Deutsches Zentrum für Luft- und Raumfahrt
German Aerospace Center

Balancing and walking control of a torque controlled humanoid robot

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Research Group on „Dynamic Control of Legged Humanoid Robots“

DLR - Institute for Robotics and Mechatronics

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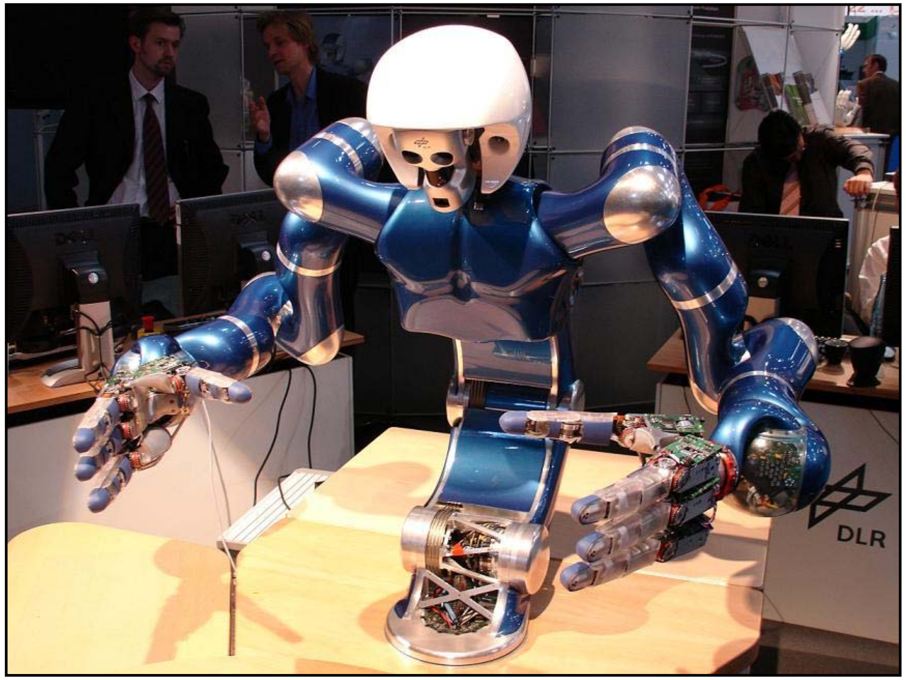
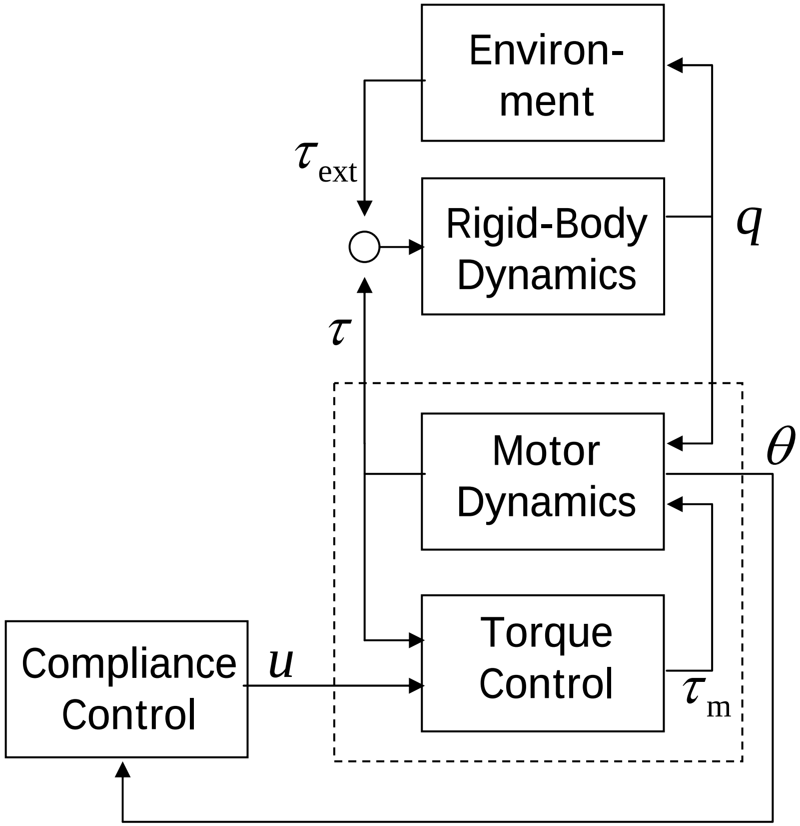
Compliant Manipulation

Joint torque sensing & control for manipulation





Robustness:
Passivity Based Control

\+

Performance:
Joint Torque Feedback
(noncollocated)

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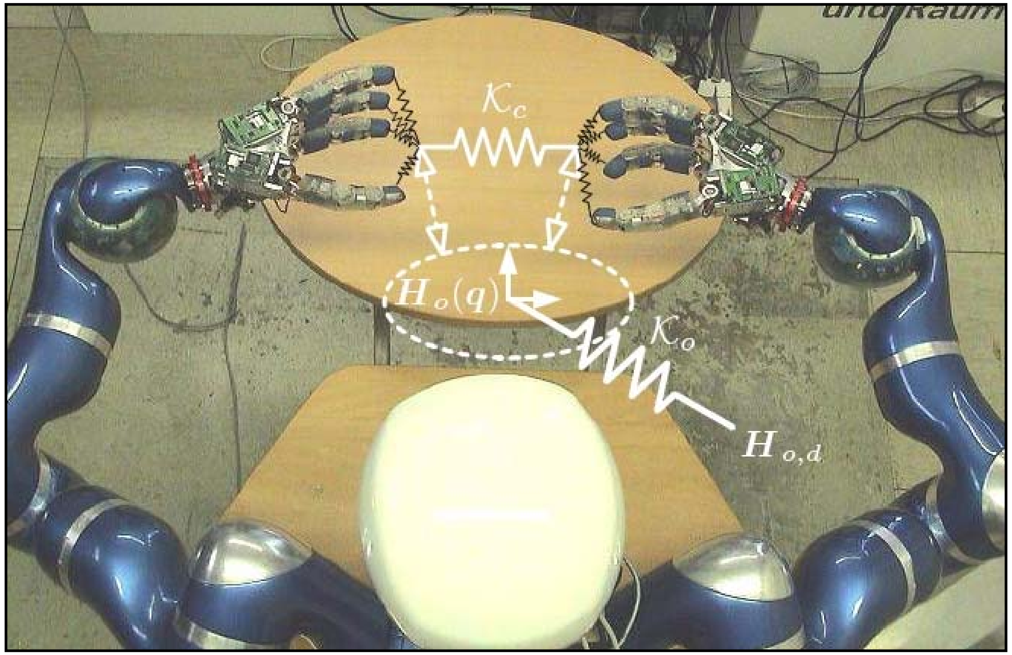
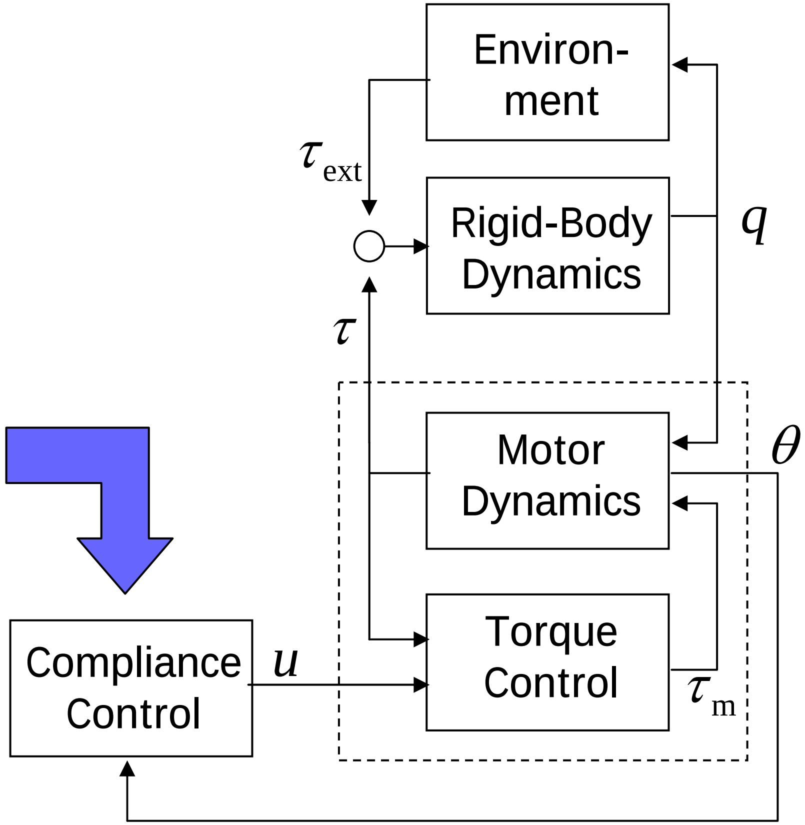
Compliant Manipulation

DLR





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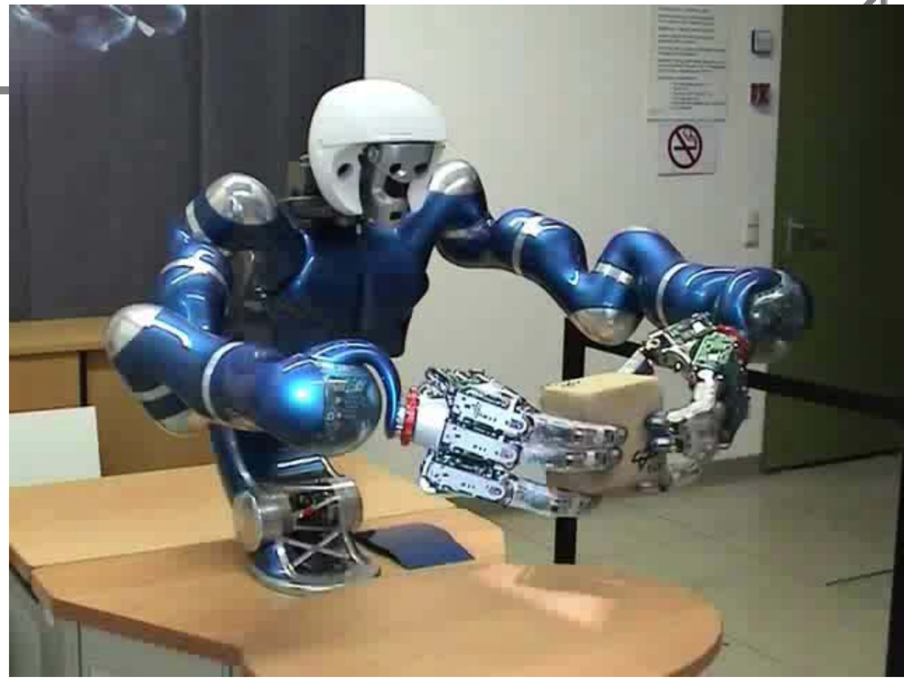
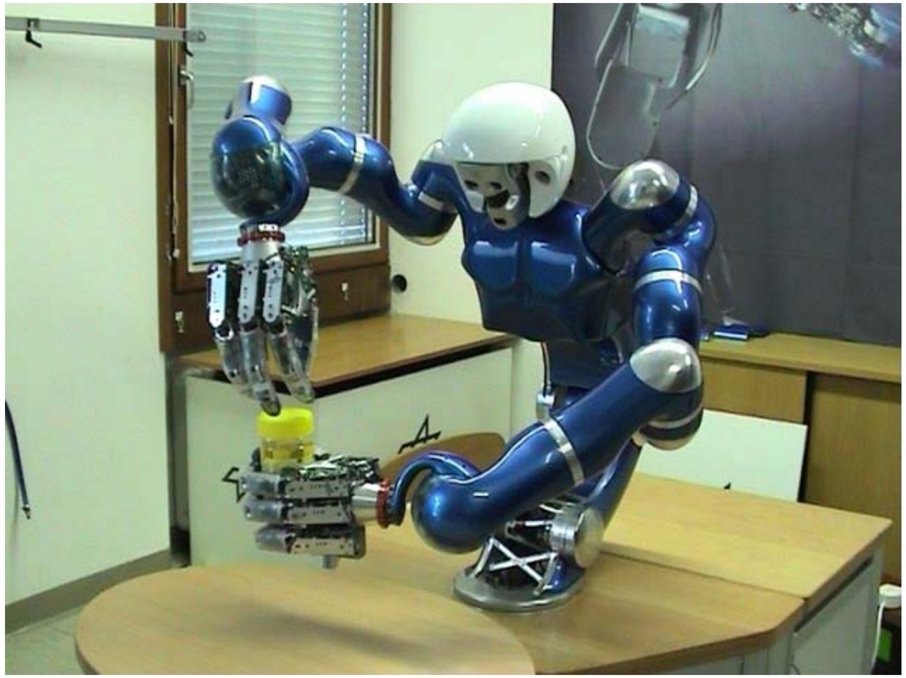
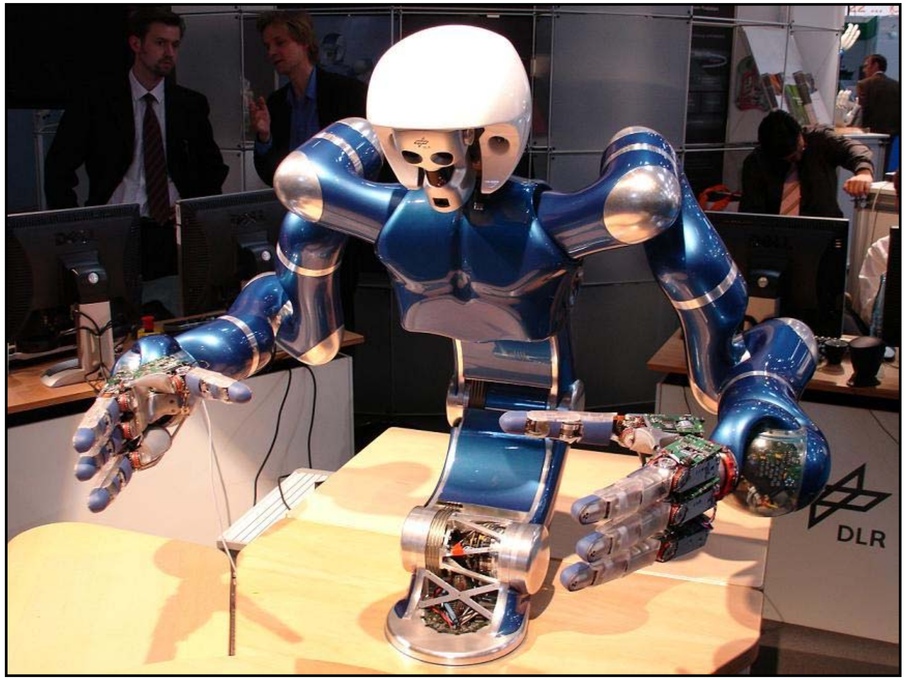


