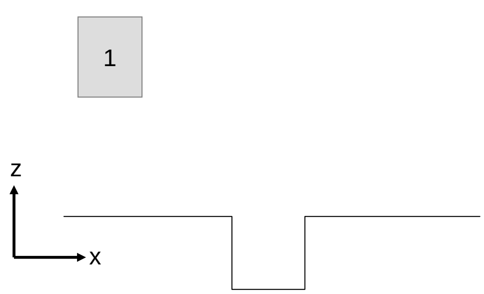
Peg In Hole

Case 3: Close Fit

Inoue '74



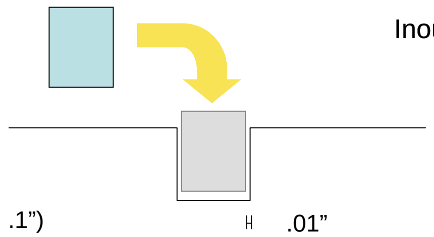
Positioning error > .01 and
Starting position is uncertain (± .1")



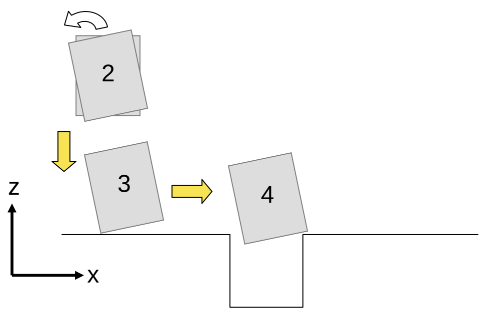
Peg In Hole

Case 3: Close Fit

Inoue ‘74



Positioning error > .01 and
Starting position is uncertain (± .1”)

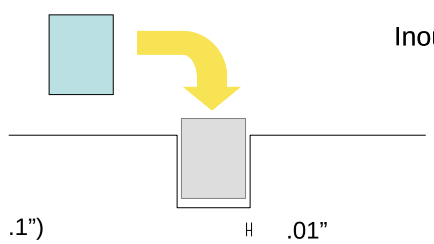


1) Position Control θ to .1
2) DROP-INTO

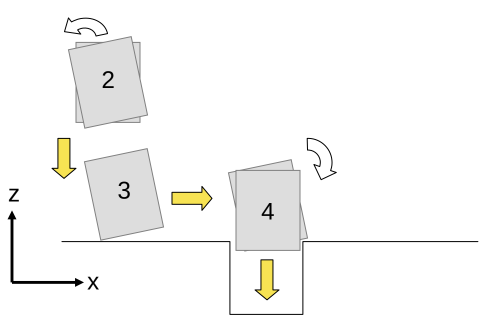
Peg In Hole

Case 3: Close Fit

Inoue ‘74



Positioning error > .01 and
Starting position is uncertain (± .1”)



1) Position Control θ to .1
2) DROP-INTO
3) Torque θ until τ > threshold
4) PUSH-INTO

Continuous Strategies

- Discrete branching:
  - Advantageous for handling Uncertainty/Tolerances
  - Very useful as part of a system
  - Could be more time efficient
- Continuous Strategies:
  - Coordination of multi-axis motions
  - Responds to continuously changing force-torque information
  - Achieves forces with greater precision

Nevins '73, Whitney '77 Raibert & Craig '81, Mason '81, Khatib '87…

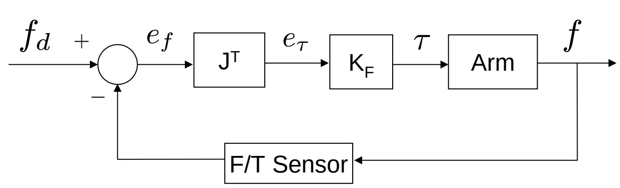
Continuous Force Control

- Feed-forward:

Continuous Force Control

- Feed-forward: $\tau = \mathbf{J^T F}$
- How do we do Feedback?

