Tutorial on Learning from Demonstration

Part 4: Teaching compliance and force control

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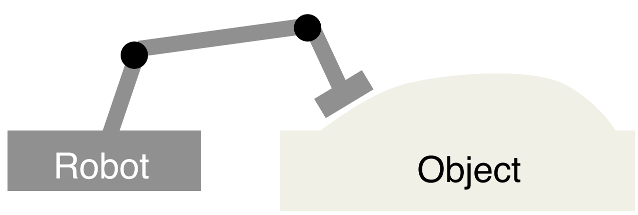
Controlling Manipulators in Contact

- Research in robot control was for a long time focused on increasing performance in free motion.
- High speed and accuracy in following trajectories does not facilitate control in contact.
- Control of position and force conflicting goals.



Hybrid Control

- Orthogonal task subspaces are controlled either in force or position

- Successful implementations with *known environments*
- Large number of extensions, including adaptive selection matrices, iterative learning control etc.

M.H. Raibert and J.J. Craig "Hybrid position/force control of manipulators" Journal of Dynamic Systems, Measurement and Control, 1981

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Parallel Control

- Does not require specification of force and position controlled subspaces.
- Feedback control of force and position on all axes

- Priority given to force control through integral control action

S. Chiaverini and L. Sciavicco "The parallel approach to force/position control of robotic manipulators" IEEE Transactions on Robotics and Automation, 1993

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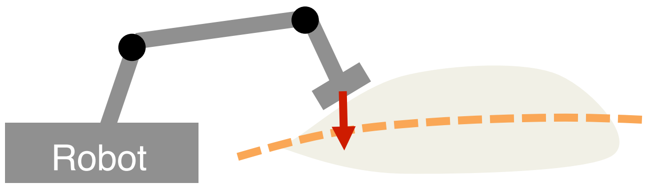
Stiffness Control

- Establish a static relationship between position error and force response

$$F = -K(x - x^d)$$



- Force feedback not required
- Behavior is nonlinear, coupled and depends on the robot dynamics.

J.K. Salisbury "Active stiffness control of a manipulator in Cartesian coordinates" IEEE Intl. Conf. on Decision and Control, 1980

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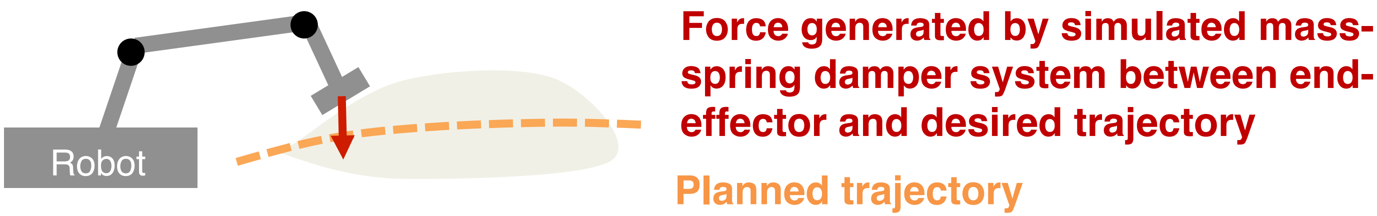
Impedance Control

- Generalization of stiffness control
- Goal: control the robot so as to obtain a certain dynamic behavior of the end-effector

$$M\ddot{\tilde{x}} + D\dot{\tilde{x}} + K\tilde{x} = F$$

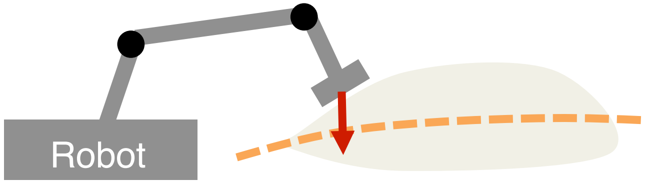


- Force sensing can be avoided if inertia-shaping is not required

N. Hogan "Impedance control: an approach to manipulation: parts I–III", Journal of Dynamic Systems, Measurement and Control, 1985

Compliant Manipulation: What is needed to specify a task?