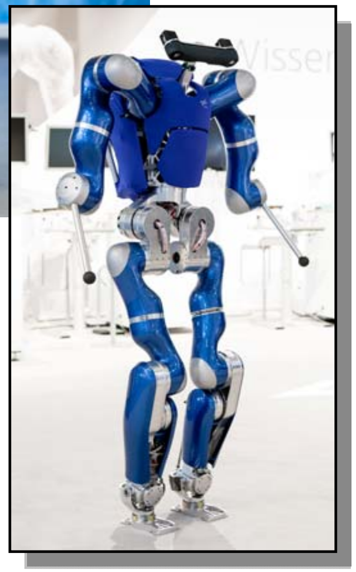


Beyond Compliant Manipulation

Joint torque sensing & control for manipulation



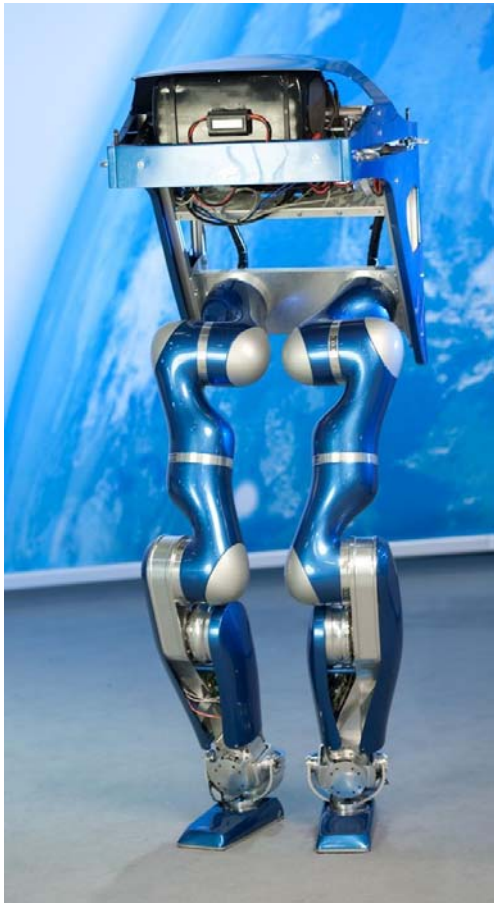
DLR-Biped [Humanoids 2010]



DLR-Biped

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!

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Torque controlled humanoid Robot (TORO)

DLR

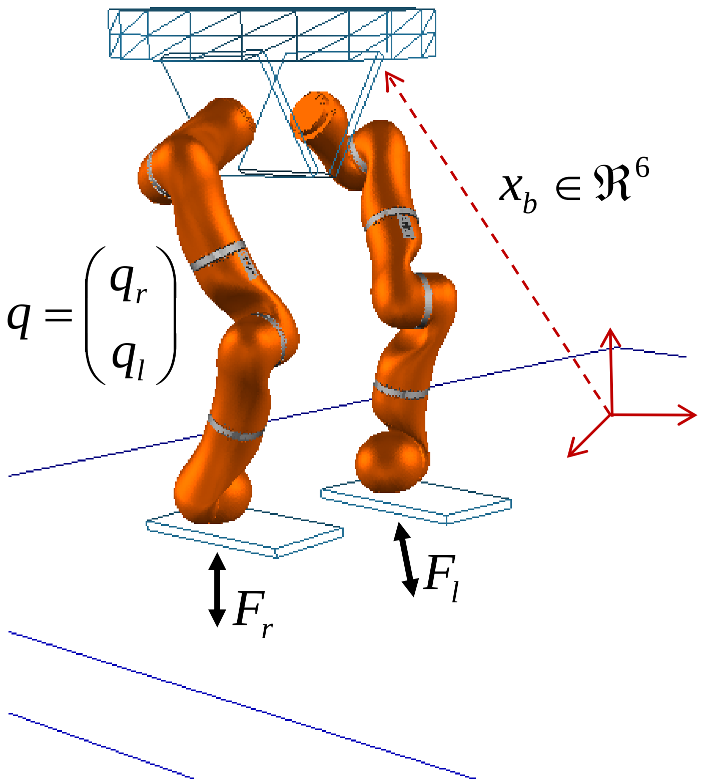
- Very recent development
  1) preliminary version: May 2012
  2) full version: December 2012 (estimated)

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

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

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

Bipedal Robot Model

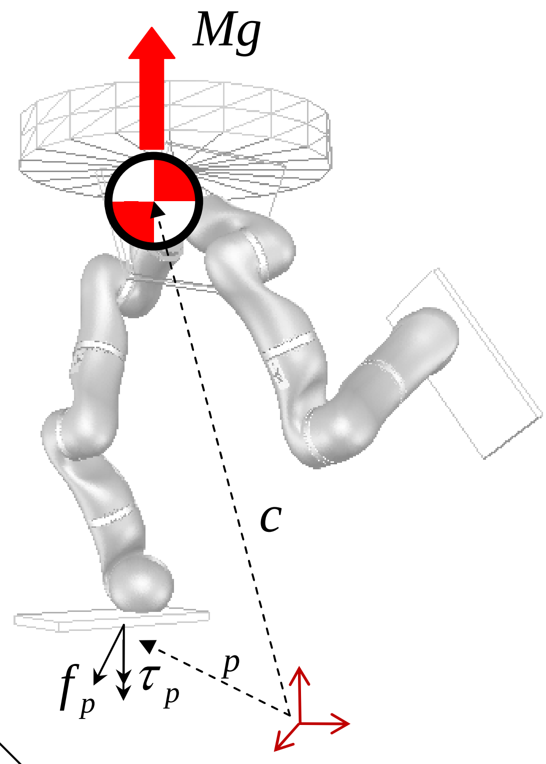


Properties for control:

- Underactuated
- Varying unilateral constraints (single support, double support, edge contact)
- Constraints on the state & control

$$\begin{bmatrix} M_x(q) & M_{xq}(q) \\ M_{qx}(q) & M(q) \end{bmatrix}\begin{pmatrix} \ddot{x}_b \\ \ddot{q} \end{pmatrix} + \overline{C}(q, \dot{x}_b, \dot{q})\begin{pmatrix} \dot{x}_b \\ \dot{q} \end{pmatrix} + \overline{g}(x_b, q) = \begin{pmatrix} 0 \\ \tau \end{pmatrix} + \begin{bmatrix} J_{br}(q)^T \\ J_r(q)^T \\ 0 \end{bmatrix} F_r + \begin{bmatrix} J_{bl}(q)^T \\ 0 \\ J_l(q)^T \end{bmatrix} F_l$$

Bipedal Robot Model



→ system structure with decoupled COM dynamics.
[Space Robotics], [Wieber 2005, Hyon et al. 2006]

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

$$\ddot{\hat{q}} \rightarrow \begin{pmatrix}\varepsilon\\ q\end{pmatrix} \qquad u \rightarrow \begin{pmatrix}\tau_p\\ \tau\end{pmatrix}$$

(c,ε)

x_b

$$\begin{bmatrix} M_x(q) & M_{xq}(q) \\ M_{qx}(q) & M(q)\end{bmatrix}\begin{pmatrix}\ddot{x}_b\\ \ddot{q}\end{pmatrix} + \overline{C}(q,\dot{x}_b,\dot{q})\begin{pmatrix}\dot{x}_b\\ \dot{q}\end{pmatrix} + \overline{g}(x_b,q) = \begin{pmatrix}0\\ \tau\end{pmatrix} + \begin{bmatrix}J_{br}(q)^T\\ J_r(q)^T\\ 0\end{bmatrix}F_r + \begin{bmatrix}J_{bl}(q)^T\\ 0\\ J_l(q)^T\end{bmatrix}F_l$$

Bipedal Robot Model

On a flat ground:

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

Conservation of angular momentum:

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

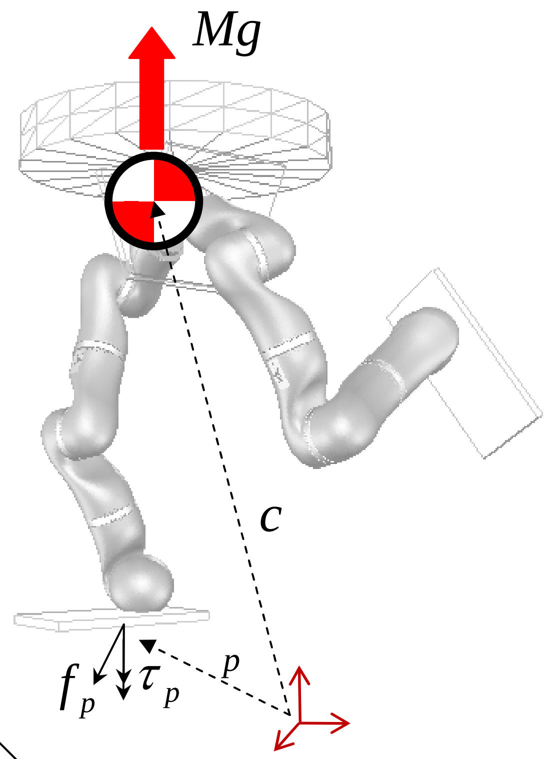
Conservation of momentum:

$$M\ddot{c} = Mg - \sum_{i=r,l} f_i$$

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

$$\begin{pmatrix} \varepsilon \\ q \end{pmatrix} \qquad (c, \varepsilon) \Uparrow x_b \qquad \begin{pmatrix} \tau_p \\ \tau \end{pmatrix}$$

