Balancing and walking control of a torque controlled humanoid robot

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Compliant Manipulation

Joint torque sensing & control for manipulation

Robustness: Passivity Based Control

Performance: Joint Torque Feedback (noncollocated)

\[
\begin{align*}
\tau_{\text{ext}} & \quad \tau \quad \theta \\
q & \quad \tau_m \\
\end{align*}
\]
Compliant Manipulation

Robustness: Passivity Based Control

Performance: Joint Torque Feedback (noncollocated)
Beyond Compliant Manipulation

Joint torque sensing & control for manipulation

DLR-Biped [Humanoids 2010]
Experimental biped walking machine [Humanoids 2010]

- 6 DOF / leg
- ~50 kg
- Drive technology of the DLR arm
- Newly designed lower leg
- Slim foot design: 19 x 9,5cm
- Sensors:
  - joint torque sensors
  - force/torque sensors in the feet
  - IMU in the trunk
- Developed within 10 month by student projects.
- Allow for position controlled walking (ZMP) and joint torque control!
Torque controlled humanoid Robot (TORO)

- Very recent development
  1) preliminary version: May 2012
  2) full version: December 2012 (estimated)

- Research interests:
  - Whole body motion/dynamics
  - Multi-contact interaction

- Weight: ~68kg / 75kg (complete)

- Modified hip kinematics:
  compact design for locating the total COM close to the hip joints
Properties for control:

- Underactuated
- Varying unilateral constraints
  (single support, double support, edge contact)
- Constraints on the state & control
\[ \begin{bmatrix} M & 0 \\ 0 & \hat{M}(q) \end{bmatrix} \begin{bmatrix} \ddot{c} \\ \ddot{\hat{q}} \end{bmatrix} + \begin{bmatrix} 0 \\ \hat{C}(\hat{q}, \dot{\hat{q}}) \end{bmatrix} + \begin{bmatrix} -Mg \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ u \end{bmatrix} - \sum_{i=r,l} \begin{bmatrix} I & 0 \\ J_i(\hat{q})^T & \end{bmatrix} F_i \]

Bipedal Robot Model

→ system structure with decoupled COM dynamics.

[Space Robotics], [Wieber 2005, Hyon et al. 2006]
Bipedal Robot Model

On a flat ground:

\[ \tau_p = \dot{L} - c \times Mg - p \times (M\ddot{c} - Mg) \]

Conservation of angular momentum:

\[ \dot{L} = c \times Mg + \sum \tau_i \]

Conservation of momentum:

\[ M\ddot{c} = Mg - \sum_{i=r,l} f_i \]
On a flat ground: the center of pressure = ZMP

\[ \tau_p = \dot{L} - c \times Mg - p \times (M\ddot{c} - Mg) \]

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

\[
\begin{bmatrix}
M_x(q) & M_{xq}(q) \\
M_{qx}(q) & M(q)
\end{bmatrix}
\begin{bmatrix}
\dddot{x}_b \\
\ddot{q}
\end{bmatrix}
+ \bar{C}(q, \dot{x}_b, \dot{q}) \begin{bmatrix}
\dot{x}_b \\
\dot{q}
\end{bmatrix}
+ \bar{g}(x_b, q)
= \begin{bmatrix}
0 \\
\tau
\end{bmatrix}
+ \begin{bmatrix}
J_{br}(q)^T \\
J_r(q)^T
\end{bmatrix} F_r
+ \begin{bmatrix}
J_{bl}(q)^T \\
0 \\
J_l(q)^T
\end{bmatrix} F_i
\]
Current Research Interests

Walking Control

Compliant Balancing
State of the art walking control for fully actuated robots

1. Pattern Generator for desired CoM and ZMP motion
2. ZMP based Stabilizer

- e.g. Preview Control [Kajita, 2003]
- e.g. [Choi et al., 2007]
- Model Predictive Control [Wieber, 2006]
Control Approach: Capture Point

Definition of the “Capture Point” (Pratt 2006, Hof 2008):

