Compliant control for grasping and balancing

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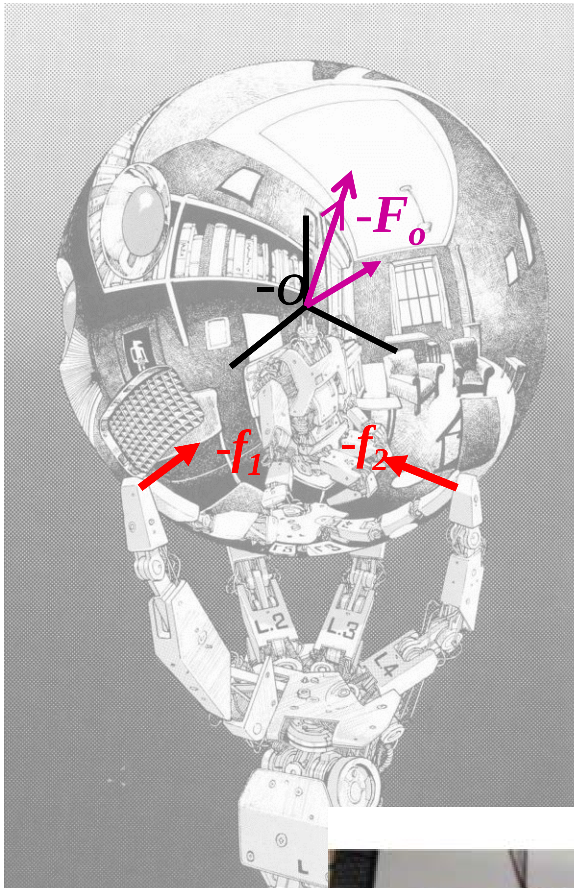
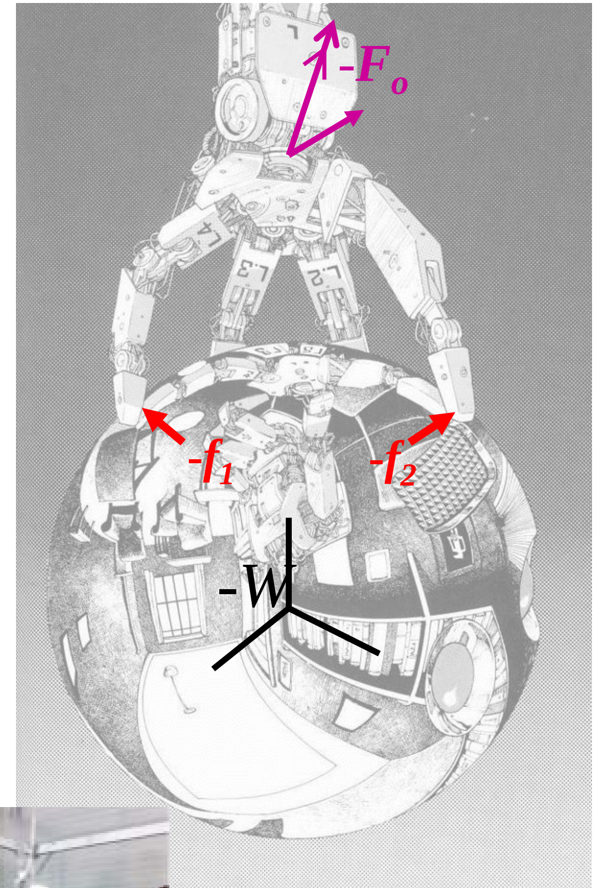
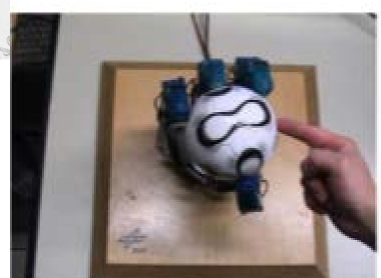
I. INITIAL THOUGHTS

Balancing and walking – fundamentally similar







From Grasping to Walking…

Grasping……………………….....…………………….and Walking

[Thing, The Addams Family]

On hands

Number of DOFs
Manipulation abilities
Cost
Control complexity

Applications in industry
Robustness

Synergies are great

…you just have to unlearn them

Passive walking

-Energy efficiency

-Low control effort

-Low cost of transport

WR: 30h49m2s, 65 km! (May 2011)

6 onboard computers

Hip motor, 2 ankle motors, 1 steering motor

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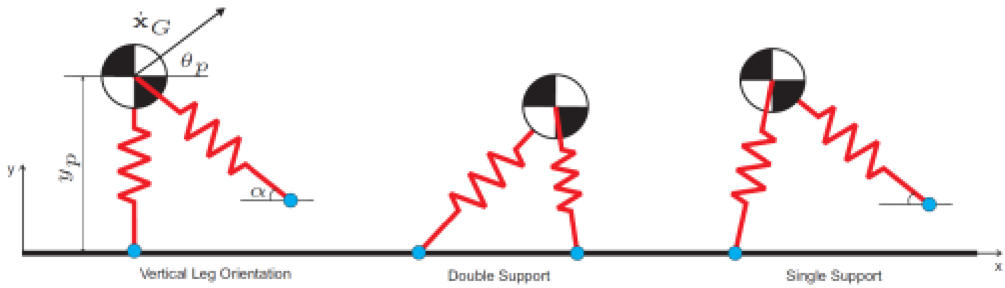
Template models for walking/running



