An Attractor-based Whole-Body Motion Control (WBMC) System

Tests with the COMAN Robot

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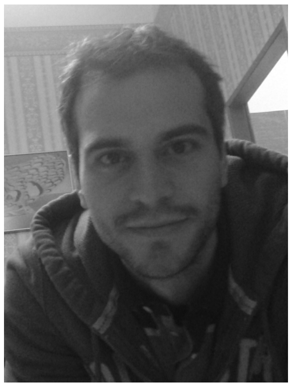
“Whole-Body Control for Robots in the Real World” Workshop @ IROS 2014

Credits



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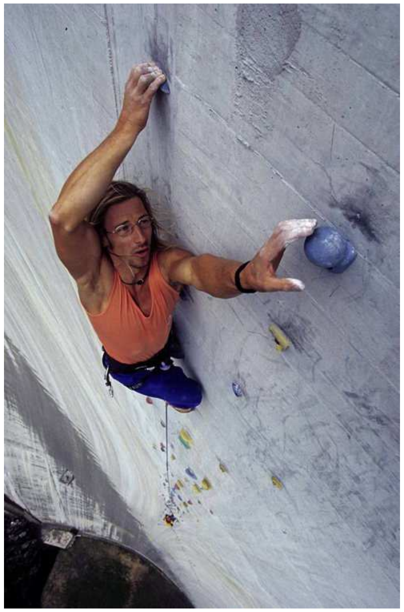
Aims and Scope

Novel Whole-Body Motion Control (WBMC) System

- Exploitation of full-body capabilities in the execution of a task
- Coordination among multiple tasks



Aims and Scope

Novel Whole-Body Motion Control (WBMC) System

Peters et al.

Nakamura

Sentis et al.

Gienger et al.

Righetti et al.

Del Prete et al.

Kajita et al.

Mistry et al.

Saab et al.

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Novel Whole-Body Motion Control (WBMC) System

Inverse Kinematics

Nakamura

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Novel Whole-Body Motion Control (WBMC) System

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Inverse Dynamics

Peters et al.

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Mistry et al.

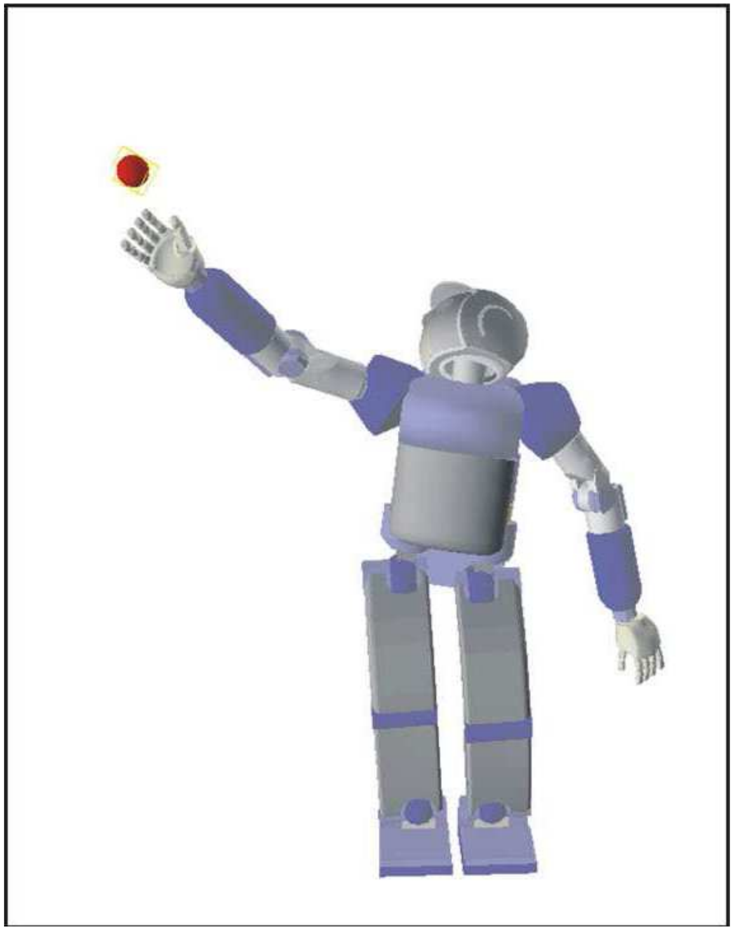
Saab et al.

Background

Null-space-based approaches

"(…) prioritization was established by projecting lower priority tasks within the residual redundancy (i.e. the null-space) of higher priority tasks. In this context, null space projections impose that lower priority tasks do not introduce acceleration and force components in higher priority tasks (…)"

(L. Sentis, 2007)



Background

Null-space-based approaches

PROS

- Works properly in the majority of the scenarios
- High priority tasks not affacted by other tasks

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Null-space-based approaches

PROS

- Works properly in the majority of the scenarios
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CONS

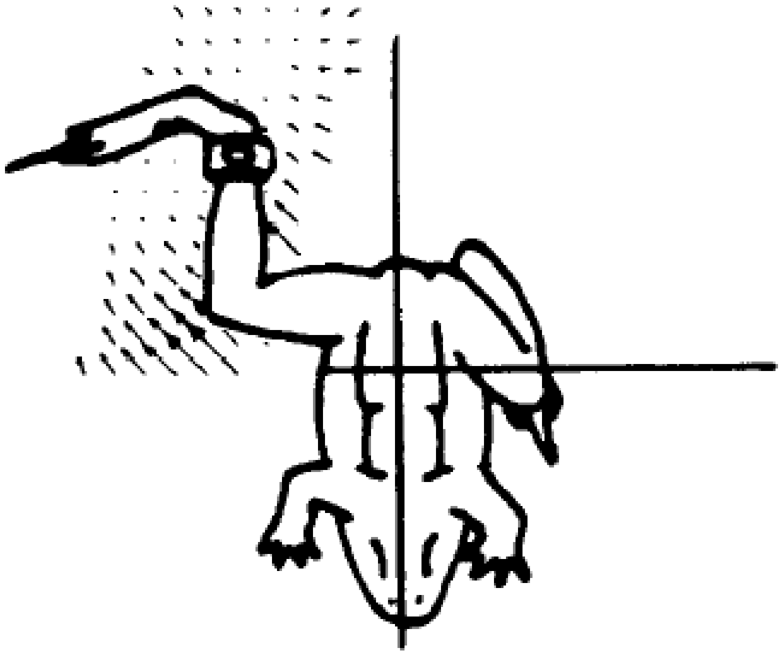
- Unfeasibility issue
- Constrained by redundancy availability
- Problem of transitions
- Requires strict priorities

Motivation

More flexible (or compliant) solution --> *Attractor*-based approach

Biological inspiration

Convergent Force Fields (CFFs)



"It was concluded that fixed-pattern force fields elicited in the spinal cord may be viewed as movement primitives. These force fields could form building blocks for more complex behaviors"