- Nominal motion plan
  - Static reference trajectory
  - Parameterized policies
  - Dynamical system

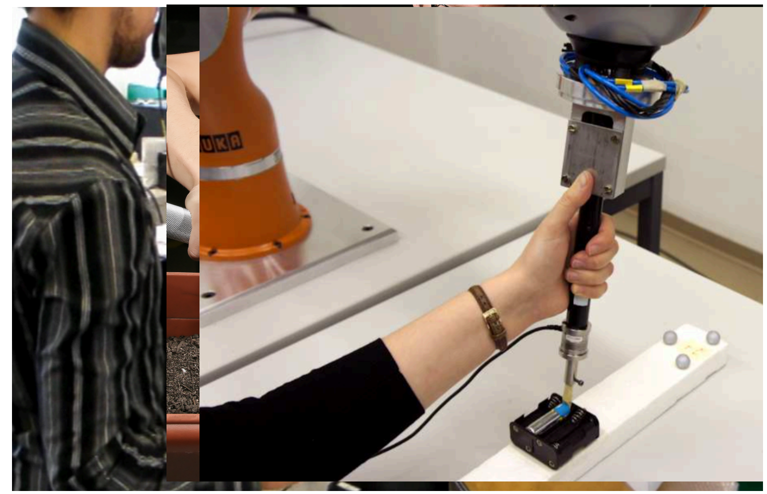


$$M(\ddot{x} - \ddot{x}^d) + D(\dot{x} - \dot{x}^d) + K(x - x^d) = F - F^d$$

- Compliance parameters
  - Selection matrices (hybrid control)
  - Impedance parameters

Capturing contact forces

- Haptic devices
- Instrumented tools
- Kinesthetic teaching with force sensors



L. Rozo et al. “A robot learning from demonstration framework to perform force-based manipulation tasks”, Intelligent Service Robotics 2013

P. Kormushev et al. “Imitation learning of positional and force skills demonstrated via kinesthetic teaching and haptic input”, Advanced Robotics 2011

A.L. Pais et al. “Task Parametrization Using Continuous Constraints Extracted from Human Demonstrations”, Transactions on Robotics 2015.

Task models including contact forces

Desired position and force

Demonstrated data

Position
Force

→ Task model → Controller

Not enough information!

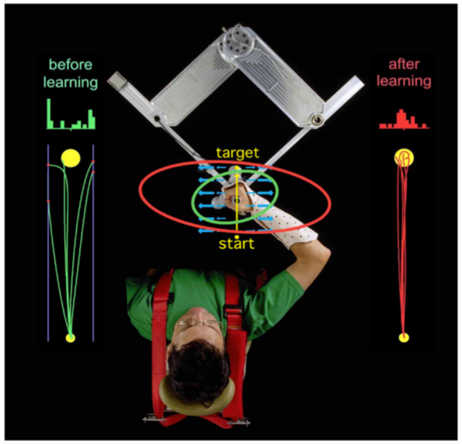
Need to select impedance parameters in accordance with the task.

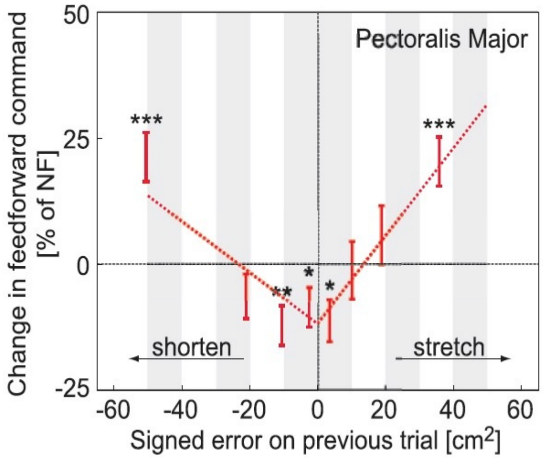
Assumption: Aspects of the task with low variance across multiple demonstrations should be reproduced.

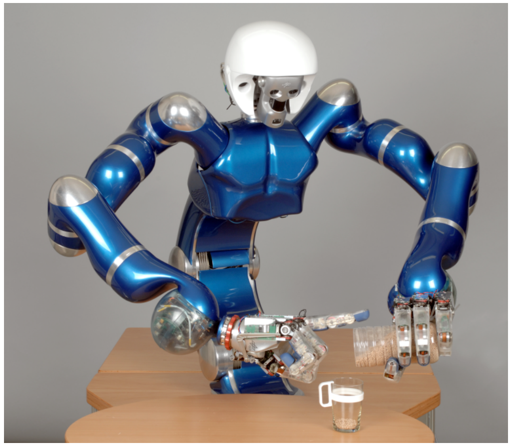
S. Calinon et al. "Learning-based control strategy for safe human-robot interaction exploiting task and robot redundancies" IROS 2010

A.L. Pais et al. "Task Parametrization Using Continuous Constraints Extracted from Human Demonstrations", Transactions on Robotics 2015.