SLIP

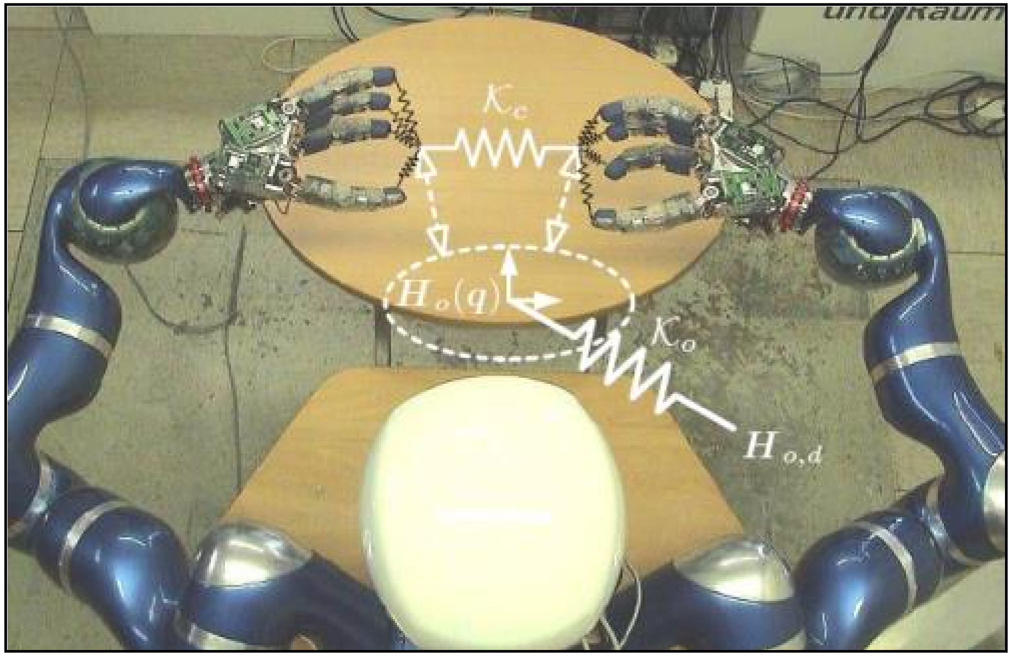
[Garofalo, Ott, ICRA 2012]

