Development and Control of Compliant Humanoid Robots at DLR

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Overview

1) Design & Control of compliant robots
   - Torque Controlled Robots
   - Elastic Robots

2) Control of humanoid robots
   - Compliant Control
   - Bipedal Walking
Robot Model with Torque Sensors

\[
M(q)\ddot{q} + C(q, \dot{q})\dot{q} + g(q) = \underbrace{\varepsilon}_e + K(\theta - q) + \tau_{\text{ext}}
\]

\[
B\ddot{\theta} + K(\theta - q) = \tau_m
\]
Advantages of Torque Sensing

- Light-weight robot with elastic joints
- Joint torque sensor
- Torque Control
- Movement accuracy
- Safe human-robot-interaction
- active vibration damping
- Identification
- Disturbance Observer
- collision reaction
- compliance control

Segment
Elasticity
Motor

Joint torque $\theta$
Joint torque sensor $q$
Joint torque $\tau$
Joint torque $\tau_m$
Advantages of Torque Sensing

- Light-weight robot with elastic joints
  - Joint torque sensor
    - Torque Control
    - Movement accuracy
      - Safe human-robot-interaction
        - Disturbance Observer
          - Identification
        - Compliance control
          - Collision reaction
            - Active vibration damping

Advantages of Torque Sensing

- Light-weight robot with elastic joints
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- Torque Control
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- Safe human-robot-interaction
  - active vibration damping
  - Identification
  - Disturbance Observer
  - compliance control
  - collision reaction
  - Elasticity
  - Motor

\[ M(q)\ddot{q} + C(q, \dot{q})\dot{q} + g(q) = \tau + \tau_{\text{ext}} + \tau_{f,q} \]
\[ B\ddot{\theta} + \tau = \tau_m + \tau_f \]
Advantages of Torque Sensing

- Light-weight robot with elastic joints
- Joint torque sensor
  - Torque Control
  - Movement accuracy
  - Safe human-robot-interaction
    - active vibration damping
    - Identification
    - Disturbance Observer
    - collision reaction
    - compliance control

- Joint elastic segment
  - Motor
  - Elasticity

- Joint torque sensor

- Light-weight robot

Compliant Manipulation
Joint torque sensing & control for manipulation

Robustness:
Passivity Based Control

Performance:
Joint Torque Feedback (noncollocated)

[Ott & Albu-Schäffer, TRO 2008]
Compliant Manipulation
Joint torque sensing & control for manipulation

**Equilibrium:** \( g(q) = K(\theta - q) + \tau_{ext} \)
\( \tau_{ext} = \frac{\partial V(q)}{\partial q} \)

\( \bar{q}(\theta) \)

- Compensation of the static effects of \( K \)
- Allows to fulfill requirements on the link side accuracy!
- Computation of \( \bar{q}(\theta) \) by contraction analysis!

**Robustness:**
Passivity Based Control

**Performance:**
Joint Torque Feedback (noncollocated)
Compliant Manipulation

Robustness: Passivity Based Control

Performance: Joint Torque Feedback (noncollocated)
Humanoid Robots at DLR

Joint torque sensing & control

Bimanual (Humanoid) Manipulation
- Compliant actuation
- Antagonistic actuation for fingers
- Variable stiffness actuation in arm
- Robustness to shocks and impacts

Legged Humanoid

Space Qualified Joint Technology

Anthropomorphic Hand-Arm System
Antropomorphic Hand/Arm System

- **Antropomorphic design**: Size, kinematics, force and dynamics of human arm and hand
- **Actuation principle**: Variable stiffness in all joints (3 types)
  - 27 DoF
  - 50 motors
  - 108 position sensors

[Grebenstein, Albu-Schäffer et al, ICRA 2011]
Types of actuation

Floating Spring Joint (4 DoF)
- big motor for positioning
- small motor to change stiffness
- one single spring

Bidirectional Antagonism with Variable Stiffness Actuation (3 DoF)
- 2 equivalent motors
- asymmetric cam disc shape
- redundant joint actuation

Antagonism (20 DoF Hand):
- 2 equivalent motors
- in-tendon progressive spring mechanism
Motivation for physical compliance

Robustness

Performance
Control Challenges: Vibration Damping

1) Modal decoupling (link side)
\[ M = Q^{-T} M_Q Q^{-1} \]
\[ K = Q^{-T} Q^{-1} \]

2) Use torque feedback to achieve decoupling in \( M, K, \) and \( B \)
\[ \tau_m = \left( I - BB_d^{-1} \right) \tau + BB_d^{-1} u \]
\[ B_d = \alpha M + \beta K \]

3) SISO design in decoupled coordinates
\[ \dot{M} \approx 0, \dot{Q} \approx 0 \]
\[ \begin{pmatrix} \dot{\theta} \\ \dot{q} \end{pmatrix} \rightarrow \begin{pmatrix} Q^{-1} \dot{\theta} \\ Q^{-1} \dot{q} \end{pmatrix} \]

\[ M(q) \ddot{q} + C(q, \dot{q}) \dot{q} + g(q) = K(\theta - q) + \tau_{\text{ext}} \]
\[ B \ddot{\theta} + K(\theta - q) = \tau_m \]

