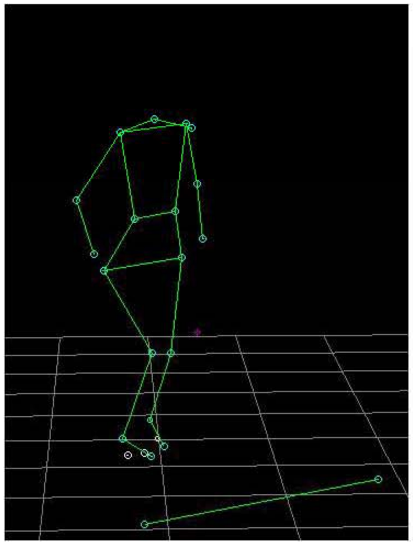
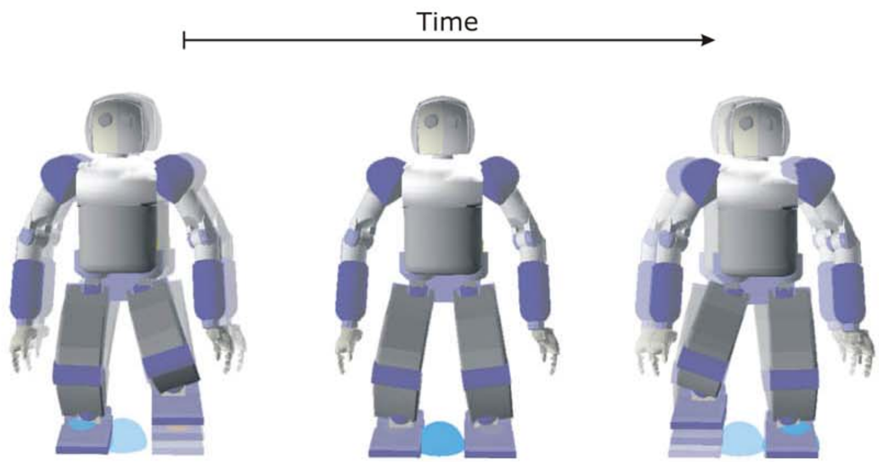
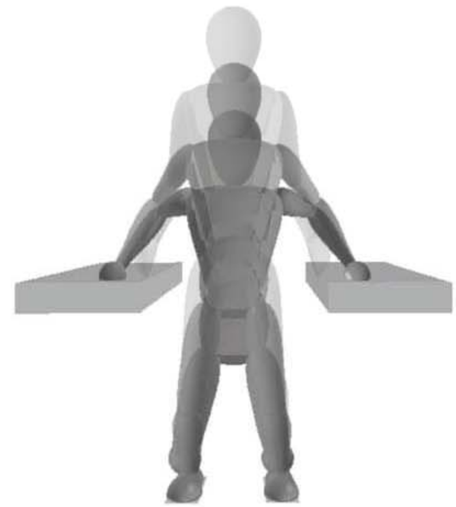
Control of Humanoid Robots







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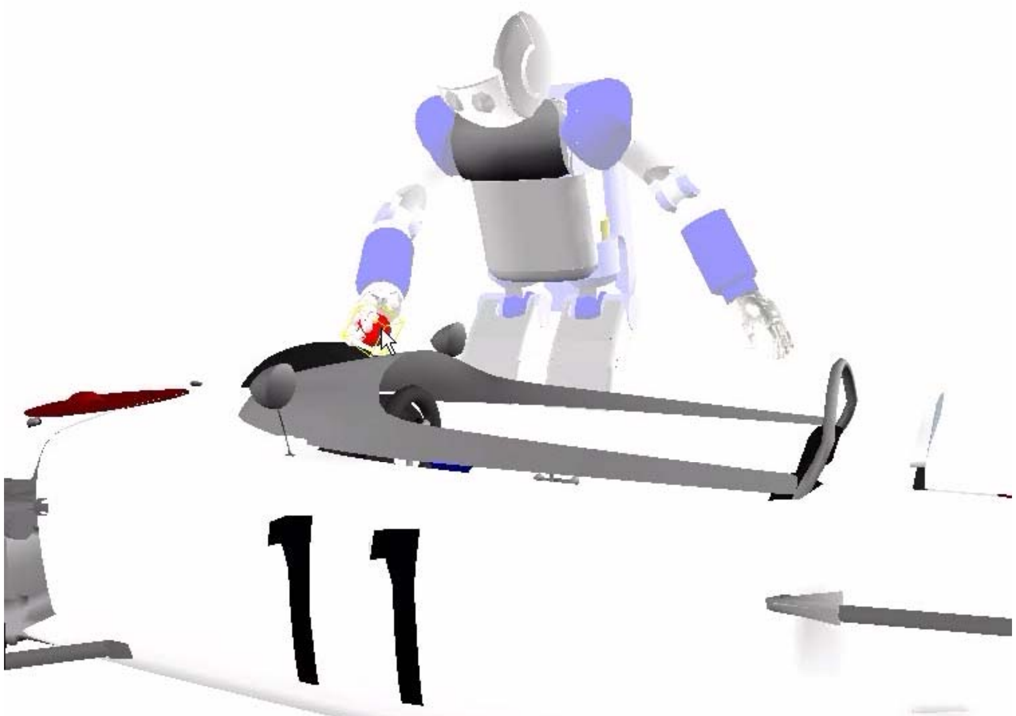
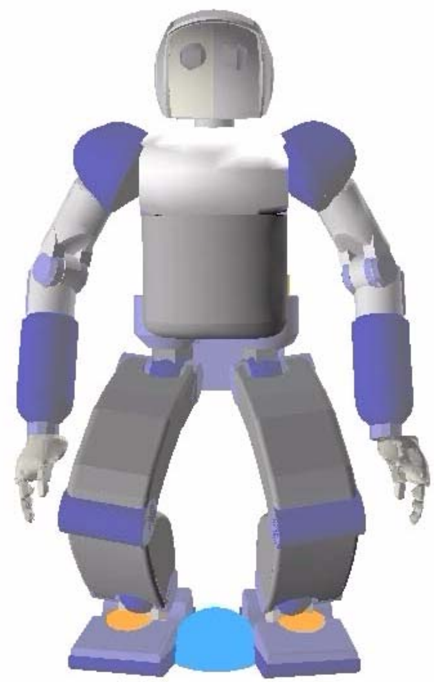
May 2nd, 2008
University of California at Merced

Challenges

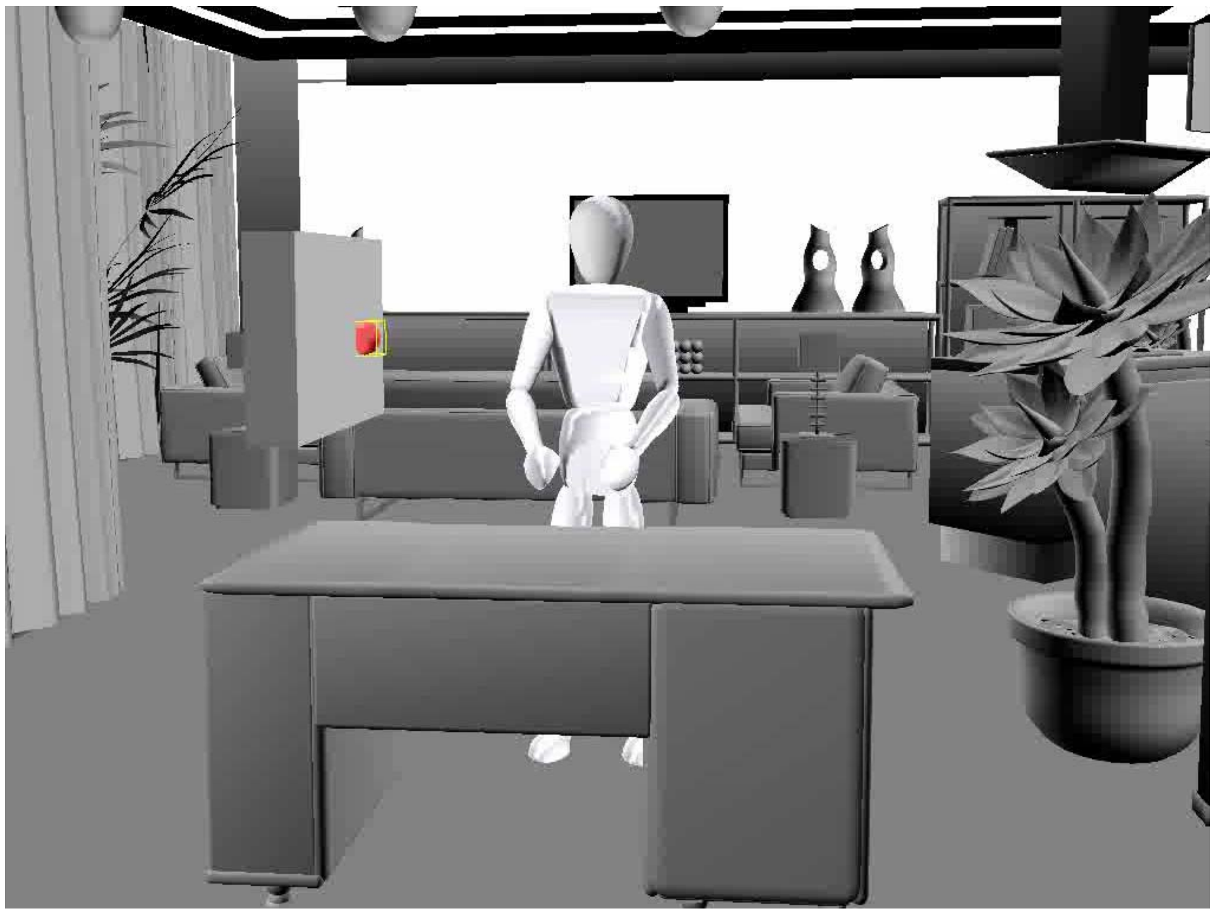
- How can we create and execute complex behaviors?
- How can we respond and adapt to the environment?