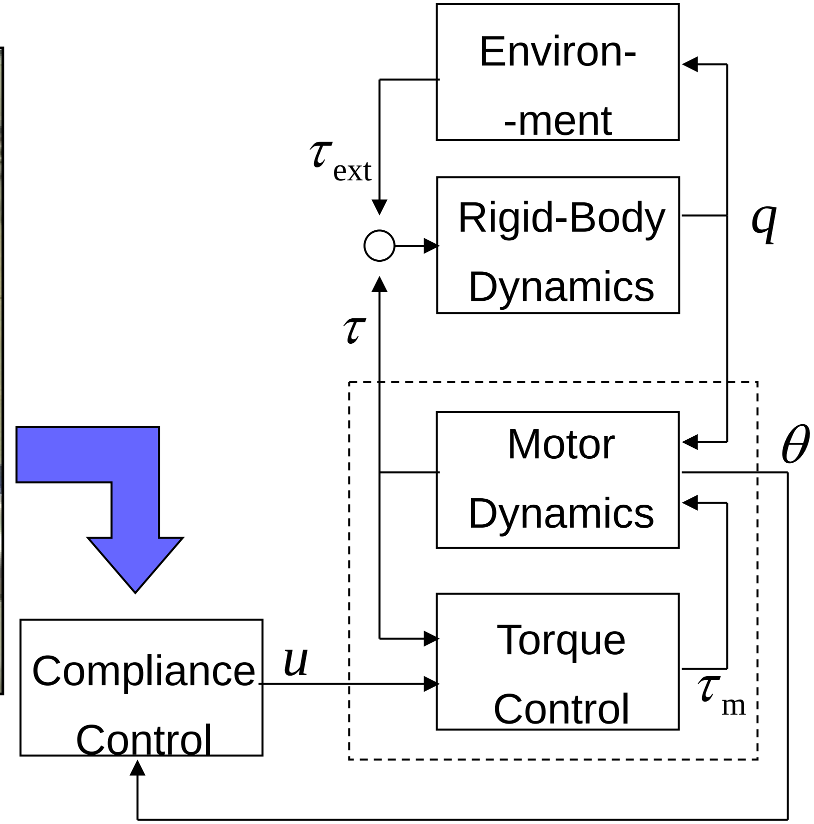
Next American Ninja Warrior…

…that naturally deals with both locomotion and manipulation

II. COMPLIANT MANIPULATION AND GRASPING

Compliant manipulation



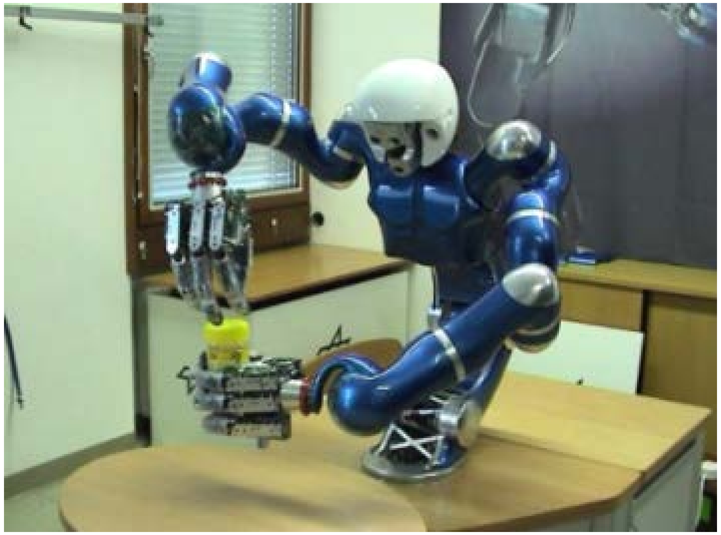


Robustness:
Passivity Based Control

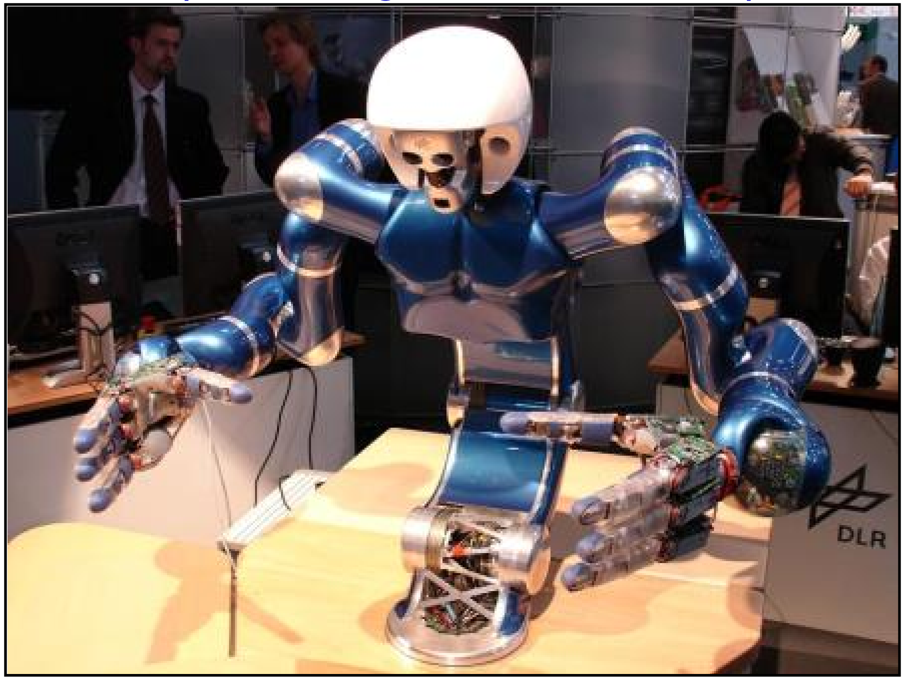
Performance:
Joint Torque Feedback

Robotic manipulation – compliant control

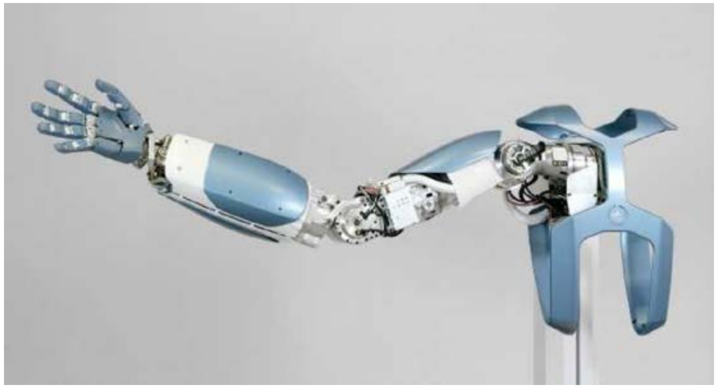
https://www.youtube.com/watch?v=ZPwpGpMoAxs



Joint torque sensing & control for manipulation



Legged Humanoid



Anthropomorphic Hand-Arm System

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

[Grebenstein et al., Humanoids 2010]

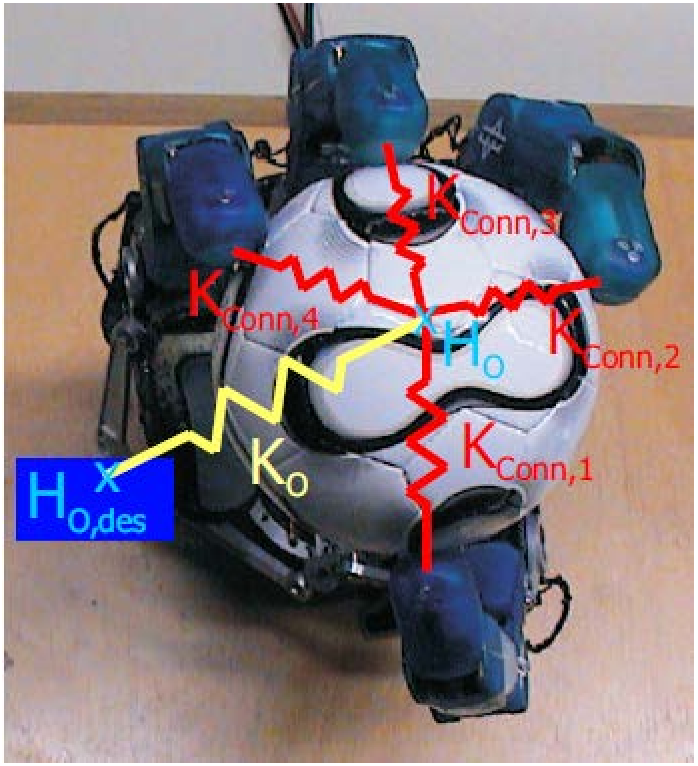
Hand-arm system (Hasy)