[Petit, Albu-Schäffer, ICRA 2011]
Control Challenges: Vibration Damping

1) Modal Decoupling (link side)
2) Use torque feedback to achieve decoupling in $M$, $K$, and $B$
3) SISO design in decoupled coordinates

Control Challenges: Vibration Damping

$\dot{\theta} \rightarrow \left( Q^{-1} \theta \right)$

General Flexible Joint Model

[Petit, Albu-Schäffer, ICRA 2011]
Control Challenges: Stiffness Design

Compliance \( C = K^{-1} \) given as a series interconnection of active and passive stiffness elements

\[
C = C_a + C_p
\]

1) Use physical springs in the joints to set desired stiffness as close as possible

\[
\min \left\| C_{des} - C_p \right\|
\]

2) Use active compliance to realize precise Cartesian compliance

\[
\min \left\| C_{des} - C_p - C_a \right\| \quad \text{with} \quad C_a > 0
\]

[Petit, Albu-Schäffer, IROS 2011]

Utilizes variability of the stiffness!
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   - Bipedal Walking
Bipedal Walking Robots at DLR

- Joint torque sensing & control
- Small foot size: 19 x 9,5 cm
- IMU in head & trunk
- FTS in feet for position based control
- Sensorized head (stereo vision & kinect)
- Simple prosthetic hands (iLIMB)

TORO, preliminary version (2012)
TORO (2013)
TORO (2014)
- Height: 1.74 m
- Mass: 76.4 kg
- Battery duration: approx. 1 hour
- 25 Joints can be operated in position and torque controlled mode (legs, arms, waist). Joints are based on the DLR-KUKA-Lightweight-Arm III
- 2 Joints are operated in position controlled mode (neck)
- Prosthetic hands with 12 DoF in total
Motivation for compliant control

completely stiff  compliant control  fully compliant
Balancing & Posture Control

Compliant COM control [Hyon & Cheng, 2006]

\[ F_{COM} = Mg - K_P (c - c_d) - K_D (\dot{c} - \dot{c}_d) \]

Trunk orientation Control

\[ T_{HIP} = \frac{\partial \dot{V}(R, K_R)}{\partial \dot{\omega}} + D_R (\omega - \omega_d) \]
Balancing & Posture Control

Compliant COM control [Hyon & Cheng, 2006]

\[ F_{COM} = Mg - K_P (c - c_d) - K_D (\dot{c} - \dot{c}_d) \]

**Desired wrench:** \( W_d = (F_{COM}, T_{HIP}) \)

Trunk orientation Control

\[ T_{HIP} = \frac{\partial \hat{V}(R, K_R)}{\partial \omega} \hat{\omega} + D_R (\omega - \omega_d) \]

**IMU measurements**
Balancing & Posture Control

Compliant COM control [Hyon & Cheng, 2006]

\[ F_{COM} = Mg - K_p (c - c_d) - K_D (\dot{c} - \dot{c}_d) \]

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Trunk orientation Control

\[ T_{HIP} = \frac{\partial \dot{V}(R, K_R)}{\partial \omega} + D_R (\omega - \omega_d) \]
Grasping & Balancing

**Force distribution:** How to realize a desired force/torque on the COM via the available contact points. A similar problem has been solved also in robot grasping by constrained optimization!

\[ F_o \]

\[ f_1 \]

\[ f_2 \]

\[ W \]
Force distribution

Relation between balancing wrench & contact forces

\[ G_i = \begin{bmatrix} R_i \\ \hat{p}_i R_i \end{bmatrix} \]

\[ W_d = \begin{bmatrix} G_1 & \cdots & G_N \end{bmatrix} \begin{bmatrix} f_1 \\ \vdots \\ f_N \end{bmatrix} = \begin{bmatrix} G_F \\ G_T \end{bmatrix} f_C \]

Constraints:
- Unilateral contact: \( f_{i,z} > 0 \) (implicit handling of ZMP constraints)
- Friction cone constraints
Force distribution

Relation between balancing wrench & contact forces

\[ G_i = \begin{bmatrix} R_i \\ \hat{p}_i R_i \end{bmatrix} \]

\[ W_d = \begin{bmatrix} G_1 & \cdots & G_n \end{bmatrix} \begin{bmatrix} f_1 \\ \vdots \\ f_n \end{bmatrix} \]

Constraints:

- Unilateral contact: \( f_{i,z} > 0 \) (implicit handling of ZMP constraints)
- Friction cone constraints

Formulation as a constraint optimization problem

\[ f_C = \arg \min \left\{ \alpha_1 \| F_{COM} - G_F f_C \|^2 + \alpha_2 \| T_{HIP} - G_T f_C \|^2 + \alpha_3 \| f_C \|^2 \right\} \quad \alpha_1 \gg \alpha_2 \gg \alpha_3 \]
Contact force control via joint torques