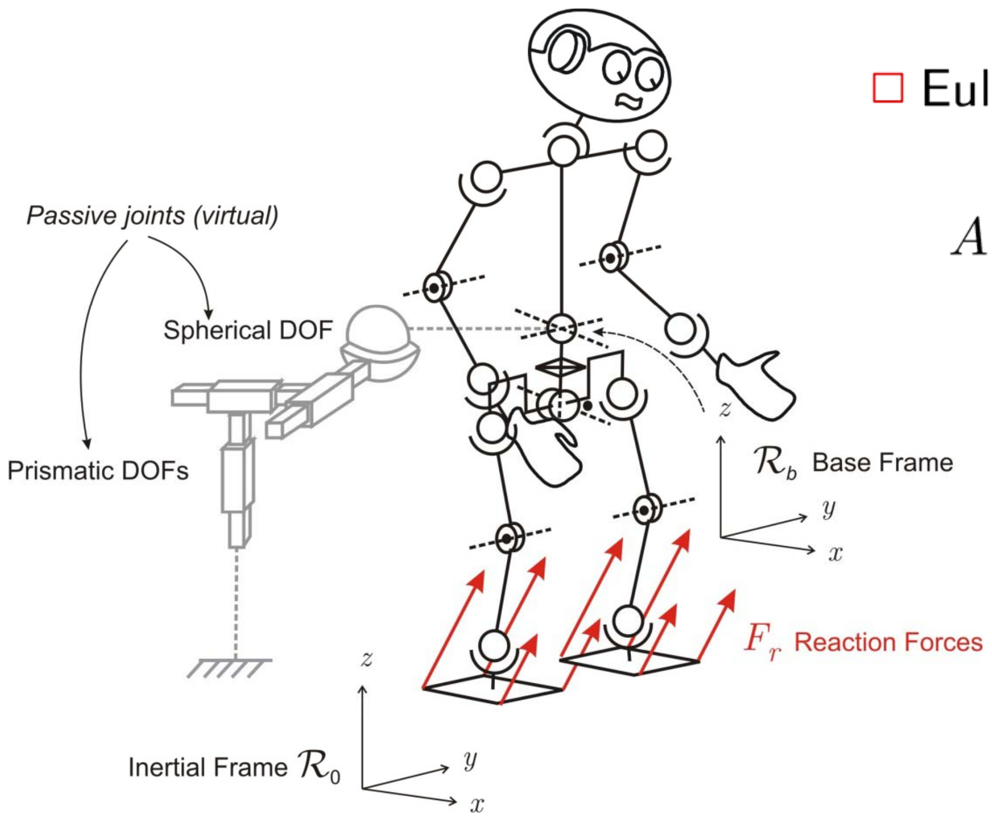


Approach:

1. Unified torque-based control framework
2. Control of humanoids under multiple contacts
3. Motion reconstruction by direct control of marker data
4. Online walking pattern generation
5. Discussion



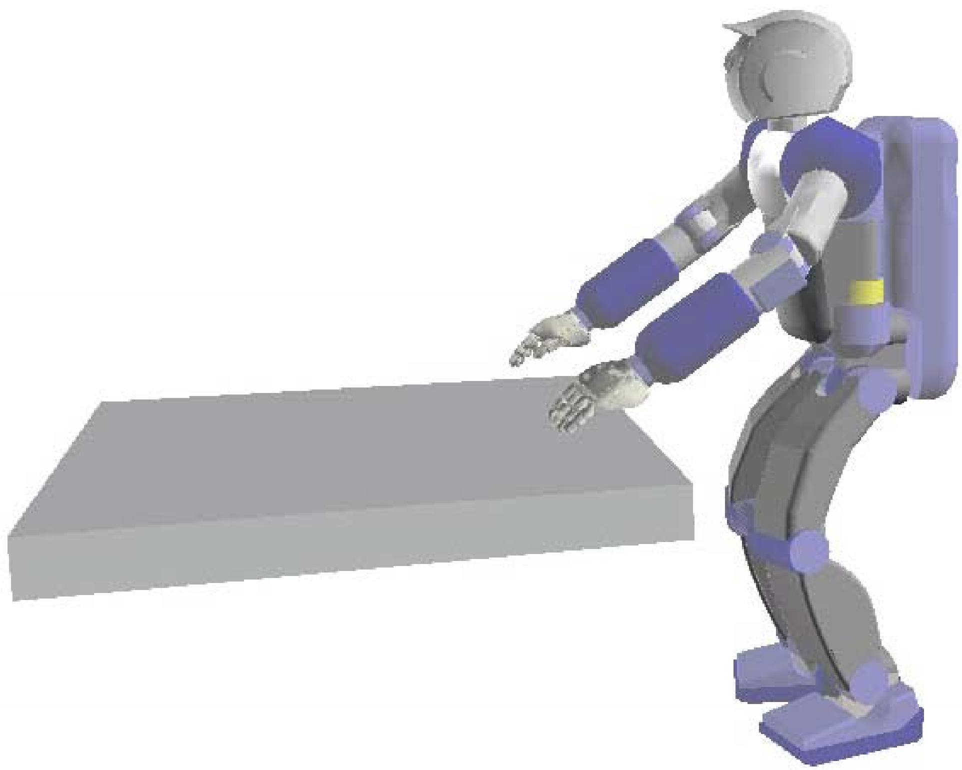
Kinematic and dynamic models



- Euler-Lagrange:

$$A \begin{pmatrix} \dot{\vartheta}_b \\ \ddot{q} \end{pmatrix} + b + g + J_s^T F_r = \begin{pmatrix} 0_{6\times 1} \\ \Gamma \end{pmatrix}$$

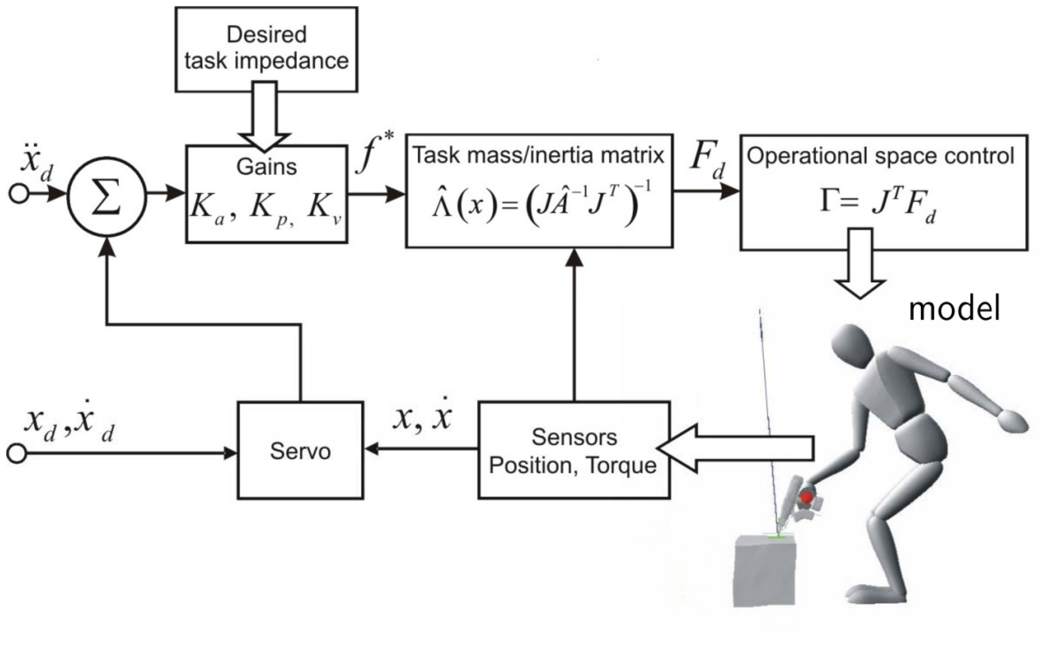
Demo: interactive falling



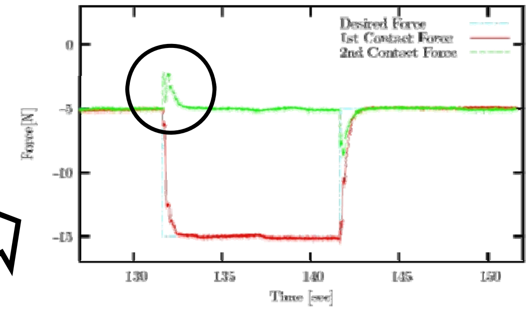
Operational-space torque control

- Operational space control:

Integrates motion, force, and the robot's dynamic model into unified torque commands

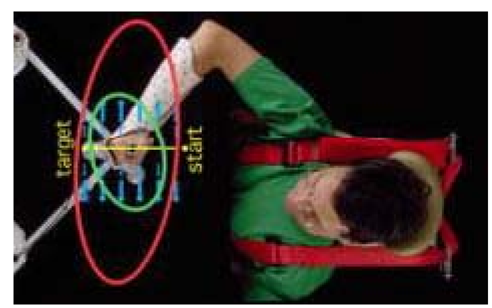


Effective contact

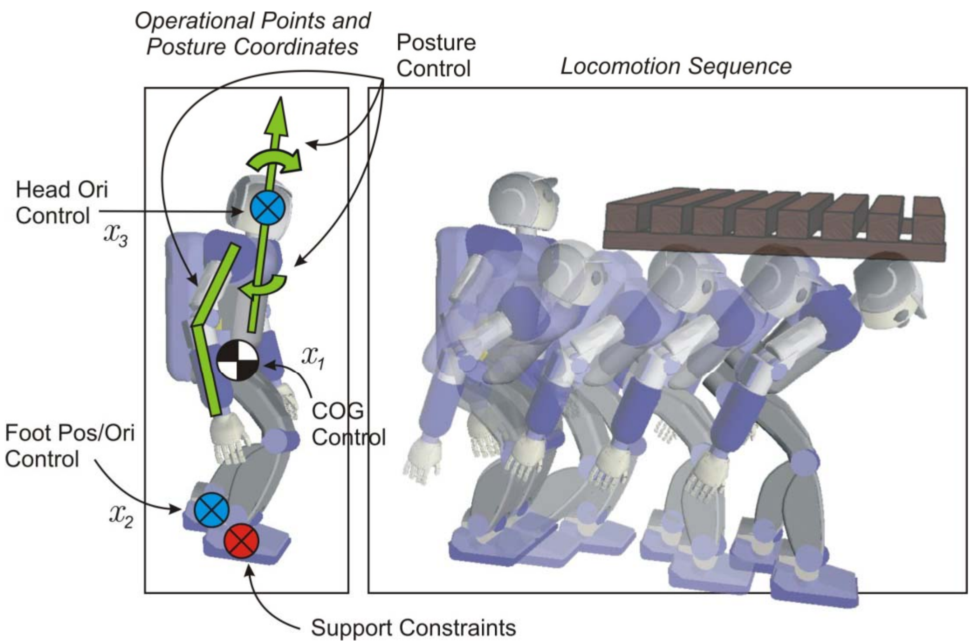


Adaptive behaviors

Torque analysis



Torque control



- Task descriptors:

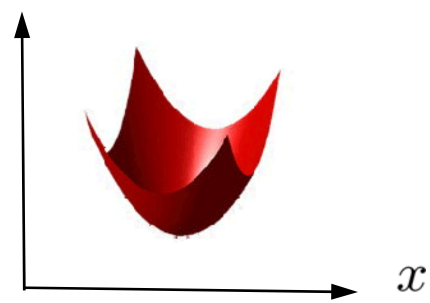
$$x \triangleq \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{pmatrix} \qquad J^* \triangleq \begin{pmatrix} J_1^* \\ J_2^* \\ \vdots \\ J_N^* \end{pmatrix}$$

- Force to torque mapping:

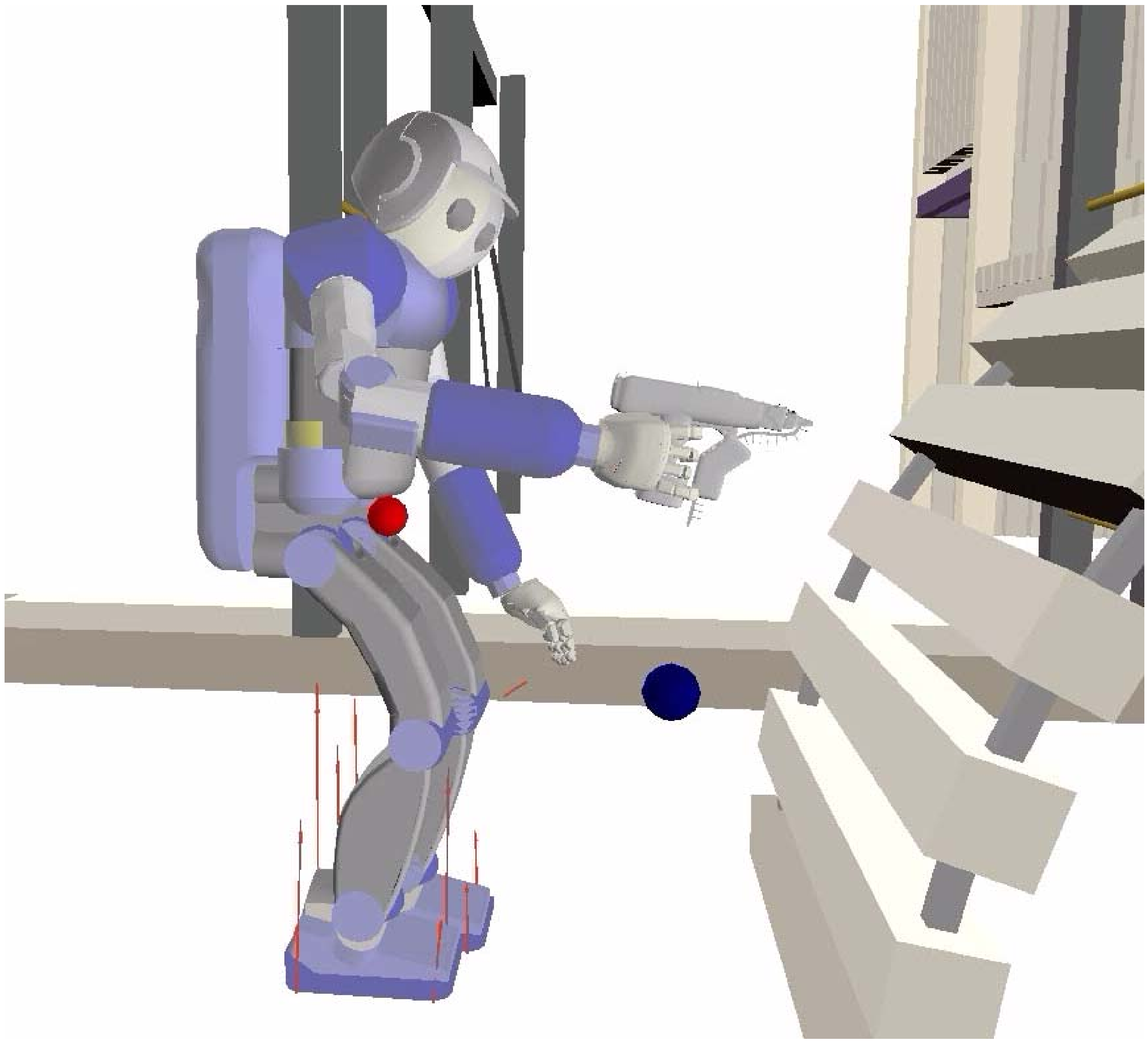
$$\Gamma = J^{*T} F$$

$$F = -K_p \Delta V - K_v \dot{x}$$

$$V = \| x - x_{\text{des}} \|^2$$



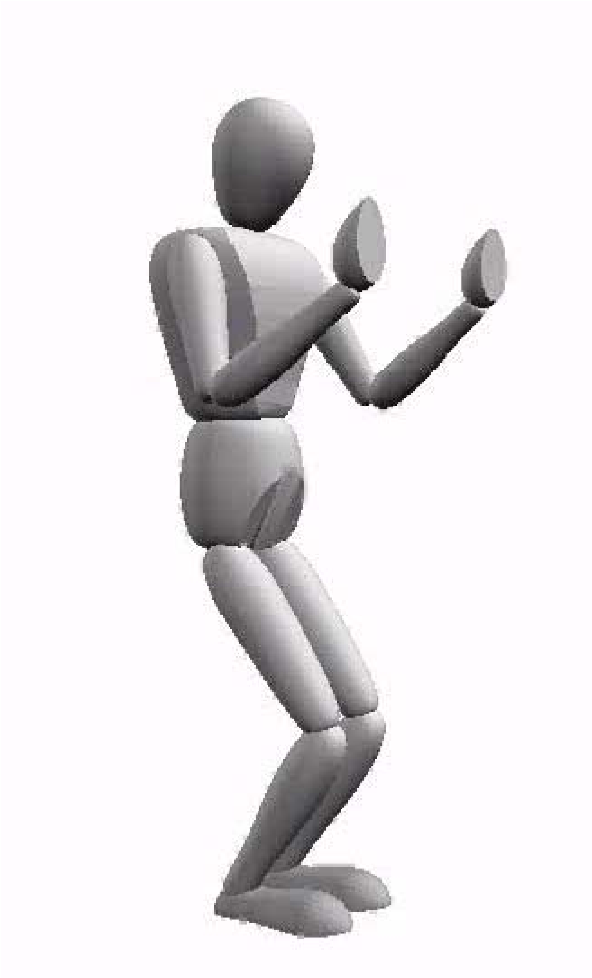
Demo: interactive manipulation



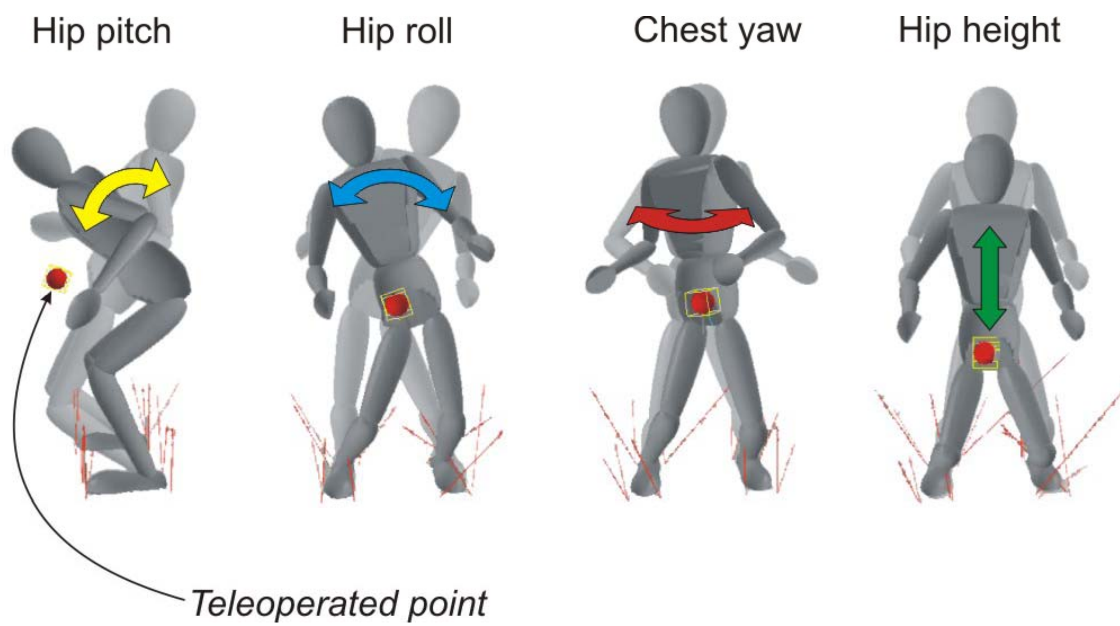
Redundancy

- Force to torque mapping:

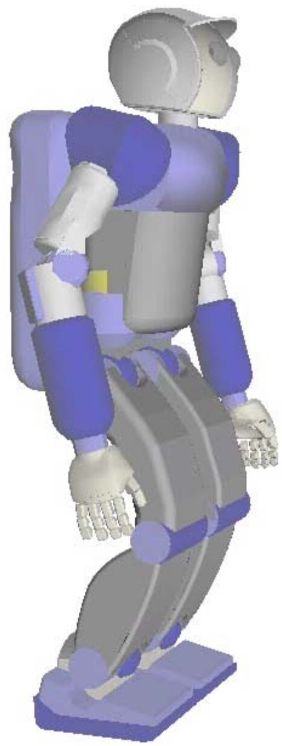
$$\Gamma = J^{*T} F + N^{*T} \Gamma_{\text{posture}}$$