https://www.youtube.com/watch?v=nw_PRZeiNs8

https://www.youtube.com/watch?v=qVaaGld401I

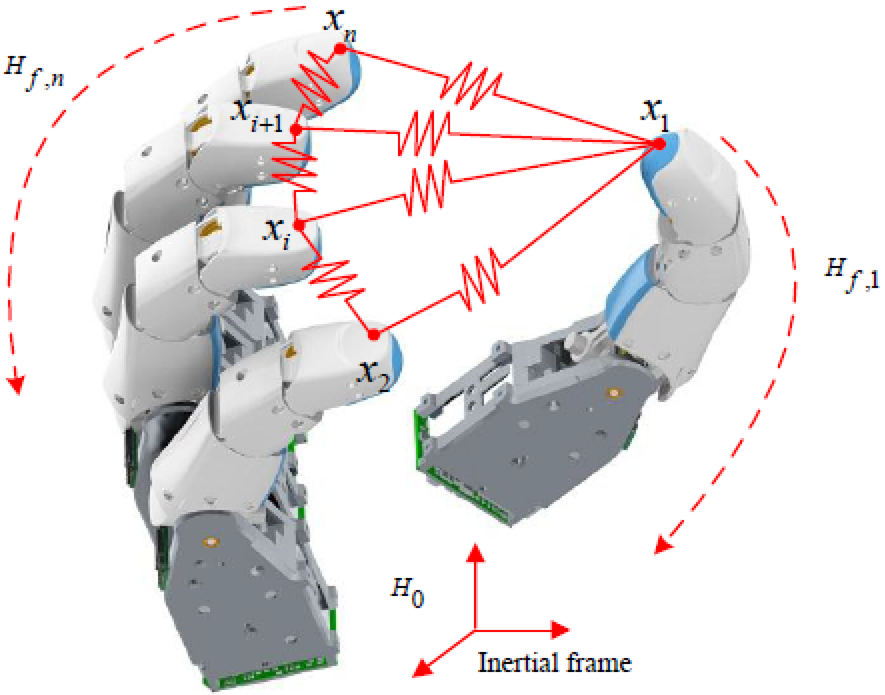
[Grebenstein et al., Humanoids 2010]

Compliant grasp



Object-level impedance

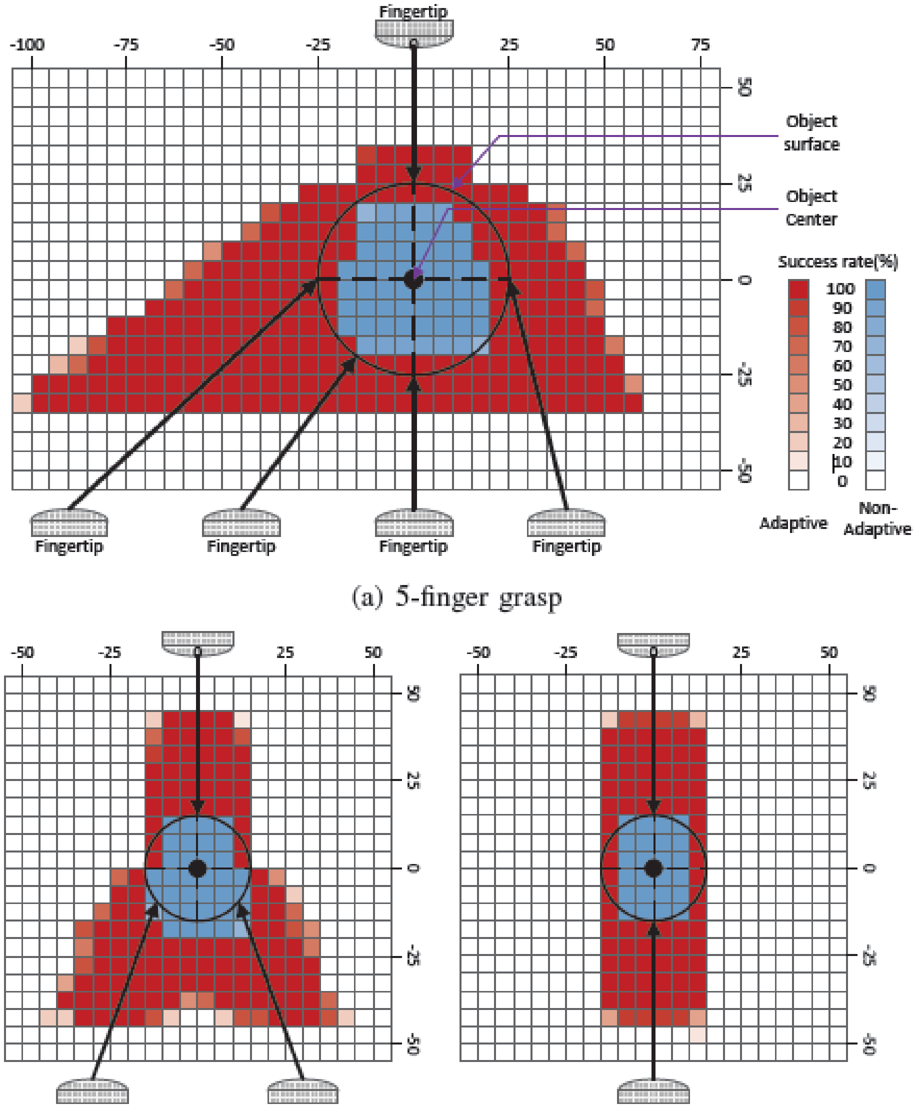
[Wimbock-Ott, IROS06]



Multi-finger impedance

[Chen, Roa et al, ICRA15]