Multibody robot model:
COM as a base coordinate → system structure with decoupled COM dynamics.

\[
\begin{bmatrix}
  M & 0 \\
  0 & \dot{M}(q)
\end{bmatrix}
\ddot{\hat{q}}
+ \begin{bmatrix}
  0 \\
  \dot{C}(\hat{q}, \dot{q})
\end{bmatrix}
+ \begin{bmatrix}
  -Mg \\
  0
\end{bmatrix}
= \begin{bmatrix}
  0 \\
  u
\end{bmatrix}
- \sum_{i=r,i} \begin{bmatrix}
  I & 0
\end{bmatrix}
J_i(\hat{q})^T F_i
\]

\[
M \ddot{c} = Mg - \sum f_i
\]

\[
\tau = \sum J_i(\hat{q})^T f_i
\]

Passivity based compliance control
(well suited for balancing)
Experiments using the lower body
Experiments using whole body

Balancing with uncertainty of the ground
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   ✓ Bipedal Walking
Walking Stabilization

Template model: \( \ddot{x} = \omega^2 (x - p) \)

\[
\begin{align*}
(x, \dot{x}) & \downarrow \\
(x, \xi) & \\
\xi & = x + \frac{1}{\omega} \dot{x}
\end{align*}
\]

\[
\begin{align*}
\dot{\xi} & = \omega (\xi - p) \\
\dot{x} & = \omega (\xi - x)
\end{align*}
\]

(Pratt 2006, Hof 2008)

[Englsberger, Ott, IROS 2013]
Walking Stabilization

Template model:
\[ \ddot{x} = \omega^2 (x - p) \]

\[ \xi = x + \frac{1}{\omega} \dot{x} \]

\[ \dot{\xi} = \omega (\xi - p) \quad \ddot{x} = \omega (\xi - x) \]

(Pratt 2006, Hof 2008)

[Englsberger, Ott, IROS 2013]
Capture Point Control

\[ \xi = \omega (\xi - p) \]

[Englsberger, Ott, et. al., IROS-2011, ICRA-2012, at-2012]
Capture Point Control

$\mathbf{p}_{\text{CP}}$ control

[Englsberger, Ott, et al., IROS 2011]

ZMP Control

Robot Dynamics

Trajectory Generator

$\boldsymbol{q}$

$\mathbf{\theta}$

Footprint

Collaboration with Nicolas Perrin

Dynamic Walking

based on the Divergent Component of Motion
# Extension to 3D walking

<table>
<thead>
<tr>
<th>2D</th>
<th>3D</th>
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<tbody>
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<td>Capture Point (CP)</td>
<td>„Divergent Component of Motion“ (DCM) [Takenaka]</td>
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</table>
| \[
\xi = x + b\dot{x} \]
| ZMP (steers CP) | Virtual Repellent Point (steers DCM) |

**COM dynamics:**  
\[ m\ddot{x} = F \]  
\[ mg + F_{ext} \]  

**DCM dynamics:**  
\[ \dot{\xi} = -\frac{1}{b}x + \frac{1}{b}\dot{\xi} + \frac{b}{m}F \]  

[Englsberger, Ott, IROS 2013]
Extension to 3D walking

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COM dynamics:  \[ m \ddot{x} = F \]
(not a template model)

\[ mg + F_{ext} \]

DCM dynamics:
\[ \xi = -\frac{1}{b} x - \frac{1}{b} \xi + \frac{b}{m} F \]

[Englsberger, Ott, IROS 2013]
Virtual Repellent Point (VRP)

Enhanced Centroidal Moment Pivot point (eCMP)

\[
F = mg - \frac{\Delta z_{vrp}}{b} (x - r_{vrp})
\]

\[
b = \sqrt{\frac{\Delta z_{vrp}}{g}}
\]

\[
r_{vrp}
\]

\[
F_g
\]

\[
F_{ext}
\]

\[
F_{ext} = \frac{mg}{\Delta z_{vrp}} (x - r_{ecmp})
\]

\[
n(x - \xi)
\]

\[
\xi = -\frac{1}{b} x + \frac{1}{b} \xi + \frac{b}{m} F
\]

\[
\dot{\xi} = \frac{1}{b} (\xi - r_{vrp})
\]

\[
\dot{x} = \frac{1}{b} (x - \xi)
\]
DCM Tracking Control

DCM dynamics

\[ \dot{\xi} = \frac{1}{b} (\xi - r_{vrp}) \]

Desired closed loop

\[ \dot{\xi} - \dot{\xi}_d = -k (\xi - \xi_d) \]

Tracking control:

\[ r_{vrp,c} = \xi + k b (\xi - \xi_d) - b \dot{\xi}_d \]

Required leg force:

\[ F_{leg,c} = \frac{mg}{\Delta z_{vrp}} (x - (r_{vrp,c} - [0 0 \Delta z_{vrp}]^T)) \]
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Thank you very much for your attention!