Task-based postures

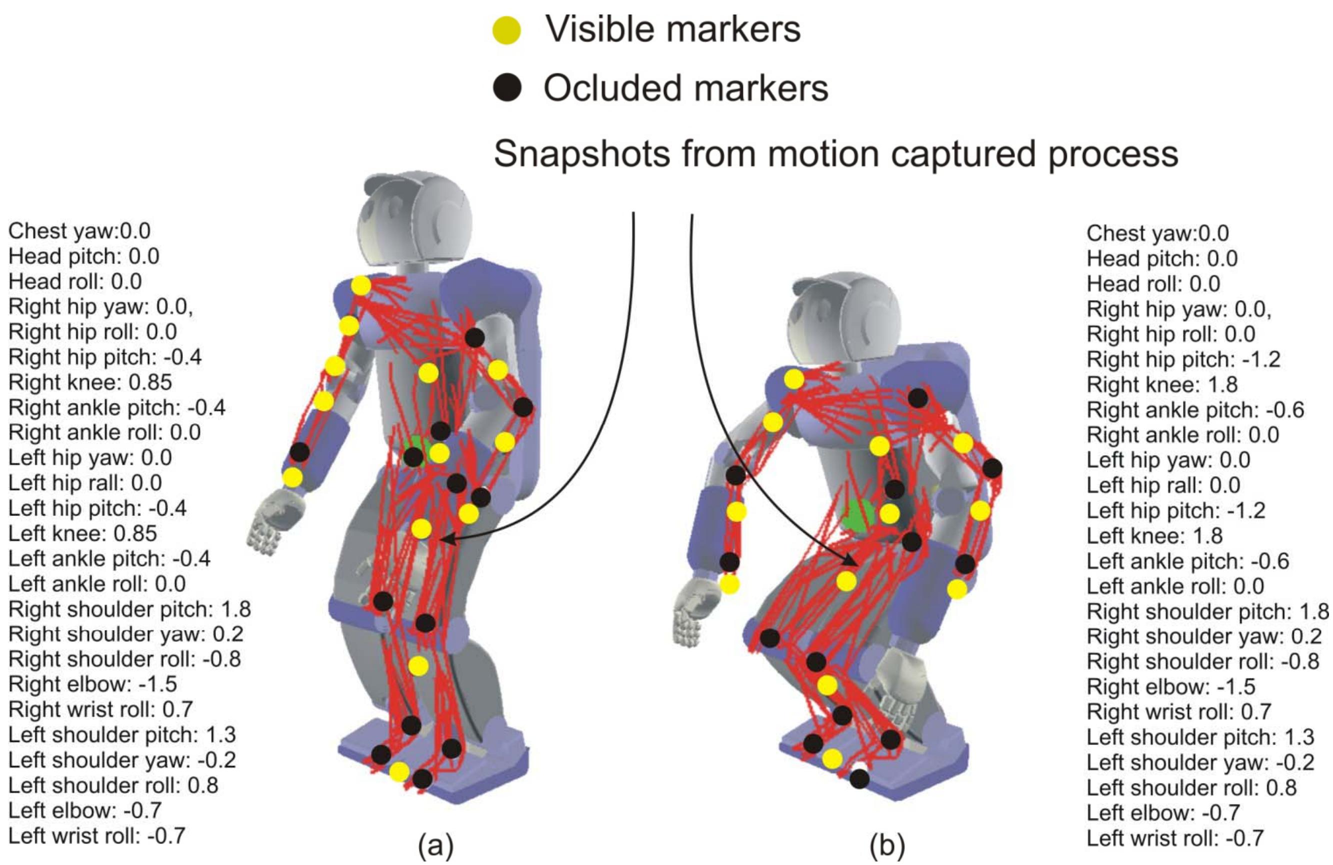


Example: crouched walk

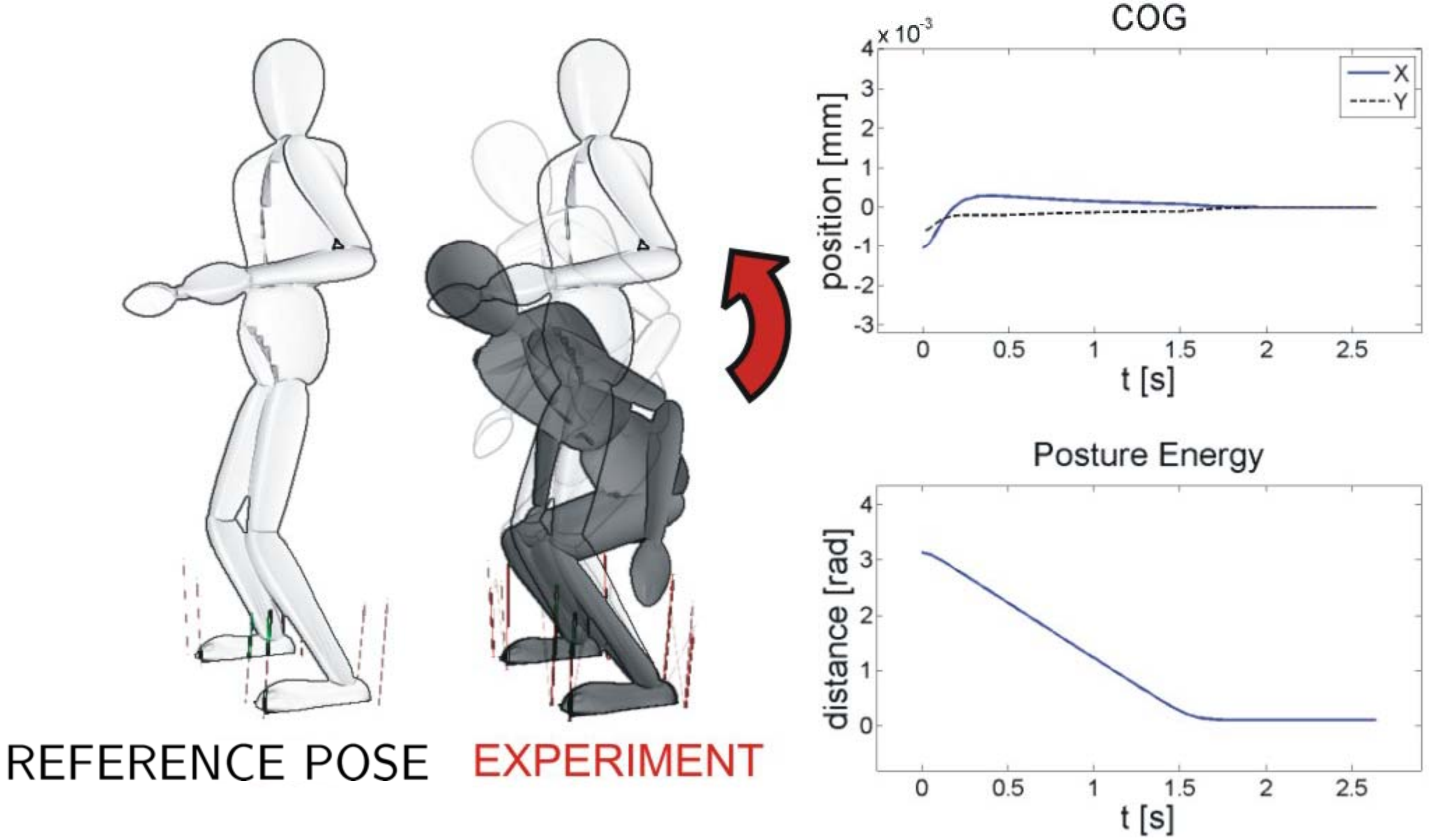


Criteria-based postures

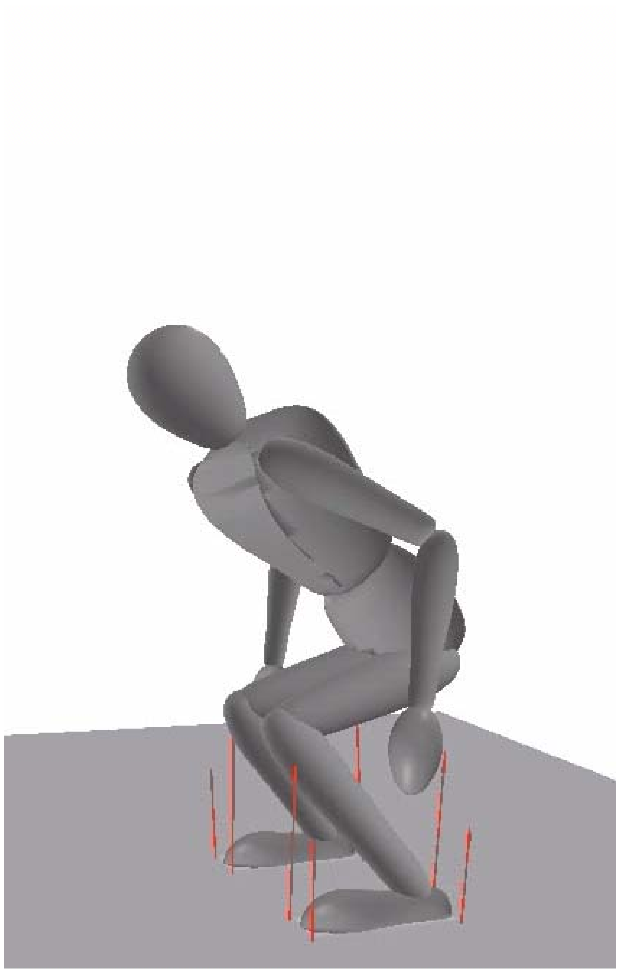
$$V_p(q_s) = \parallel q_s - q_{\text{human}} \parallel^2$$