Force-based Feedback Control



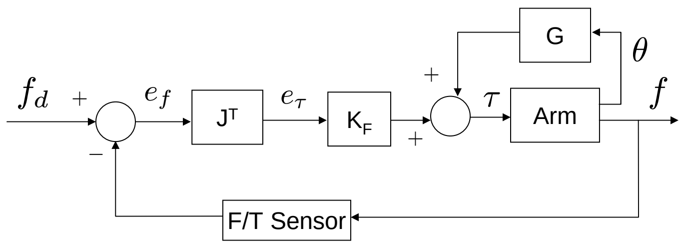
$$\tau = -K_F J^T (f - f_d)$$

Is K_F in Joint Space or Workspace?

Will it work well?

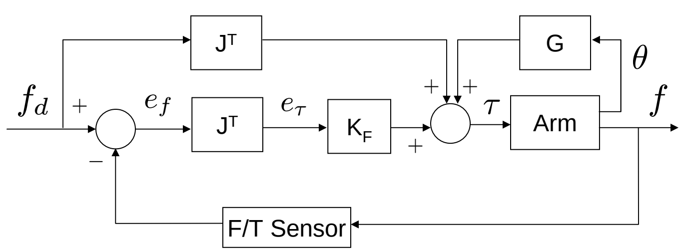
Whitney '85

Force-based Control (Linearization)



$$\tau = G - K_F J^T (f - f_d)$$

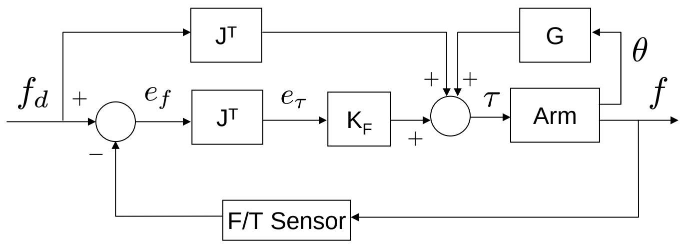
Force-based Control (Feed-forward)



$$\tau = J^T f_d + G - K_F J^T (f - f_d)$$

Similar to Volpe '93

Force-based Control (Feed-forward Term)