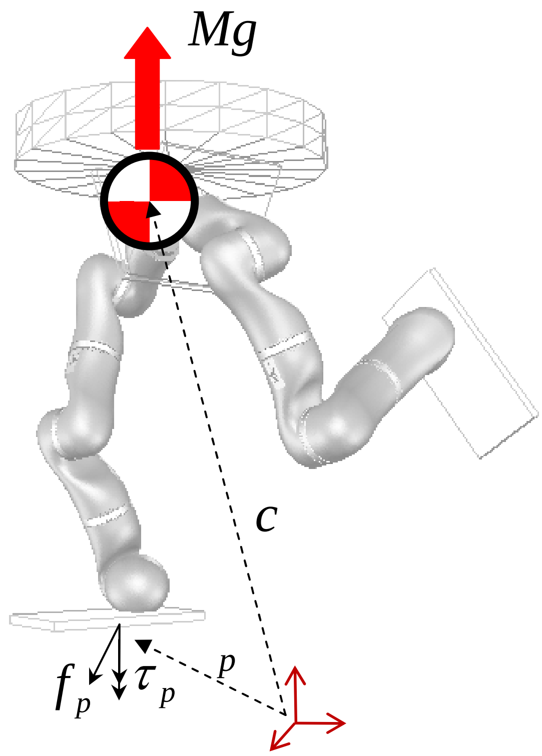
$$\begin{bmatrix} M_x(q) & M_{xq}(q) \\ M_{qx}(q) & M(q) \end{bmatrix} \begin{pmatrix} \ddot{x}_b \\ \ddot{q} \end{pmatrix} + \overline{C}(q, \dot{x}_b, \dot{q}) \begin{pmatrix} \dot{x}_b \\ \dot{q} \end{pmatrix} + \overline{g}(x_b, q) = \begin{pmatrix} 0 \\ \tau \end{pmatrix} + \begin{bmatrix} J_{br}(q)^T \\ J_r(q)^T \\ 0 \end{bmatrix} F_r + \begin{bmatrix} J_{bl}(q)^T \\ 0 \\ J_l(q)^T \end{bmatrix} F_l$$



Bipedal Robot Model

On a flat ground: the center of pressure = ZMP

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



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

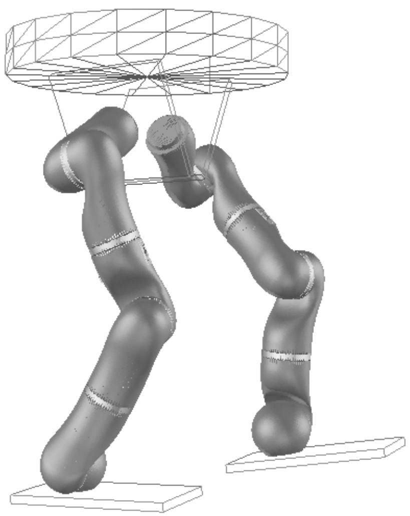
(c, ε)

x_b

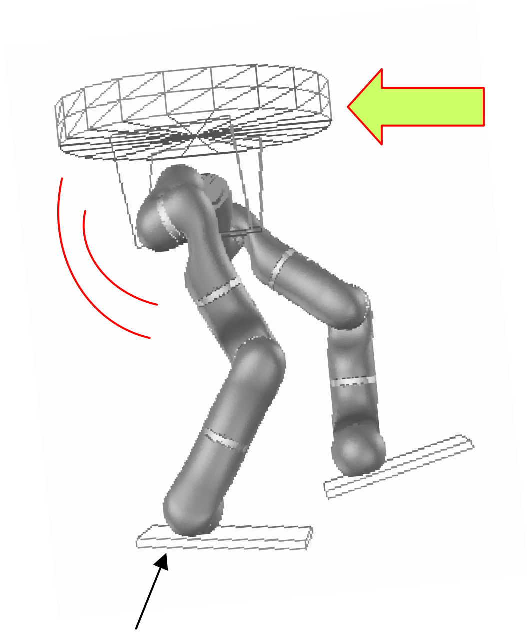
$$\begin{bmatrix} M_x(q) & M_{xq}(q) \\ M_{qx}(q) & M(q) \end{bmatrix} \begin{pmatrix} \ddot{x}_b \\ \ddot{q} \end{pmatrix} + \bar{C}(q, \dot{x}_b, \dot{q}) \begin{pmatrix} \dot{x}_b \\ \dot{q} \end{pmatrix} + \bar{g}(x_b, q) = \begin{pmatrix} 0 \\ \tau \end{pmatrix} + \overbrace{\begin{bmatrix} J_{br}(q)^T \\ J_r(q)^T \\ 0 \end{bmatrix} F_r + \begin{bmatrix} J_{bl}(q)^T \\ 0 \\ J_l(q)^T \end{bmatrix} F_l}$$

Current Research Interests

Walking Control



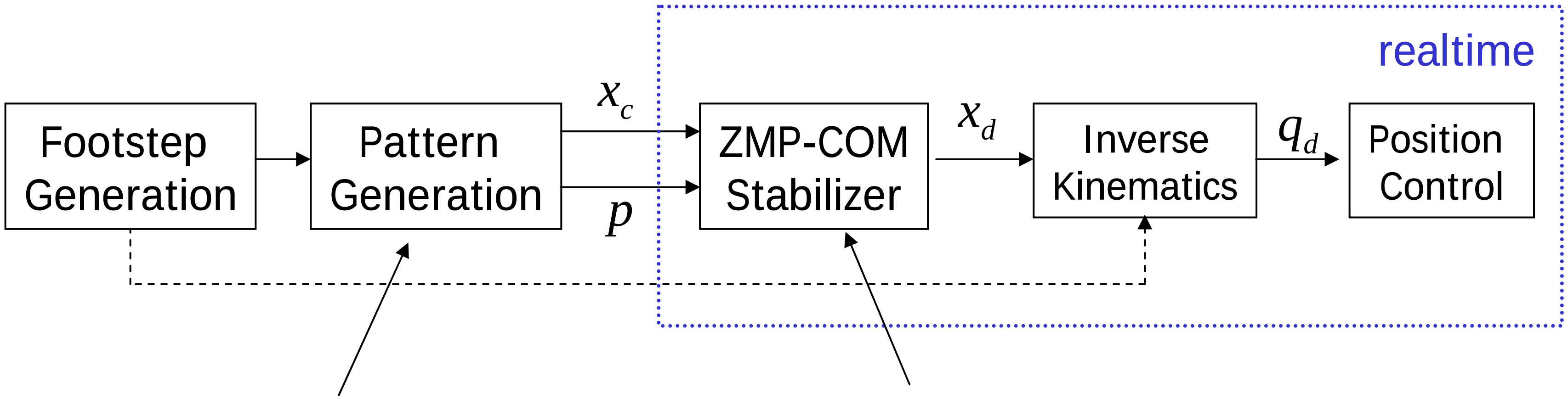
Compliant Balancing



State of the Art Walking Control

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]

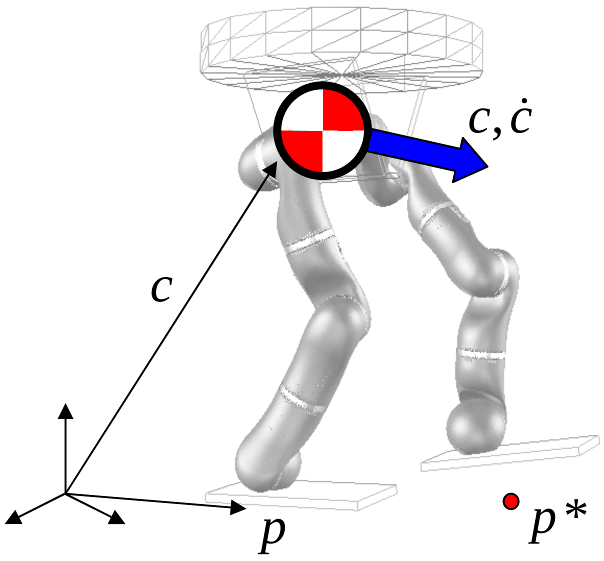
Model Predictive Control [Wieber, 2006]

e.g. [Choi et al., 2007]

Control Approach: Capture Point

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

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



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

$$L \approx c \times M\dot{c} \qquad \tau_{px} = 0$$

$$z = const \qquad \tau_{py} = 0$$

$$\ddot{x} = \omega^2 (x - p) \qquad \omega = \sqrt{\frac{g}{z}}$$

ZMP (p)

Computation of the Capture Point:

$$p = \text{const} \longrightarrow x(t) = \cosh(\omega t)\, x(0) + \sinh(\omega t)\frac{\dot{x}(0)}{\omega} + (1 - \cosh(\omega t))\, p$$

$$x(t \to \infty) = p$$

$$p* = x_0 + \frac{\dot{x}_0}{\omega}$$

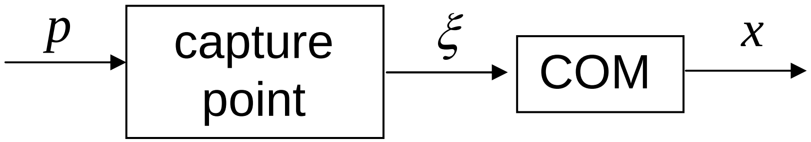
Capture Point Dynamics

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

$$\xi = x + \frac{\dot{x}}{\omega}$$

$$\ddot{x} = \omega^2 (x - p) \quad \Rightarrow \quad \begin{aligned} \dot{x} &= -\omega x + \omega \xi \\ \dot{\xi} &= \omega \xi - \omega p \end{aligned}$$

System structure: Cascaded system



open loop unstable

exp. stable

Capture Point Dynamics

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

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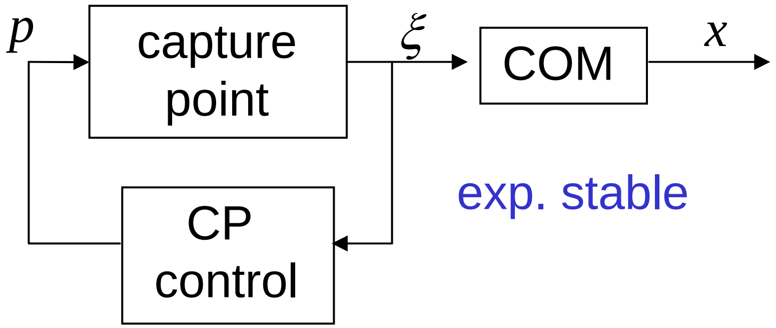
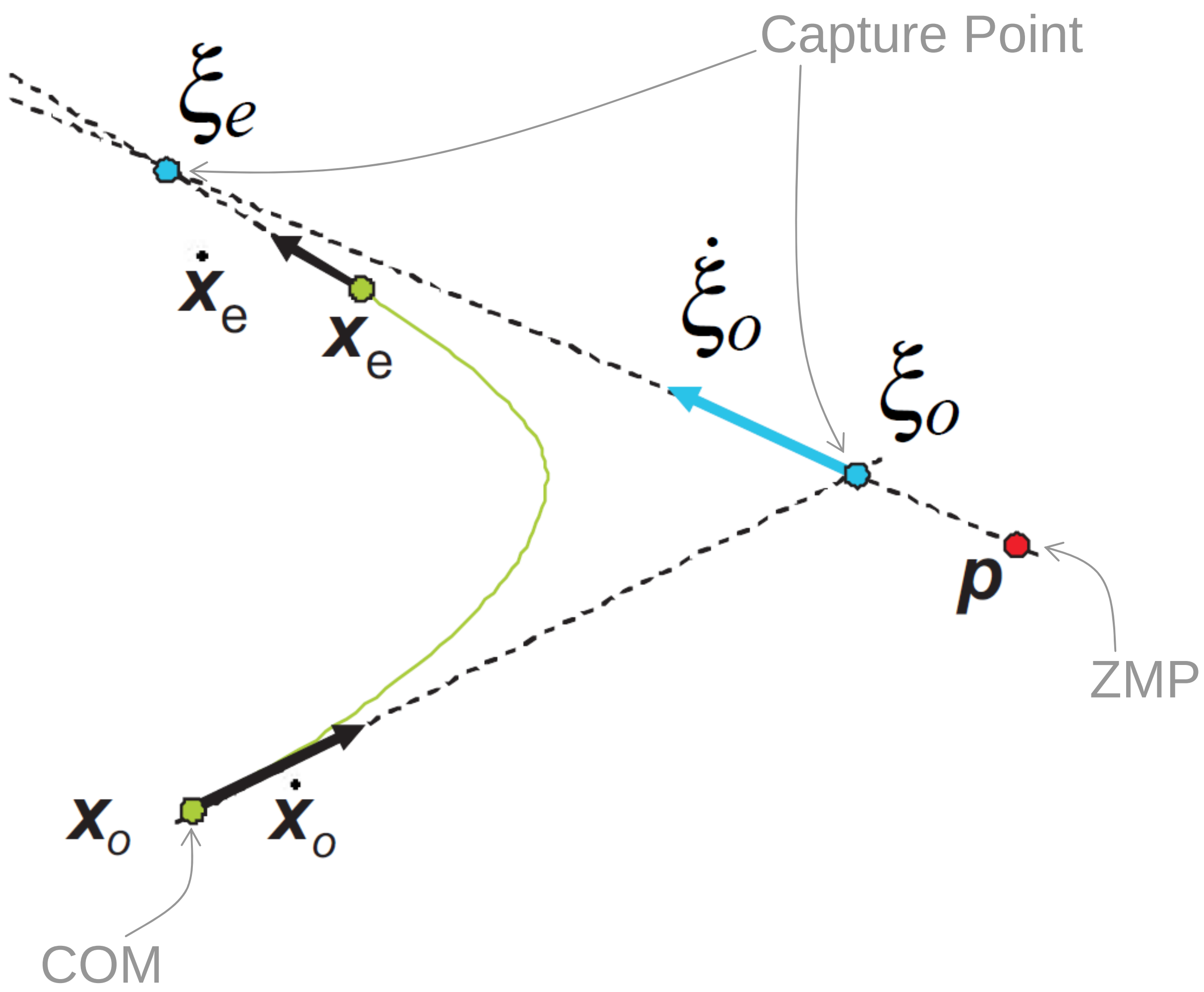


