Development and Control of Compliant Humanoid Robots at DLR

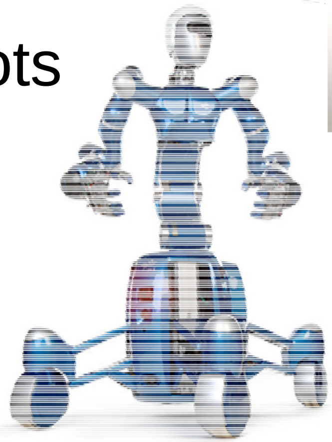
Christian Ott

German Aerospace Center (DLR)

HELMHOLTZ ASSOCIATION

DLR

Overview



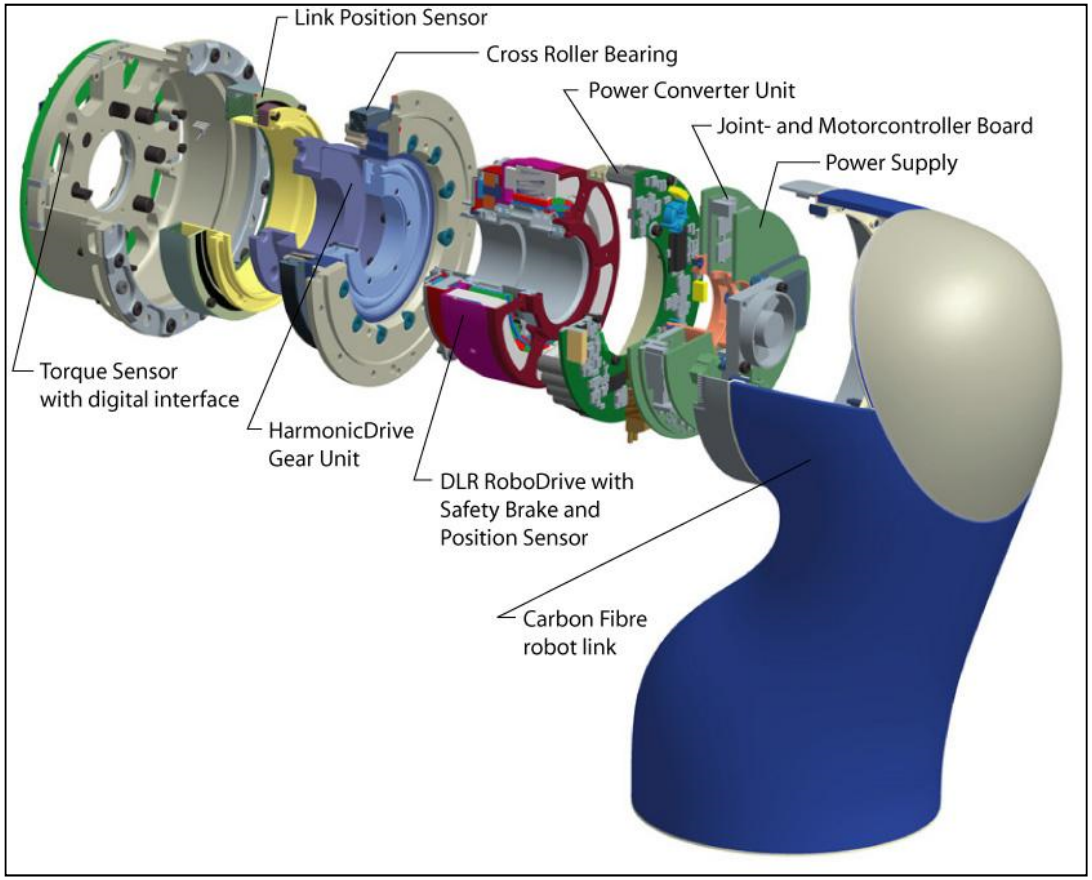
1) Design & Control of compliant robots

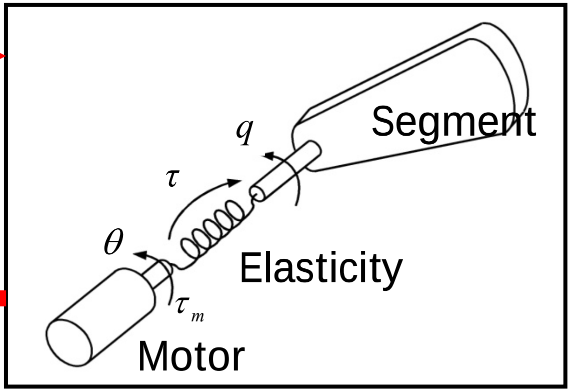
- ✓ Torque Controlled Robots
- ✓ Elastic Robots

2) Control of humanoid robots

- ✓ Compliant Control
- ✓ Bipedal Walking

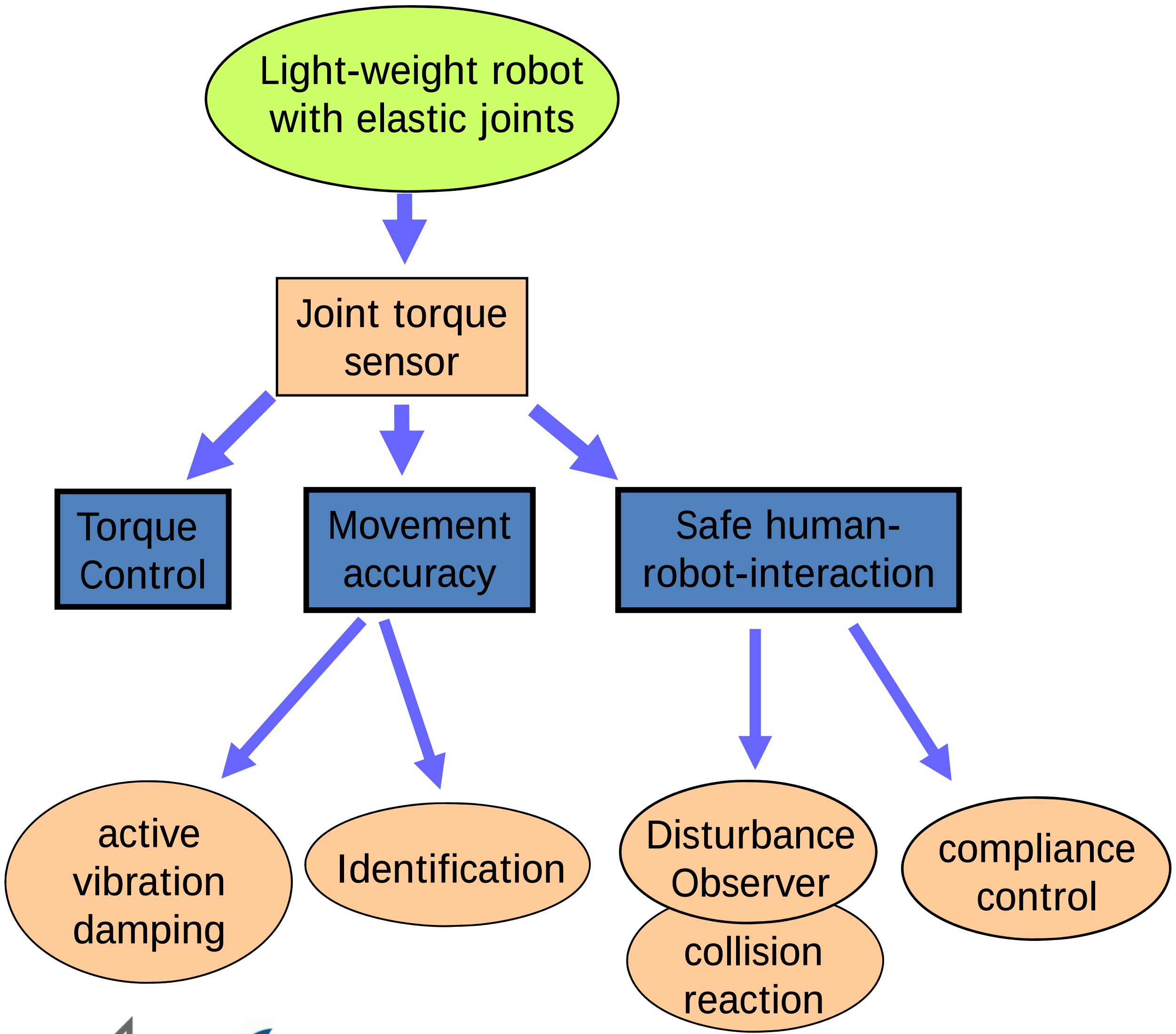
Robot Model with Torque Sensors

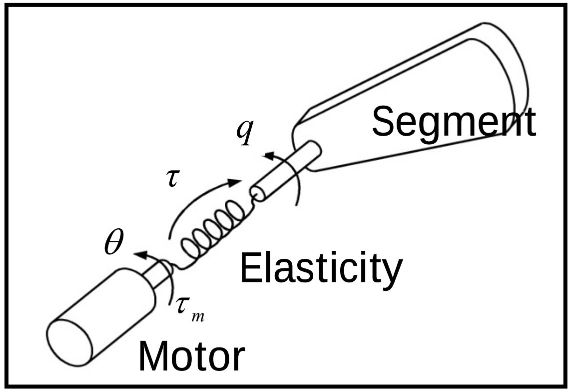




$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \overbrace{K(\theta - q)}^{\tau} + \tau_{ext}$$
$$B\ddot{\theta} + K(\theta - q) = \tau_m$$

Advantages of Torque Sensing





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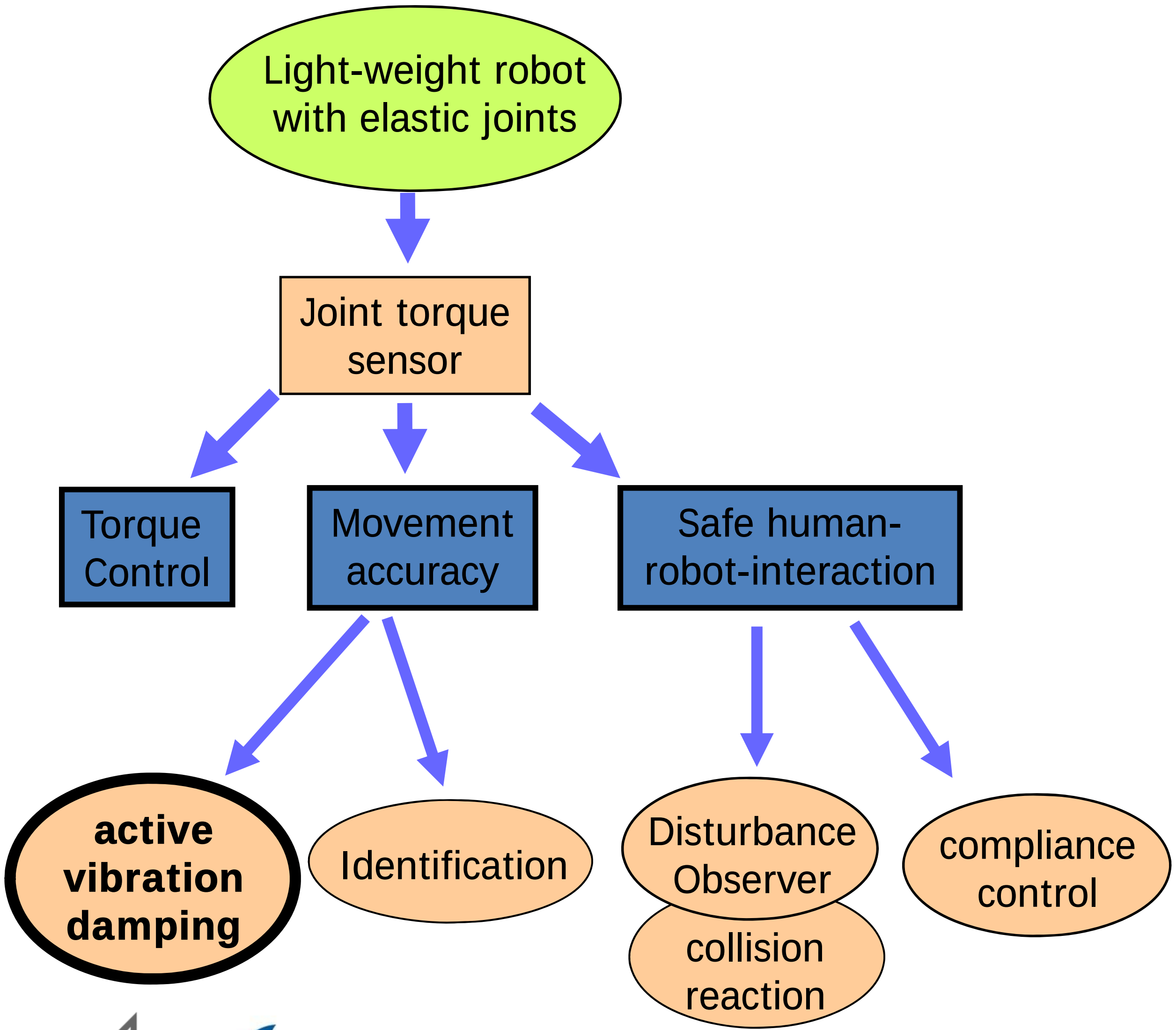