$$\tau = J^T f_d + G - K_F J^T (f - f_d)$$

- Non-zero steady-state error
- Can be oscillatory

Similar to Volpe '93

Options

- Integral Control

$$\tau = J^T f_d + G - K_{FI} \int_0^t J^T (f - f_d) dt$$

- Increase Feed-Forward Term

Volpe '93

Options

- Integral Control

$$\tau = \cancel{J^T f_d} + G - K_{FI} \int_0^t J^T (f - f_d) dt$$

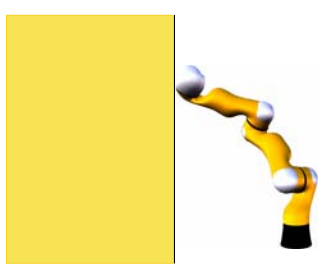
- Increase Feed-Forward Term

Volpe '93

Position-based Force Control

Workspace dynamics: $\bar{G}(q) = f$

Workspace dynamics with contact: $\bar{G}(q) = f + f_E$



Position-based Force Control

Workspace dynamics: $\bar{G}(q) = f$

Workspace dynamics with contact: $\bar{G}(q) = f + f_E$

Generic Position Controller: $f = \bar{G}(q) - K_p(x - x_d)$

Controlled System Dynamics: $\bar{G}(q) = \bar{G}(q) - K_p(x - x_d) + f_E$

Mike Stilman (RIM@GT) 8803 Lecture 14 2/21/2008 21

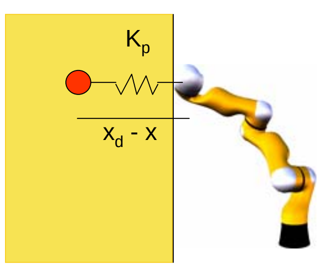
Position-based Force Control

Workspace dynamics: $\bar{G}(q) = f$

Workspace dynamics with contact: $\bar{G}(q) = f + f_E$

Generic Position Controller: $f = \bar{G}(q) - K_p(x - x_d)$

Controlled System Dynamics: $\bar{G}(q) = \bar{G}(q) - K_p(x - x_d) + f_E$



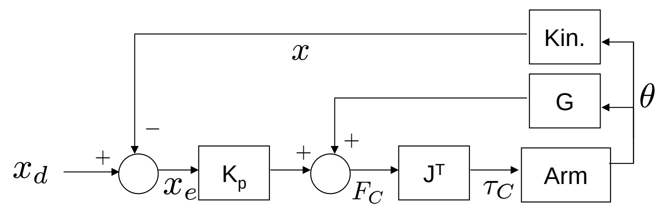
$$K_p(x - x_d) = f_E$$

$$x_d = -K_p^{-1} f_E + x$$

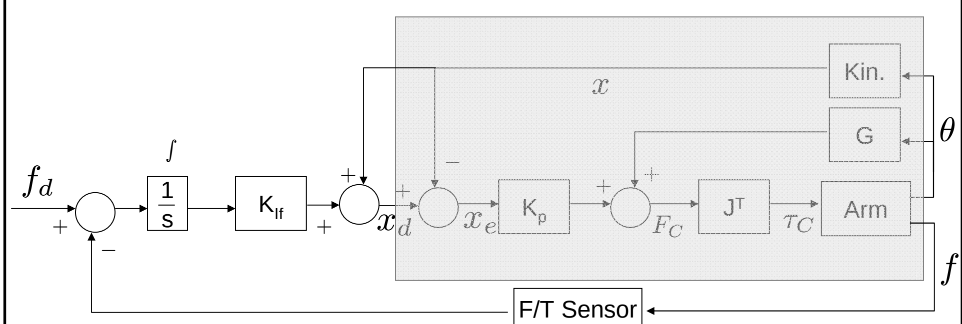
Mike Stilman (RIM@GT) 8803 Lecture 14 2/21/2008 22

Position-based Force Control: Feedback

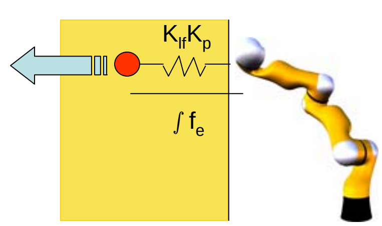
Position Control:



Position-based Force Control: Feedback



Force Control



Position Control + Force Control

Impedance Control

- Continuous relationship between position/force
- Simulates behavior of a simple mechanical system

Hybrid Control

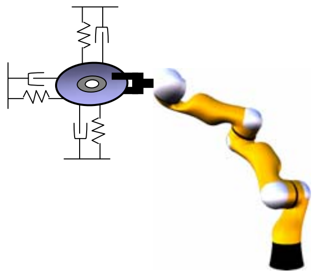
- Selection Matrix identifies directions for position/force
- Allows for precise positioning and force control

Impedance Control

How would the robot respond if its dynamics were actually:

$$\mathbf{M_d}\ddot{\mathbf{x}} - \mathbf{D_d}\dot{\mathbf{x}}_\mathbf{e} - \mathbf{K_d}\mathbf{x_e} = \mathbf{f_E} \qquad \mathbf{x_e} = (\mathbf{x} - \mathbf{x_r})$$

- Position tracking when force = 0
- Compliance when force > 0
- Restoration to tracking when force is removed