S.F. Giszter, F.A. Mussa-Ivaldi, E. Bizzi,
Convergent Force Fields Organized in the Frog's Spinal Cord
The Journal of Neuroscience, 13(2):467-491 (1993)

The attractors

[Pics from Google Images]

The attractors

Attractor: atomic control module that affects the state of the robot driving it towards a more preferred one

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$$\boxed{\tau = f\left(g\left(q, \dot{q}\right)\right)}$$

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Any "physical" or "derived" measure

The attractors

Attractor: atomic control module that affects the state of the robot driving it towards a more preferred one

$$\boxed{\tau = f\left(\underbrace{g(q,\dot{q})}\right)}$$

Any "physical" (e.g., joint/task position) or "derived" (CoM location, ZMP location, angular momentum) measure

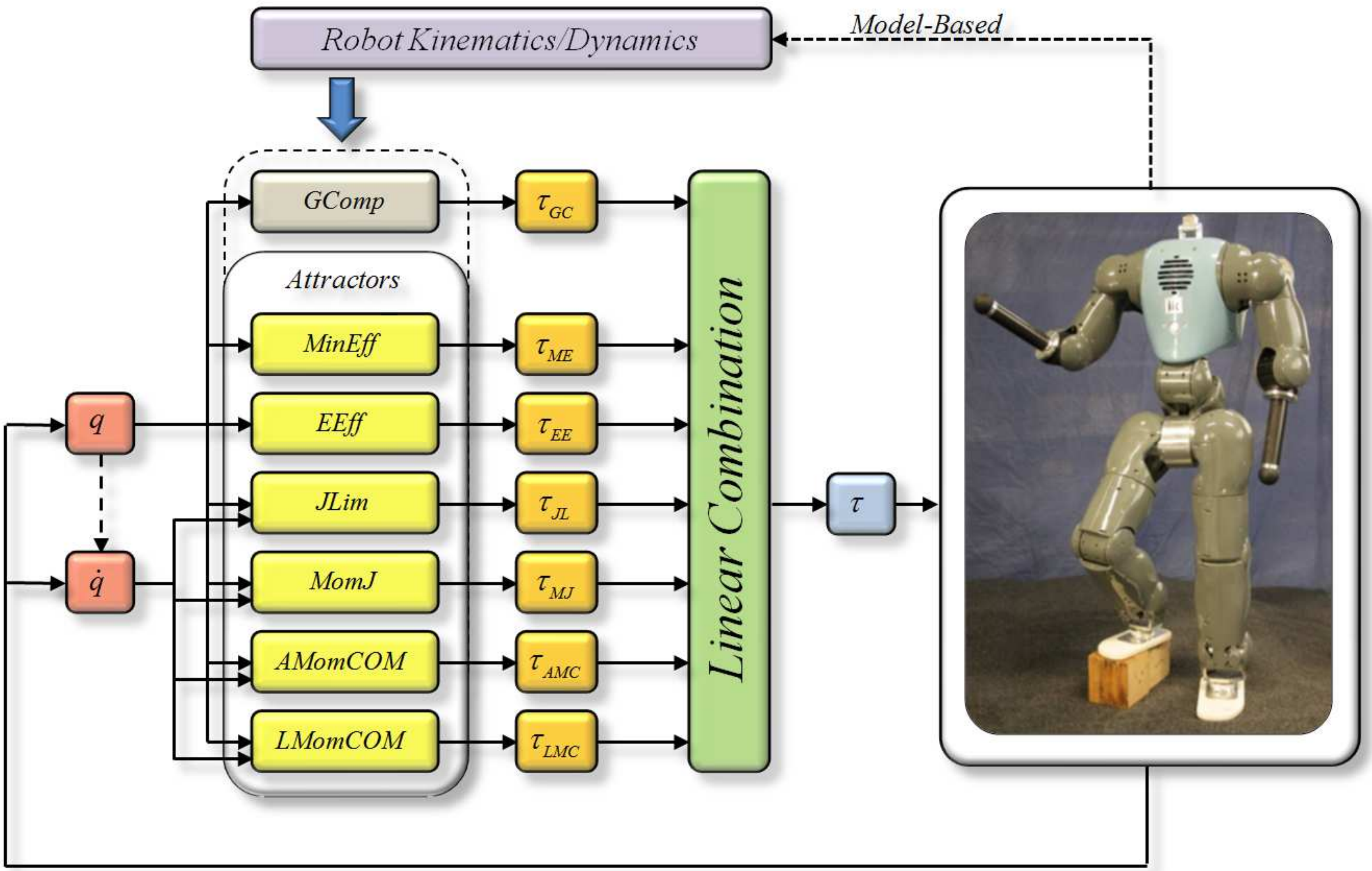
The attractors

Attractor: atomic control module that affects the state of the robot driving it towards a more preferred one

$$\boxed{\tau = f\left(g\left(q,\dot{q}\right)\right)}$$

$$f = \nabla g = \left[\frac{\partial g}{\partial q_1} \cdots \frac{\partial g}{\partial q_n}\right] \qquad f = \nabla g = \left[\frac{\partial g}{\partial \dot{q}_1} \cdots \frac{\partial g}{\partial \dot{q}_n}\right]$$

WBMC System


Robot Kinematics/Dynamics
Model-Based
GComp
Attractors
MinEff
EEff
JLim
MomJ
AMomCOM
LMomCOM
τ_{GC}
τ_{ME}
τ_{EE}
τ_{JL}
τ_{MJ}
τ_{AMC}
τ_{LMC}
Linear Combination
τ
q
$\dot{q}$

Gravity compensation

$$\tau_{GC}(q) = \left(N_C(q)S^T\right)^+ N_C(q) \cdot h(q) = P(q) \cdot h(q)$$

M. Mistry et al. (2010)

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Expanding the pseudo-inverse

$$P = \left(\left(N_C S^T\right)^T \left(N_C S^T\right)\right)^{-1} \left(N_C S^T\right)^T N_C = \left(S N_C^T N_C S^T\right)^{-1} S N_C$$

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M. Mistry et al. (2010)

$$N_C S^T \rightarrow (29\times 23)$$

$$SV_C \rightarrow (17\times 23)$$

$$\tau_{GC}(q) = \left(\left(SV_C(q)\right)^+\right)^T V_C^T(q)\cdot h(q) = P(q)\cdot h(q)$$

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Equilibrium

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"A system of particles is in static equilibrium whan all the particles are at rest and the total force on each particle is permanently zero"

(H.C. Corben, *Classical Mechanics*, p.113, 1960)

[Pic from Google Images]

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1. The resultant force/torque acting on the system is zero

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4. The system is "internally" at rest

[Pic from Google Images]

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$$F_{COM} = 0_{6\times1}$$

$$\tau_j = 0_{n\times1}$$

$$v_{COM} = 0_{6\times1}$$

$$v_j = 0_{n\times1}$$

[Pic from Google Images]

MinEff

1. The resultant force/torque acting on the system is zero
2. The “internal” torques generated by the external forces applied to the system are all zero

MinEff

$$h(q) + J_{ext}(q)^T F_{ext} = 0$$

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$$E = \tau_{GC}^T W \tau_{GC}$$