exp. stable

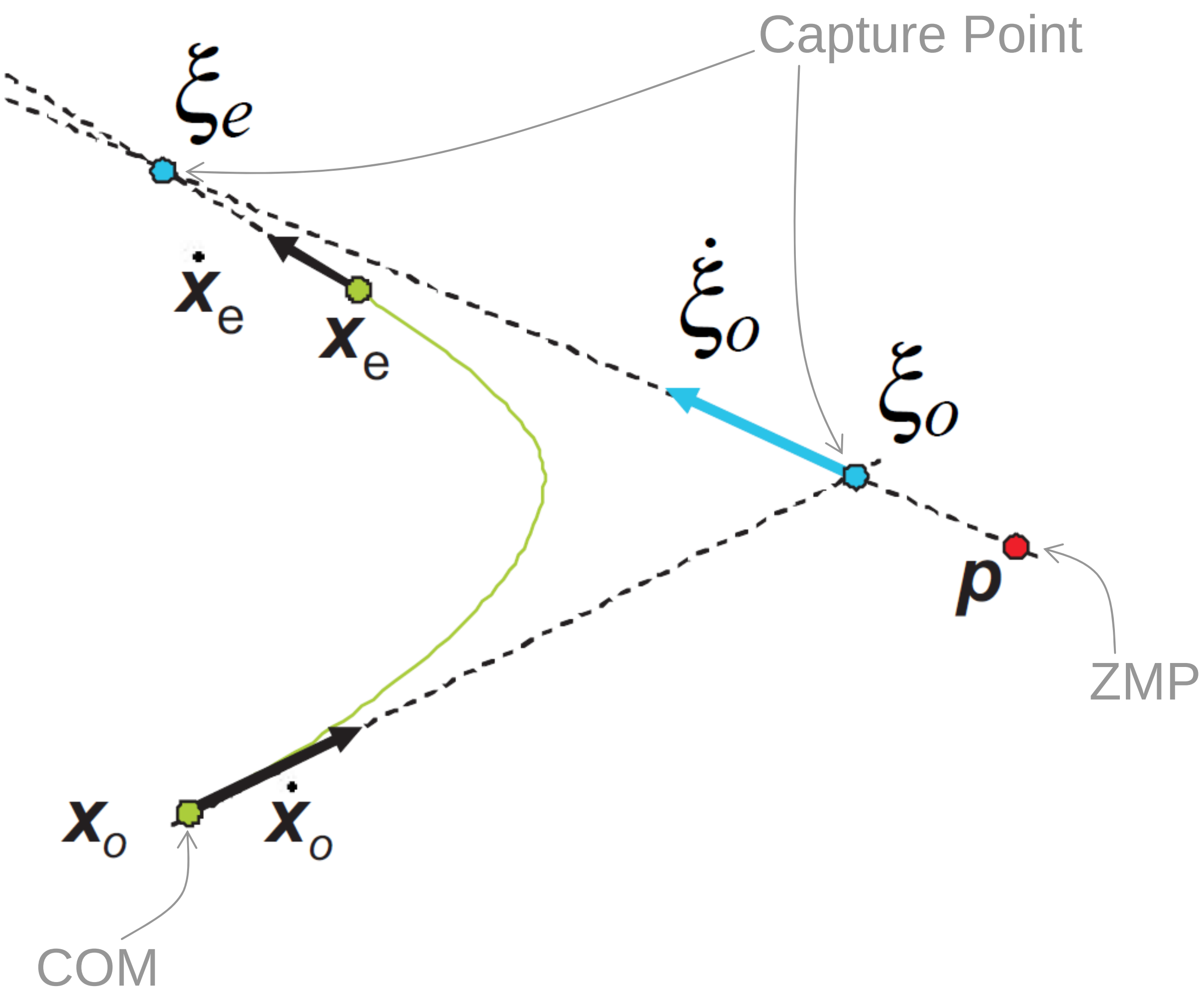
[Englsberger, Ott, et. al., IROS 2011]

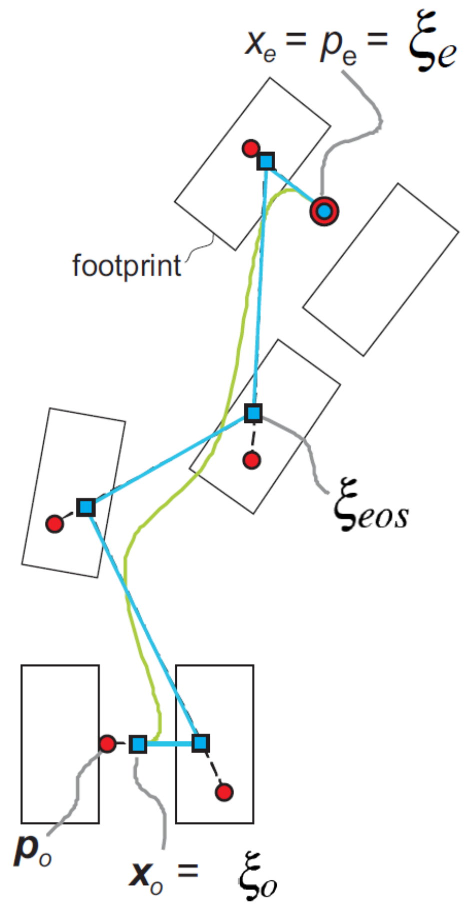
Shifting the Capture Point



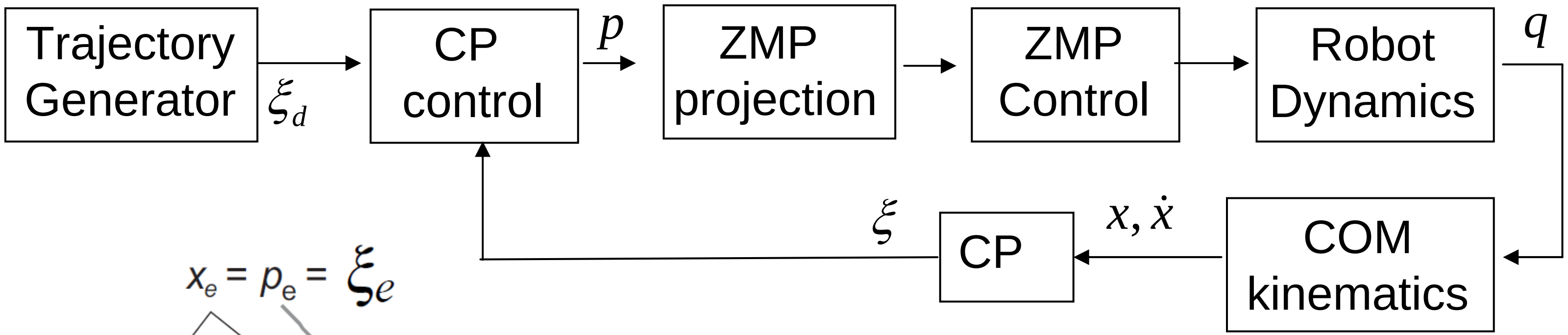
- COM velocity always points towards CP
- ZMP „pushes away“ the CP on a line
- COM follows CP