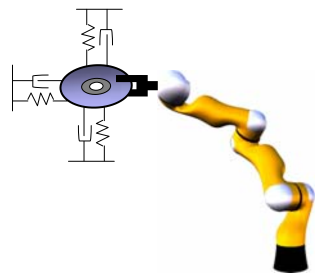
Impedance Control

How would the robot respond if its dynamics were actually:

$$\mathbf{M_d}\ddot{\mathbf{x}} - \mathbf{D_d}\dot{\mathbf{x}}_\mathbf{e} - \mathbf{K_d}\mathbf{x_e} = \mathbf{f_E} \qquad \mathbf{x_e} = (\mathbf{x} - \mathbf{x_r})$$

- Position tracking when force = 0
- Compliance when force > 0
- Restoration to tracking when force is removed

$$\ddot{\mathbf{x}} = \mathbf{M_d}^{-1}(\mathbf{f_E} + \mathbf{D_d}\dot{\mathbf{x}}_\mathbf{e} + \mathbf{K_d}\mathbf{x_e})$$



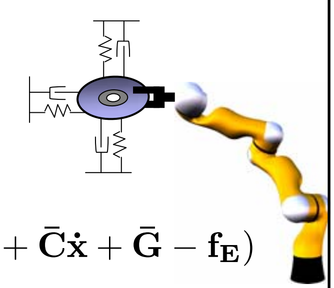
Impedance Control

How would the robot respond if its dynamics were actually:

$$\mathbf{M_d}\ddot{\mathbf{x}} - \mathbf{D_d}\dot{\mathbf{x}}_\mathbf{e} - \mathbf{K_d}\mathbf{x_e} = \mathbf{f_E} \qquad \mathbf{x_e} = (\mathbf{x} - \mathbf{x_r})$$

- Position tracking when force = 0
- Compliance when force > 0
- Restoration to tracking when force is removed

$$\ddot{\mathbf{x}} = \mathbf{M_d}^{-1}(\mathbf{f_E} + \mathbf{D_d}\dot{\mathbf{x}}_\mathbf{e} + \mathbf{K_d}\mathbf{x_e})$$



Notice the similarity to workspace computed torque:

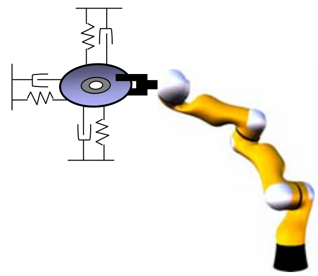
$$\tau = \mathbf{J^T}(\bar{\mathbf{M}}(\mathbf{M_d}^{-1}(\mathbf{f_E} + \mathbf{D_d}\dot{\mathbf{x}}_\mathbf{e} + \mathbf{K_d}\mathbf{x_e})) + \bar{\mathbf{C}}\dot{\mathbf{x}} + \bar{\mathbf{G}} - \mathbf{f_E})$$

Position-based Impedance Control

$$\mathbf{M_d \ddot{x} - D_d \dot{x}_e - K_d x_e = f_E} \qquad \mathbf{x_e = (x - x_r)}$$

1) Simulate the system response to $\mathbf{f_E}$

$$\begin{aligned}
\mathbf{\ddot{x}(t + \Delta t)} &= \mathbf{M_d^{-1}(f_E + D_d \dot{x}(t) + K_d x(t))} \\
\mathbf{\dot{x}(t + \Delta t)} &= \mathbf{\dot{x}(t) + \ddot{x}(t)\Delta t} \\
\mathbf{x(t + \Delta t)} &= \mathbf{x(t) + \dot{x}(t)\Delta t}
\end{aligned}$$



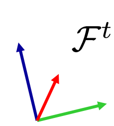
2) Track simulated $\mathbf{x}$ (possibly $\mathbf{\dot{x}}$)

Hybrid Control

- Task Constraint: **Restriction on the freedom of motion of the manipulator**
- Cannot move in some direction
- Can control forces/moments in that direction