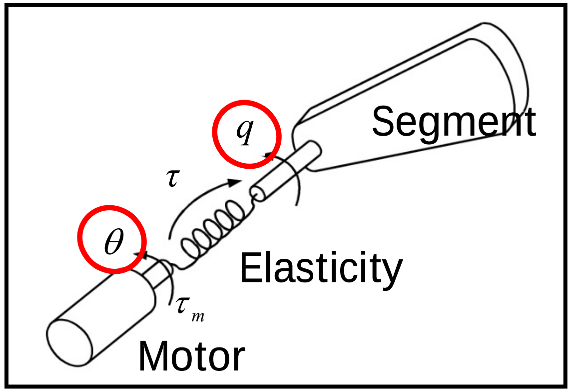

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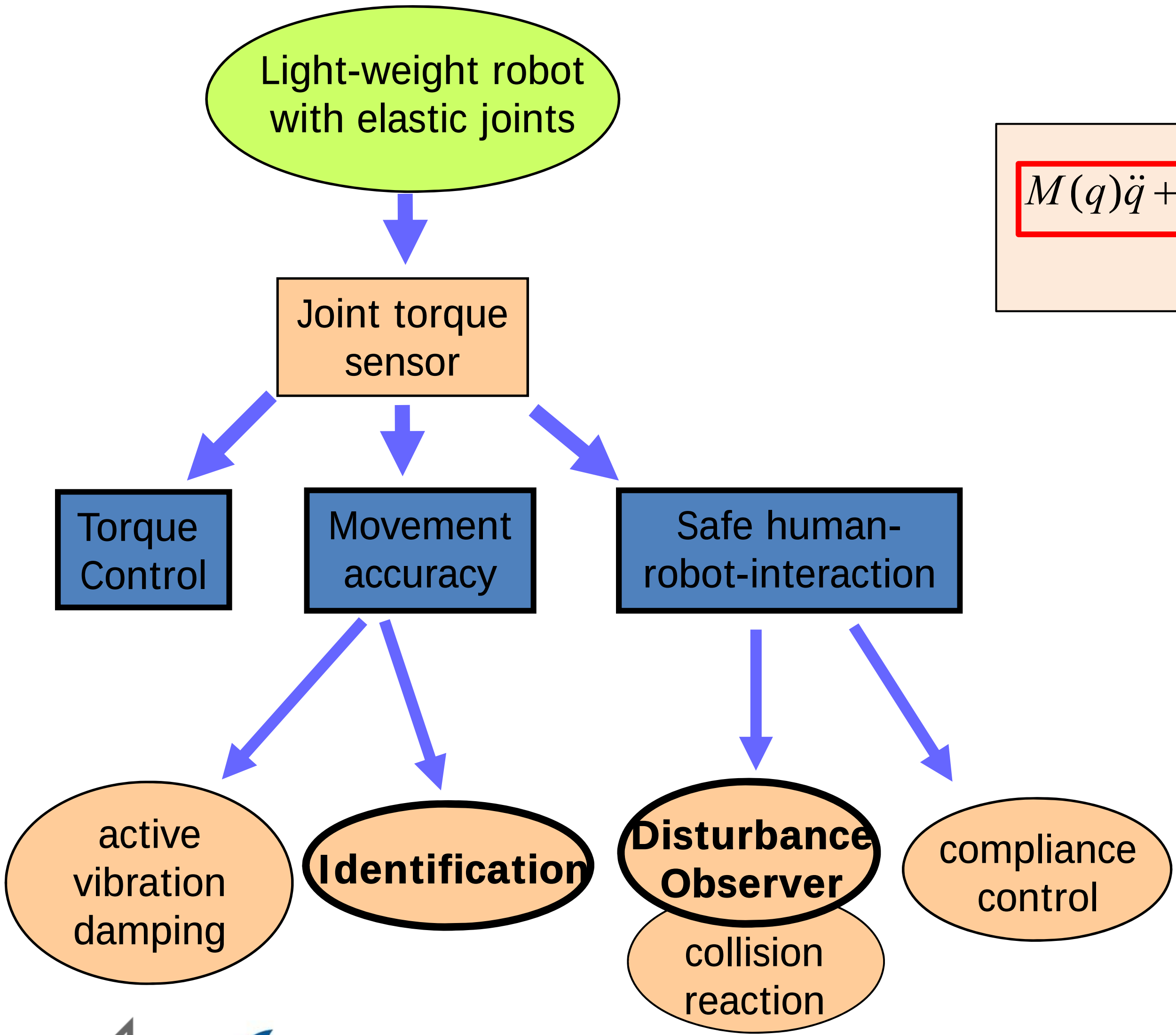
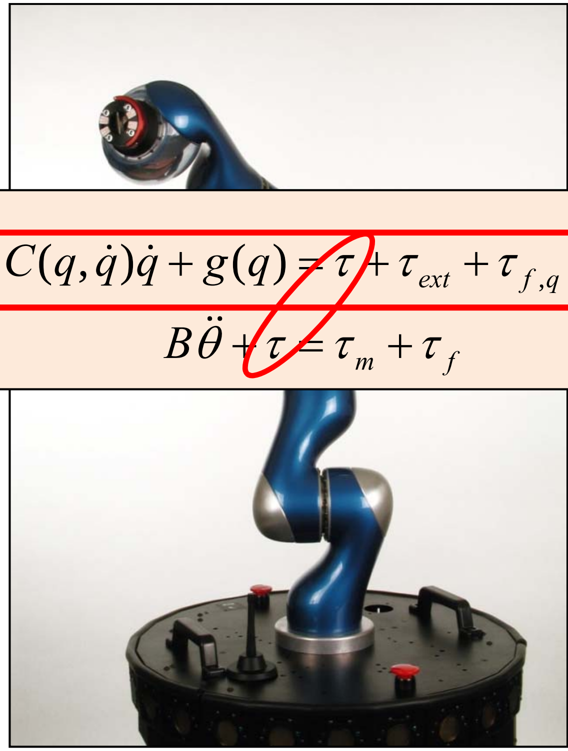
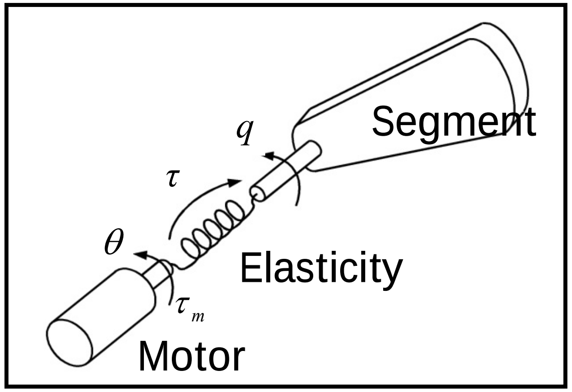




$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau + \tau_{ext} + \tau_{f,q}$$

$$B\ddot{\theta} + \tau = \tau_m + \tau_f$$



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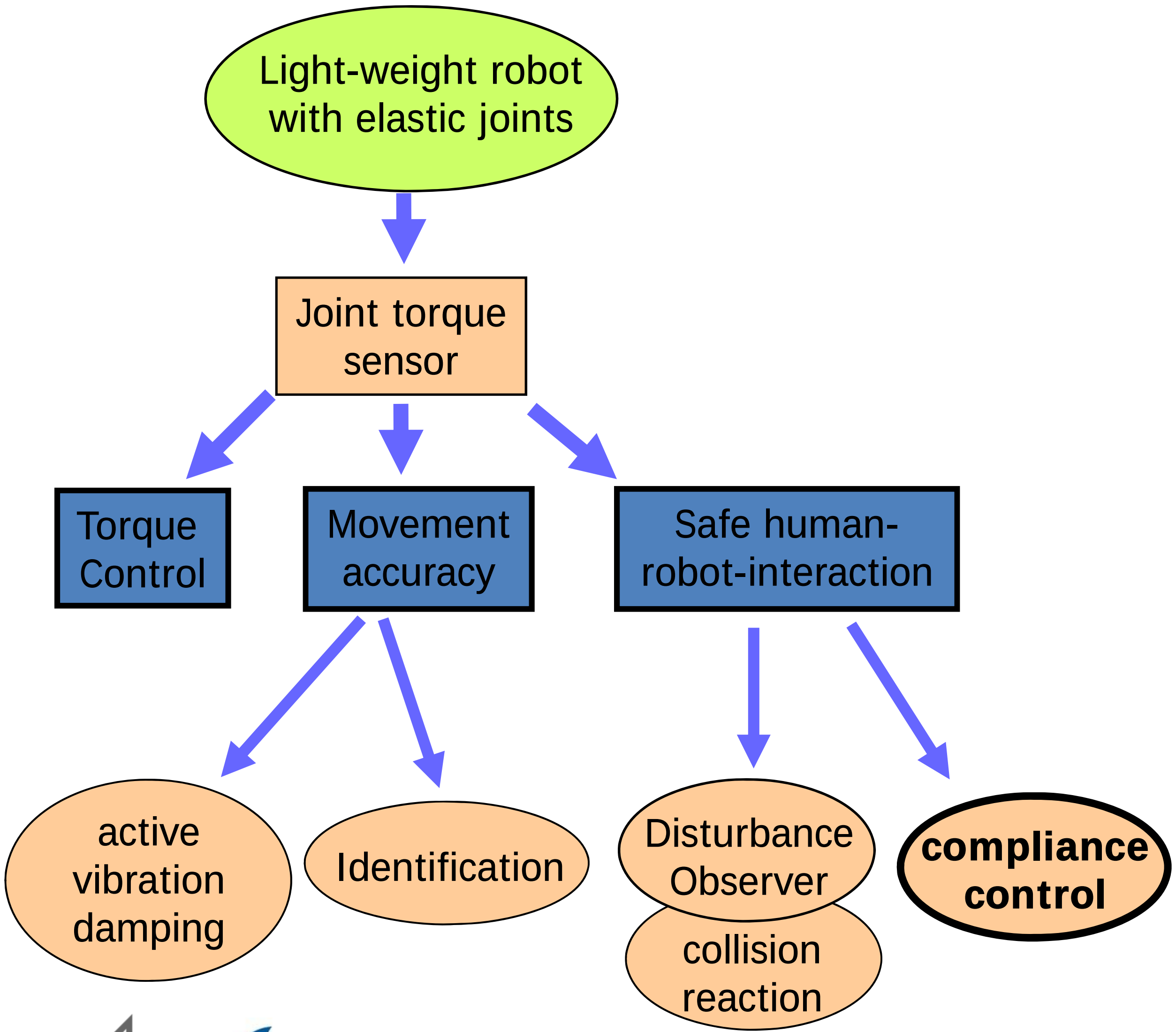
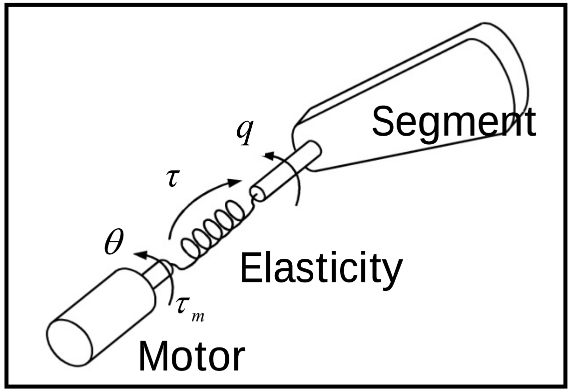
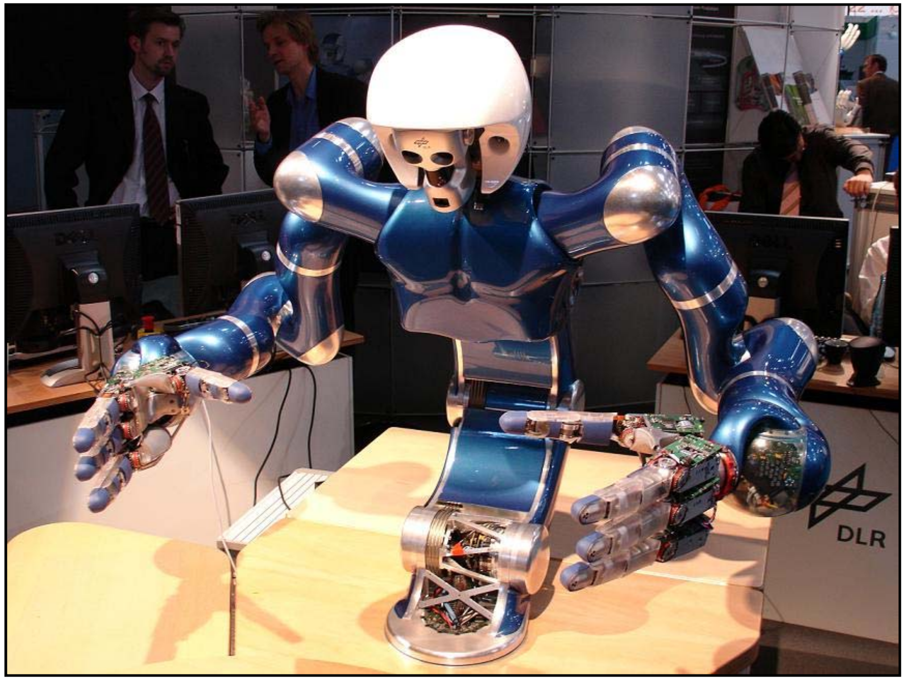