Compliant grasp



(a) 5-finger grasp

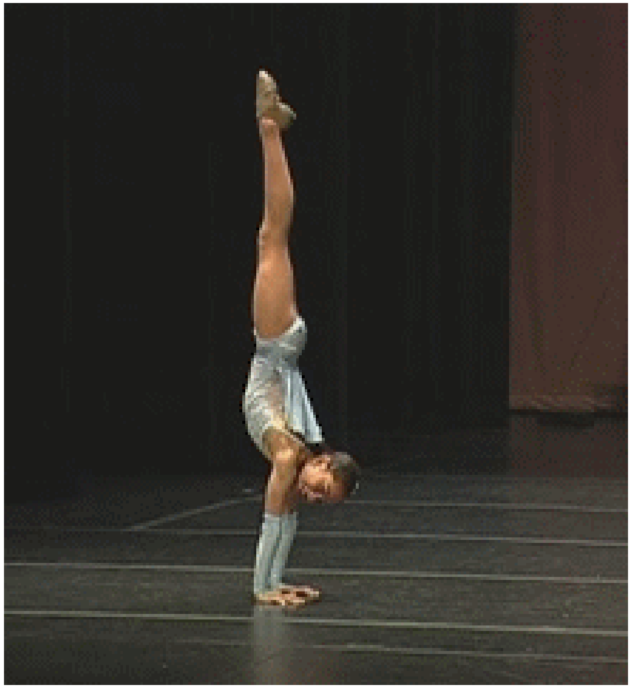
(b) 3-finger grasp

(c) 2-finger grasp

[Chen, Roa et al, ICRA15]

III. COMPLIANT BALANCING

From Manipulation to Walking



Convert arms in legs!

DLR Biped

Experimental biped walking machine

6 DOF / leg

~50 kg

Drive technology of the DLR arm

Newly designed lower leg

Slim foot design: < 10cm

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.

[Ott et al., 2010]

DLR Biped

Current version:

- 76 kg, 1.74 m
- 25 DoF (body) + 2DoF (neck) + 2x6 DoF (hands)
- 2 IMU's, joint position and torque sensors, F/T sensors at the feet
- 1 ASUS Xtion Pro, Stereo cameras
- Autonomy: 1h

DLR-Biped

(2010-2012)

TORO, preliminary version

(2012)

TORO (2013)

TOrque controlled

humanoid RObot

TORO (2014)

Improved version

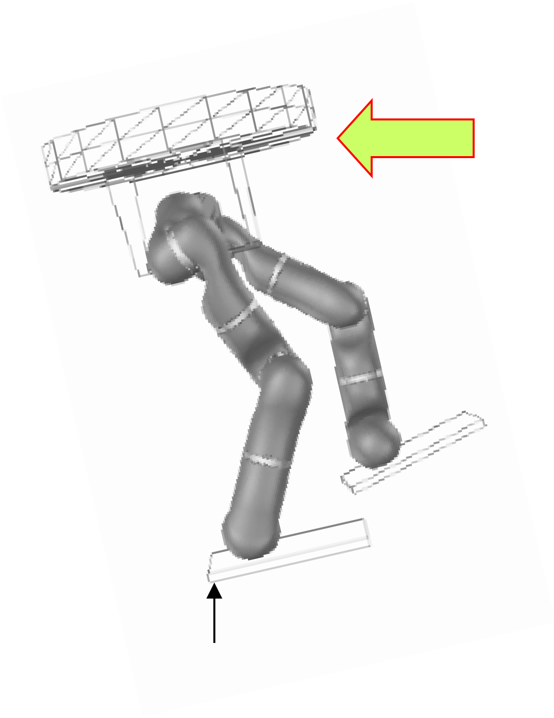
[Englsberger, Roa et al, HUMANOIDS14]

Walking with the DLR Biped

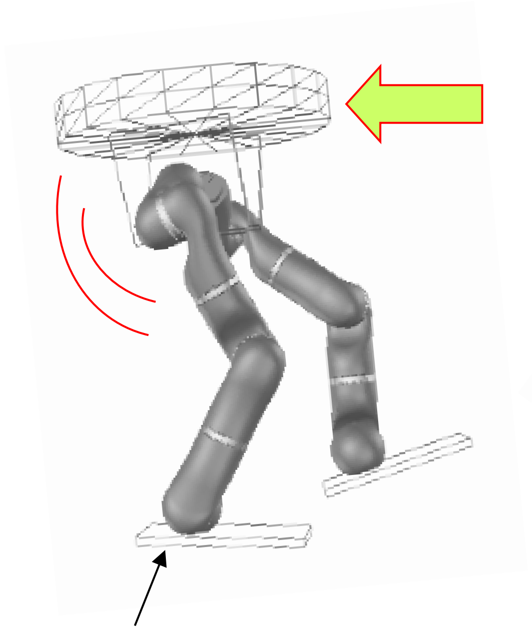
https://www.youtube.com/watch?v=PfqfjcblZ0Q