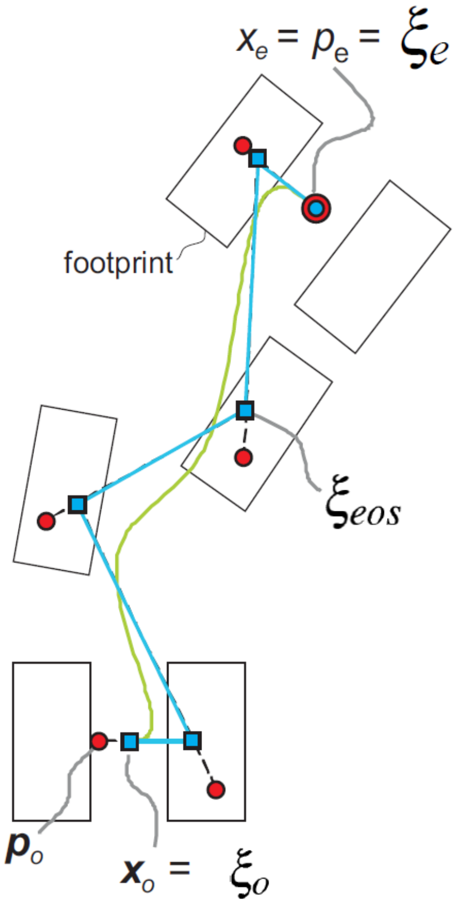
Shifting the Capture Point

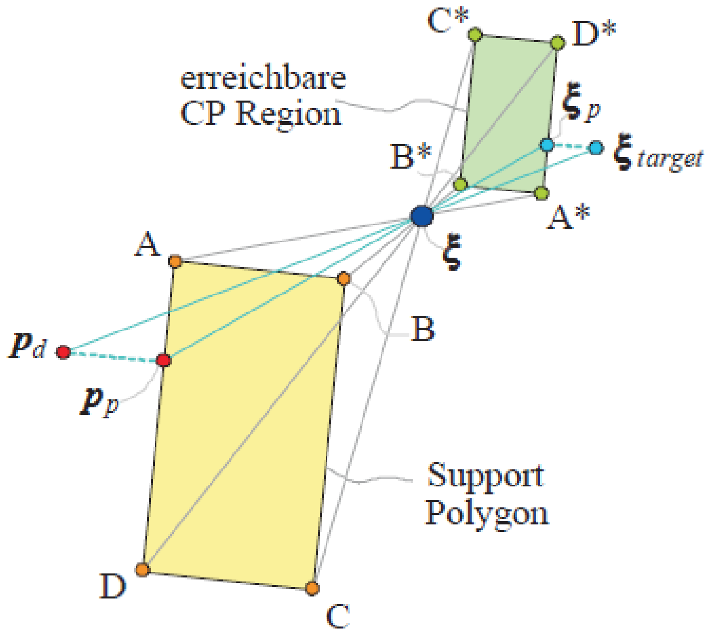




Capture Point Control

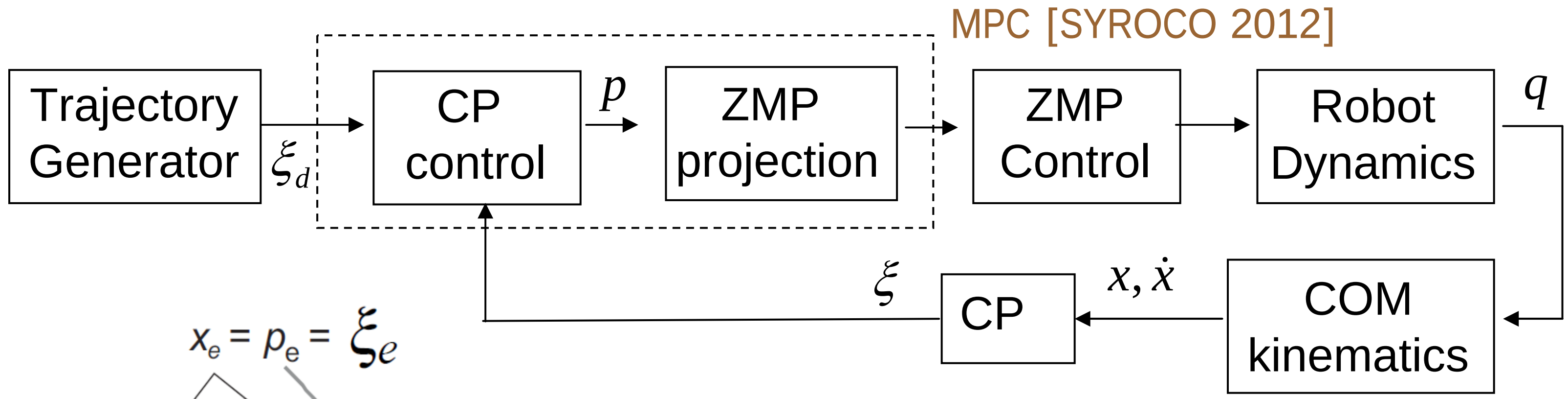


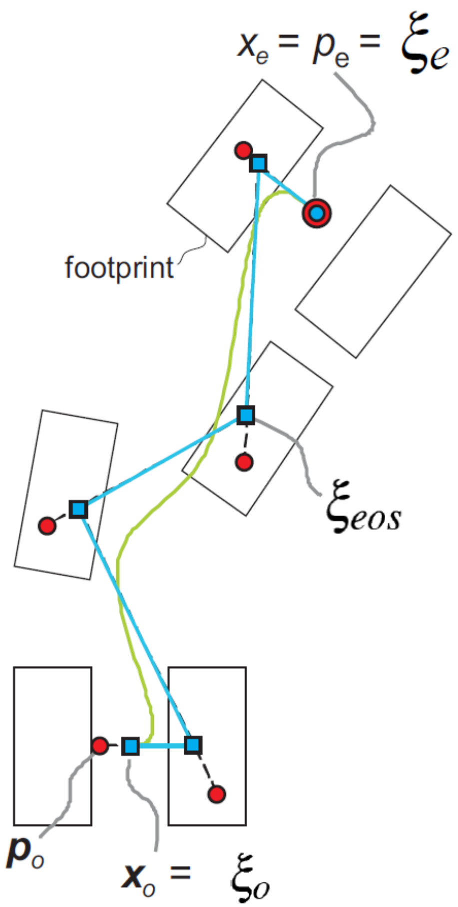


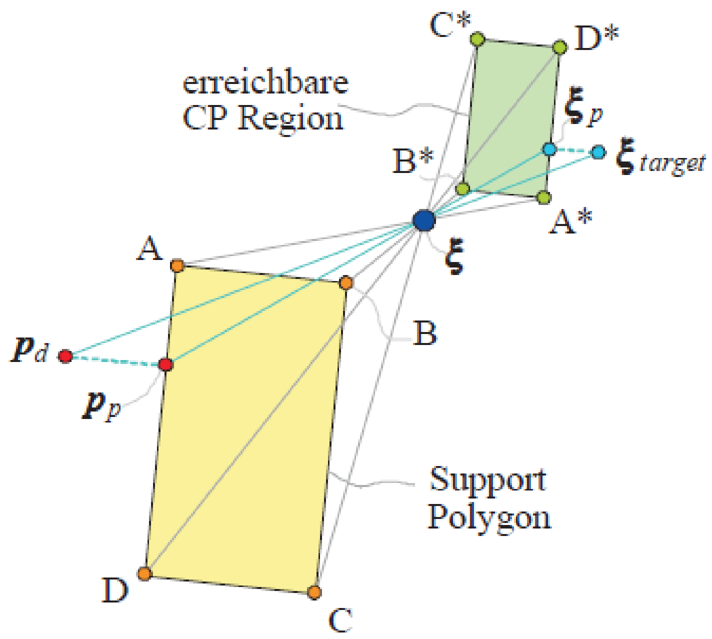


[Englsberger, Ott, et. al., IROS 2011]

Capture Point Control



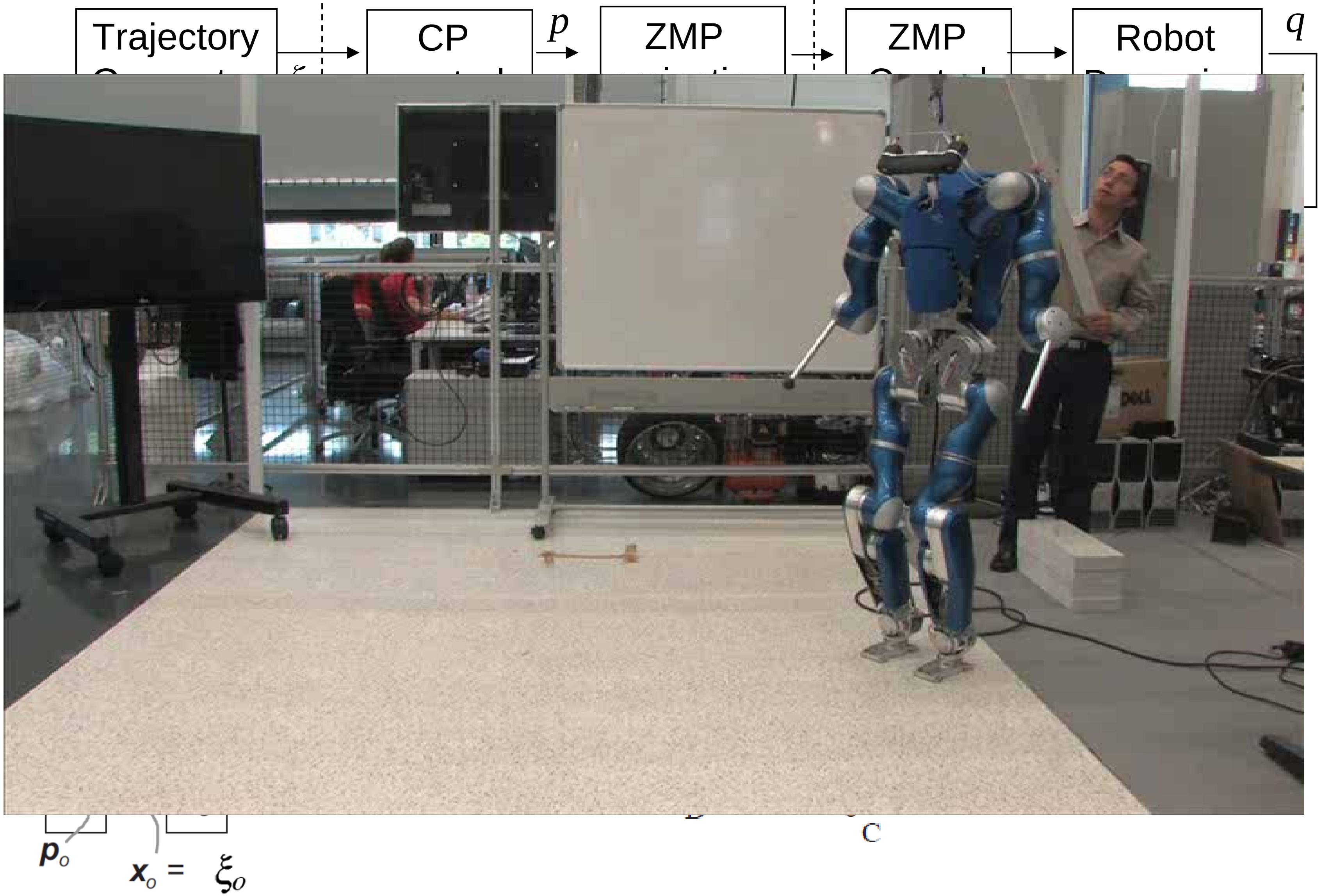




[Englsberger, Ott, et. al., IROS 2011]

Capture Point Control

MPC [SYROCO 2012]

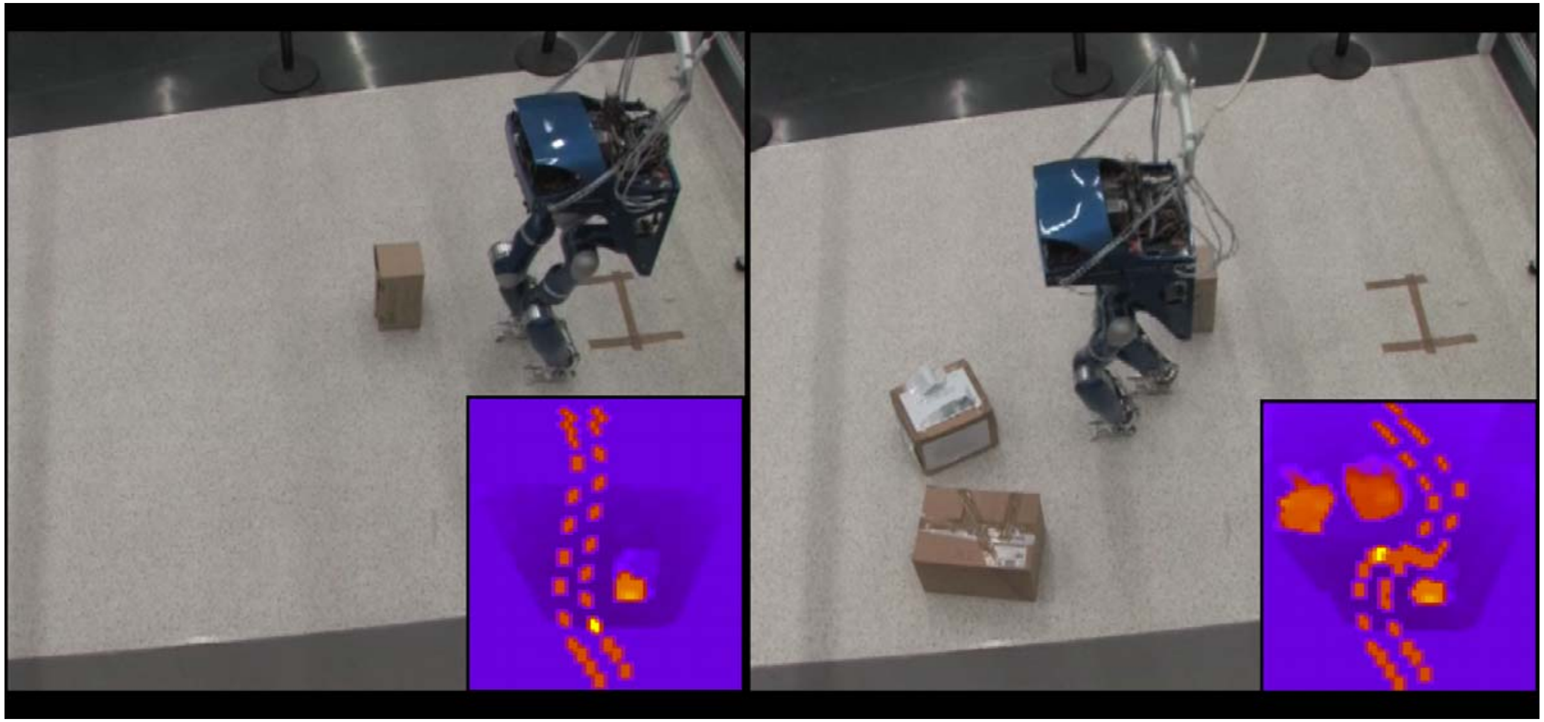


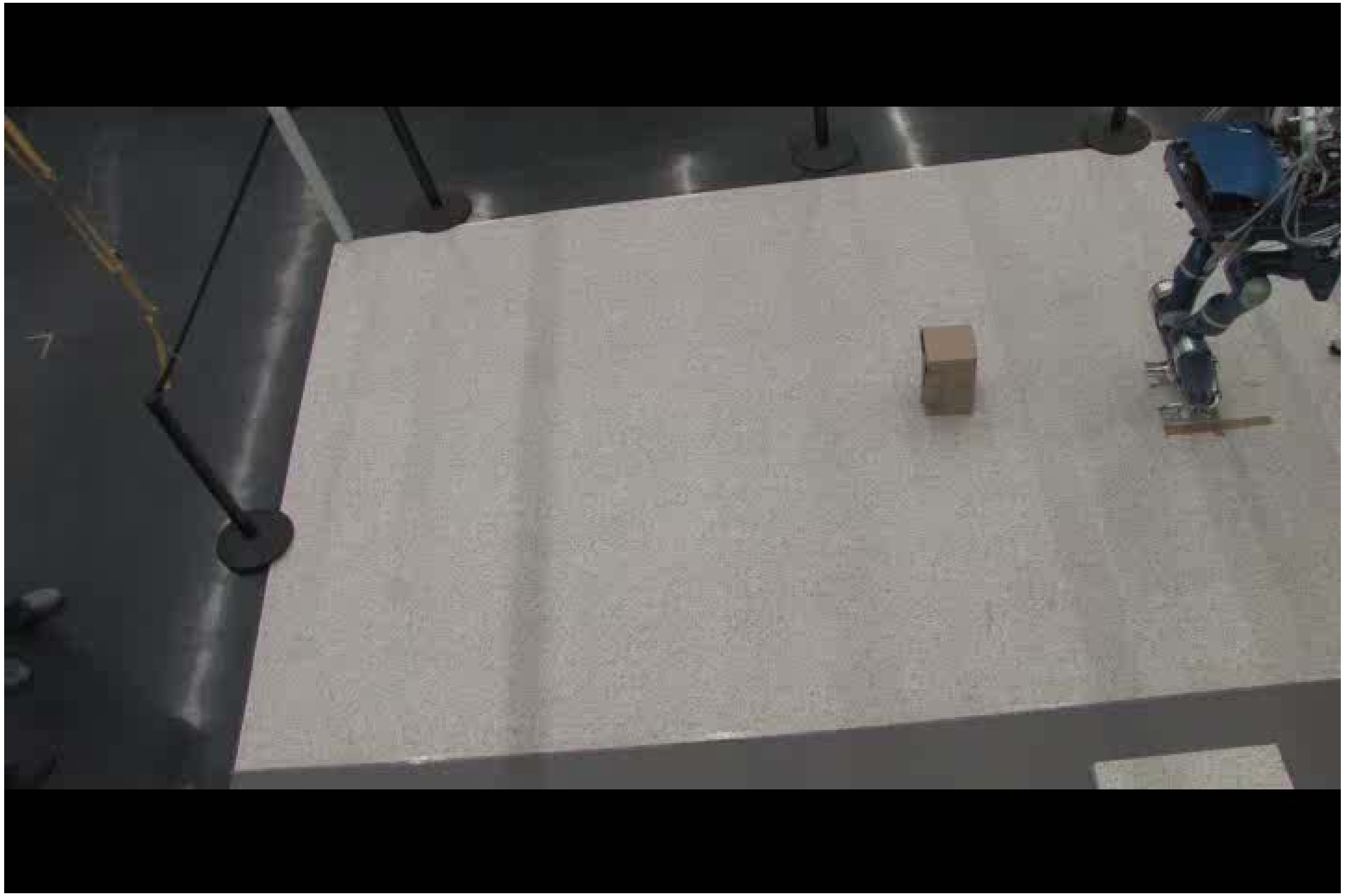
[Englsberger, Ott, et. al., IROS 2011]