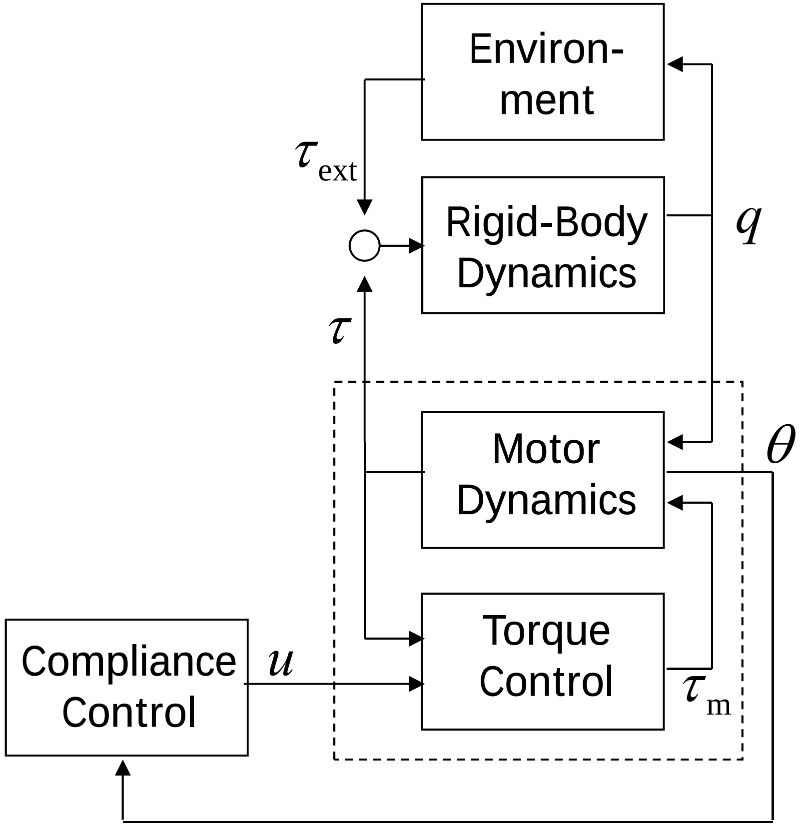


[Ott & Albu-Schäffer, TRO 2008]

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

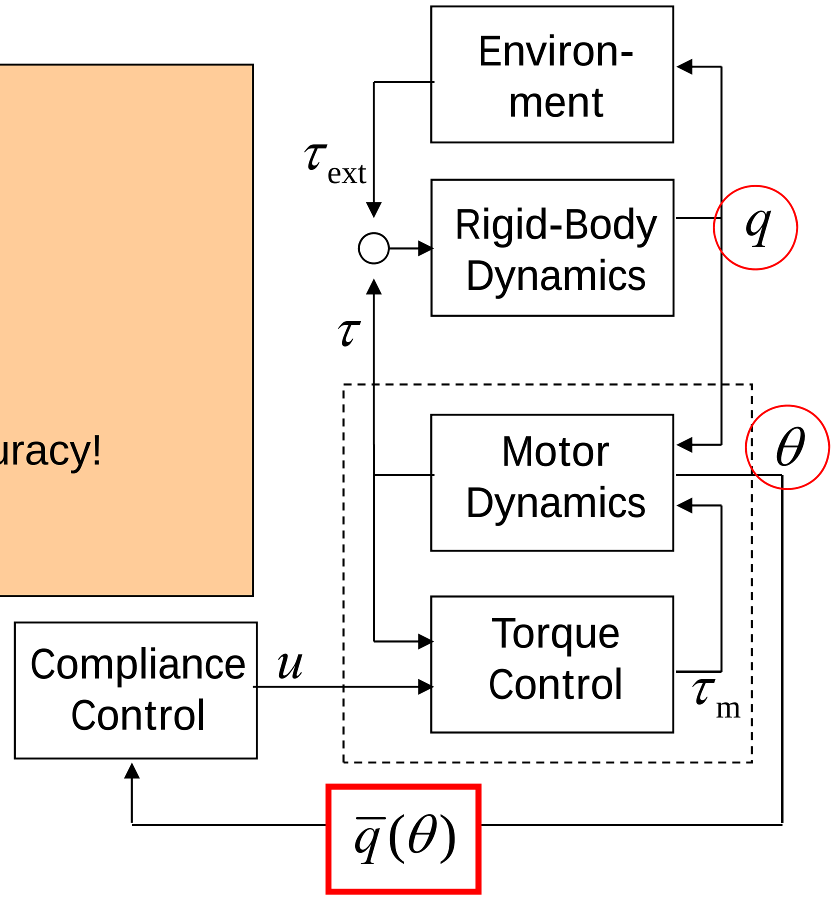
Equilibrium: $g(q) = K(\theta - q) + \tau_{ext}$ $\quad \tau_{ext} = \dfrac{\partial V(q)}{\partial q}$

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

→ Compensation of the static effects of K

→ Allows to fulfill requirements on the link side accuracy!

→ Computation of $\bar{q}(\theta)$ by contraction analysis!



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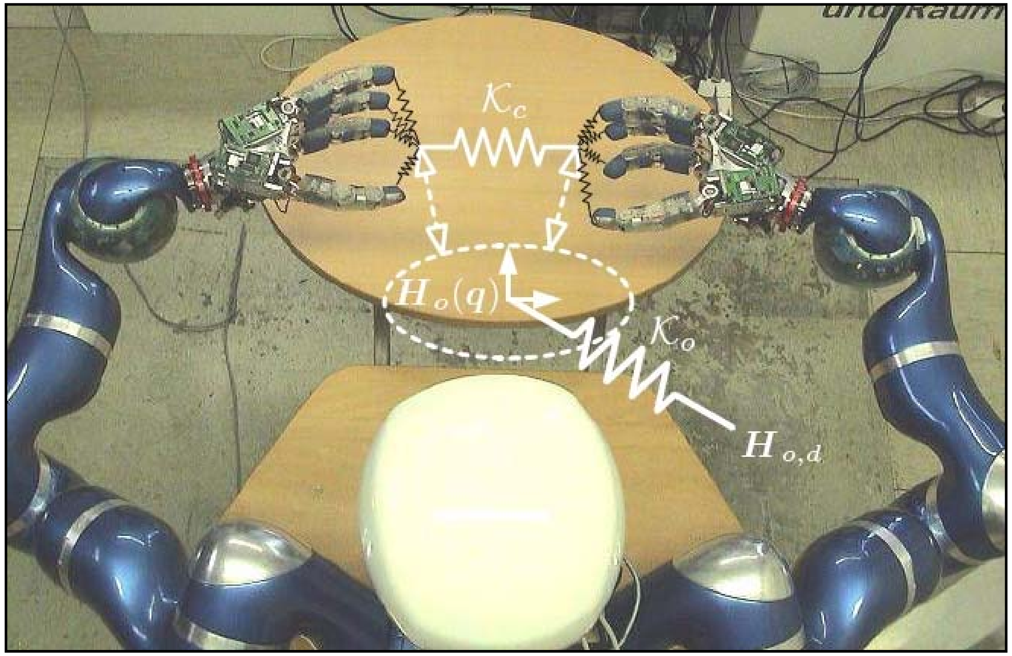

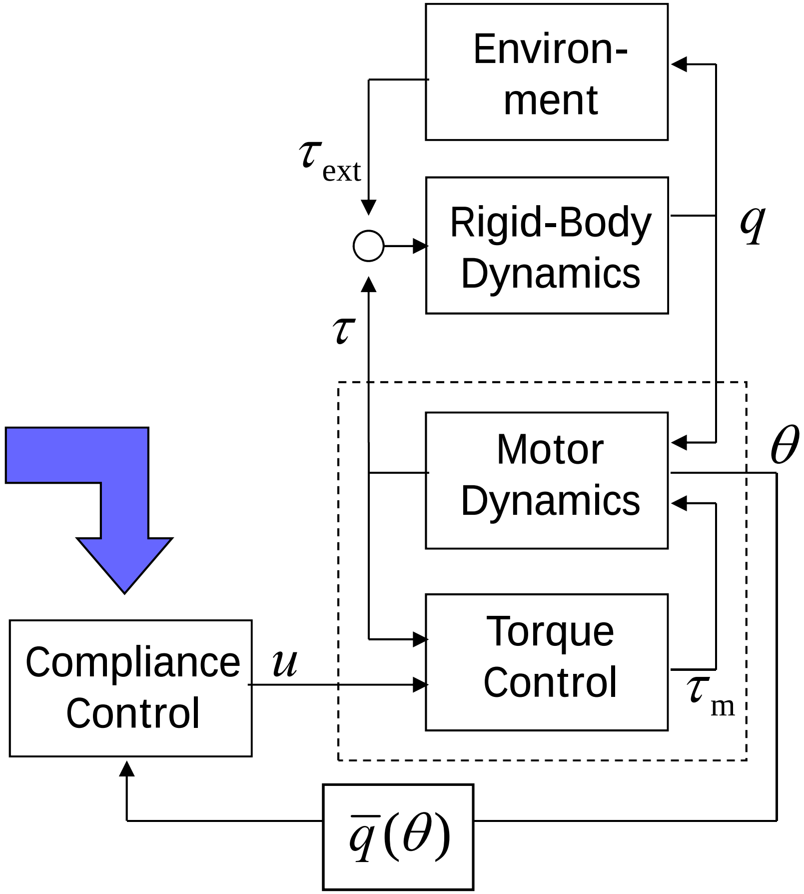

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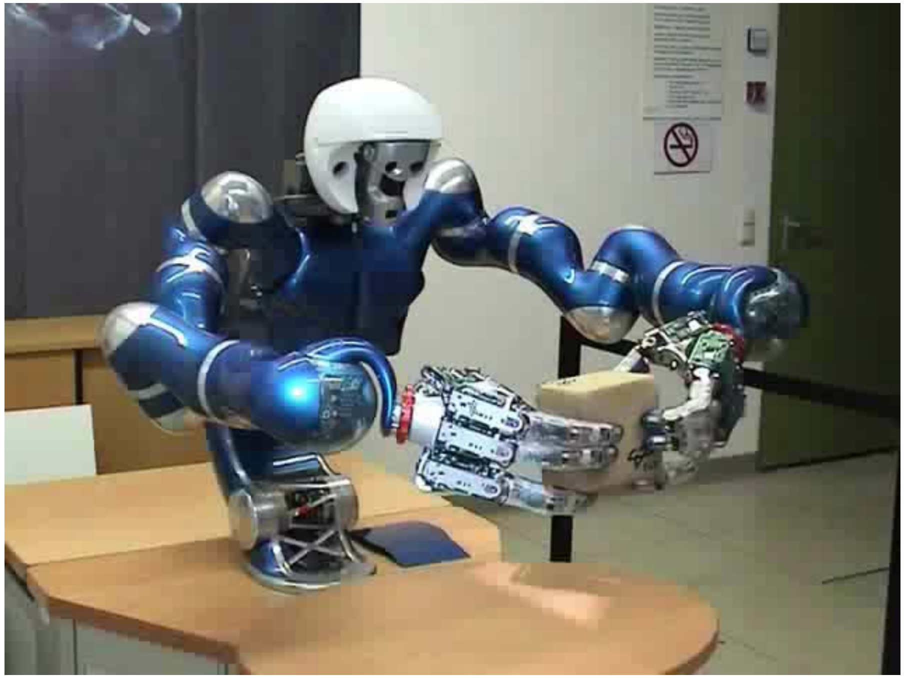
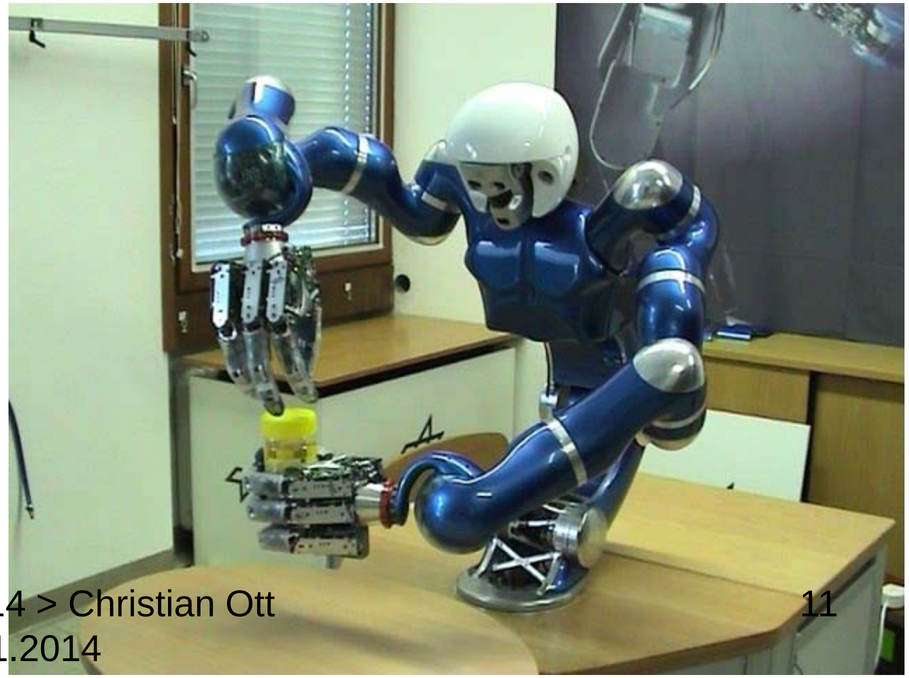
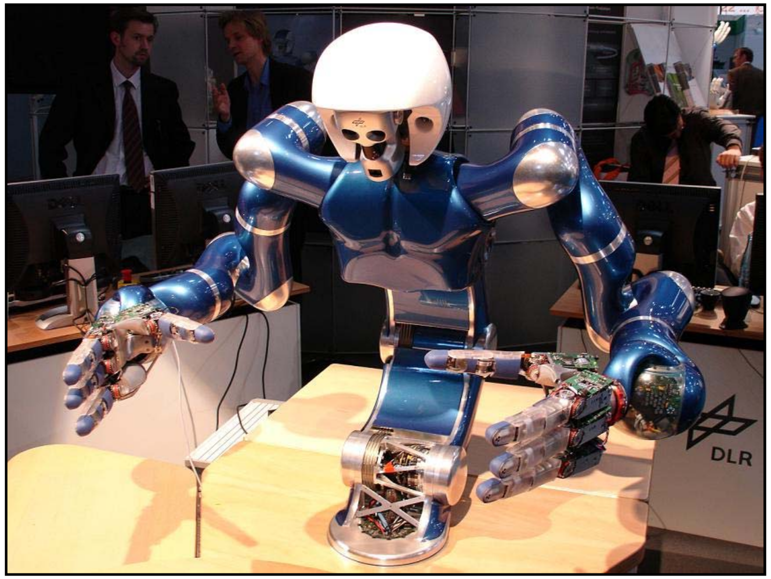