Motivation for compliant control

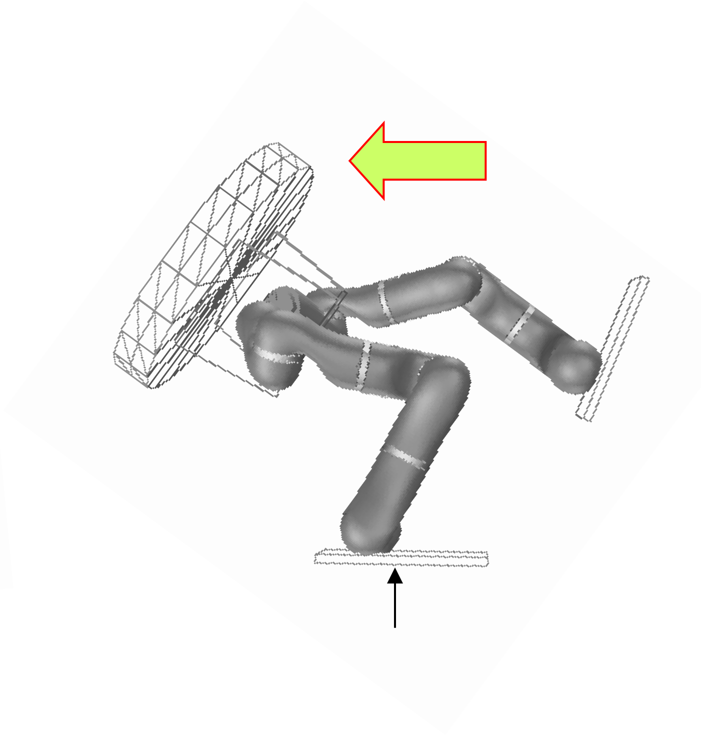
completely stiff



compliant control



fully compliant



Balancing & Posture Control

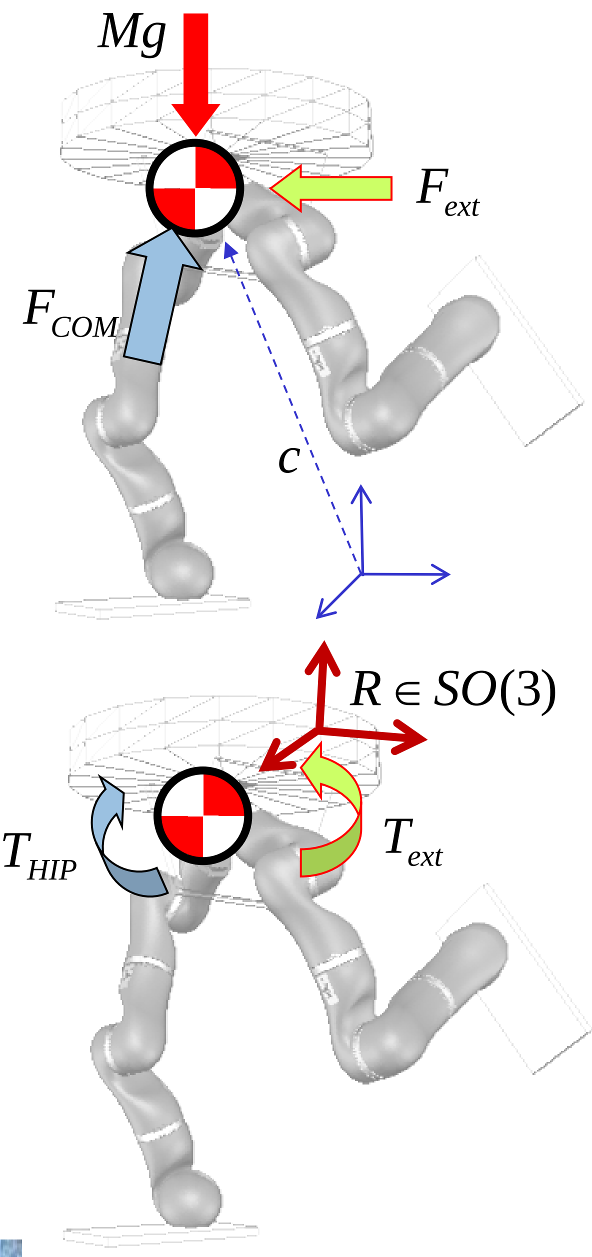
Compliant COM control [Hyon & Cheng, 2006]

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

Trunk orientation Control

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

IMU measurements



[Ott ,Roa, HUMANOIDS11]

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

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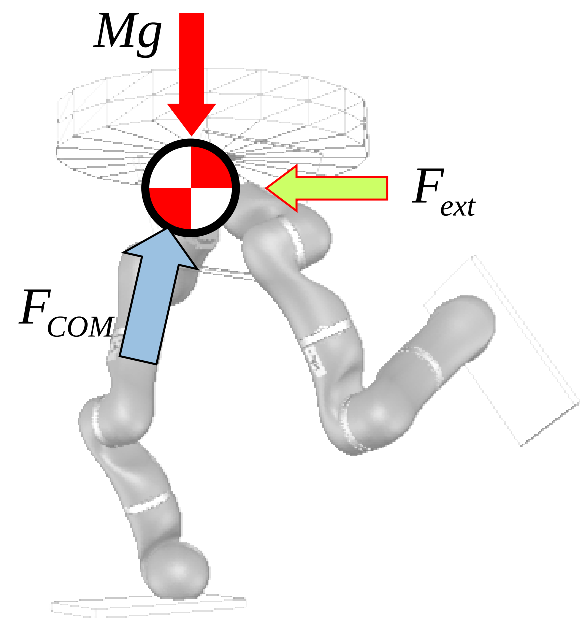