Applications

1) Vision based walking

- stereo vision (Hirschmüller)
- visual SLAM (Chilian, Steidel)
- online footstep planning, collaboration with N. Perrin (IIT)





Applications

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! → slippery)

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

Extension to nonlinear models

Simplified model

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

$$\xi = x + \frac{\dot{x}}{\omega}$$

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

General model

$$\ddot{x} = \frac{g + \ddot{z}}{z}(x - p) + \frac{\dot{L}}{Mz} \qquad z = z(t)$$

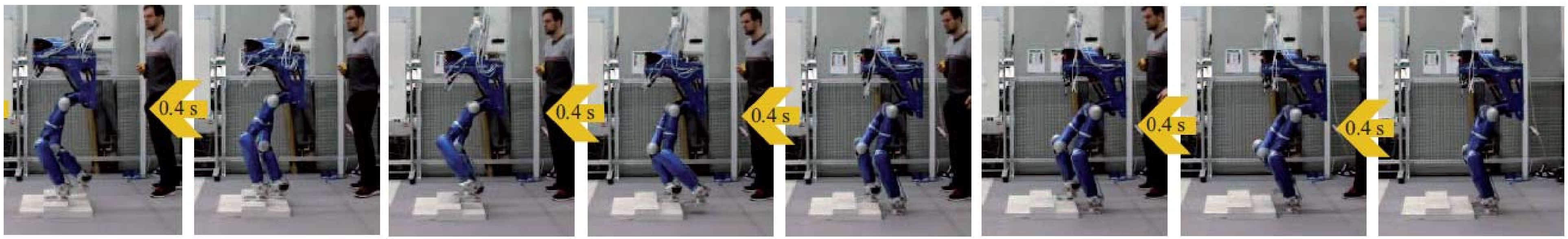
$$\xi = x + \frac{\dot{x}}{\omega(t)} \qquad \omega(t) = \sqrt{\frac{g}{z(t)}}$$

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

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

Feedback linearization
→ timevarying cascaded dynamics

$$\begin{pmatrix} \dot{x} \\ \dot{\xi} \end{pmatrix} = \begin{bmatrix} -\omega(t) & \omega(t) \\ 0 & \omega(t) \end{bmatrix} \begin{pmatrix} x \\ \xi \end{pmatrix} + \begin{bmatrix} 0 \\ -\omega(t) \end{bmatrix} \hat{p}$$



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Current Research Interests

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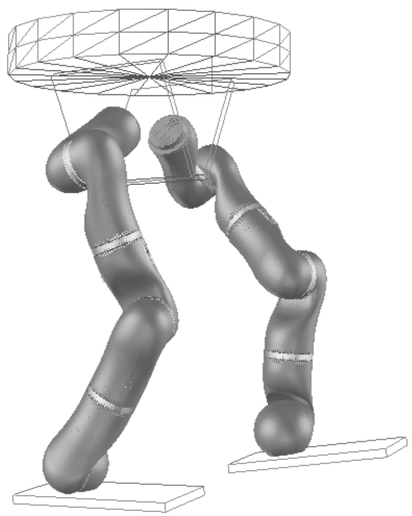
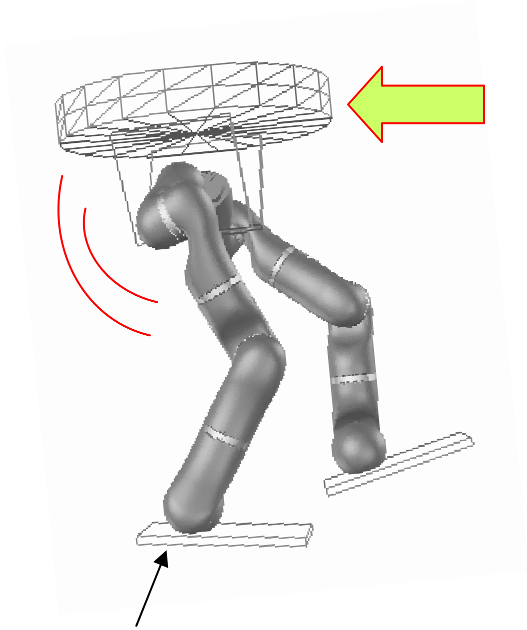


Use of the Capture Point

… simplifies control

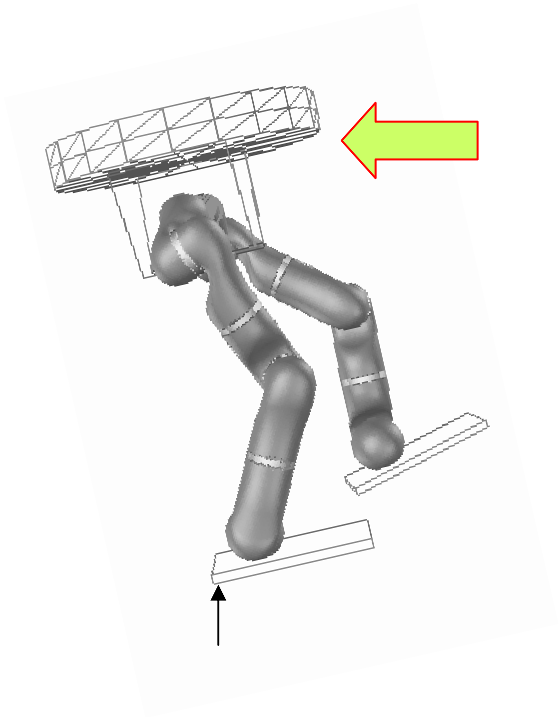
… simplifies motion planning

Compliant Balancing

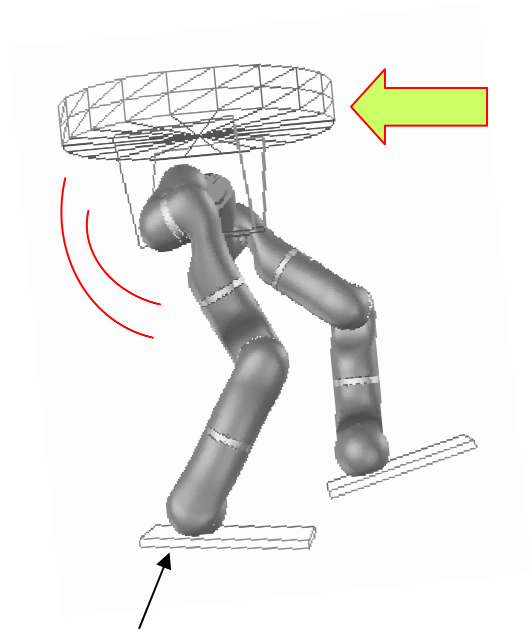


Motivation for compliant control

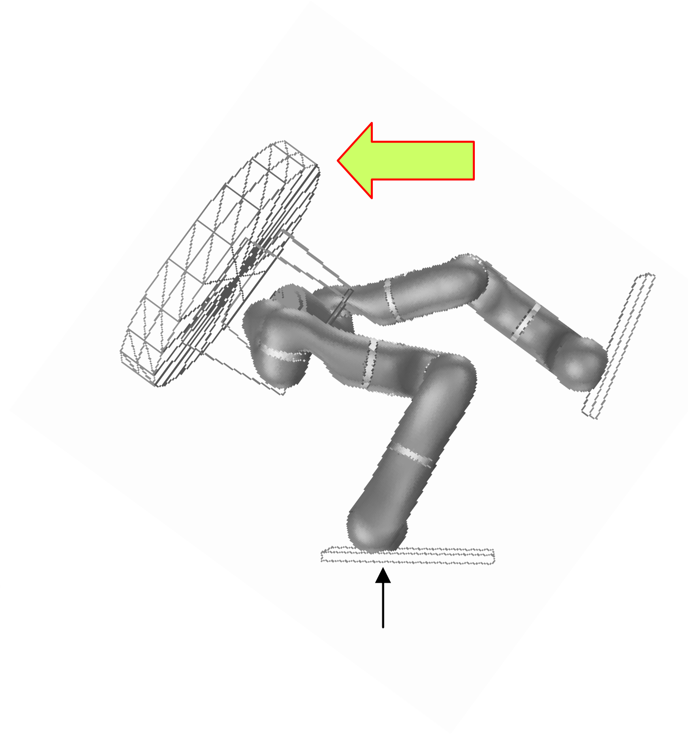
completely stiff



compliant control



fully compliant



Balancing & Posture Control

Compliant COM control [Hyon & Cheng, 2006]

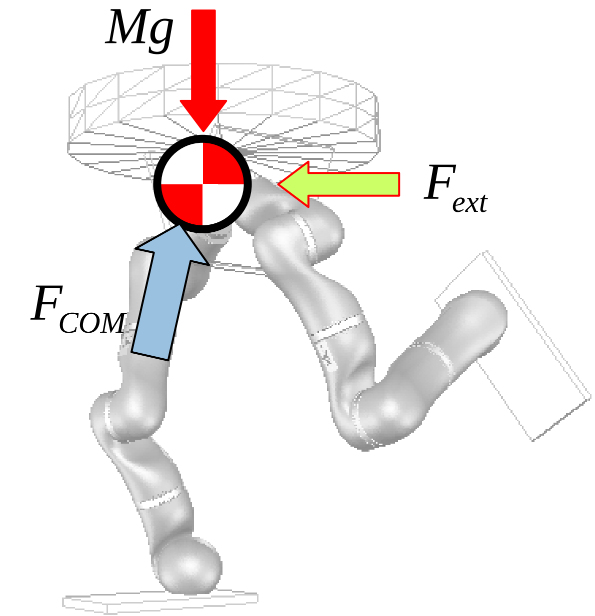
$$F_{COM} = Mg - K_P(c - c_d) - K_D(\dot{c} - \dot{c}_d)$$

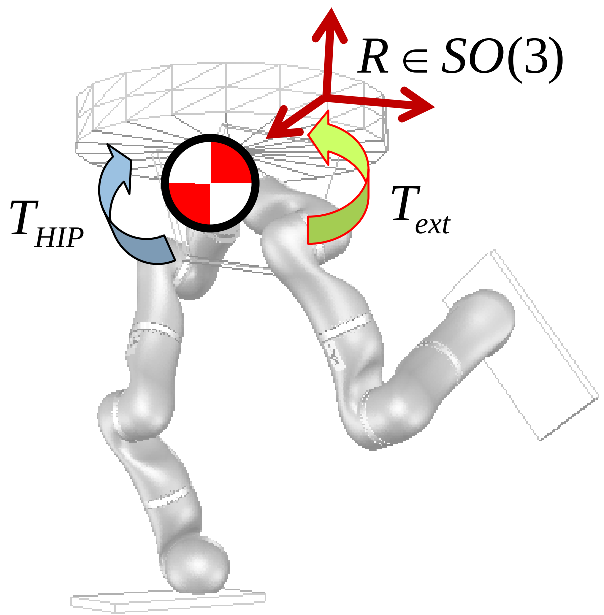
Desired wrench: $W_d = (F_{COM}, T_{HIP})$