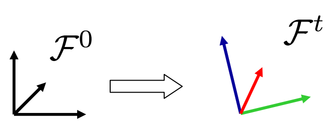
- Degrees of freedom are coordinates in a task frame

$$\mathbf{x} = [\ \mathbf{x}_1 \ \cdots \ \mathbf{x}_n\ ]^T$$



- Task frame is a transformed world frame

$$\mathcal{F}^t = \mathbf{T}_t^0 \mathcal{F}^0$$

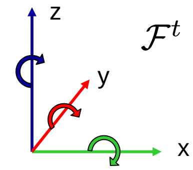


Hybrid Control

- A motion constraint is described by a selection matrix:

$$\mathbf{S} = \begin{bmatrix} s_1 & & \\ & \cdots & \\ & & s_n \end{bmatrix} \qquad \mathbf{S}\dot{\mathbf{x}} = \mathbf{0}$$

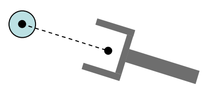
- Coordinates – Cartesian + Fixed Axis (Roll, Pitch Yaw)

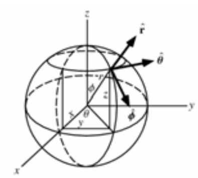


$$\mathbf{R}_B^t = R(z_t, \phi)R(y_t, \theta)R(x_t, \psi)$$

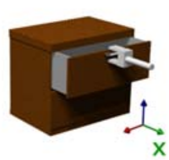
$$\mathbf{S_{RPY}} = \mathbf{I}[\; s_x \quad s_y \quad s_z \quad s_\psi \quad s_\theta \quad s_\phi \;]^{\mathbf{T}}$$

- Alternative Coordinates:



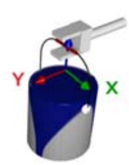


Examples of Constraints

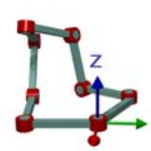


[0 1 1 1 1 1]

[1 1 1 1 1 0]

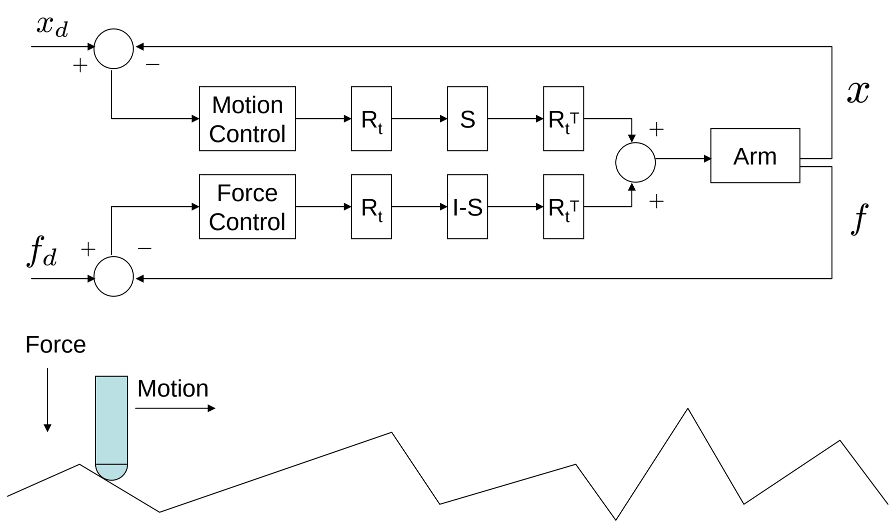


Parameterized [0 0 0 1 1 0]



Parameterized [1 1 1 1 1 0]

Hybrid Control



Best of Both Worlds

- Use task frame to set a center of compliance for impedance control
- Use Impedance Control (not motion control) in hybrid system
- Vary the parameters of Impedance Control according to direction

Summary

We looked at:

- Logic Branching
- Continuous Force Control (Force and Position Based)
- Hybrid Postion/Force Strategies

Your goal:

- Think about how these strategies can help you accomplish the task
- Which subtasks require which type of control?