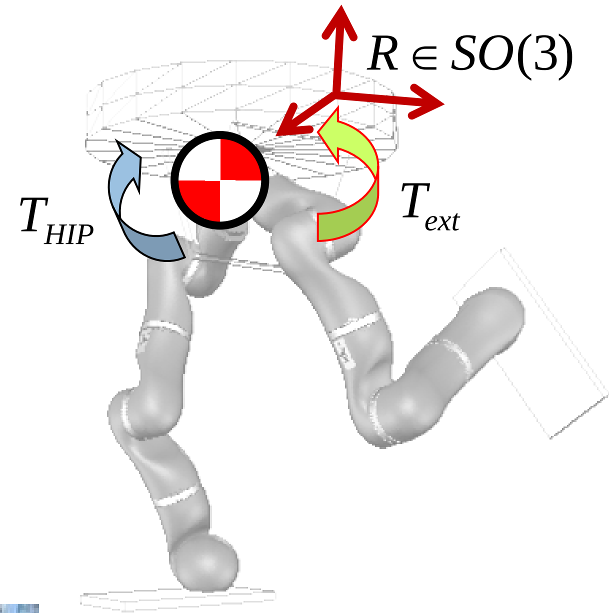

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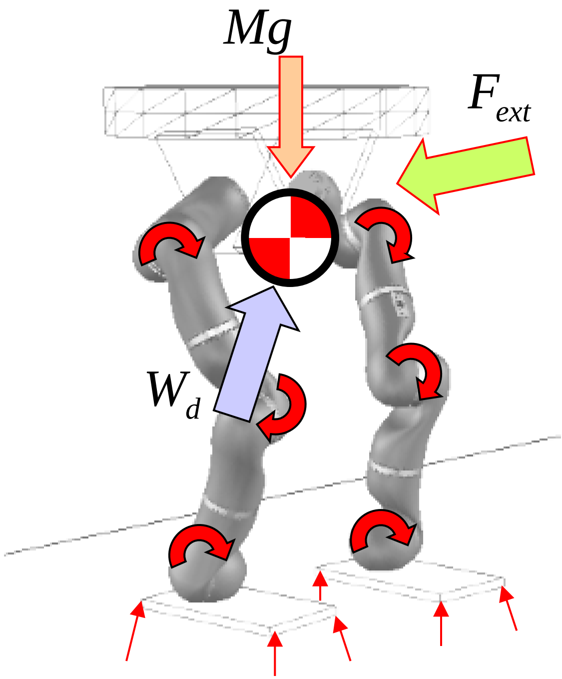

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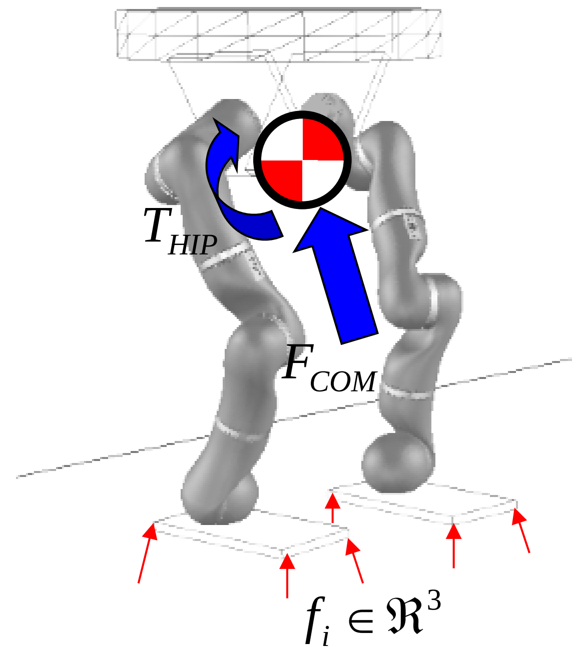
[Ott ,Roa, HUMANOIDS11]

Balancing & Posture Control

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 constrained 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, HUMANOIDS11]

Balancing & Posture Control

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

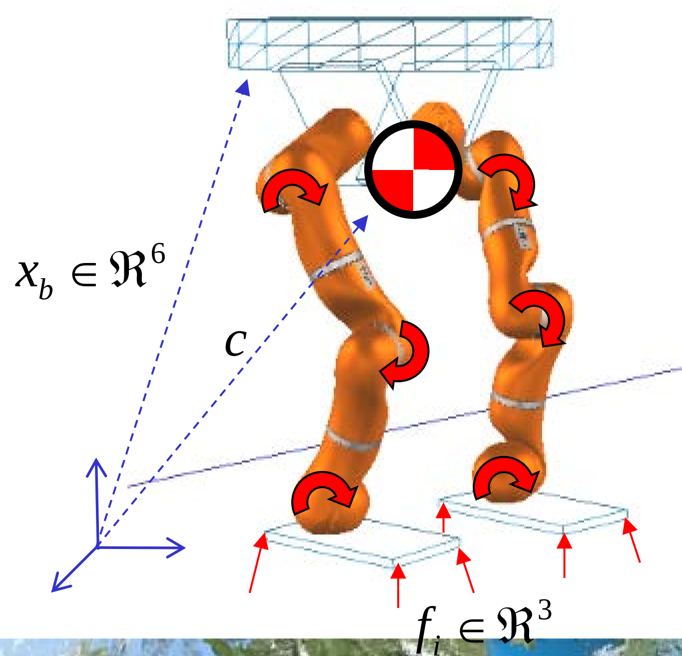
$x_b \Rightarrow (c, \varepsilon)$

[Wieber 2005, Hyon et al. 2006]