Trunk orientation Control

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

IMU measurements





Balancing & Posture Control

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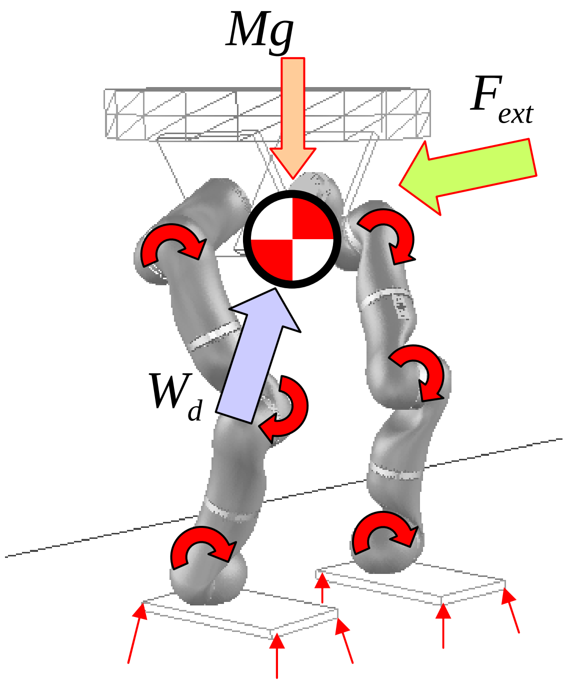
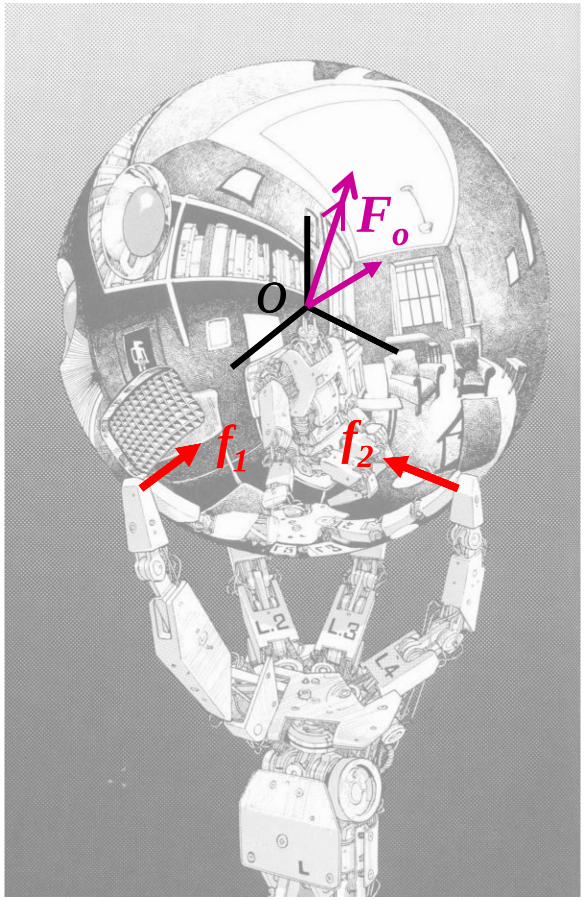
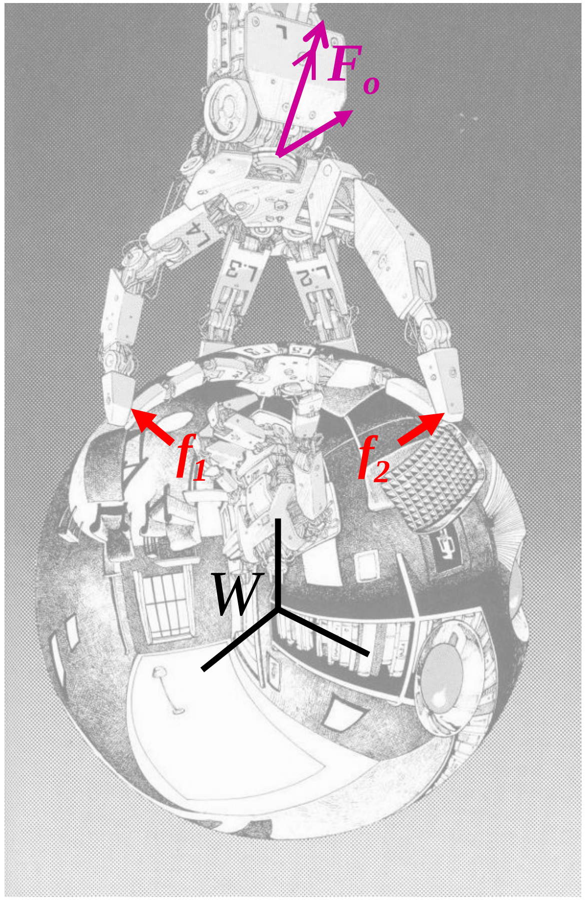


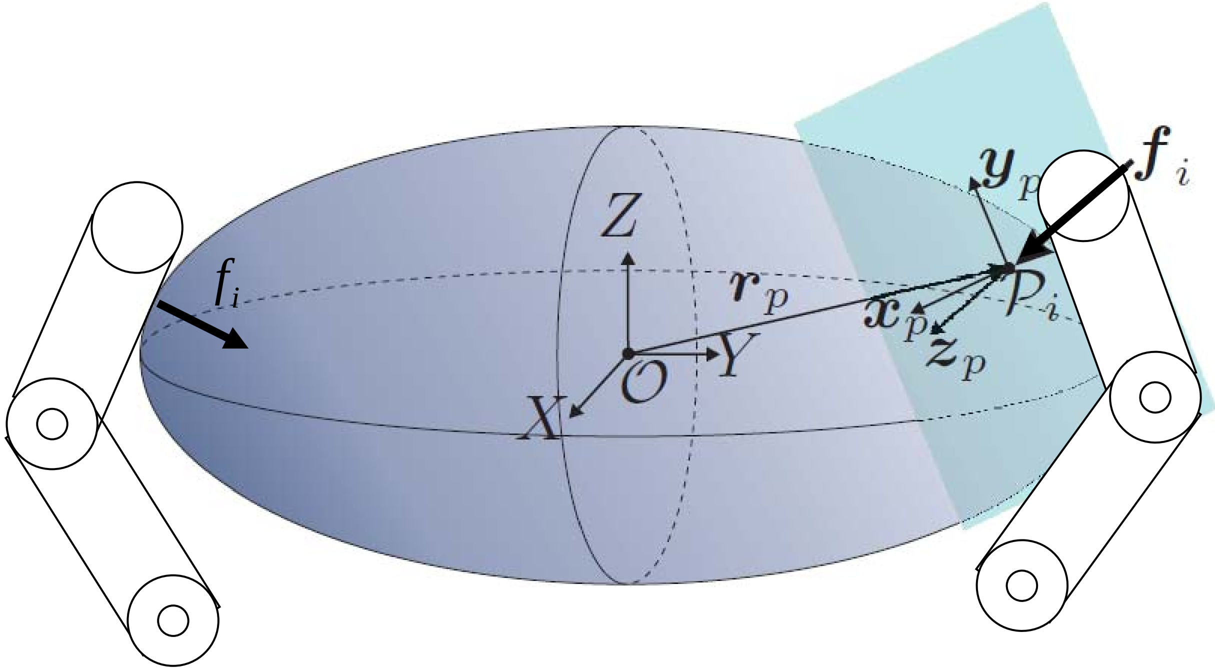
Grasping and Balancing

- Force distribution: Similar problems!





Force Distribution in Grasping



Net wrench acting on the object:

$$\underbrace{W_O}_{se(3)} = G_1 F_1 + \cdots + G_\eta F_\eta = \underbrace{\begin{bmatrix} G_1 \cdots G_\eta \end{bmatrix}}_{\text{Grasp Map}} \underbrace{\begin{pmatrix} F_1 \\ \vdots \\ F_\eta \end{pmatrix}}_{F_C \in se(3)^\eta}$$

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

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

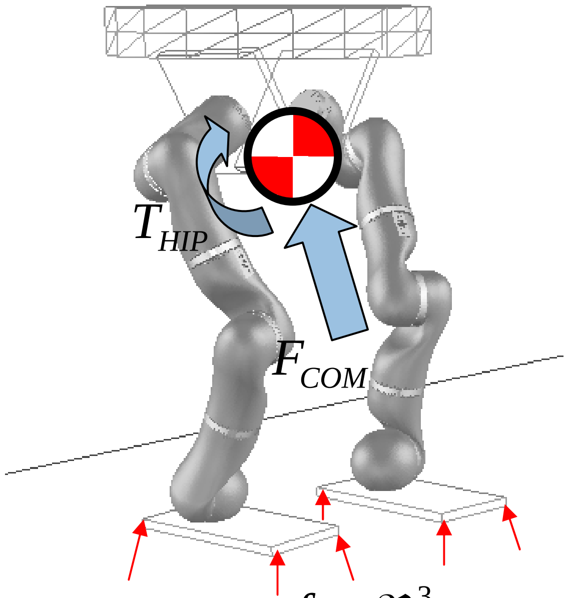
friction cone (FC^η)

Force distribution

Relation between balancing wrench & contact forces

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

$$W_d = \underbrace{\left[G_1 \cdots G_\eta \right]}_{\begin{bmatrix} G_F \\ G_T \end{bmatrix}} \underbrace{\begin{pmatrix} f_1 \\ \vdots \\ f_\eta \end{pmatrix}}_{f_C}$$



Constraints:

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

Formulation as a constraint optimization problem

$$f_C = \arg\min \left\{ \alpha_1 \left\| F_{COM} - G_F f_C \right\|^2 + \alpha_2 \left\| T_{HIP} - G_T f_C \right\|^2 + \alpha_3 \left\| f_C \right\|^2 \right\} \qquad \alpha_1 >> \alpha_2 >> \alpha_3$$

Contact force control via joint torques

Multibody robot model:

COM as a base coordinate → system structure with decoupled COM dynamics.

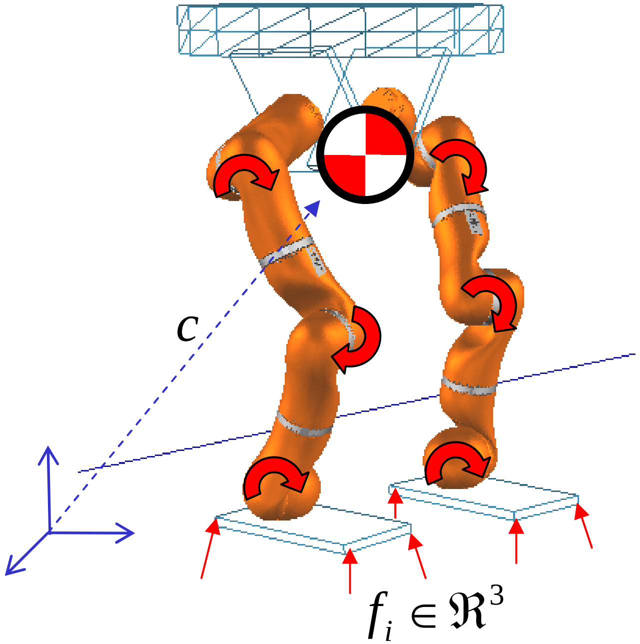
[Space Robotics], [Wieber 2005, Hyon et al. 2006]