Humanoid Robots at DLR

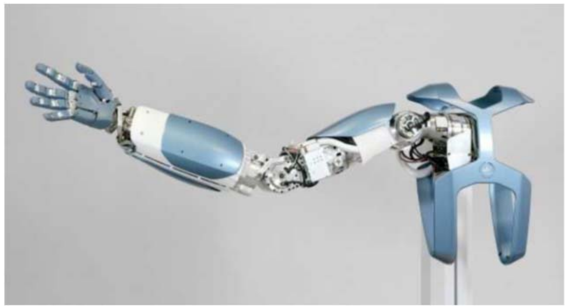
Joint torque sensing & control

Bimanual (Humanoid) Manipulation



Legged Humanoid

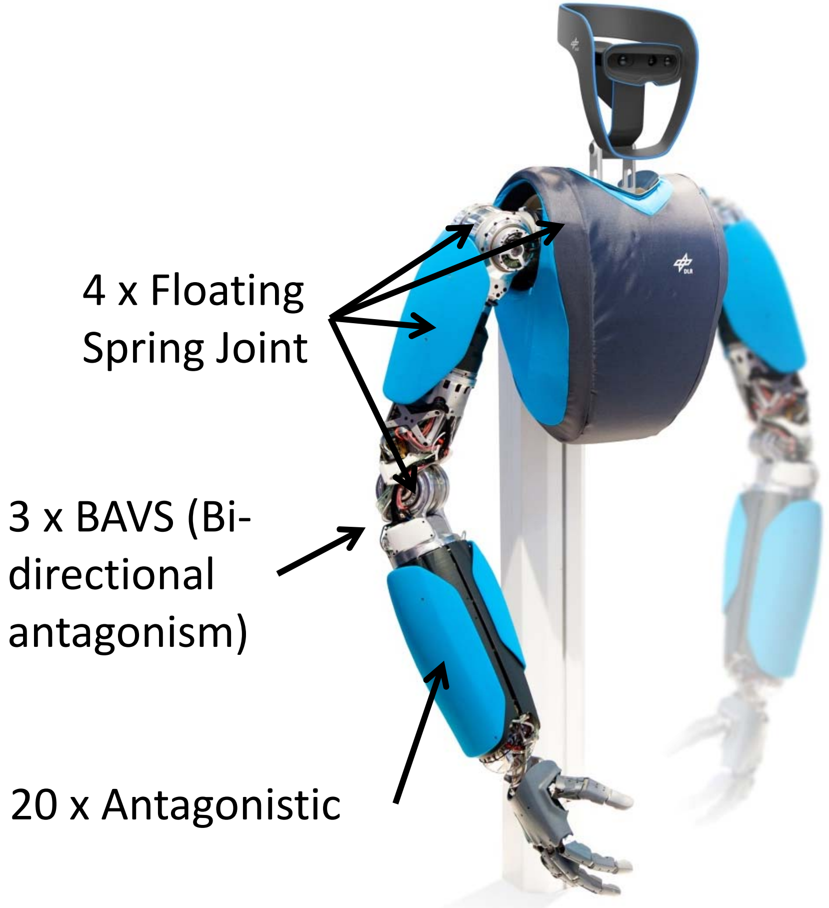
Space Qualified Joint Technology



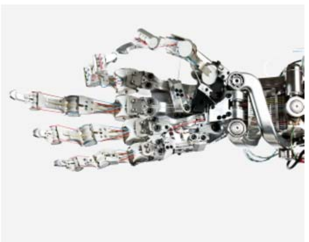
- Compliant actuation
- Antagonistic actuation for fingers
- Variable stiffness actuation in arm
- Robustness to shocks and impacts

Anthropomorphic Hand-Arm System

Antropomorphic Hand/Arm System



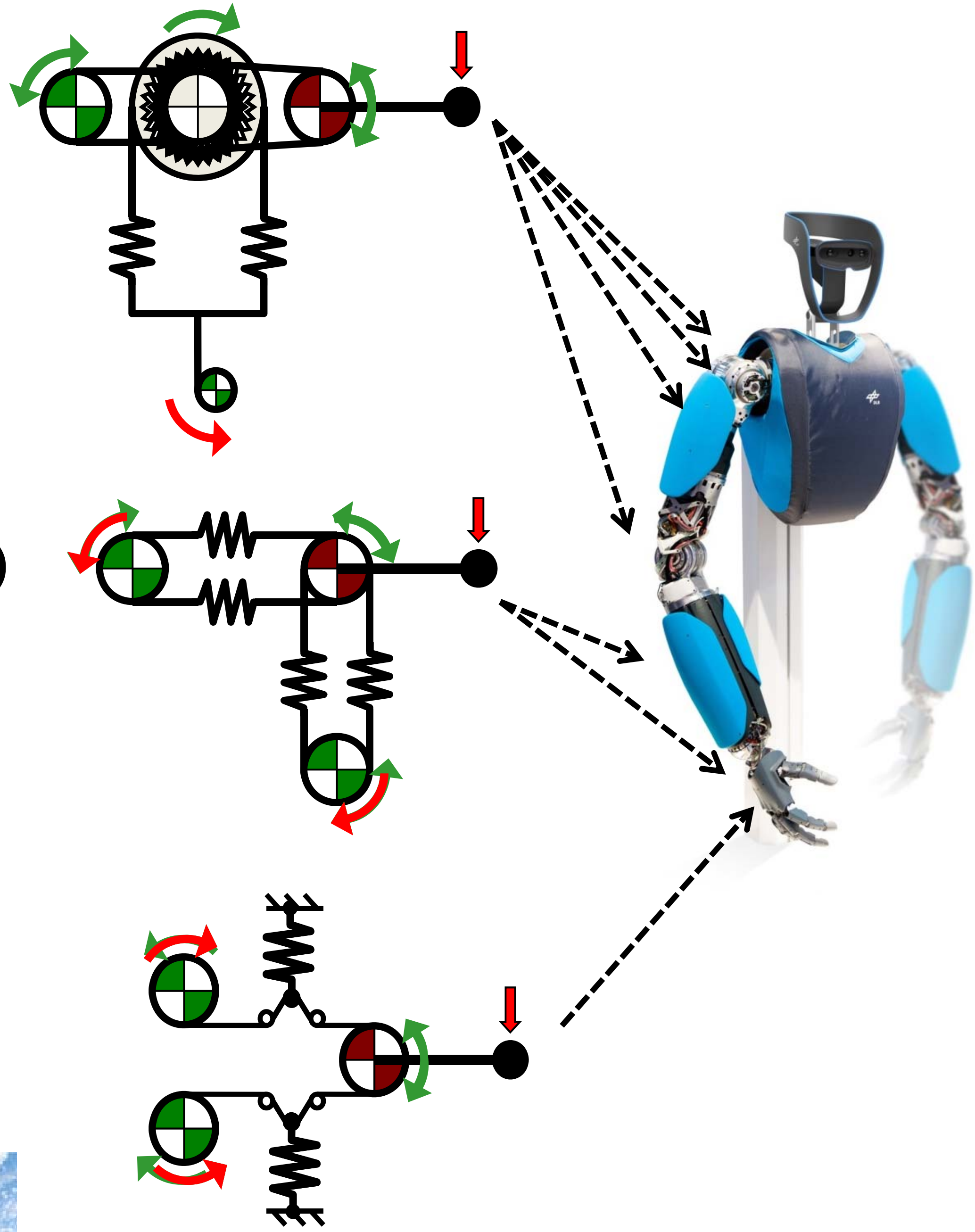
- **Antropomorphic design:** Size, kinematics, force and dynamics of human arm and hand
- **Actuation principle:** Variable stiffness in all joints (3 types)
  - *27 DoF*
  - *50 motors*
  - *108 position sensors*


Tendon driven fingers


Antagonistic finger actuation

[Grebenstein, Albu-Schäffer et al, ICRA 2011]

Types of actuation



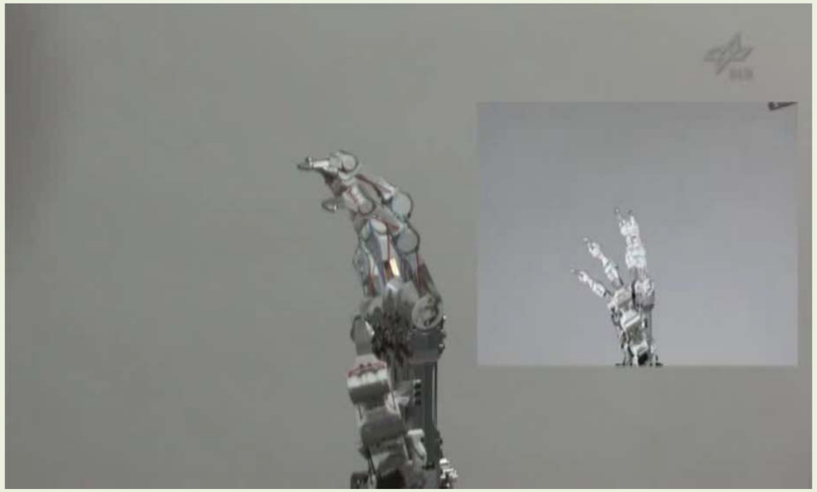
Floating Spring Joint (4 DoF)
- big motor for positioning
- small motor to change stiffness
- one single spring

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

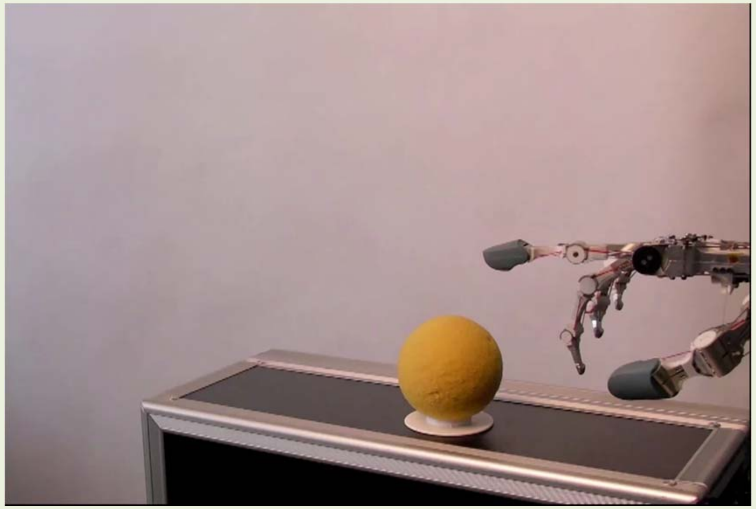
Antagonism (20 DoF Hand):
- 2 equivalent motors
- in-tendon progressive spring mechanism

Motivation for physical compliance

Robustness



Performance



Control Challenges: Vibration Damping

1) Modal decoupling (link side)

$$M = Q^{-T} M_Q Q^{-1}$$

$$K = Q^{-T} Q^{-1}$$

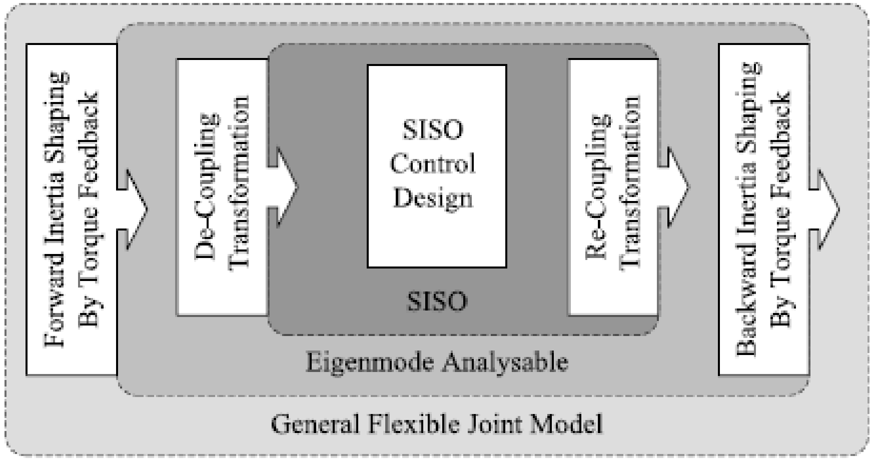
$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \overbrace{K(\theta - q)}^{\tau} + \tau_{ext}$$

$$B\ddot{\theta} + K(\theta - q) = \tau_m$$

2) Use torque feedback to achieve decoupling in M, K, and B

$$\tau_m = \left(I - BB_d^{-1}\right)\tau + BB_d^{-1}u$$

$$B_d = \alpha M + \beta K$$



[Petit, Albu-Schäffer, ICRA 2011]