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

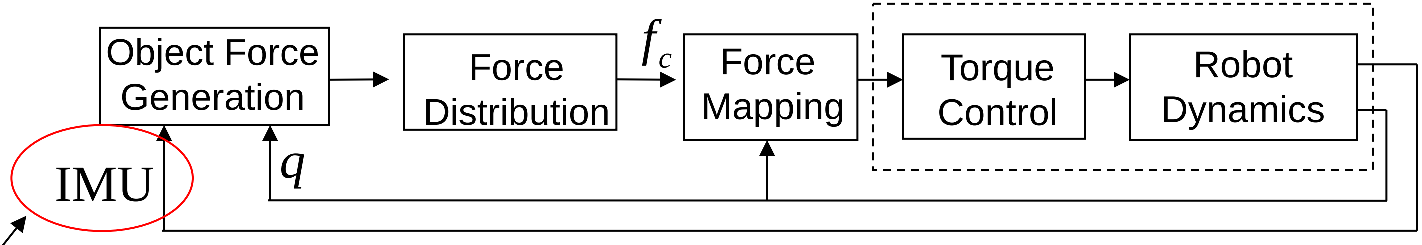
$$M\ddot{c} = Mg - \sum f_i$$

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



[Ott ,Roa, HUMANOIDS11]

Torque based balancing



for orientation control and COM computation

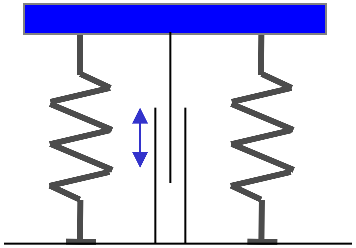
https://www.youtube.com/watch?v=teri9muJnTk

[Ott ,Roa, HUMANOIDS11]

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

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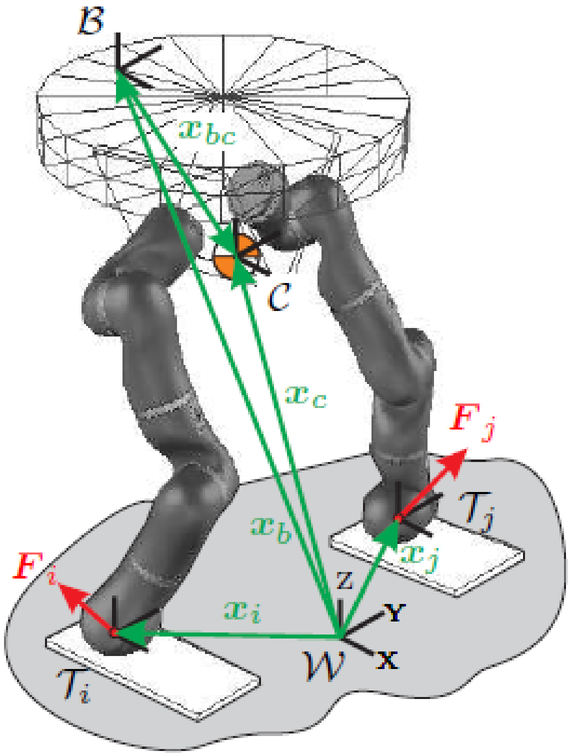
Multi-contact balancing

Change of formulation:



$$\min_{\boldsymbol{F}_{\text{bal}}^{\text{ctrl}}} \frac{1}{2} \left(\boldsymbol{F}_{\text{bal}}^{\text{ctrl}} - \boldsymbol{F}_{\text{bal}}^{\text{def}}\right)^T \boldsymbol{Q} \left(\boldsymbol{F}_{\text{bal}}^{\text{ctrl}} - \boldsymbol{F}_{\text{bal}}^{\text{def}}\right)$$

with respect to the following constraints:

$$\boldsymbol{R}_c \boldsymbol{G}^T \begin{pmatrix} \boldsymbol{F}_{\text{bal}}^{\text{ctrl}} \\ -\boldsymbol{F}_{\text{int}}^{\text{ctrl}} \end{pmatrix} = \begin{bmatrix} m\boldsymbol{I} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{M}_{11} & \boldsymbol{M}_{12} \end{bmatrix} \begin{pmatrix} \ddot{\boldsymbol{x}}_c^d \\ \dot{\boldsymbol{\omega}}_c^d \\ \ddot{\boldsymbol{q}}^{\text{ref}} \end{pmatrix} \begin{bmatrix} \boldsymbol{C}_1 \\ \boldsymbol{C}_2 \end{bmatrix} \begin{pmatrix} \dot{\boldsymbol{x}}_c^d \\ \boldsymbol{\omega}_c^d \\ \dot{\boldsymbol{q}}^{\text{ref}} \end{pmatrix} + \begin{pmatrix} m\boldsymbol{g}_0 \\ \boldsymbol{0} \end{pmatrix} + \boldsymbol{F}_c^{\text{ctrl}}$$

$$f_{i,\perp}^{\text{ctrl}} \geq f_i^{\text{min}} \qquad \forall i = 1 \ldots \psi$$

$$\left\| \boldsymbol{f}_{i,\|}^{\text{ctrl}} \right\| \leq \mu_i \cdot \left| f_{i,\perp}^{\text{ctrl}} \right| \qquad \forall i = 1 \ldots \psi$$

$$\boldsymbol{p}_i \in \mathcal{S}_i \qquad \forall i = 1 \ldots \psi.$$

Multi-contact balancing (and other control applications)

https://www.youtube.com/watch?v=LBemI9AmTT4

Summary

- (Active) compliant control principles work well for grasping and manipulation

- Natural compliance should also be exploited
  - Contact compliance in grasping (not avoiding contacts)
  - Heel-toe transition in walking (not flat foot)

- Goal: multi-purpose compliant humanoid robot?

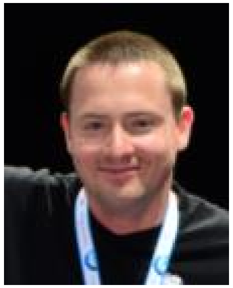
Parkour

Sonny, I Robot

Acknowledgments







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Thanks for your attention!

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