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$$\nabla E = \left[\frac{\partial E}{\partial q_1} \cdots \frac{\partial E}{\partial q_n} \right]^T$$

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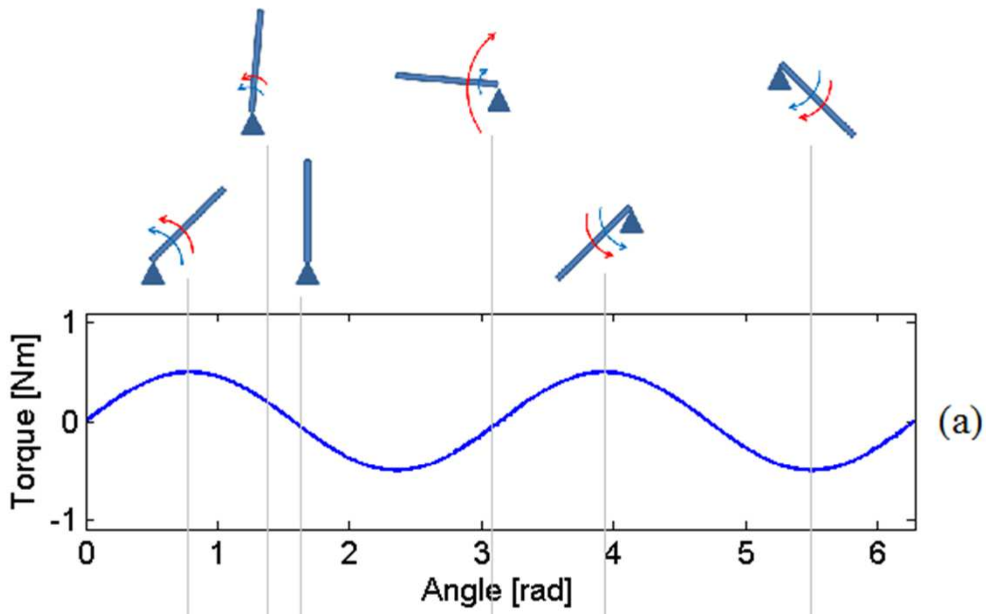
$$\tau_{ME} = -k_{ME} \nabla E$$



MinEff

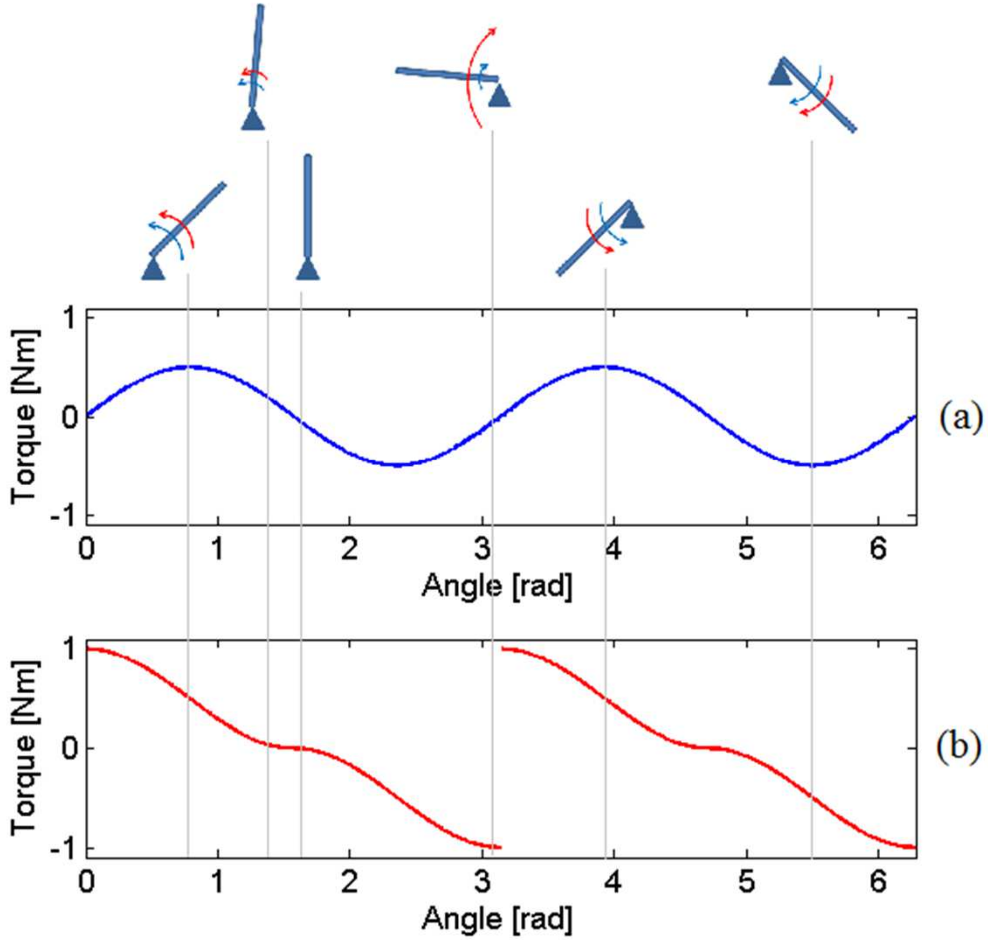
$$\tau_{GC} = 0 \longleftarrow h(q) + J_{ext}(q)^T F_{ext} = 0$$

$$E = \tau_{GC}^T W \tau_{GC}$$

$$\nabla E = \left[\frac{\partial E}{\partial q_1} \cdots \frac{\partial E}{\partial q_n} \right]^T$$

$$\cancel{\tau_{ME} = -k_{ME} \nabla E}$$

$$\tau_{ME} = -k_{ME} sign(\nabla E) \circ (\tau_{GC} \circ \tau_{GC})$$



MomJ

4. The system is "internally" at rest

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Joint velocities have to be attracted to zero

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Joint velocities have to be attracted to zero → damping

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Joint velocities have to be attracted to zero ⇒ damping

$$\tau_{MJ} = -k_{MJ}\dot{q}$$

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MomJ

Joint velocities have to be attracted to zero → damping

$$\tau_{MJ} = -k_{MJ}\dot{q}$$

- Each joint connects two subsystems that have an inertia that is typically different from the inertia seen by other joints
- Each joint is affected by the motion of the other joints to which it is connected

4. The system is "internally" at rest

MomJ

Joint velocities have to be attracted to zero ⇒ damping

$$\cancel{\tau_{MJ} = -k_{MJ}\dot{q}}$$

Joint momentum

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MomJ

Joint velocities have to be attracted to zero ⇒ damping

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Joint momentum

$$h_j = M\dot{q}$$

D.E. Orin et al. (2013)

