Compliant Manipulation: Challenges in Learning and Control

Organized by Klas Kronander, Aude Billard, Etienne Burdet and Jonas Buchli
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• Jose Millán
• Francesco Mondada
• Jamie Paik
• Herbert Shea

• Jonas Buchli
• Tobias Delbruck
• Roger Gassert
• Fumiya Iida
• Robert Riener
• Roland Siegwart

• Rolf Pfeifer
• Davide Scaramuzza

• Gianni Di Caro
• Luca Gambardella
Scenario driven research focused on three areas

Wearable Robotics
- Exoskeletons
- Intelligent prostheses
- Brain-machine interfaces

Rescue Robotics
- Mapping of disaster areas
- Collaboration between air and ground based robots
- Agile legged robots with manipulation capabilities

Active Environment
- Acceptance of robotics in daily lives
- Educational robots
<table>
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<th>Time</th>
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<th>Speaker</th>
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<td>8:30 - 8:55</td>
<td><strong>Introduction</strong></td>
<td>Klas Kronander</td>
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<td>09:00 – 09:40</td>
<td>Modeling actuators to facilitate compliant manipulation</td>
<td>Neville Hogan</td>
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<td>09:45 – 10:00</td>
<td>On using Passivity Layer for Distributed Control of Cooperative Object Manipulation</td>
<td>Stefano Stramigioli</td>
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<td>10:00 – 10:30</td>
<td><strong>Coffee break</strong></td>
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<td>10:30 – 11:10</td>
<td>Unlocking the treasure trove: Learning impedance control</td>
<td>Jonas Buchli</td>
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<td>11:15 – 12:00</td>
<td>Compliant Motion and Hydraulic Actuators for Robots</td>
<td>Yosihiko Nakamura</td>
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<td>12:00 – 13:30</td>
<td><strong>Lunch break</strong></td>
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<td>13:30 – 14:10</td>
<td>Robot learning by imitation and exploration with probabilistic dynamical systems</td>
<td>Sylvain Calinon</td>
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<td>14:15 – 14:55</td>
<td>Human-human interaction in compliant connection</td>
<td>Atsushi Takagi</td>
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<td>15:00 – 15:45</td>
<td><strong>Interactive poster session and coffee break</strong></td>
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<td>15:45 – 16:00</td>
<td>Dual Arm Impedance Control with a Compliant Humanoid: Application to a Valve Turning Task</td>
<td>Jinho Lee</td>
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<td>16:00 – 16:40</td>
<td>Enhancing soft robotic agility through compliance and human imitation</td>
<td>Matthew Howard</td>
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<td>16:45 – 17:00</td>
<td><strong>Wrap up and closing</strong></td>
<td>Klas Kronander</td>
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## Interactive session, 15:00 – 15:40

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<th>Speaker(s)</th>
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<tr>
<td>B. Ponton et al.</td>
<td>“Learning compliant locomotion on a quadruped robot”</td>
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<td>J.D. Langsfeld et al.</td>
<td>“Incorporating failure-to-success transitions in imitation learning for a dynamic pouring task”</td>
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<td>Y. Yun et al.</td>
<td>“Three Compliant Fingers in ReNeu Lab to Achieve No Delay, High Stability, and Statistical Model-based Control”</td>
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<td>A. Cohen and S. Berman</td>
<td>&quot;Motor Control Variables and dynamic Motion primitives&quot;</td>
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<tr>
<td>M. Khansari-Zadeh et al.</td>
<td>“Learning a unified model for motion generation and interaction control”</td>
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<tr>
<td>Y. Brodisky et al.</td>
<td>“On using Passivity Layer for Distributed Control of Cooperative Object Manipulation”</td>
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<tr>
<td>S. Sakai</td>
<td>“Application of robust structure for impedance controls”</td>
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<tr>
<td>A. Ajoudani et al.</td>
<td>“Dual Arm Impedance Control with a Compliant Humanoid: Application to a Valve Turning Task”</td>
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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.

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

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
Impedance Control

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

\[ M\ddot{x} + D\dot{x} + K\ddot{x} = F \]

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

Impedance Control: Implementation aspects

• Can be emulated on position controlled platforms by measuring the force and integrating a reference position trajectory (admittance control)

• Backdrivable torque controlled platforms: force sensor not required if inertia shaping can be omitted

• Active research field, e.g. robustness to model imperfections and delayed and/or noisy feedback signals

In interactive session: S. Sakai “Application of robust structure for impedance controls”

In interactive session: Y. Brodisky et al. “On using Passivity Layer for Distributed Control of Cooperative Object Manipulation”
Realizing object or tool impedance

• In grasping or bimanual manipulation, there are several contact points between the tool/object and the robot(s)

• How to control the contact points so as to maintain a certain impedance of the object?


M. Li et al. “Learning Object-level Impedance Control for Robust Grasping and Dexterous Manipulation”, ICRA 2014

In interactive session: A. Ajoudani et al. “Dual Arm Impedance Control with a Compliant Humanoid: Application to a Valve Turning Task”
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
Motion Representation Using Dynamical Systems

\[ \dot{x} = f(x) \]

Multidimensional Kinematic Variable:
- e.g. End-effector position/orientation,
- joint angles

Streamlines of a *globally asymptotically* stable autonomous DS

Target

\[ x_1 \]

\[ x_2 \]

\[ \| x \| \]

Target

Reproductions

Khansari-Zadeh and Billard “Stable Estimator of Dynamical Systems” IEEE TRO. 2011
Motion Generation with Dynamical Systems


Gribovskaya et al. "Learning non-linear multivariate dynamics of motion in robotic manipulators." IJRR 2010


In interactive session: Cohen and Berman "Motor Control Variables and dynamic Motion primitives"

In interactive session: M. Khansari-Zadeh, K. Kronander, A. Billard and O. Khatib “Learning a unified model for motion generation and interaction control”
Locally Modulated Dynamical Systems

Assume availability of an original dynamical system:

- No introduction of equilibrium points.
- Bounded trajectories.
- Stable original dynamics $\Rightarrow$ stable reshaped dynamics.

$M$ with full rank.

K. Kronander, M. Khansari-Zadeh and A. Billard “Incremental Motion Learning with Locally Modulated Dynamical Systems” Robotics and Autonomous Systems [submitted]
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
The human as a model


Estimating stiffness variations

• Estimation with EMG sensors, e.g. for tele-impedance
• Based on assumption of static or very slow nominal motion

\[
\begin{align*}
F_1 &= K(x_1 - x_1^d) \\
F_2 &= K(x_2 - x_2^d) \\
x_1^d &= x_2^d
\end{align*}
\] \implies F_1 - F_2 = K(x_1 - x_2)

• Estimation from kinematic data


S. Calinon et al. “Learning-based control strategy for safe human-robot interaction exploiting task and robot redundancies” IROS 2010
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
Reinforcement learning and optimal control for compliant manipulation


Ponton, Farishidan and Buchli, “Learning Compliant Locomotion on a Quadroped Robot”


Compliant Manipulation: What is needed to specify a task?

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