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

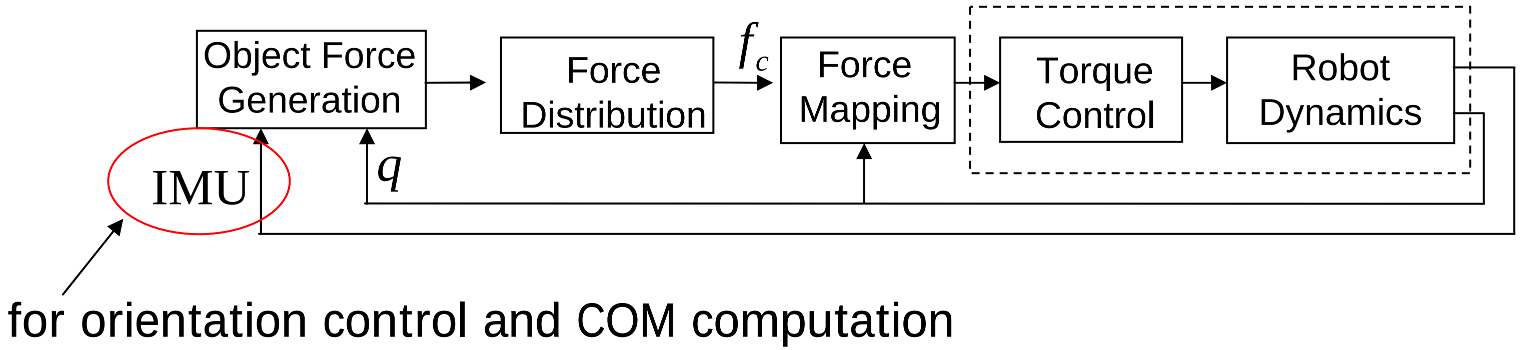
$$M\ddot{c} = Mg - \sum f_i$$

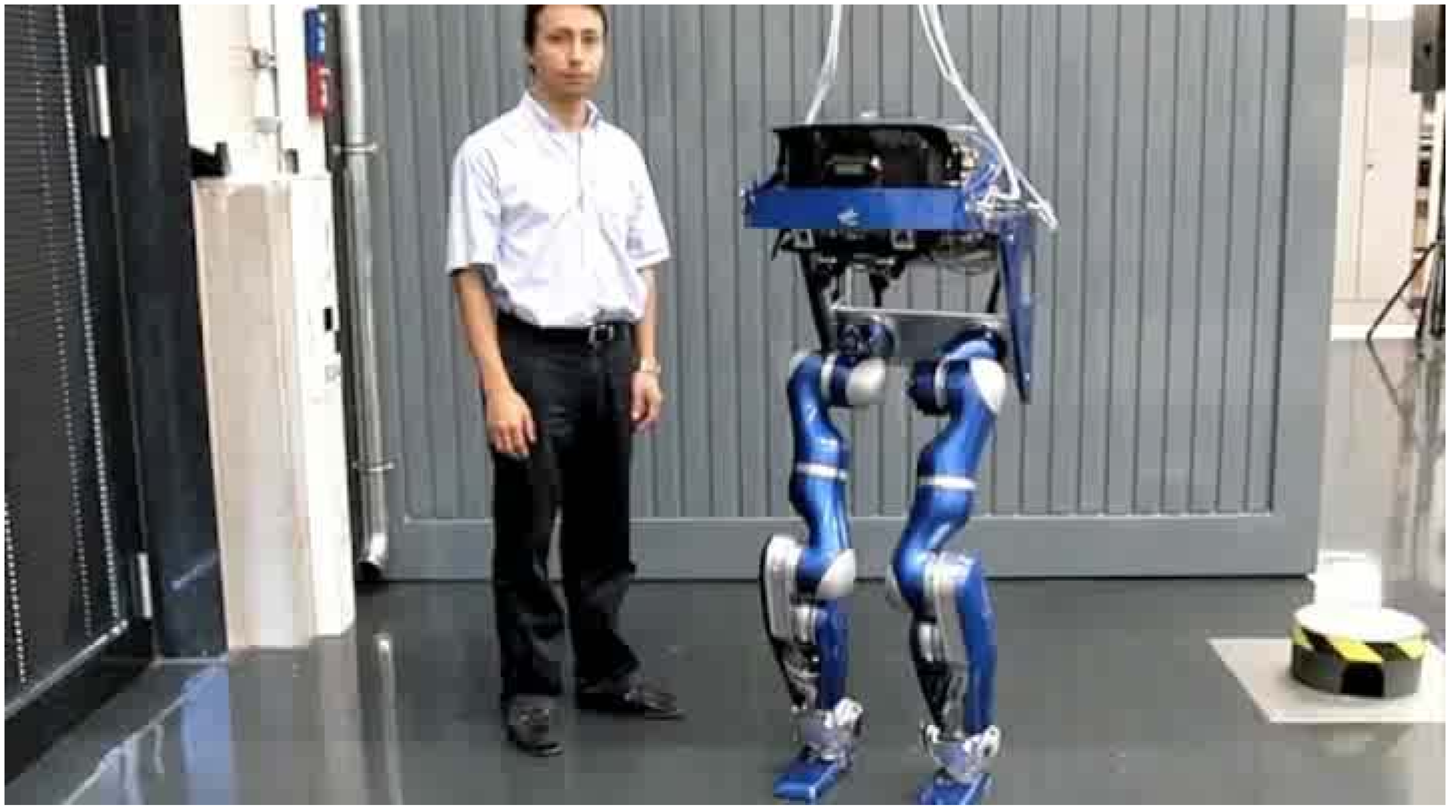
$$\tau = \sum J_i(\hat{q})^T f_i$$

Passivity based compliance control
(well suited for balancing)



Torque based balancing



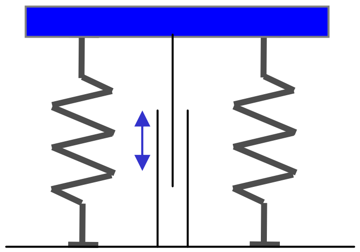


Uncertain Foot Contact

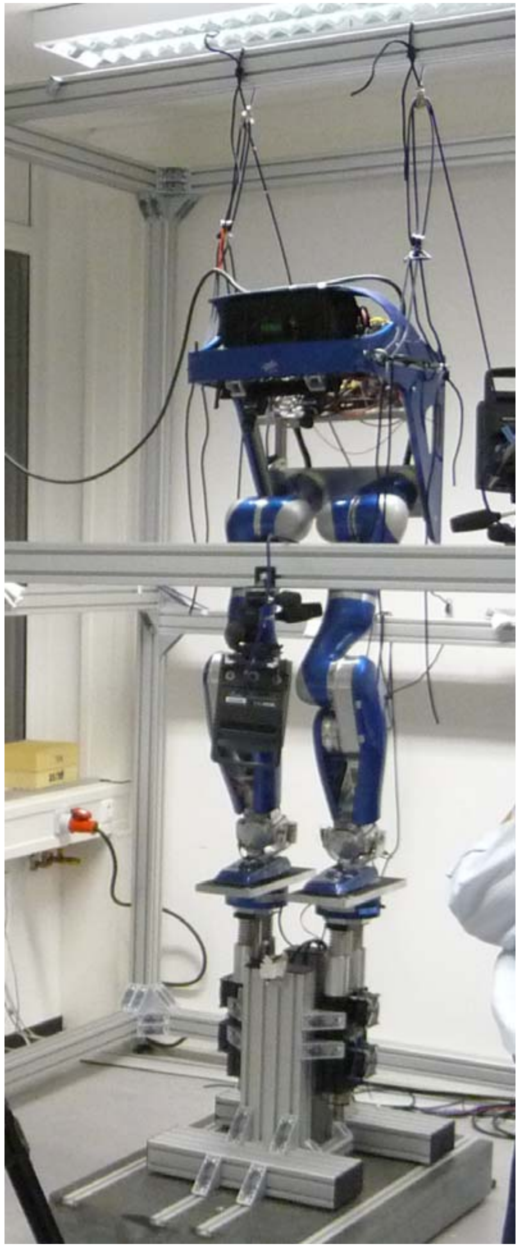
[Ott, Roa, Humanoids 2011, best paper award]

Experiments on a Perturbation Platform

- Leg perturbation setup
- Movable elastic platform

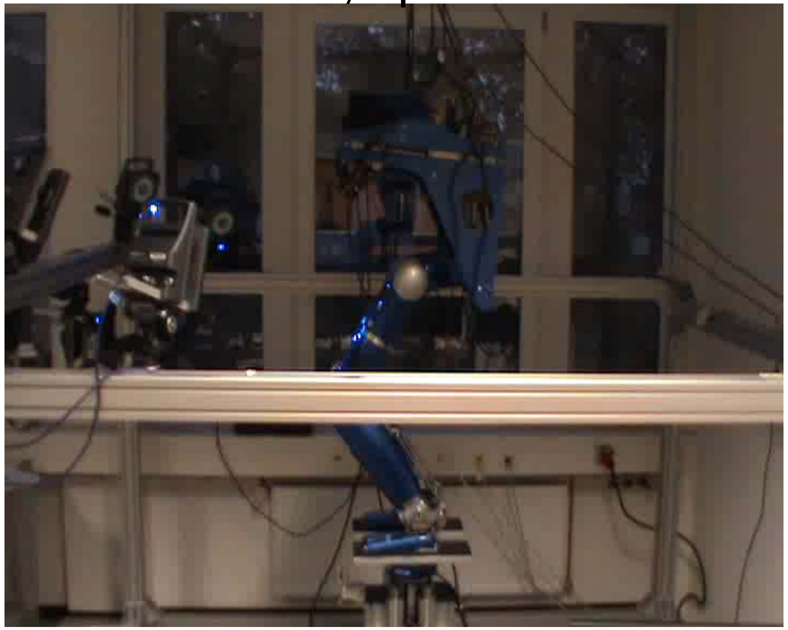


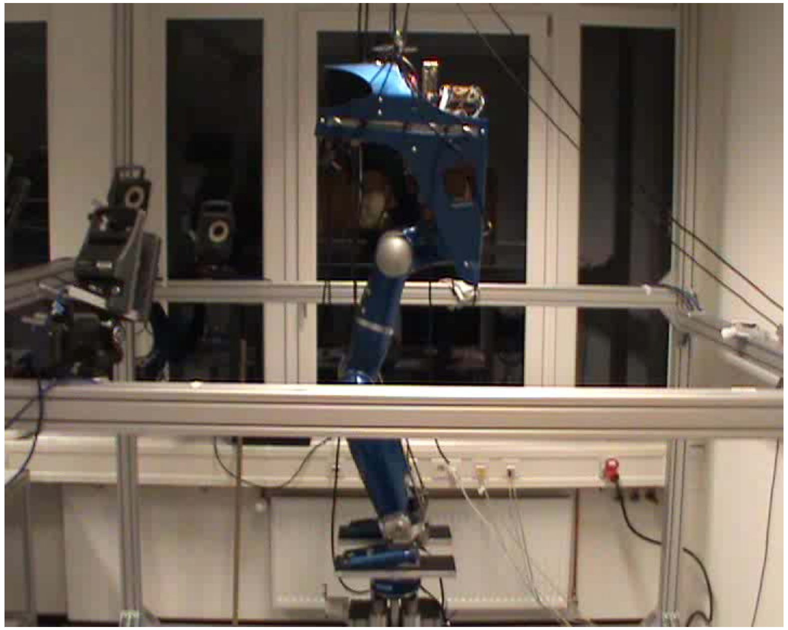
- Experimental evaluation of the robustness with respect to disturbances (frequency & amplitude) at the foot



synchronous disturbance
2mm, up to 8 Hz

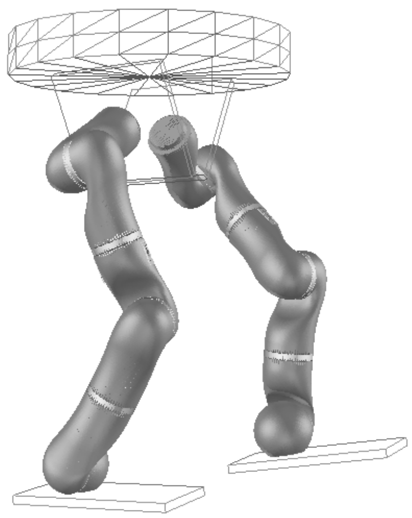
Out of phase disturbance





Current Research Interests

Walking Control

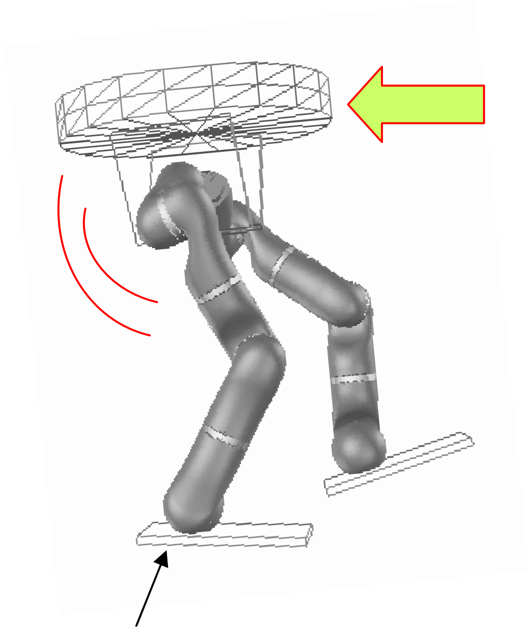


Use of the Capture Point

… 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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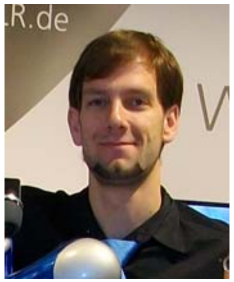

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