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MomJ

Joint velocities have to be attracted to zero $\Rightarrow$ damping

$$\cancel{\tau_{MJ} = -k_{MJ}\dot{q}}$$

Joint momentum

$$h_j = M\dot{q}$$

D.E. Orin et al. (2013)

$$\tau_{MJ} = -k_{MJ}\left(M\dot{q}\right) = -k_{MJ}\left(h_j\right)$$

4. The system is "internally" at rest

MomCOM

$$h_{g,lin} = \left(\sum_i m_i J_{T,COM,i} \right) \cdot \dot{q}$$

$$h_{g,ang} = \left(\sum_i m_i \tilde{r}_{COM,i} J_{T,COM,i} + I_i J_{R,i} \right) \cdot \dot{q}$$

$\tilde{r}_{COM,i}$

is the skew-symmetric form of

$r_{COM,i}$

MomCOM

$$h_{g,lin} = \left(\sum_i m_i J_{T,COM,i} \right) \cdot \dot{q}$$

$$\tau_{LMC,i} = -k_{LMC} \frac{\partial \left(\left\| h_{g,lin} - \bar{h}_{g,lin} \right\| \right)}{\partial \dot{q}_i} h_{g,lin}$$

$$h_{g,ang} = \left(\sum_i m_i \tilde{r}_{COM,i} J_{T,COM,i} + I_i J_{R,i} \right) \cdot \dot{q}$$

$$\tau_{AMC,i} = -k_{AMC} \frac{\partial \left(\left\| h_{g,ang} \right\| \right)}{\partial \dot{q}_i}$$

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$$\bar{h}_{g,lin} = \bar{v} \sum_i m_i$$

$\tilde{r}_{COM,i}$

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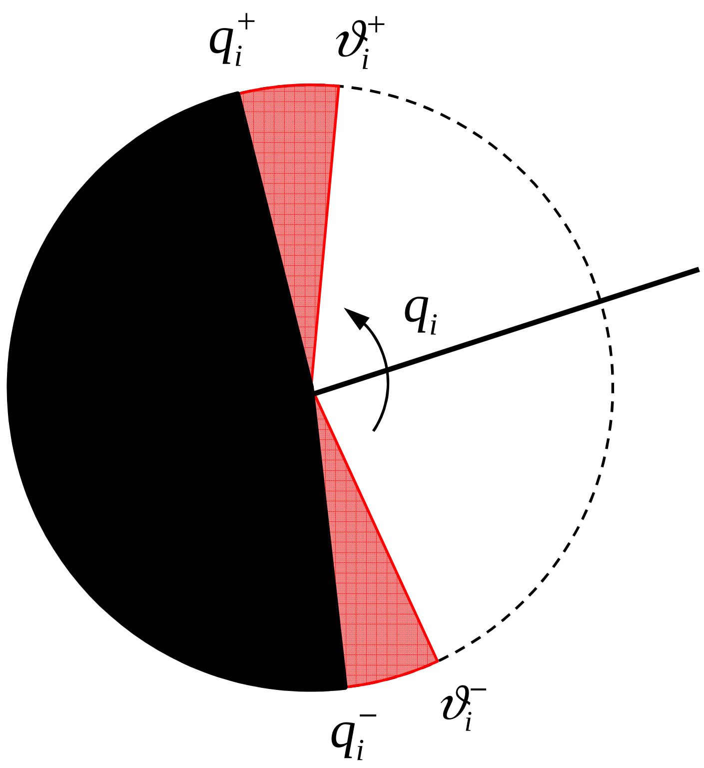
JLim

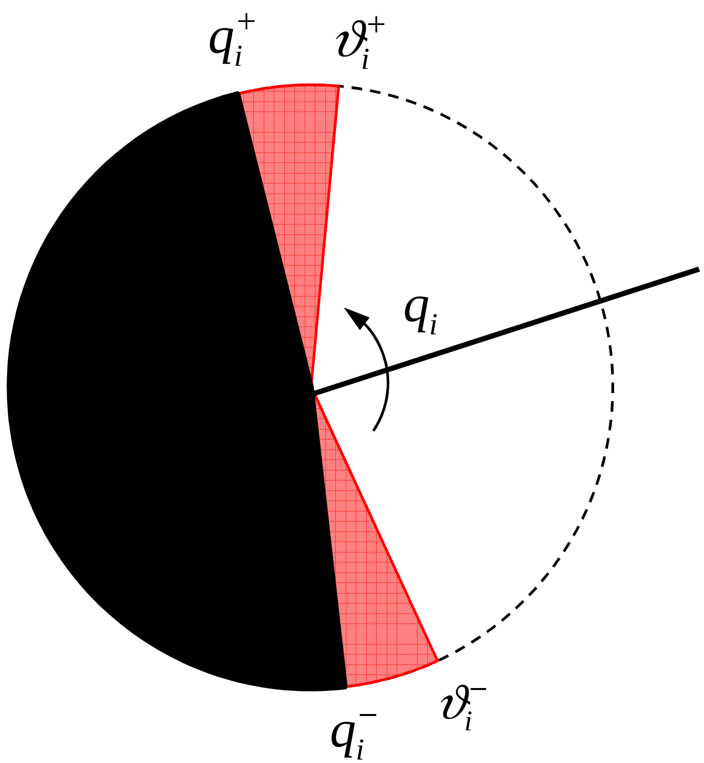
q_i^-, q_i^+ are the joint limits

$0.0 \le \Delta \le 0.5$ is a *"safety margin"*



JLim

q_i^-, q_i^+	are the joint limits	$\vartheta_i^- = q_i^- + \Delta\left(q_i^+ - q_i^-\right)$
$0.0 \le \Delta \le 0.5$	is a *"safety margin"*	$\vartheta_i^+ = q_i^+ - \Delta\left(q_i^+ - q_i^-\right)$



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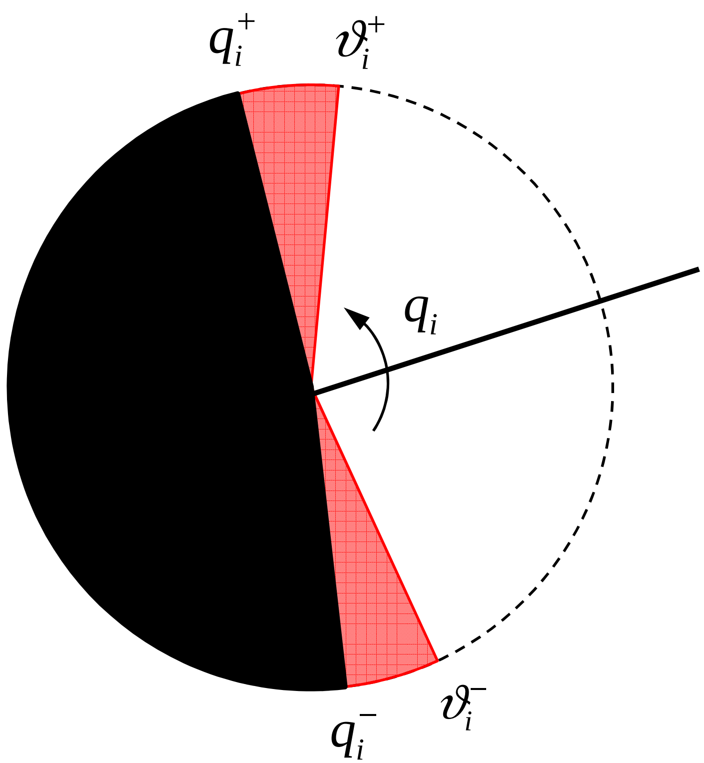

if $q_i < \vartheta_i^-$

then $\tau_{JL,i} = k_{JL,S}\left(\dfrac{q_i - \vartheta_i^-}{q_i^- - \vartheta_i^-}\right)^2 - k_{JL,D}\left(\dot{q}_i\right)$

if $\vartheta_i^- \le q_i \le \vartheta_i^+$

then $\tau_{JL,i} = 0$

if $q_i > \vartheta_i^+$

then $\tau_{JL,i} = -k_{JL,S}\left(\dfrac{q_i - \vartheta_i^+}{q_i^+ - \vartheta_i^+}\right)^2 - k_{JL,D}\left(\dot{q}_i\right)$