Point to step in order to bring the robot to stand.

\[ \tau_p = \dot{L} - c \times Mg - p \times (M\ddot{c} - Mg) \]

\[ L \approx c \times M\dot{c} \quad \tau_{px} = 0 \]
\[ z = \text{const} \quad \tau_{py} = 0 \]

\[ \ddot{x} = \omega^2 (x - p) \quad \omega = \sqrt{\frac{g}{z}} \]

Computation of the Capture Point:

\[ p = \text{const} \quad \rightarrow \quad x(t) = \cosh(\omega t)x(0) + \sinh(\omega t)\frac{\ddot{x}(0)}{\omega} + (1 - \cosh(\omega t))p \]

\[ x(t \to \infty) = p \]

\[ p^* = x_0 + \frac{\dot{x}_0}{\omega} \]
Coordinate transformation: \((x, \dot{x}) \rightarrow (x, \xi)\)

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

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

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

System structure: Cascaded system

open loop unstable

exp. stable
Capture Point Dynamics

Coordinate transformation: \((x, \dot{x}) \rightarrow (x, \xi)\)

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

\[
\ddot{x} = \omega^2 (x - p) \quad \Rightarrow \quad \dot{x} = -\omega x + \omega \xi
\]

\[
\ddot{\xi} = \omega \dot{\xi} - \omega p
\]

System structure: Cascaded system

[Englsberger, Ott, et. al., IROS 2011]
Shifting the Capture Point

- COM velocity always points towards CP
- ZMP "pushes away" the CP on a line
- COM follows CP
Shifting the Capture Point

Capture Point

ZMP

COM

$\xi_e$

$\dot{\xi}_e$

$x_e$

$\xi_0$

$p$

$\dot{\xi}_0$

$x_o$

$\dot{x}_o$

$x_o = \xi_0$

$x_e = p_e = \xi_e$

footprint

$\xi_{eos}$
Capture Point Control

Trajectory Generator $\xi_{d}$ → CP control $p$ → ZMP projection → ZMP Control → Robot Dynamics $q$

$\xi_e = p_e = \xi_d$

$\xi_{eos}$

$\xi_{0}$

$\xi_{p}$

$\xi_{target}$

Support Polygon

[Englsberger, Ott, et. al., IROS 2011]
Capture Point Control

Trajectory Generator $\xi_d$ \rightarrow CP control $p$ \rightarrow ZMP projection $\xi$ \rightarrow ZMP Control \rightarrow Robot Dynamics $q$

MPC [SYROCO 2012]

COM kinematics $x, \dot{x}$

[Englsberger, Ott, et. al., IROS 2011]
Capture Point Control

[Englsberger, Ott, et. al., IROS 2011]
1) Vision based walking
   ➔ stereo vision (Hirschmüller)
   ➔ visual SLAM (Chilian, Steidel)
   ➔ online footstep planning, collaboration with N. Perrin (IIT)
2) Optimized swingfoot trajectories: collaboration with H. Kaminaga (Univ. Tokyo)

- stride length: 70 cm
- speed: 0.5 m/s
- kinematically optimized swingfoot trajectory

- stride length: 70 cm
- speed: 0.5 m/s
- kinematically optimized torso motion
  (no angular momentum conversation! \(\rightarrow\) slippery)

[Kaminaga et al., Humanoids 2012, Sat. Dec. 1st, 14:00]
Extension to nonlinear models

**Simplified model**

\[
\dot{x} = \omega^2 (x - p)
\]

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

\[
\begin{bmatrix} \dot{x} \\ \dot{\xi} \end{bmatrix} = \begin{bmatrix} -\omega & \omega \\ 0 & \omega \end{bmatrix} \begin{bmatrix} x \\ \xi \end{bmatrix} + \begin{bmatrix} 0 \\ -\omega \end{bmatrix} p
\]