3) SISO design in decoupled coordinates

$$\dot{M} \approx 0, \dot{Q} \approx 0$$

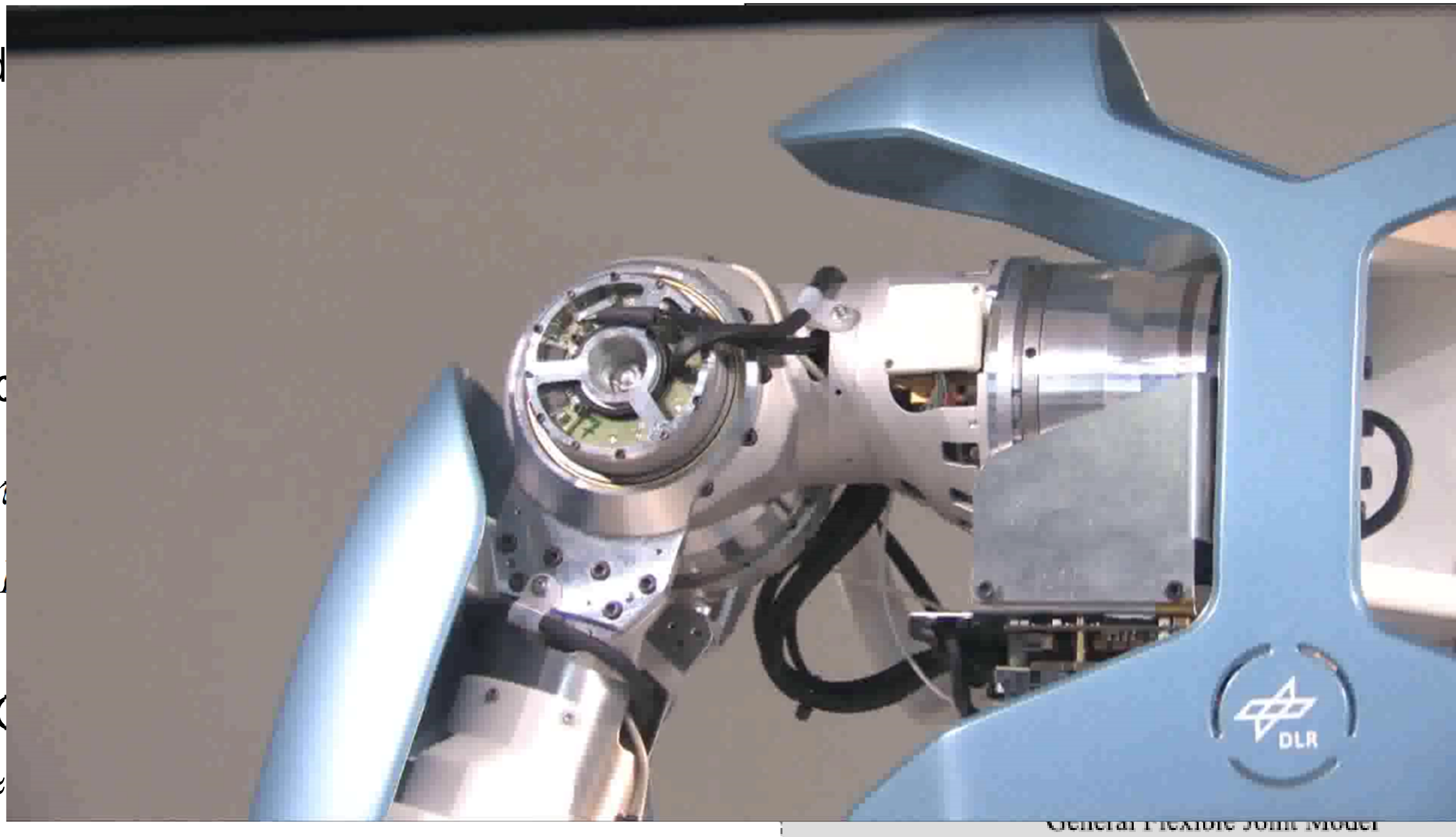
$$\begin{pmatrix} \theta \\ q \end{pmatrix} \rightarrow \begin{pmatrix} Q^{-1}\theta \\ Q^{-1}q \end{pmatrix}$$

Control Challenges: Vibration Damping

1) Mod

$+\tau_{ext}$

2) Use
decc



3) SISC

$\dot{M} \approx$

$$\begin{pmatrix} \theta \\ q \end{pmatrix} \rightarrow \begin{pmatrix} Q^{-1}\theta \\ Q^{-1}q \end{pmatrix}$$

[Petit, Albu-Schäffer, ICRA 2011]

Control Challenges: Stiffness Design

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

$$C = C_a + C_p$$

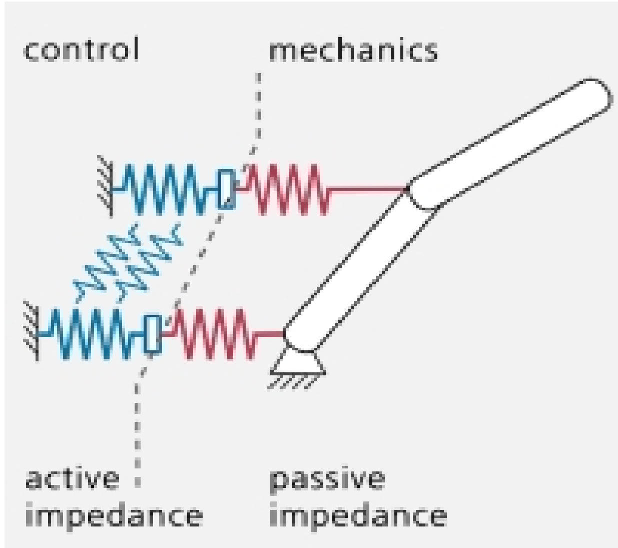
1) Use physical springs in the joints to set desired stiffness as close as possible

$$\min \left\| C_{des} - C_p \right\|$$

2) Use active compliance to realize precise Cartesian compliance

→solve a *matrix nearness problem*

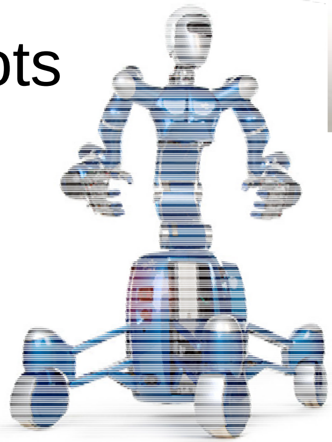
$$\min \left\| C_{des} - C_p - C_a \right\| \quad \text{with} \quad C_a > 0$$



[Petit, Albu-Schäffer, IROS 2011]

Utilizes variability of the stiffness!

Overview



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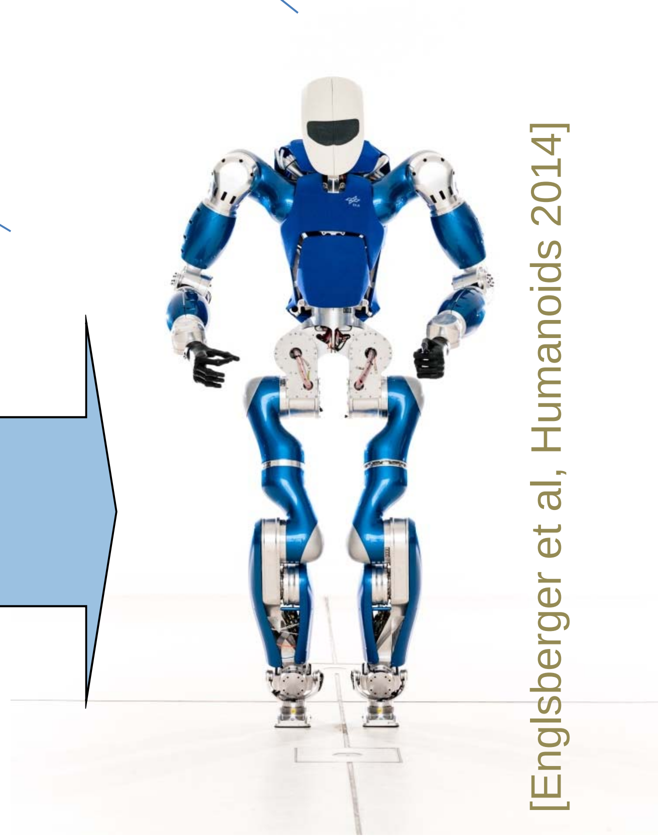
Bipedal Walking Robots at DLR

- 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)

[Ott et al, Humanoids 2010]

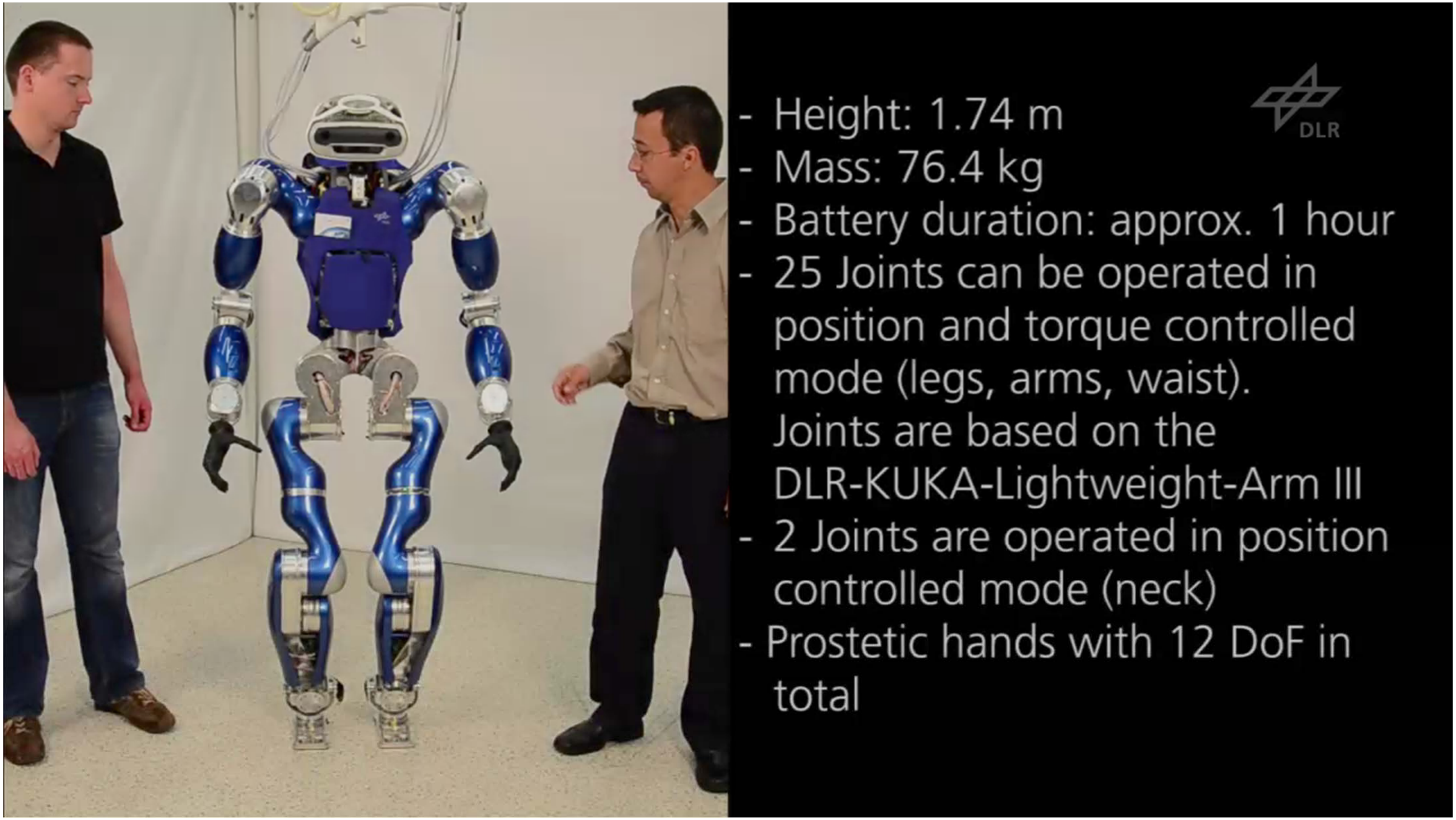
DLR-Biped
(2010-2012)

TORO, preliminary version
(2012)



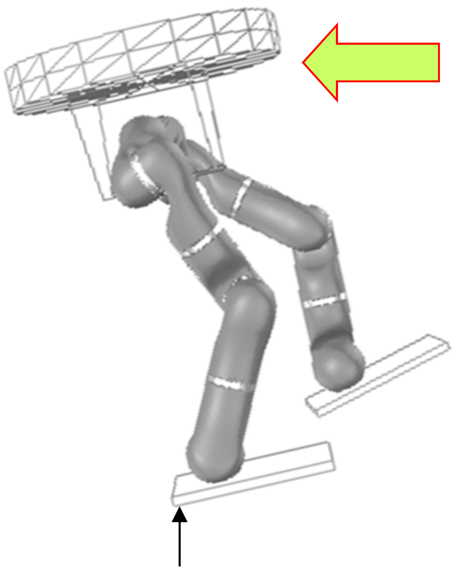
TORO (2013)
TOrque controlled
humanoid RObot

[Englsberger et al, Humanoids 2014]

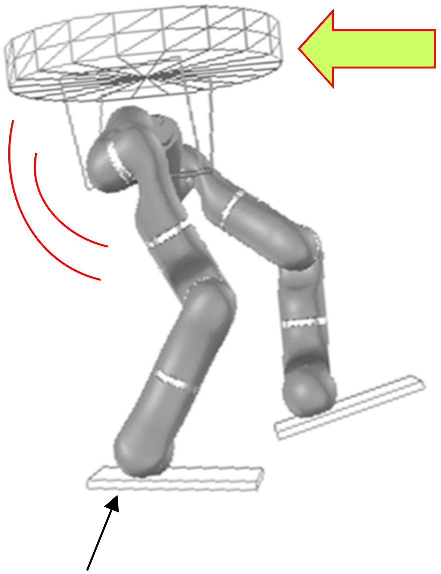

- Height: 1.74 m
- Mass: 76.4 kg
- Battery duration: approx. 1 hour
- 25 Joints can be operated in position and torque controlled mode (legs, arms, waist). Joints are based on the DLR-KUKA-Lightweight-Arm III
- 2 Joints are operated in position controlled mode (neck)
- Prostetic hands with 12 DoF in total
DLR