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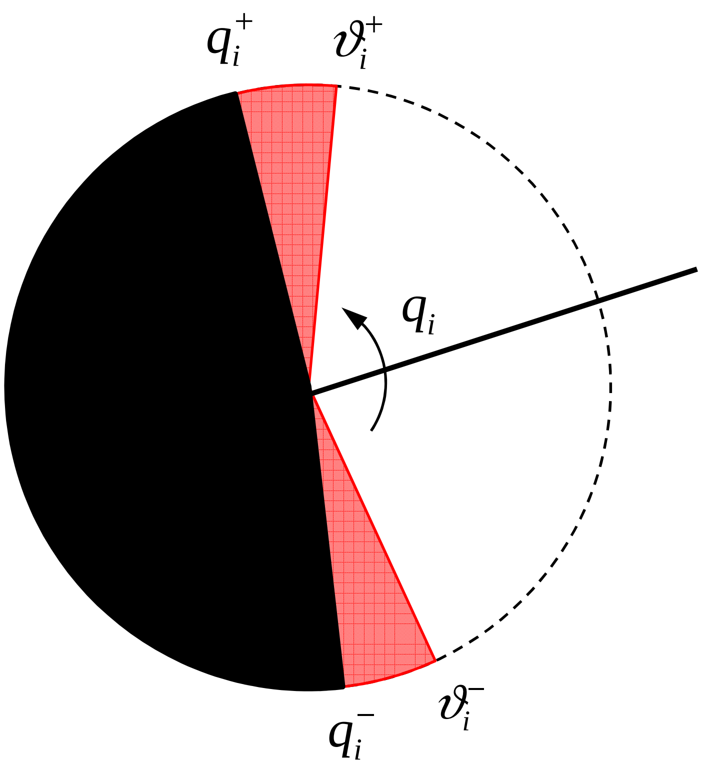

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$\tau_{JL,i} \ge 0$

if $\vartheta_i^- \le q_i \le \vartheta_i^+$

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$\tau_{JL,i} \le 0$

if $q_i > \vartheta_i^+$

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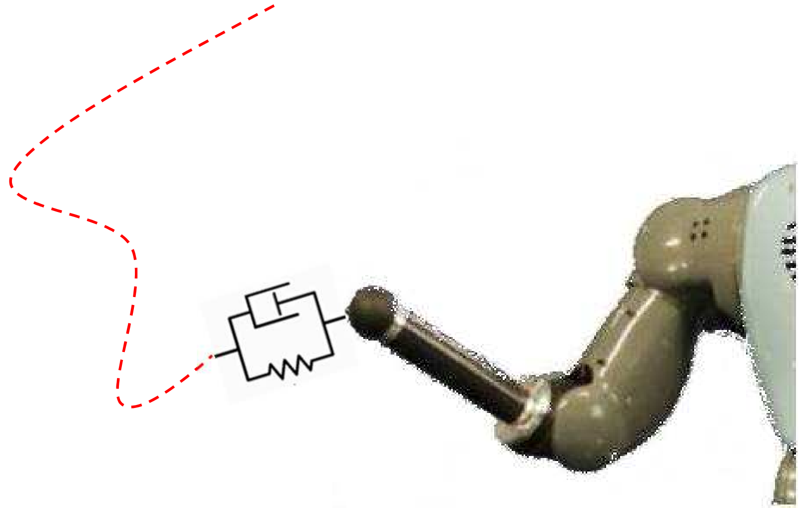
EEff

$$F_{EE} = k_{EE,S}\left(\bar{x}_{EE} - x_{EE}\right) + k_{EE,D}\left(\bar{\dot{x}}_{EE} - \dot{x}_{EE}\right)$$

$$\tau_{EE} = P\left(J_{EE}^{T} F_{EE}\right)$$

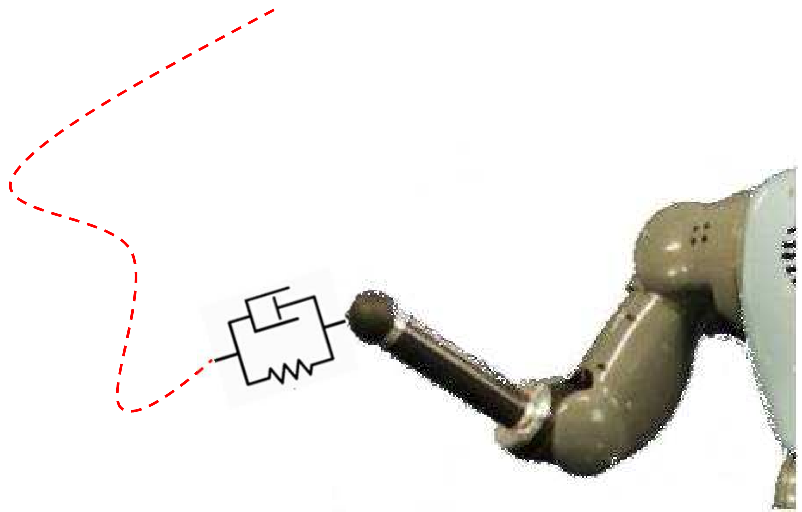


EEff

$$F_{EE} = k_{EE,S}\left(\bar{x}_{EE} - x_{EE}\right) + k_{EE,D}\left(\dot{\bar{x}}_{EE} - \dot{x}_{EE}\right)$$

$$\tau_{EE} = P\left(J_{EE}^{T} F_{EE}\right)$$

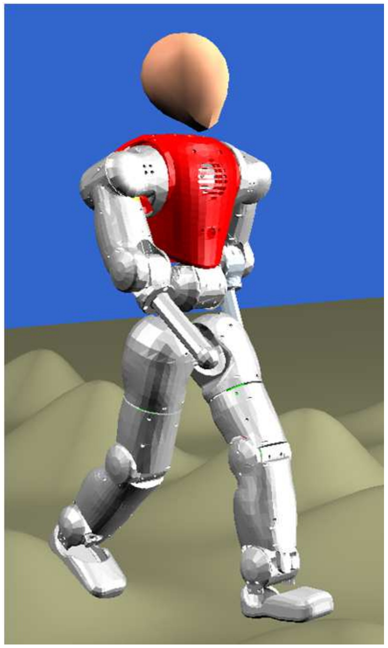
$$P = \left(\left(SV_C\right)^{+}\right)^{T} V_C^{T}$$