The human as a model







Burdet et al. "The central nervous system stabilizes unstable dynamics by learning optimal impedance." Nature 2001

Franklin et al. "CNS learns stable, accurate, and efficient movements using a simple algorithm." Journal of Neuroscience, 2008

Yang et al. "Human-like Adaptation of Force and Impedance in Stable and Unstable Interactions." IEEE Transaction on Robotics, 2011

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Estimating stiffness variations

Stiffness estimation from measurements of force and position:

$$\left.\begin{aligned} F_1 &= K(x_1 - x_1^d) \\ F_2 &= K(x_2 - x_2^d) \\ x_1^d &= x_2^d \end{aligned}\right\} \quad \Rightarrow \quad F_1 - F_2 = K(x_1 - x_2)$$

T. Tsumugiwa et al. "Variable impedance control based on estimation of human arm stiffness for human-robot cooperative calligraphic task", ICRA 2002

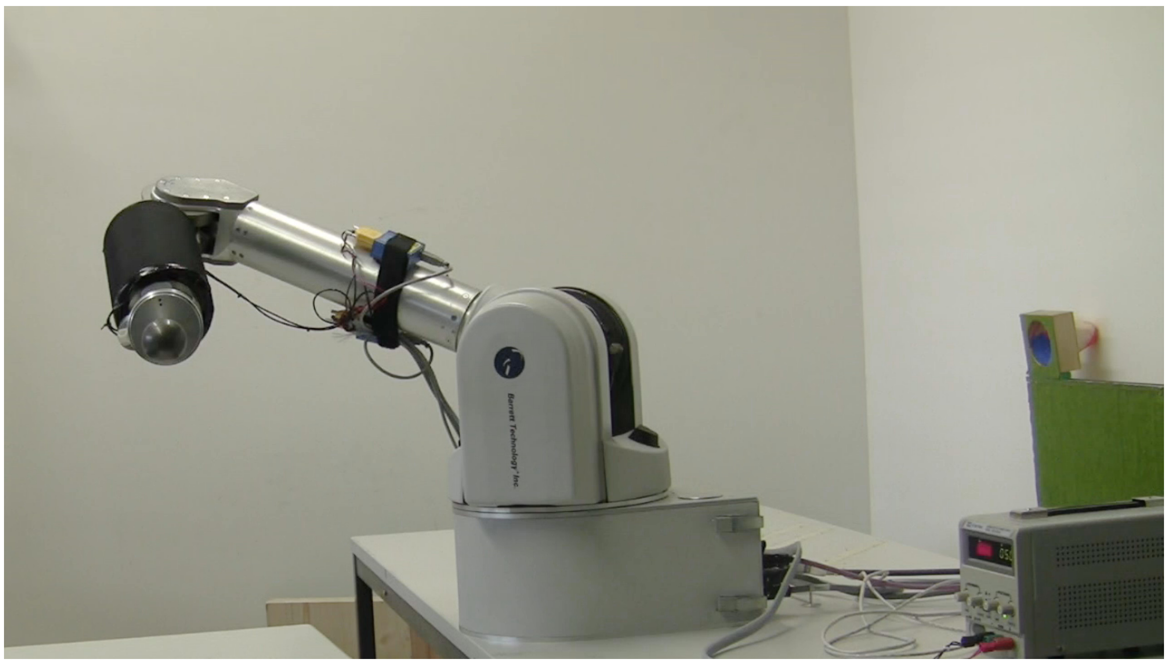
Least squares based methods

L. Rozo et al. "Learning collaborative impedance-based robot behaviors", AAAI 2013

A. Lee et al. "Learning Force-Based Manipulation of Deformable Objects from Multiple Demonstrations", ICRA 2015

An interface for teaching varying stiffness

- User shaking the robot => stiffness decrease
- User increasing the grasp pressure => stiffness increase



Kronander and Billard "Learning Compliant Manipulation through Kinesthetic and Tactile Human-Robot Interaction" IEEE Transactions on Haptics, 2013