Motivation for compliant control

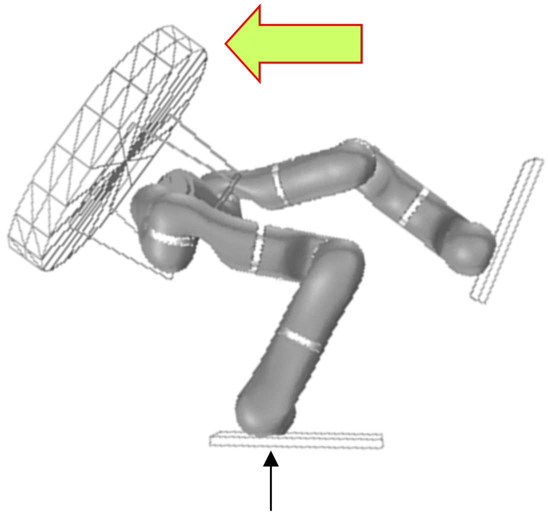
completely stiff



compliant control



fully compliant



[Ott & Roa, Humanoids 2011]

Balancing & Posture Control

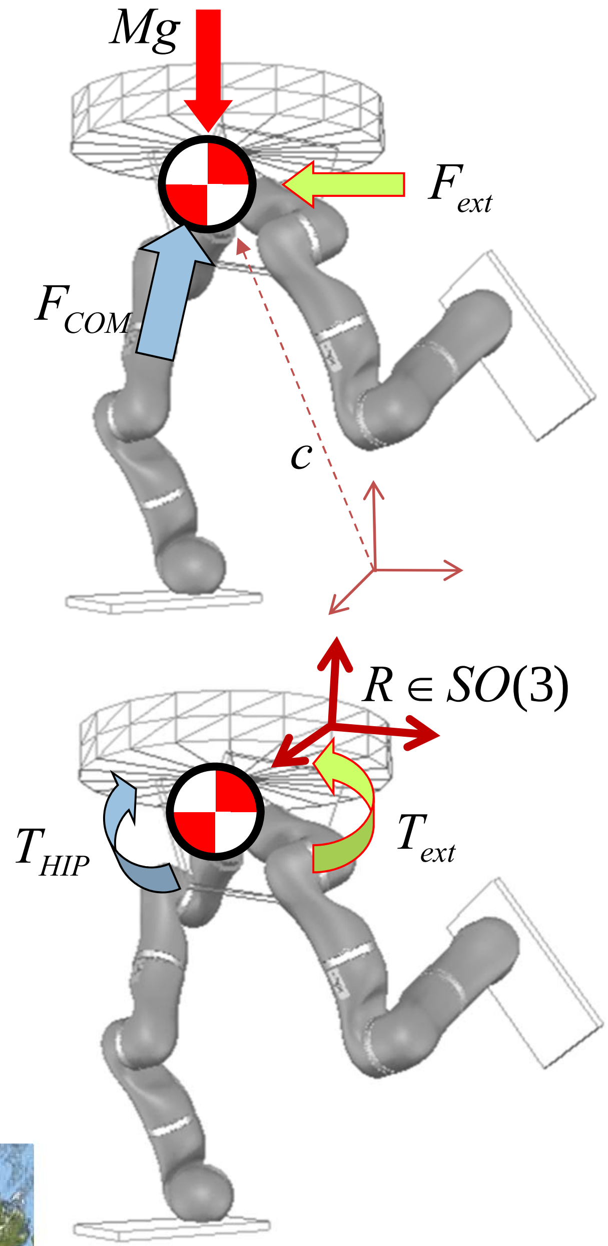
Compliant COM control [Hyon & Cheng, 2006]

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

Trunk orientation Control

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

IMU measurements



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

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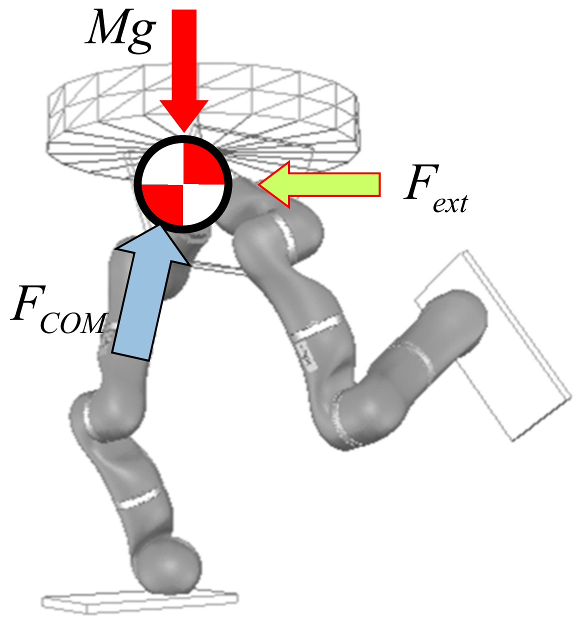

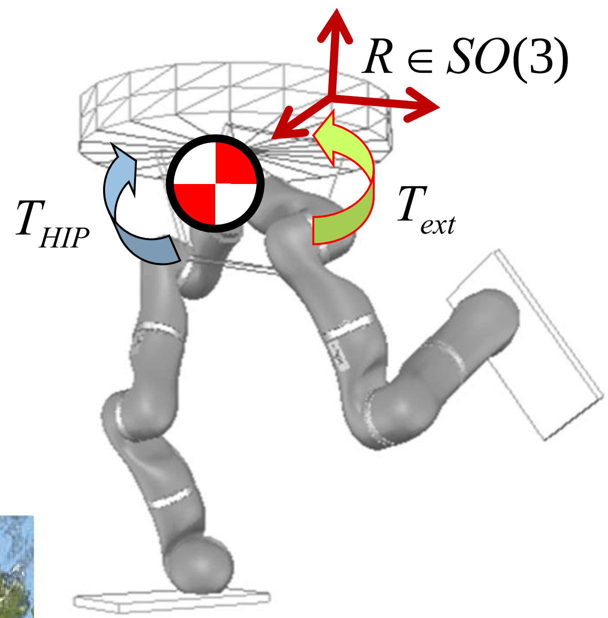

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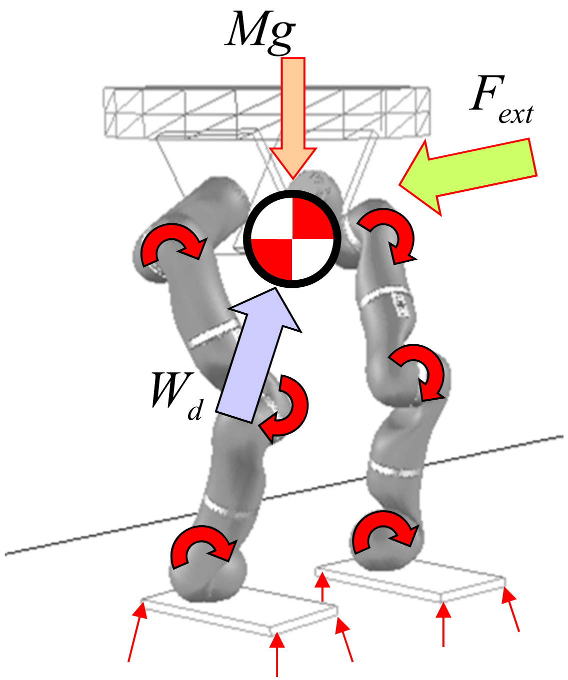
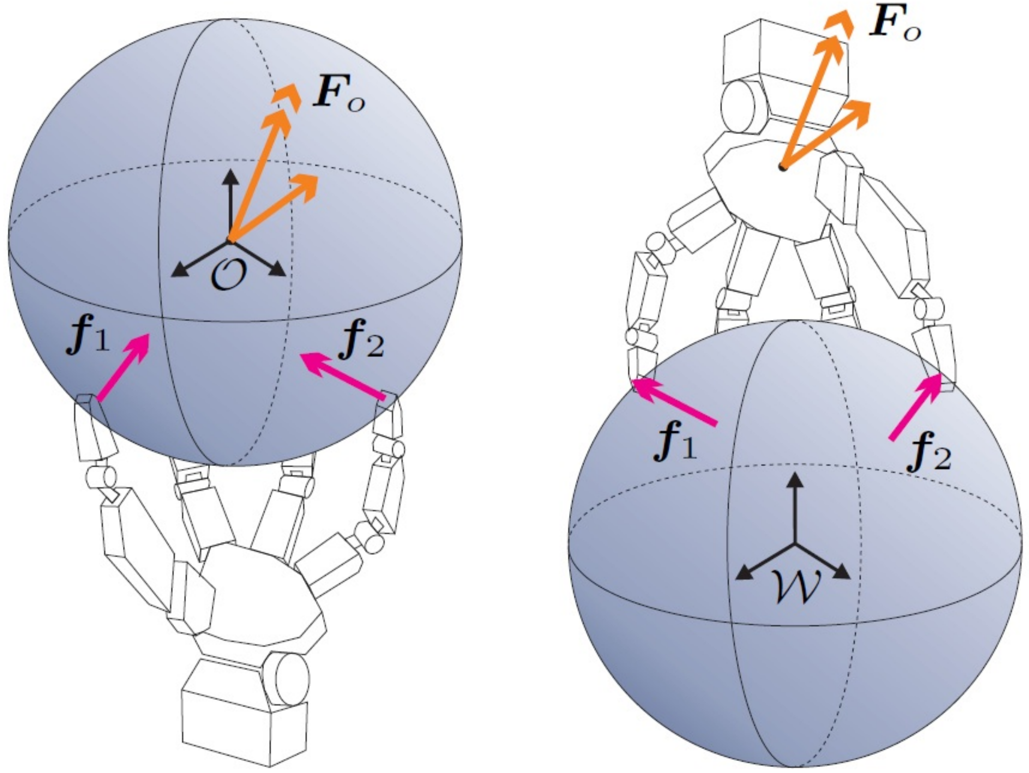


[Ott & Roa, Humanoids 2011]

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!



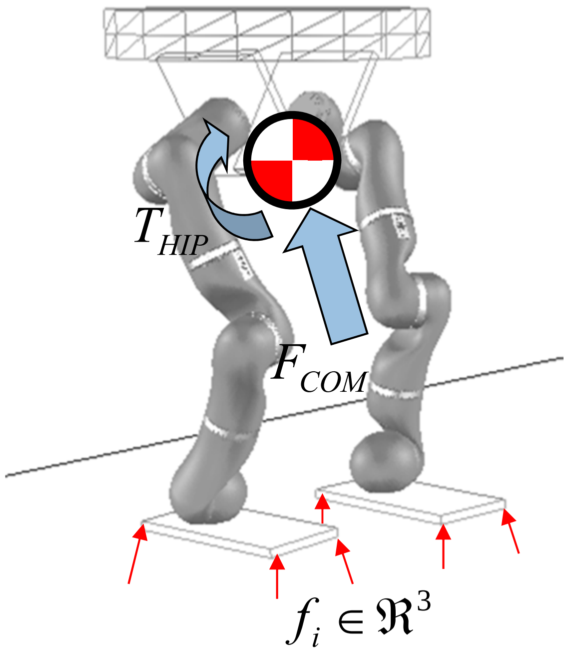
[Ott & Roa, Humanoids 2011]

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

[Ott & Roa, Humanoids 2011]

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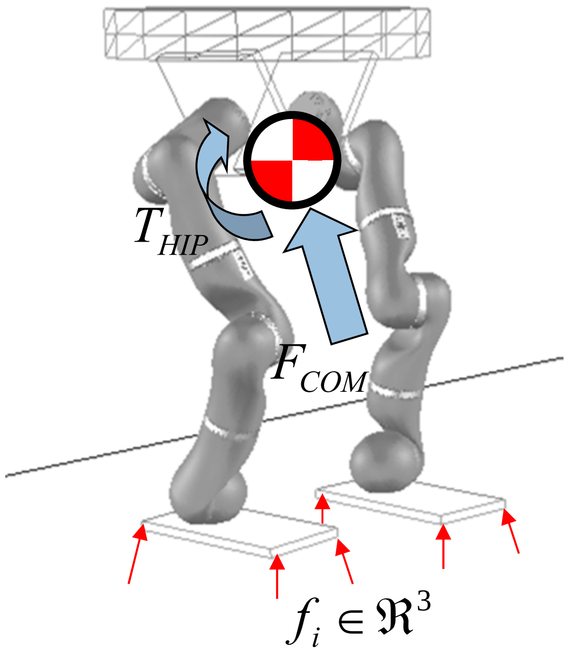

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➡ Formulation as a constraint optimization problem

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

[Ott & Roa, Humanoids 2011]

Contact force control via joint torques

Multibody robot model:

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

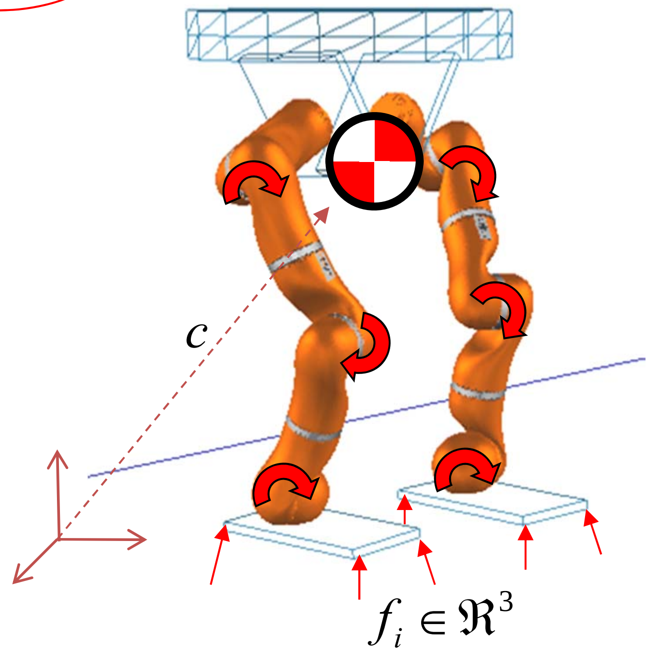
[Space Robotics], [Wieber 2005, Hyon et al. 2006]