Results in simulation

- Gcomp
- JLim
- Equilibrium
  - MinEff
  - MomJ
  - MomCOM

The 29-dofs model of COMAN was developed in Robotran, including the information on the full dynamics of the robot obtained from the CAD of the real prototype



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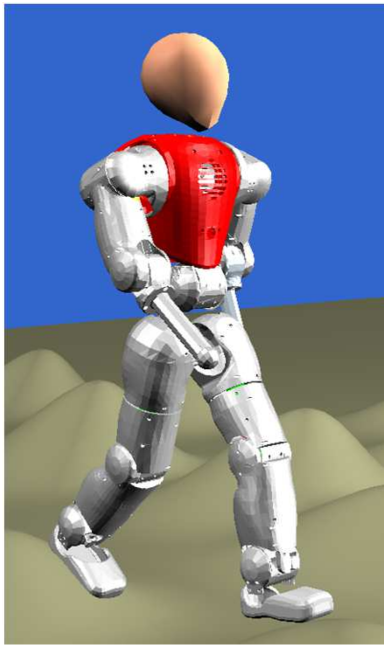
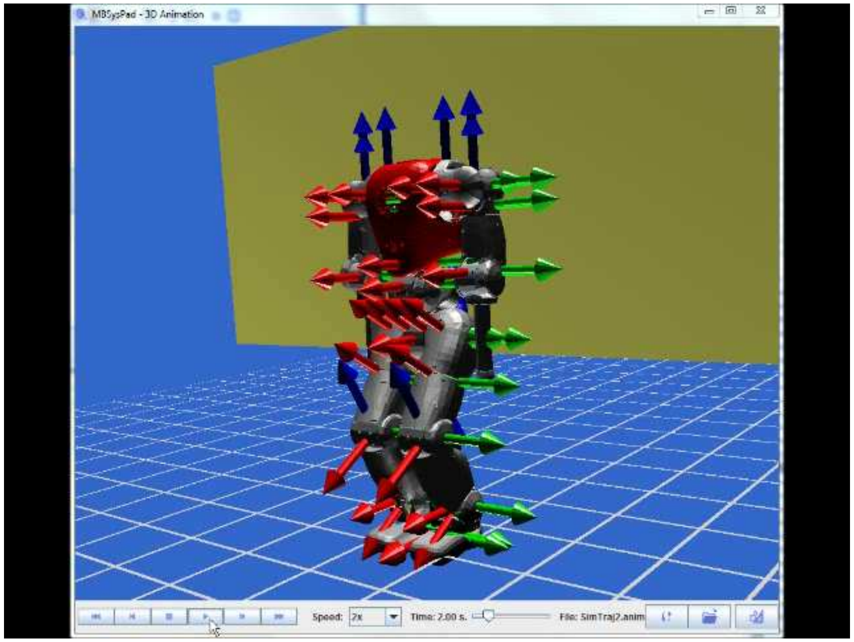


The simulation starts with COMAN standing in place with bent knees, i.e., in a non-minimum effort configuration. All initial joint velocities are set to zero.

Results in simulation



Gcomp + Jlim + MinEff + MomJ + MomCOM

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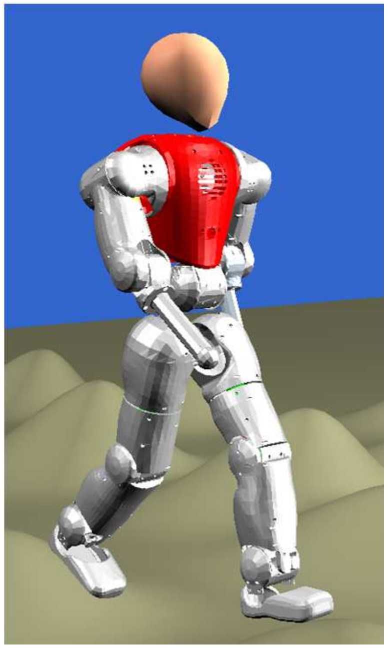

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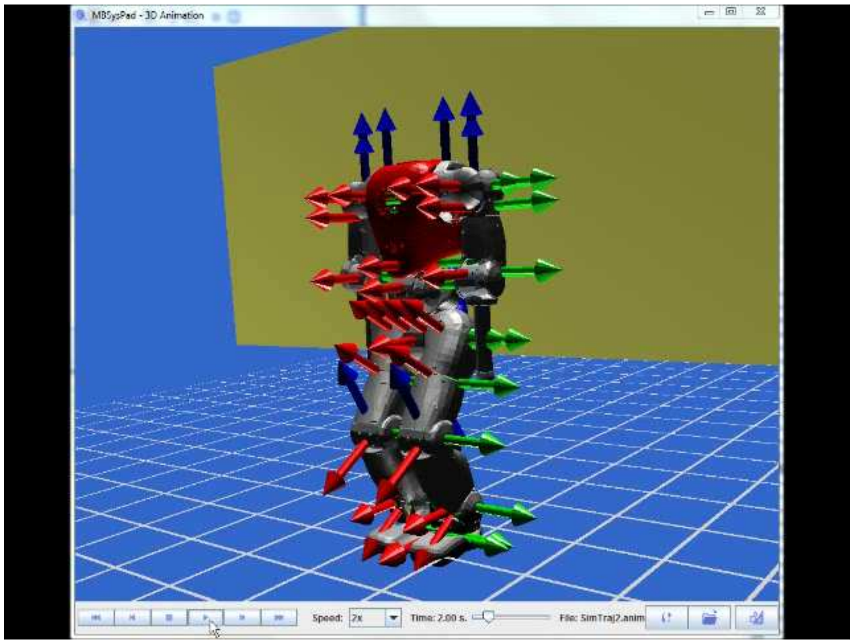
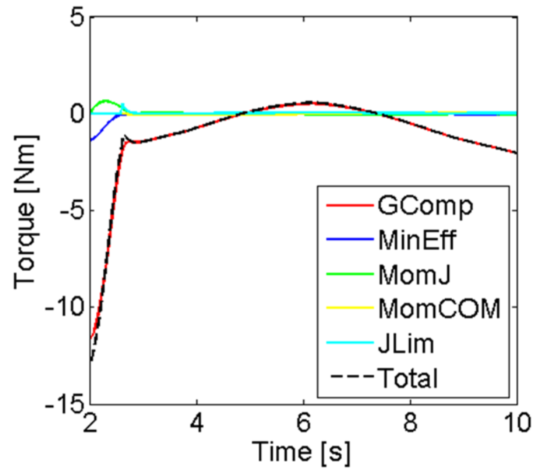
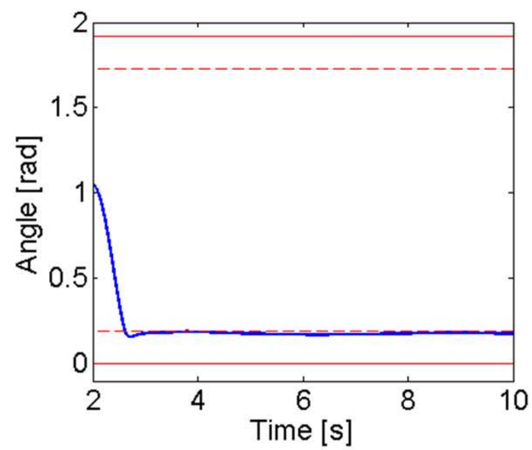
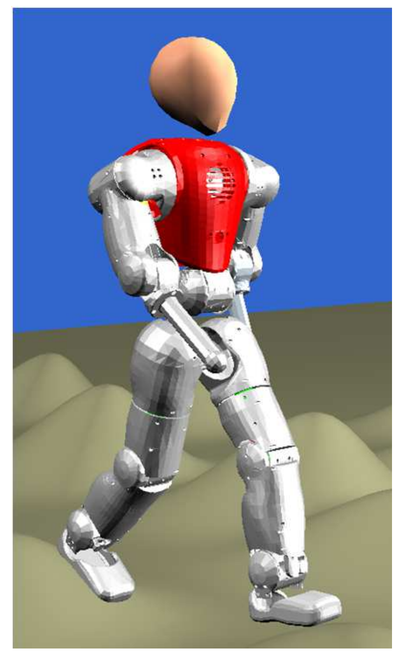