**General model**

\[
\dot{x} = \frac{g + \ddot{z}}{z} (x - p) + \frac{\dot{L}}{Mz}
\]

\[
\dot{\xi} = x + \frac{\dot{x}}{\omega(t)}
\]

\[
\omega(t) = \sqrt{\frac{g}{z(t)}}
\]

\[
\begin{bmatrix} \dot{x} \\ \dot{\xi} \end{bmatrix} = \begin{bmatrix} -\omega(t) & \omega(t) \\ \frac{\ddot{z}}{\omega(t)} - \frac{\dot{z}}{2z} & \omega(t) + \frac{\dot{z}}{2z} \end{bmatrix} \begin{bmatrix} x \\ \xi \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{g + \ddot{z}}{\omega(t)z} \end{bmatrix} p + \begin{bmatrix} 0 \\ \frac{\dot{L}}{M\omega(t)z} \end{bmatrix}
\]

[Englsberger & Ott, Humanoids 2012] Poster I-19

Feedback linearization → timevarying cascaded dynamics

\[
\begin{bmatrix} \dot{x} \\ \dot{\xi} \end{bmatrix} = \begin{bmatrix} -\omega(t) & \omega(t) \\ 0 & \omega(t) \end{bmatrix} \begin{bmatrix} x \\ \xi \end{bmatrix} + \begin{bmatrix} 0 \\ -\omega(t) \end{bmatrix} \hat{p}
\]
Current Research Interests

Walking Control

Compliant Balancing

Use of the Capture Point

… simplifies control

… simplifies motion planning
Motivation for compliant control

completely stiff

compliant control

fully compliant
Balancing & Posture Control

Compliant COM control [Hyon & Cheng, 2006]

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

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

Trunk orientation Control

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

IMU measurements
Balancing & Posture Control

Compliant COM control [Hyon & Cheng, 2006]

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

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

Trunk orientation Control

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

IMU measurements
Force distribution: Similar problems!
Net wrench acting on the object:

$$W_0 = G_1 F_1 + \cdots + G_\eta F_\eta = \begin{bmatrix} G_1 & \cdots & G_\eta \end{bmatrix} \begin{bmatrix} F_1 \\ \vdots \\ F_\eta \end{bmatrix}$$

Grasp Map

$$G_i = Ad_{PiO}^T$$

Well studied problem in grasping: Find contact wrenches $F_C \in FC^\eta$ such that a desired net wrench on the object is achieved.
Force distribution

Relation between balancing wrench & contact forces

\[ W_d = \begin{bmatrix} G_1 & \cdots & G_\eta \end{bmatrix} \begin{pmatrix} f_1 \\ \vdots \\ f_\eta \end{pmatrix} \begin{bmatrix} G_F \\ G_T \end{bmatrix} f_C \]

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

Formulation as a constraint optimization problem

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

Multibody robot model:
COM as a base coordinate \(\rightarrow\) system structure with decoupled COM dynamics.

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

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

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

Passivity based compliance control
(well suited for balancing)
Torque based balancing

Object Force Generation → Force Distribution $f_c$ → Force Mapping → Torque Control → Robot Dynamics

IMU

$q$

for orientation control and COM computation
Uncertain Foot Contact

[Ott, Roa, Humanoids 2011, best paper award]
Experiments on a Perturbation Platform

- Leg perturbation setup
- Movable elastic platform
- Experimental evaluation of the robustness with respect to disturbances (frequency & amplitude) at the foot
Out of phase disturbance

synchronous disturbance
2mm, up to 8 Hz
Current Research Interests

Walking Control

Use of the Capture Point

… simplifies control

… simplifies motion planning

Compliant Balancing

Joint torque sensing

… enables compliant control independently from precise foot-ground contact information.
Summary

- Compliance control for elastic robots based on joint torque sensing
- Walking control based on the Capture Point
- Extension of torque based compliance control to lower body balancing

Outlook

- Combination of torque based balancing and CP based walking
  - realize robust walking on uneven terrain
- Multi-contact interaction using articulated upper body
Thank you very much for your attention!

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