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

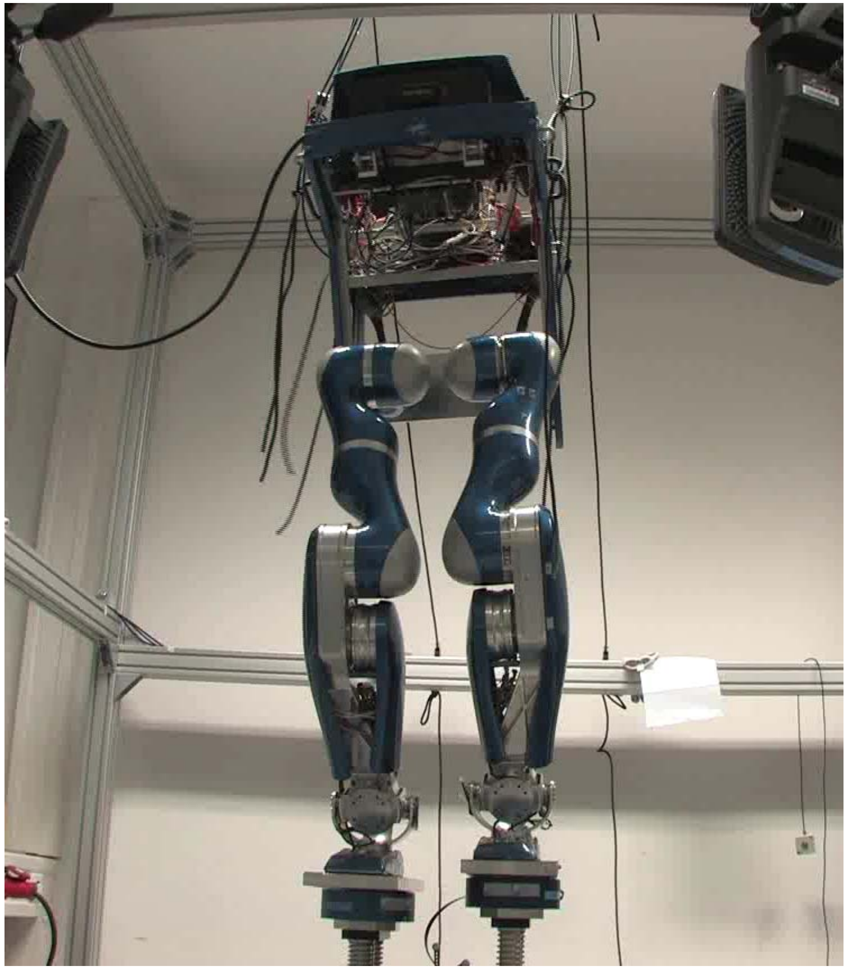
$$M\ddot{c} = Mg - \sum f_i$$

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

Passivity based compliance control
(well suited for balancing)



Experiments using the lower body



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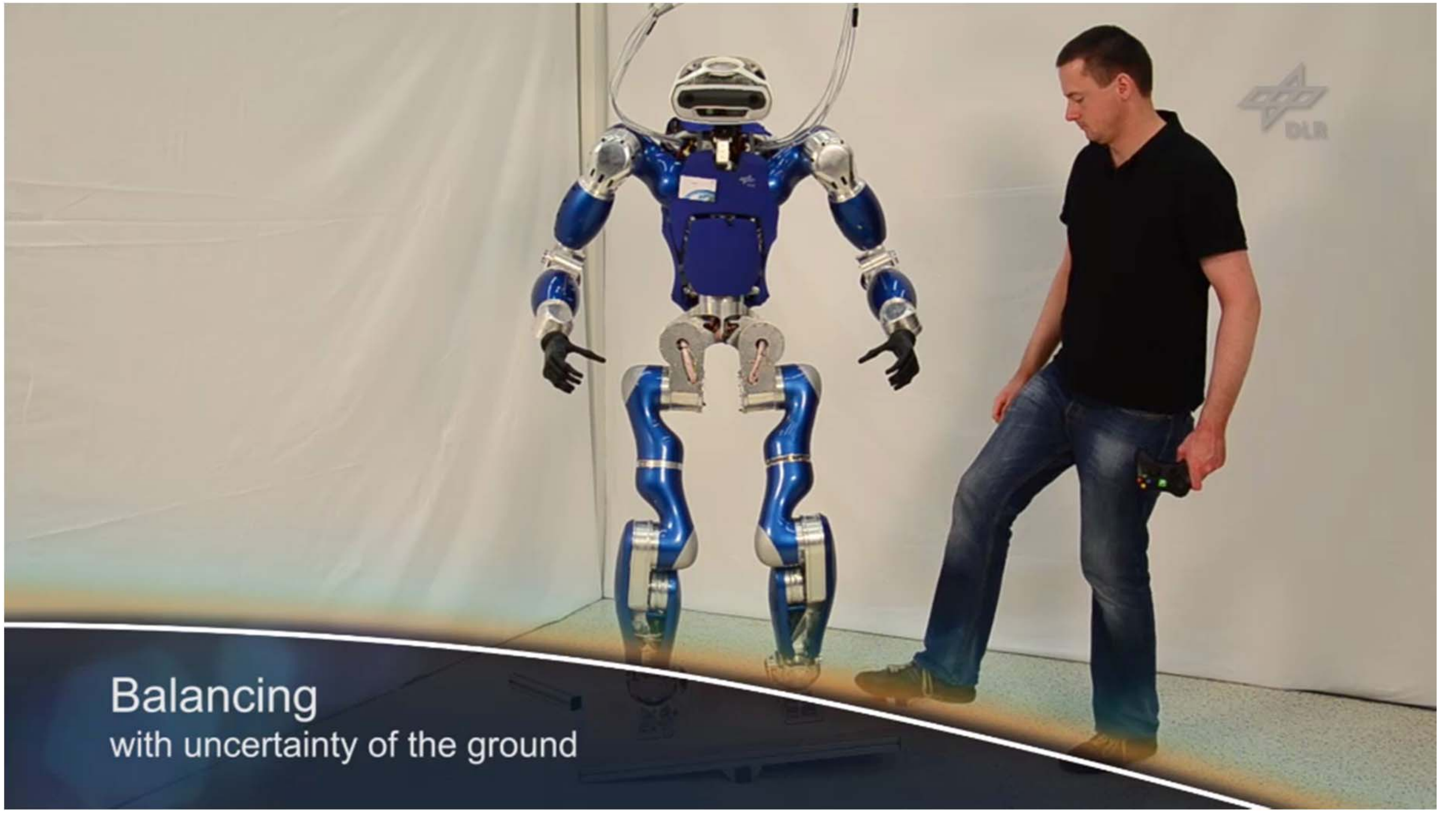

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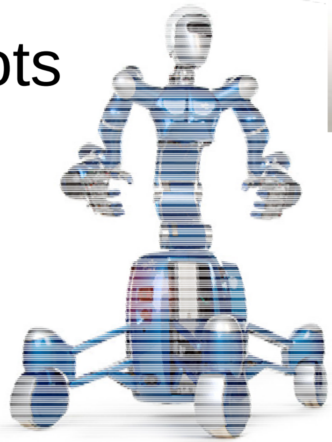

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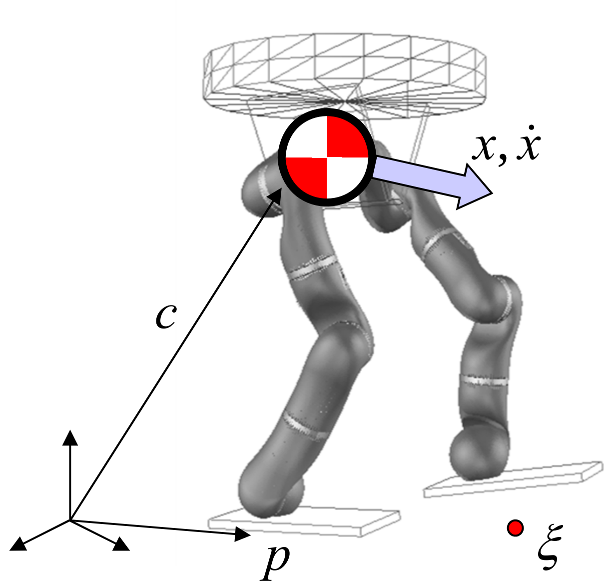
Walking Stabilization

[Englsberger, Ott, IROS 2013]



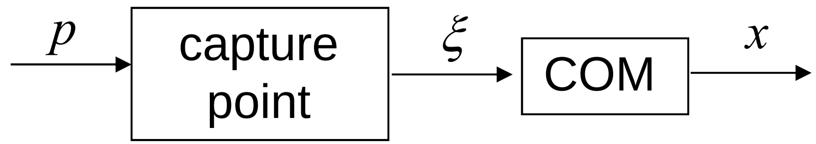
(Pratt 2006, Hof 2008)

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

$(x, \dot{x}) \downarrow (x, \xi)$

$$\xi = x + \frac{1}{\omega}\dot{x}$$

$$\dot{\xi} = \omega(\xi - p) \qquad \dot{x} = \omega(\xi - x)$$

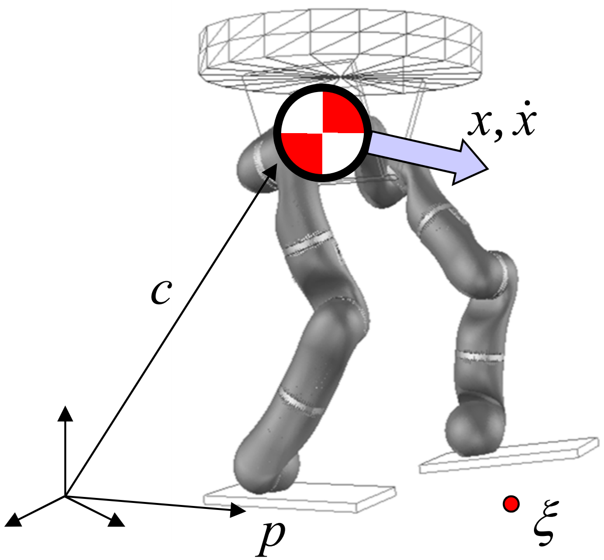


open loop unstable

exp. stable

Walking Stabilization

[Englsberger, Ott, IROS 2013]

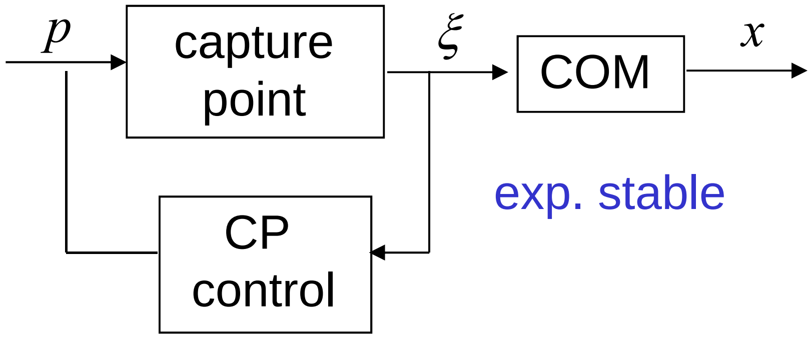


(Pratt 2006, Hof 2008)

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

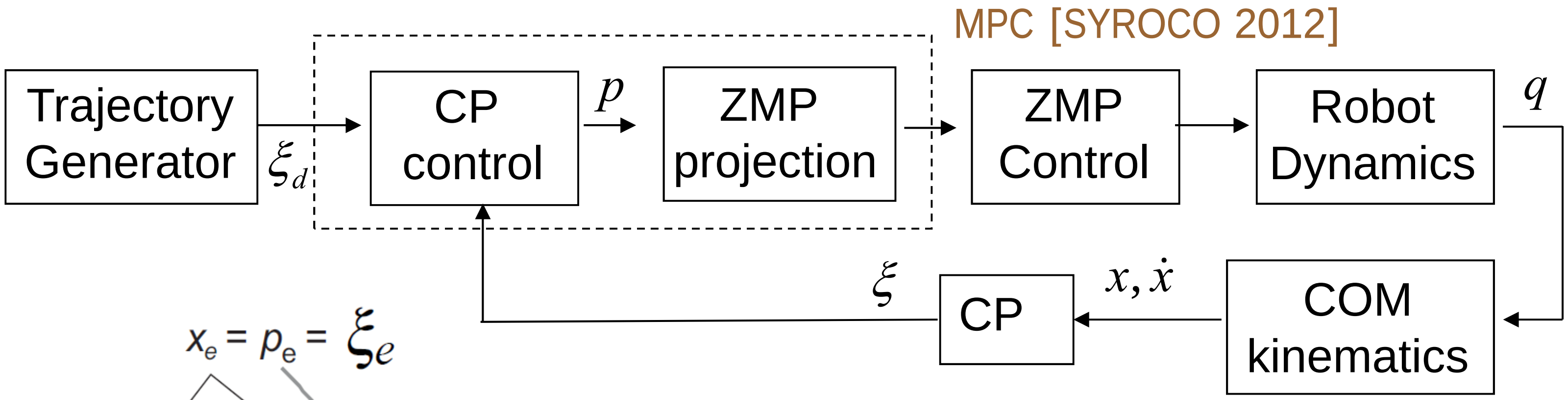
$$(x, \dot{x}) \downarrow (x, \xi) \qquad \xi = x + \frac{1}{\omega}\dot{x}$$