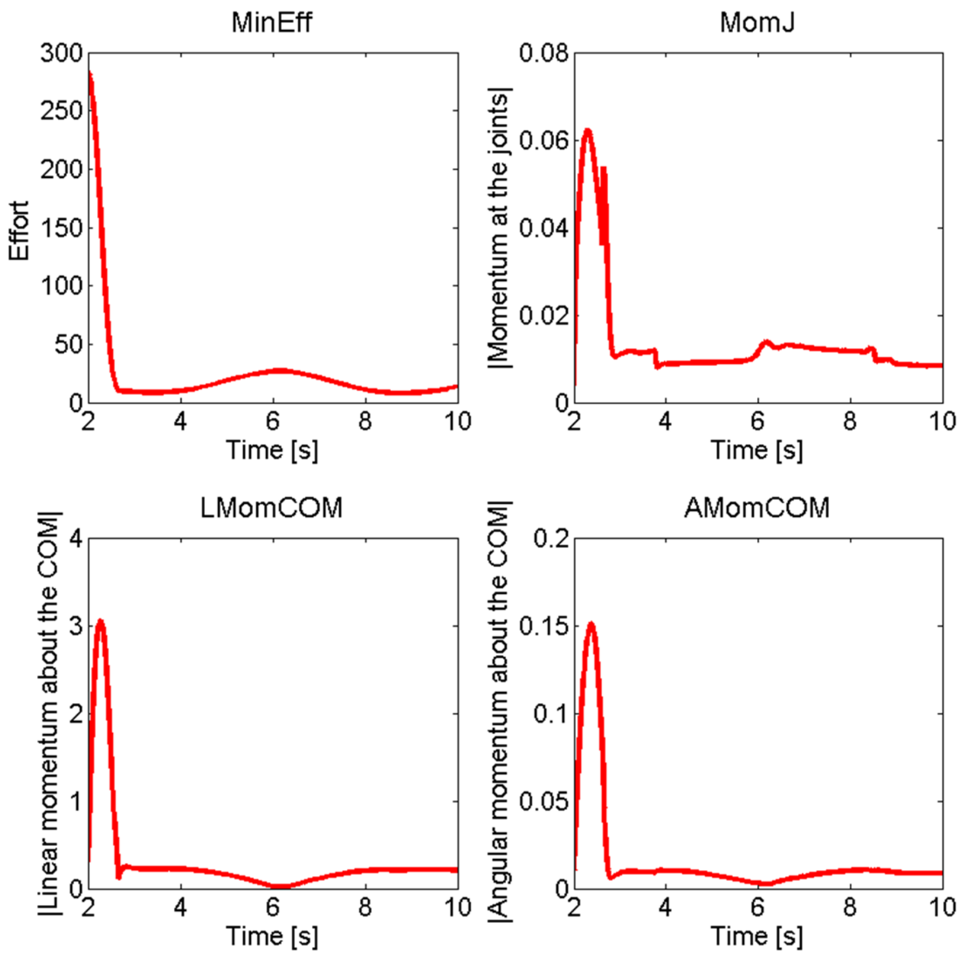


The 29-dofs model of COMAN was developed in Robotran, including the information on the full dynamics of the robot obtained from the CAD of the real prototype



Gcomp + Jlim + MinEff + MomJ + MomCOM

Results in simulation



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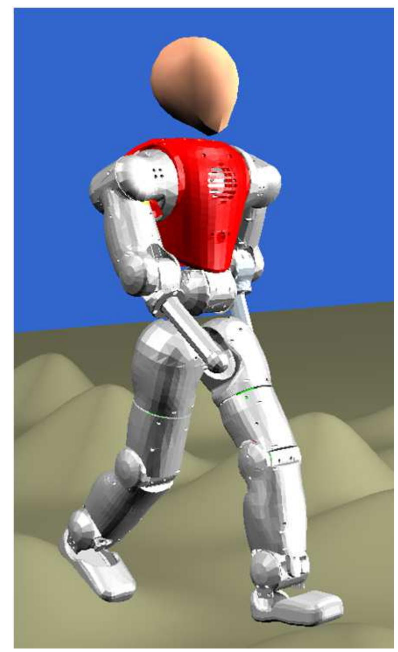

Gcomp + Jlim + MinEff + MomJ + MomCOM

Tests with the COMAN robot

- Gcomp
- Equilibrium
  - MinEff
  - MomJ

Some preliminary tests were performed with the real COMAN robot. The reference torques generated by the WBMC were tracked by a PI torque control loop at 1 kHz

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WBMC: waist pitch, roll

Zero-torque: shoulder pitch, roll of the right arm

Position: others

This experiment starts with COMAN in the minimum effort configuration, with zero joint velocities.