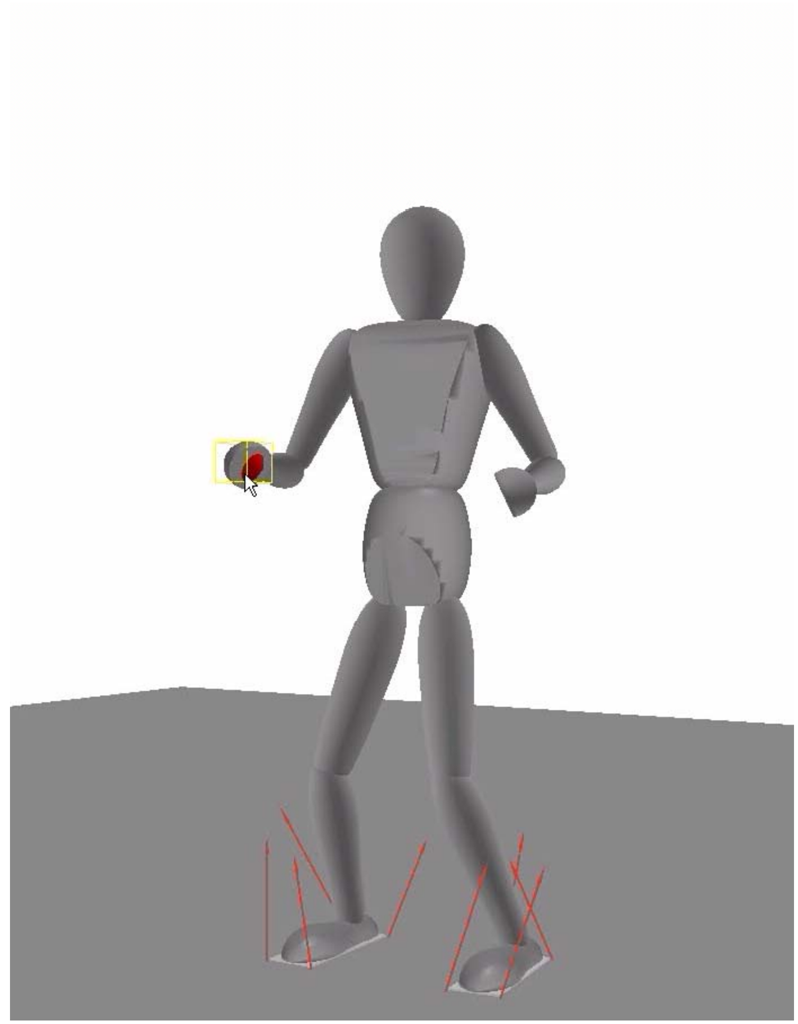


Example: upright pose

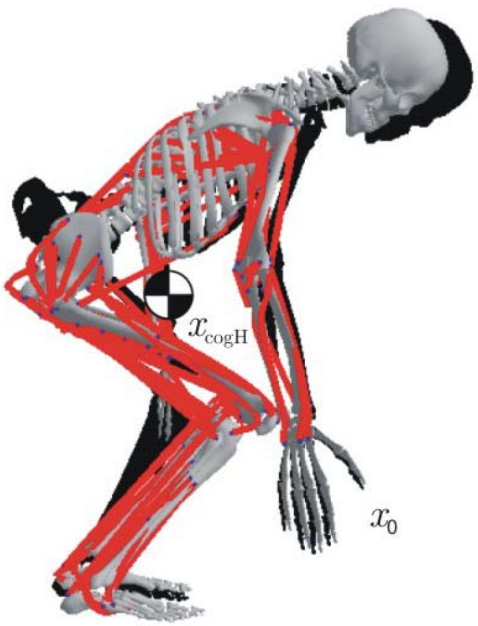


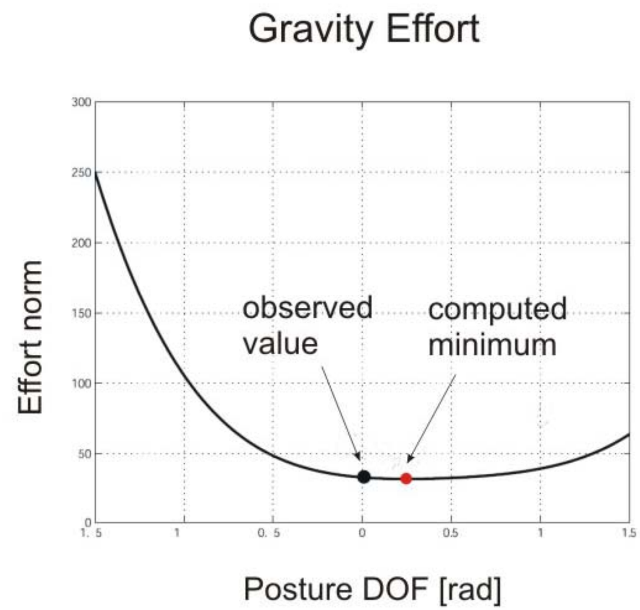
Movies





Study of the human

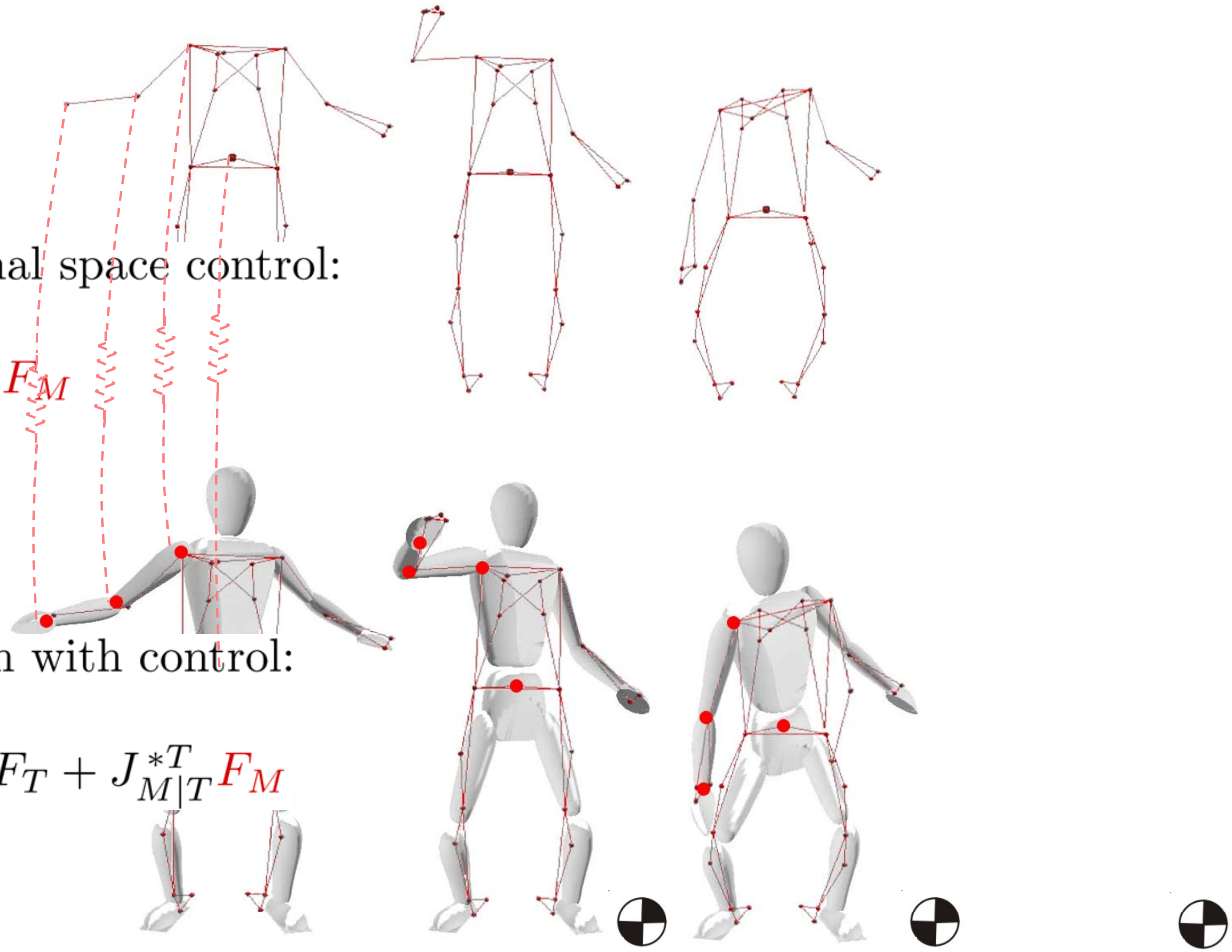




$$V_p(q) = \sum_{k=1}^{n} w_i \frac{g_i(q)^2}{\Gamma_{B_i}(q)^2}$$

$$\nabla_q V_p\big(g(q)\big) = J_{g(q)}^T g(q)$$

Method: direct marker mapping



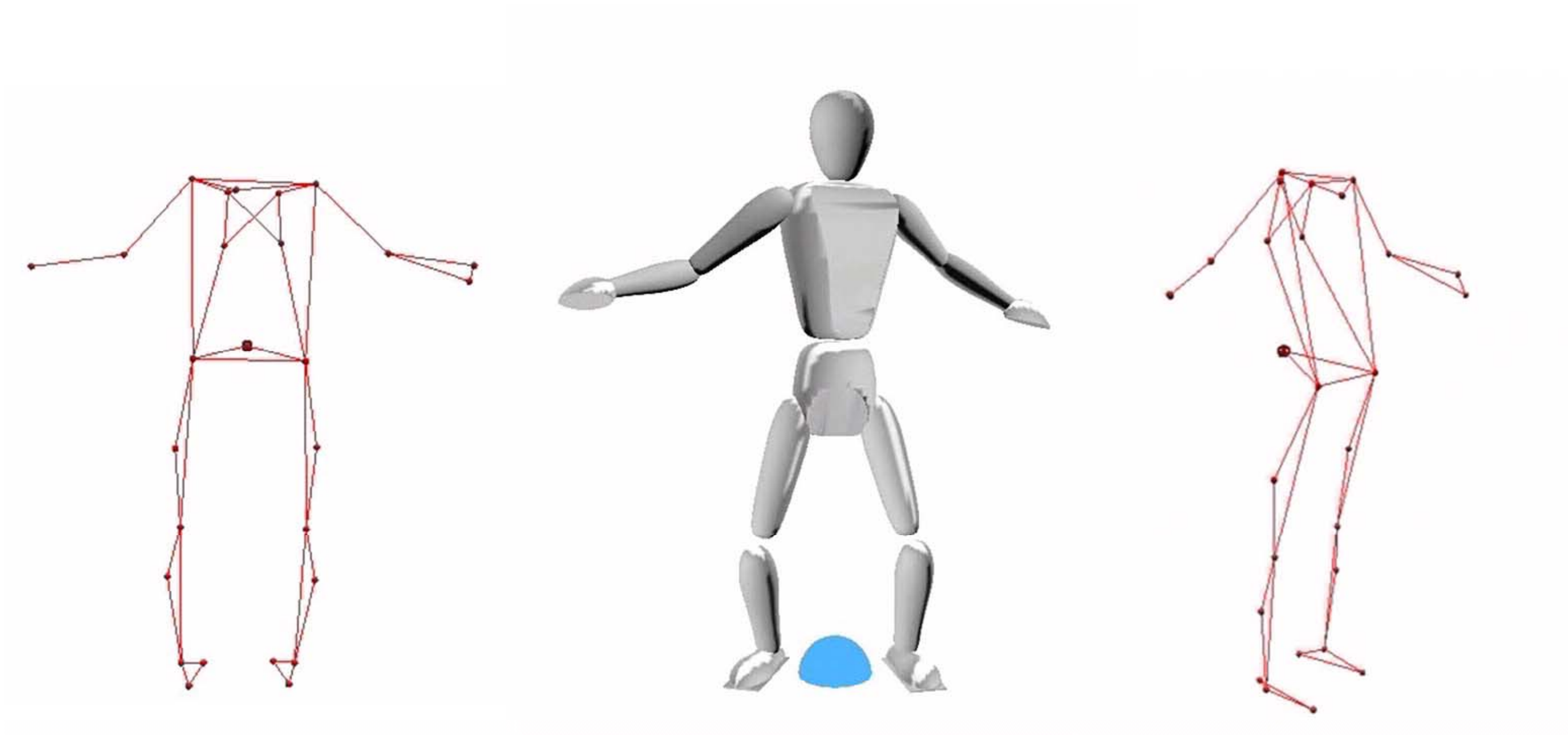
- Operational space control:

$$\Gamma = J_M^{*T} F_M$$

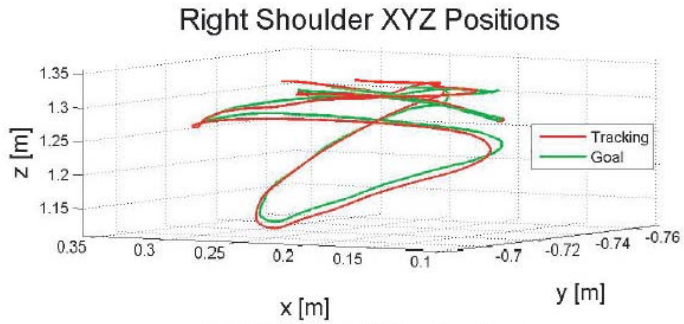
- Integration with control:

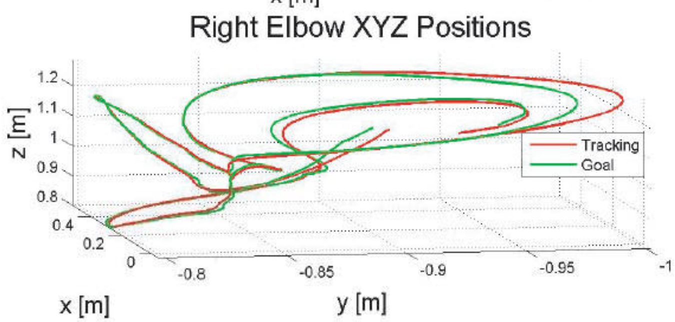
$$\Gamma = J_T^{*T} F_T + J_{M|T}^{*T} F_M$$

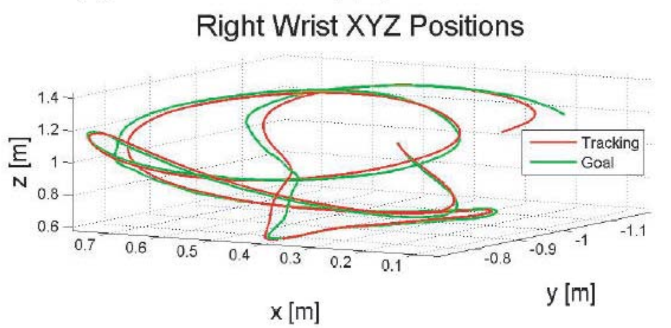
Validation: tai-chi motion reconstruction