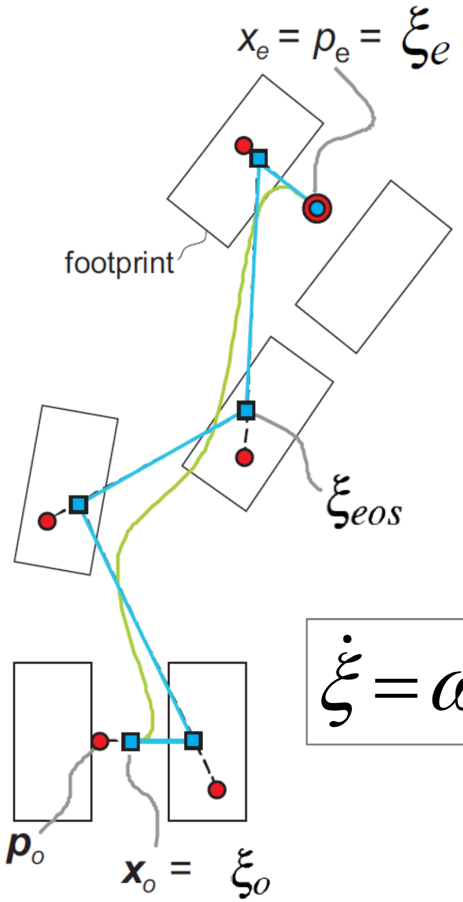
$$\dot{\xi} = \omega(\xi - p) \qquad \dot{x} = \omega(\xi - x)$$



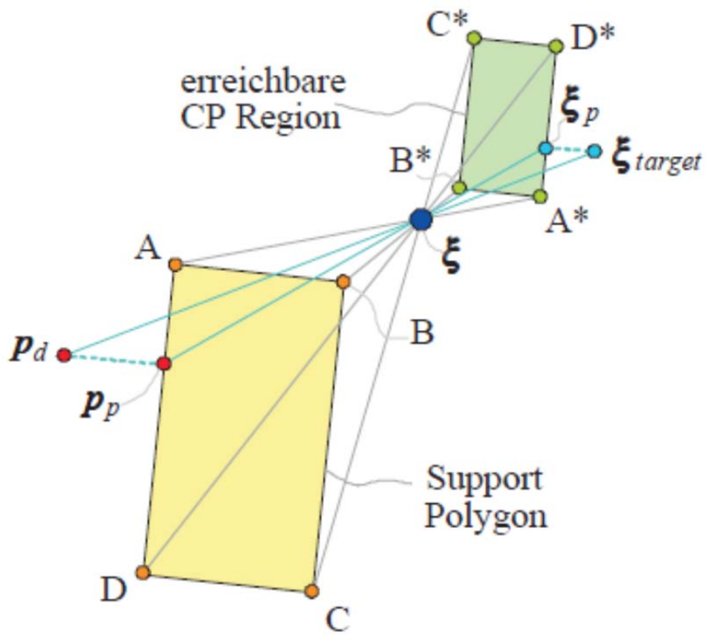
exp. stable

Capture Point Control

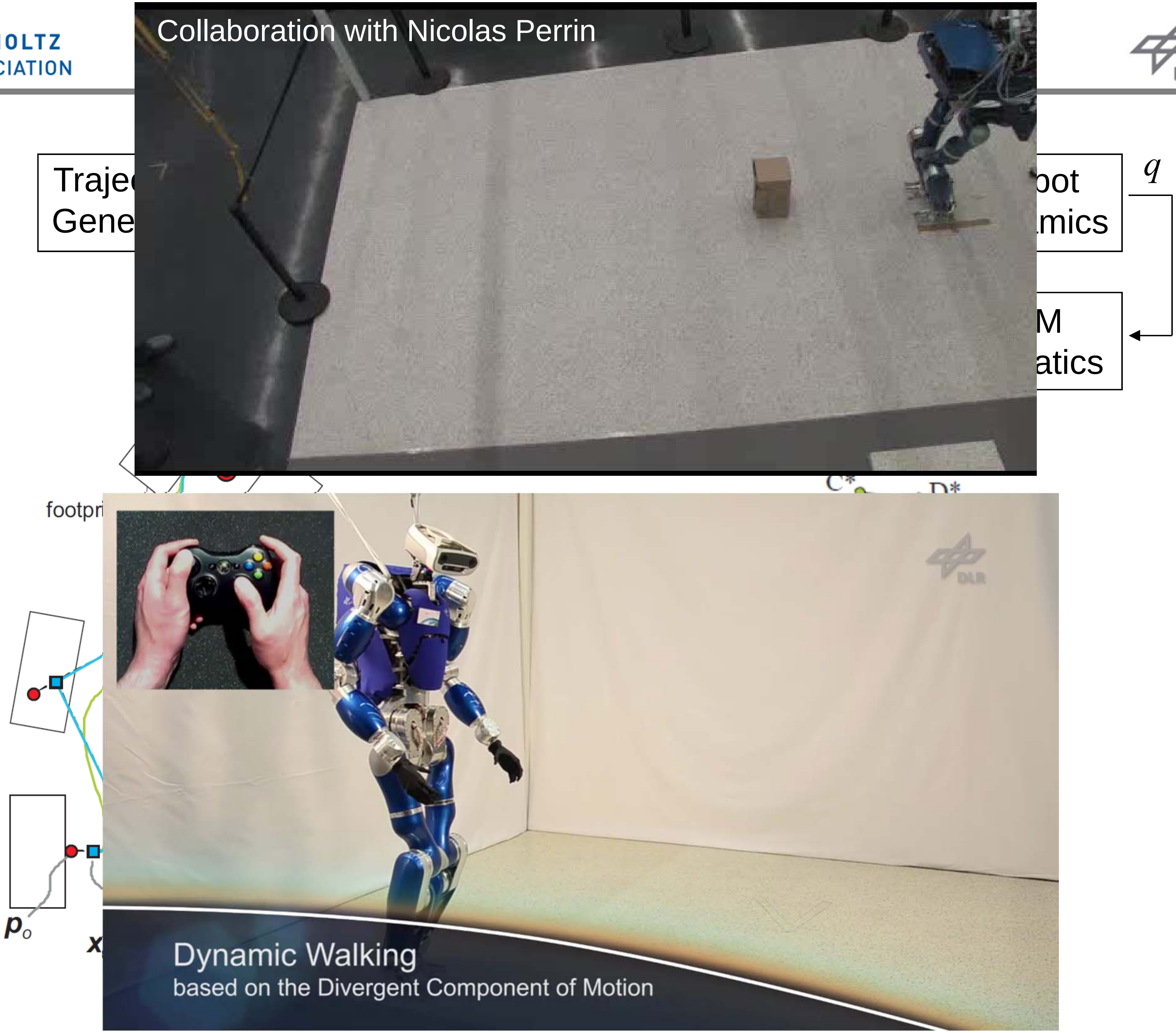




$$\dot{\xi} = \omega(\xi - p)$$



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


Collaboration with Nicolas Perrin
Dynamic Walking
based on the Divergent Component of Motion
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C*
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Extension to 3D walking

2D	3D
Capture Point (CP)	„Divergent Component of Motion“ (DCM) [Takenaka]
$\xi = x + b\dot{x}$	
ZMP (steers CP)	Virtual Repellent Point (steers DCM)

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

$\uparrow$

$mg + F_{ext}$

DCM dynamics:

$$\dot{\xi} = -\frac{1}{b}x + \frac{1}{b}\xi + \frac{b}{m}\boldsymbol{F}$$

[Englsberger, Ott, IROS 2013]

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r_{vrp}

[Englsberger, Ott, IROS 2013]

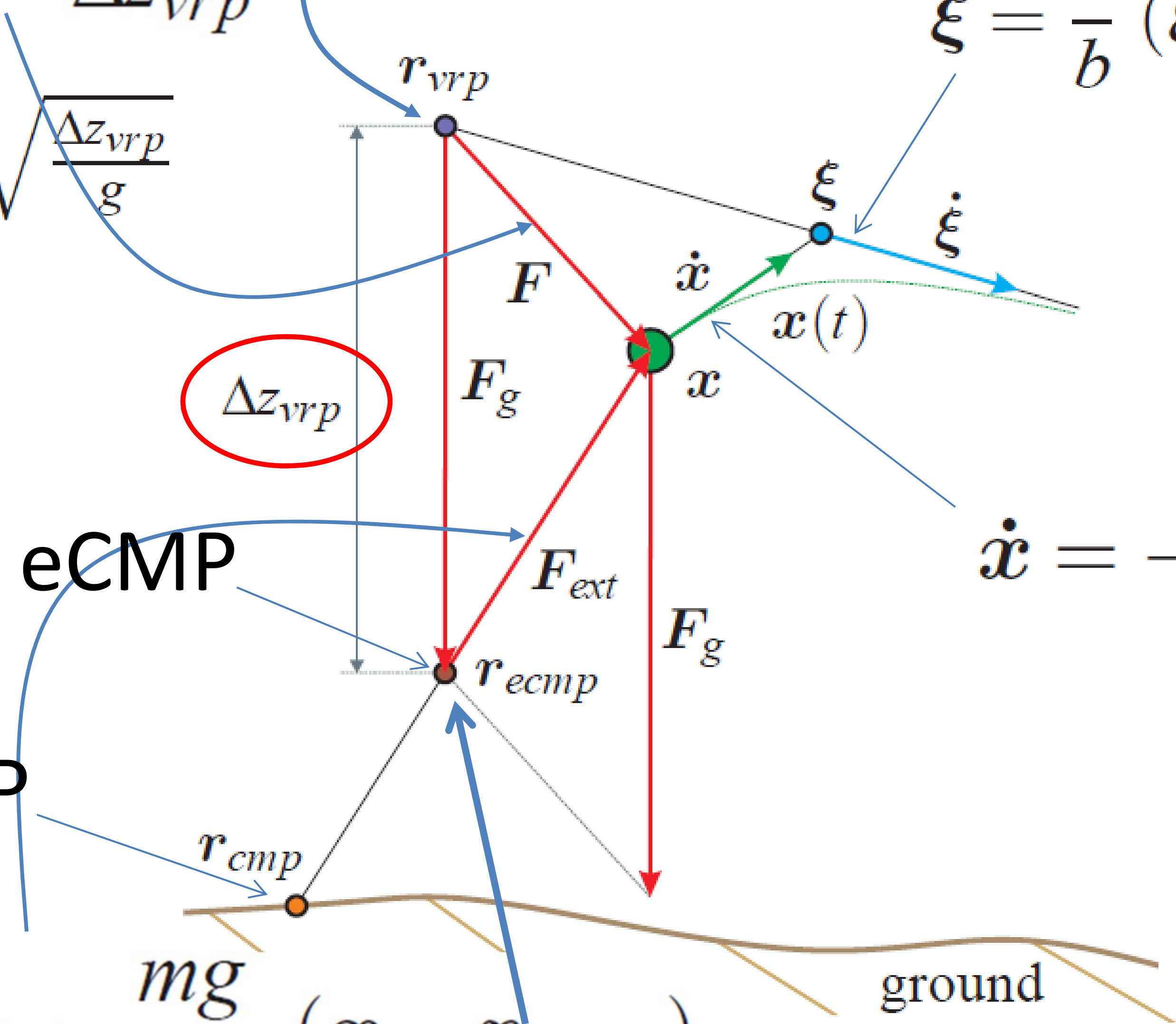
Virtual Repellent Point (V… ,

$$F = \frac{mg}{\Delta z_{vrp}}(x - r_{vrp})$$

$$\dot{\xi} = -\frac{1}{b}x + \frac{1}{b}\xi + \frac{b}{m}F$$

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

$$b = \sqrt{\frac{\Delta z_{vrp}}{g}}$$



$$\dot{x} = -\frac{1}{b}(x - \xi)$$

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

Enhanced Centroidal Moment Pivot point (eCMP)

DCM Tracking Control

DCM dynamics

$$\dot{\boldsymbol{\xi}} = \frac{1}{b}\left(\boldsymbol{\xi} - \boldsymbol{r}_{vrp}\right)$$

Desired closed loop

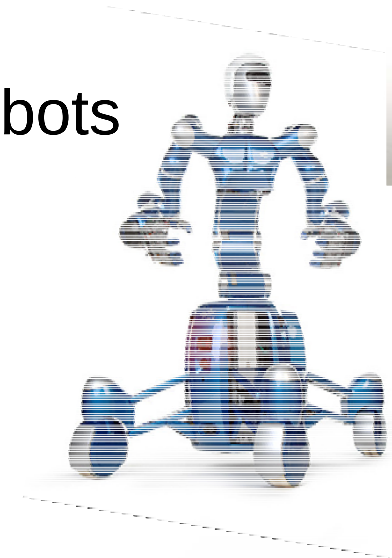
$$\underbrace{\dot{\boldsymbol{\xi}} - \dot{\boldsymbol{\xi}}_d}_{\dot{\boldsymbol{e}}_\xi} = -k\,\underbrace{\left(\boldsymbol{\xi} - \boldsymbol{\xi}_d\right)}_{\boldsymbol{e}_\xi}$$

Tracking control: $\boldsymbol{r}_{vrp,c} = \boldsymbol{\xi} + k\,b(\boldsymbol{\xi} - \boldsymbol{\xi}_d) - b\dot{\boldsymbol{\xi}}_d$

Required leg force:

$$\boldsymbol{F}_{leg,c} = \frac{mg}{\Delta z_{vrp}}\left(\boldsymbol{x} - \underbrace{\left(\boldsymbol{r}_{vrp,c} - \left[0\ 0\ \Delta z_{vrp}\right]^T\right)}_{\boldsymbol{r}_{ecmp,c}}\right)$$

Overview



1) Design & Control of compliant robots

- ✓ Torque Controlled Robots
- ✓ Elastic Robots

2) Control of humanoid robots

- ✓ Compliant Control
- ✓ Bipedal Walking

Thank you very much

for your attention!