Tests with the COMAN robot

You can find the video at:

http://www.youtube.com/watch?v=MxFuXWzi6lg

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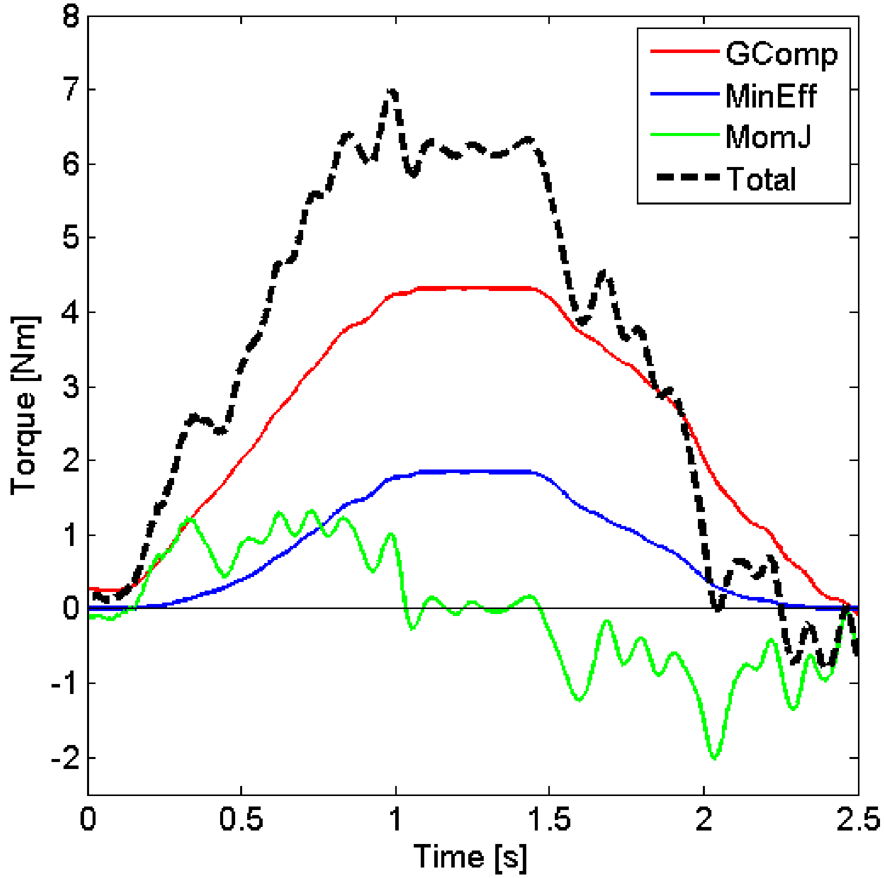

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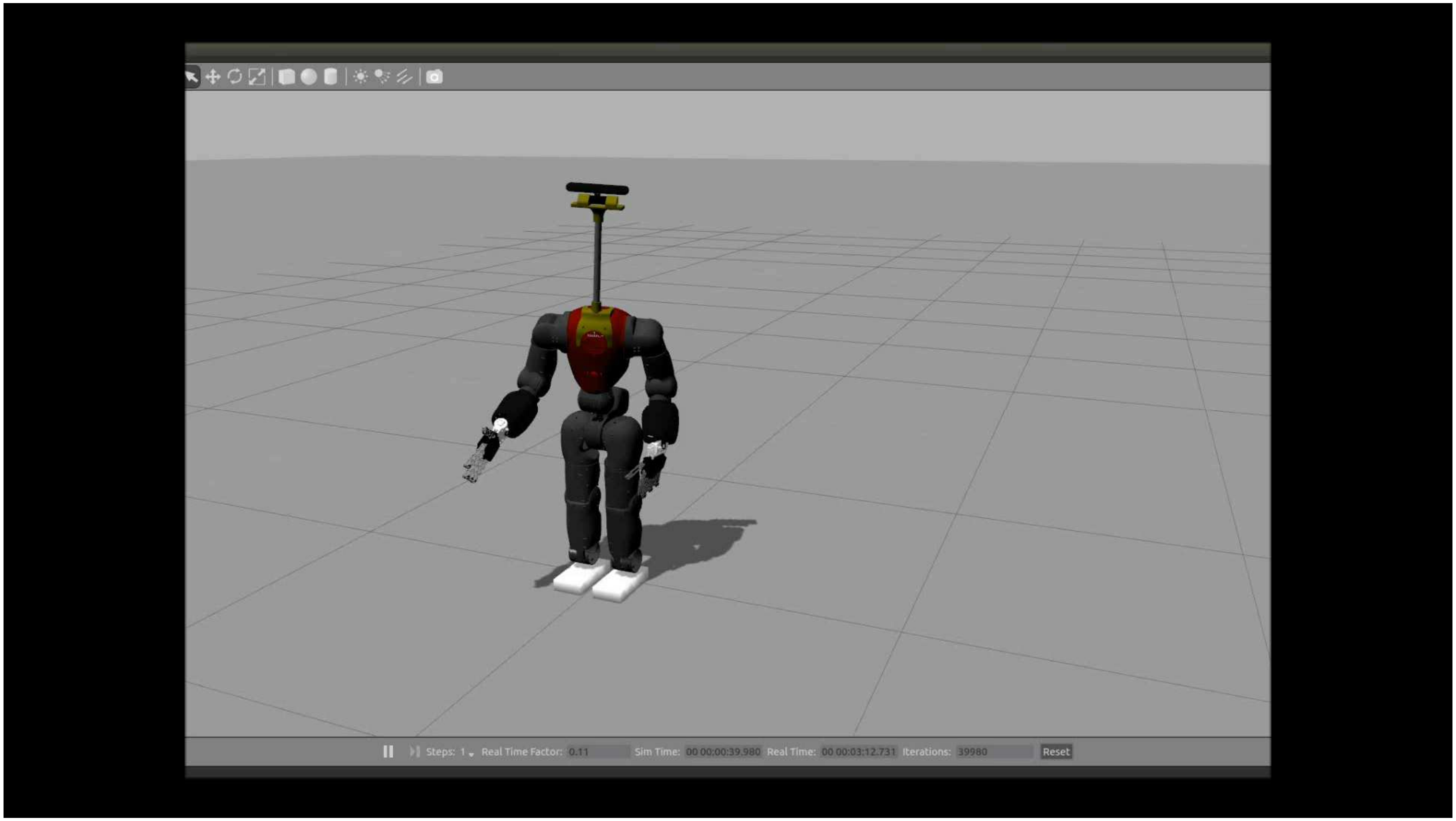

Difficulties

- Torque-control
  - Requires good low level torque tracking
- Many weights to tune
  - Takes time to tune the weight of the attractors
  - Attractors of different order make it much easier
  - Learning could be used to find an optimal set of weights

Contributions

- Introduction of the attractors: atomic control modules that affect the state of the robot driving it towards a more preferred one. Each controlled task is associated with an attractor;
- derivation of a computationally efficient gravity compensation for floating-base systems;
- use of a basic definition of equilibrium to verify the balance of the robot, based on the effort and on the momenta;
- novel use of the effort of the robot as an indicator of equilibrium;
- novel use of the joint momentum to control a robot;
- design of a complete attractor-based Whole-Body Motion Control (WBMC) system;
- validation on both simulation and with a real torque-controlled robot, the compliant humanoid COMAN.

Thank you!

Reference:

F.L. Moro, M. Gienger, A. Goswami, N.G. Tsagarakis, D.G. Caldwell,
An Attractor-based Whole-Body Motion Control (WBMC) System for Humanoid Robots
IEEE-RAS International Conference on Humanoid Robots (Humanoids), Atlanta, GA, USA (2013)