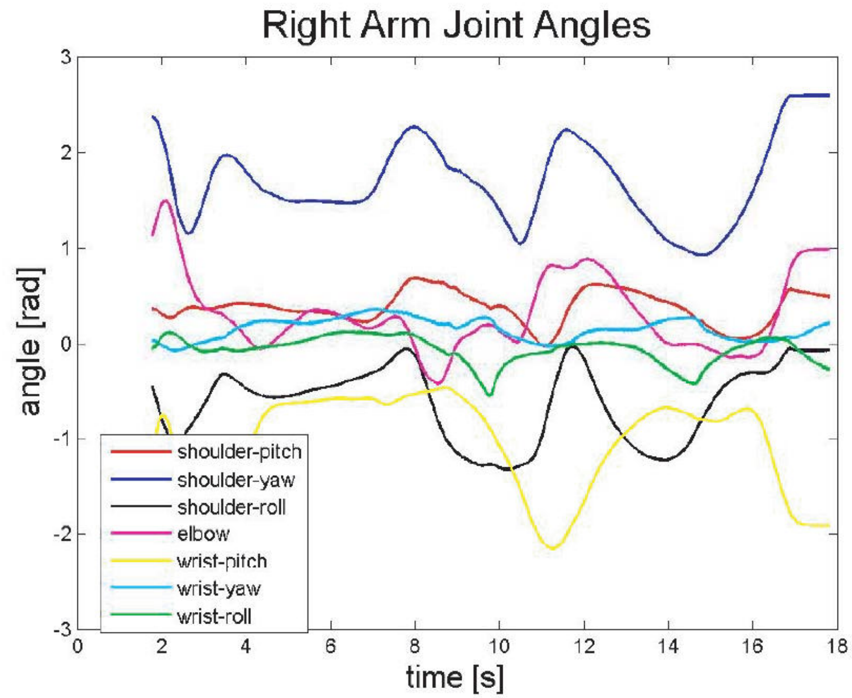


Data analysis

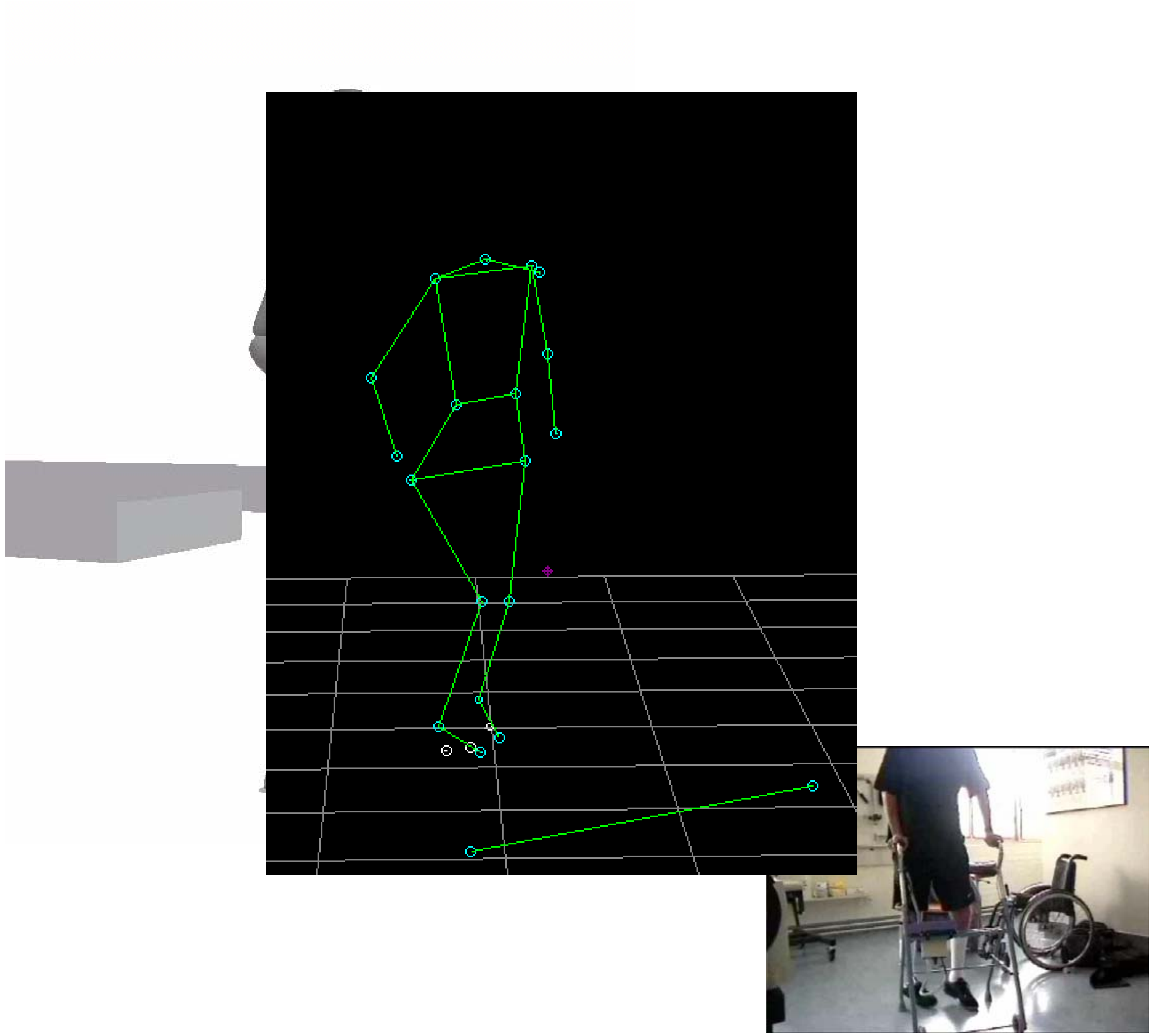




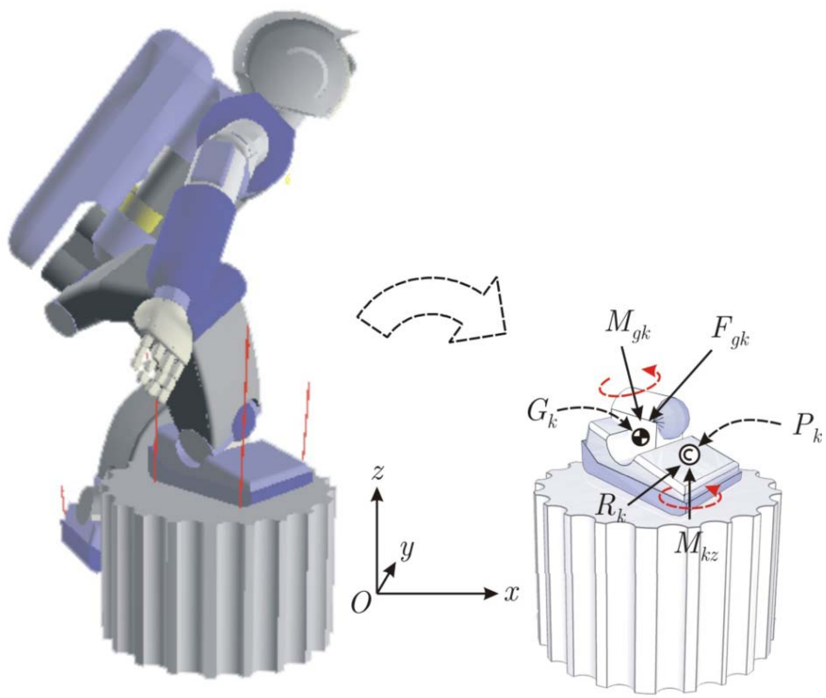




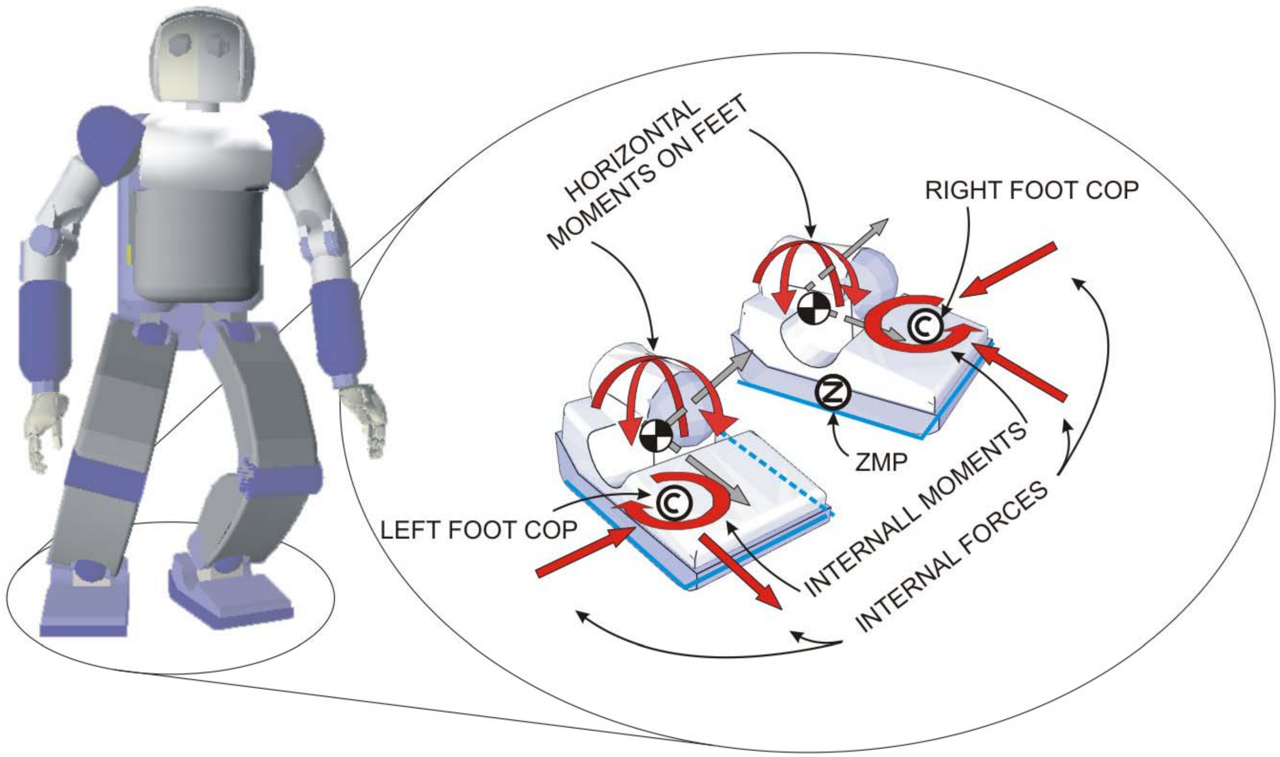
Multi-contact interactions



COP: local contact stability



COP: local contact stability

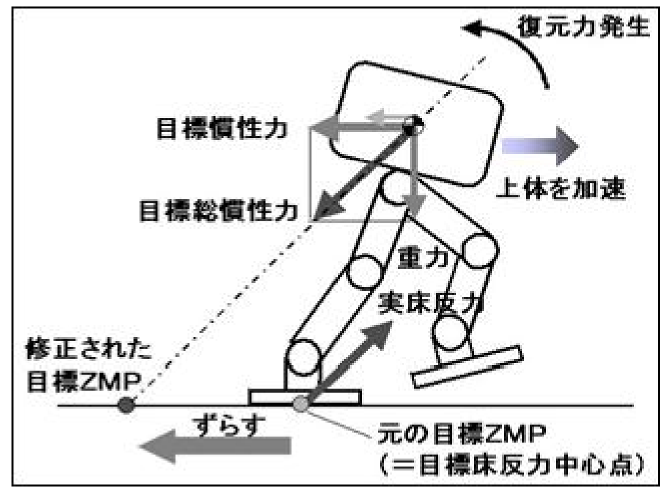


ZMP: global stability analysis

- Zero moment point (ZMP):

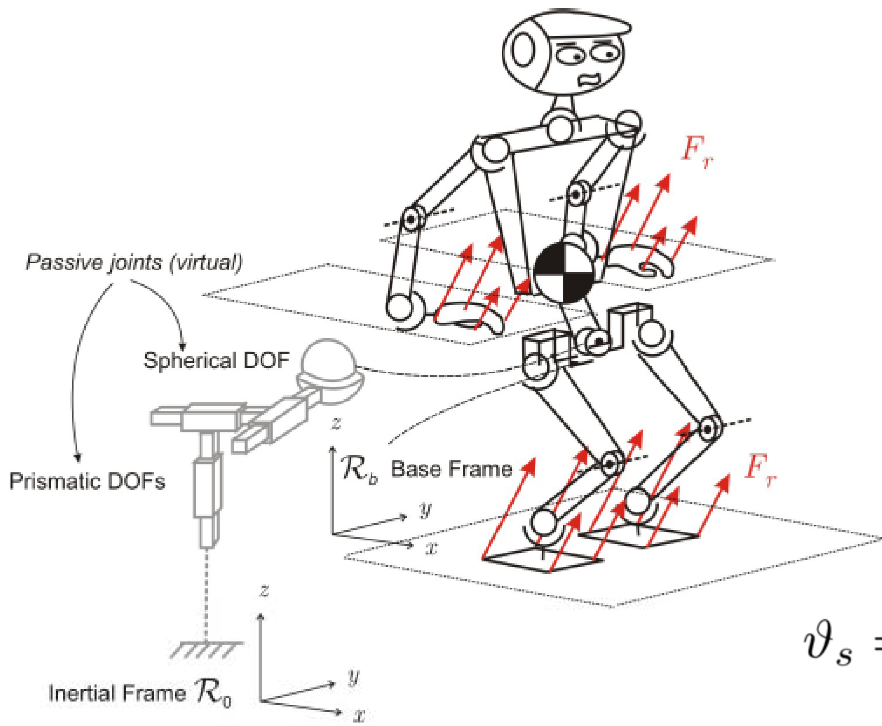
$$P_x = G_x - \frac{R_x}{R_z}\Big(G_z - P_z\Big) - M_y,$$

$$P_y = G_y - \frac{R_y}{R_z}\Big(G_z - P_z\Big) + M_x$$



Courtesy of Honda Motor Co.

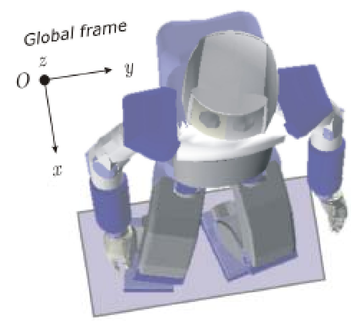
Sensorless estimation of reaction forces



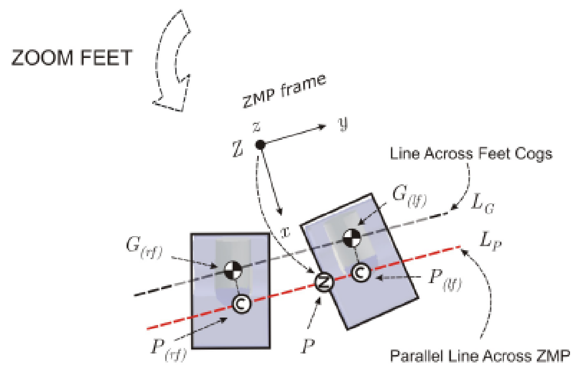
$$\vartheta_s = 0, \quad \dot{\vartheta}_s = 0.$$

$$F_r = \overline{J}_s^T S^T \Gamma - \overline{J}_s^T (b + g) + \Lambda_s \dot{J}_s \begin{pmatrix} \vartheta_b \\ \dot{q} \end{pmatrix}$$

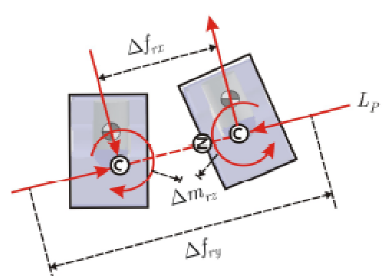
Control of centers of pressure



(a) Top view of the robot

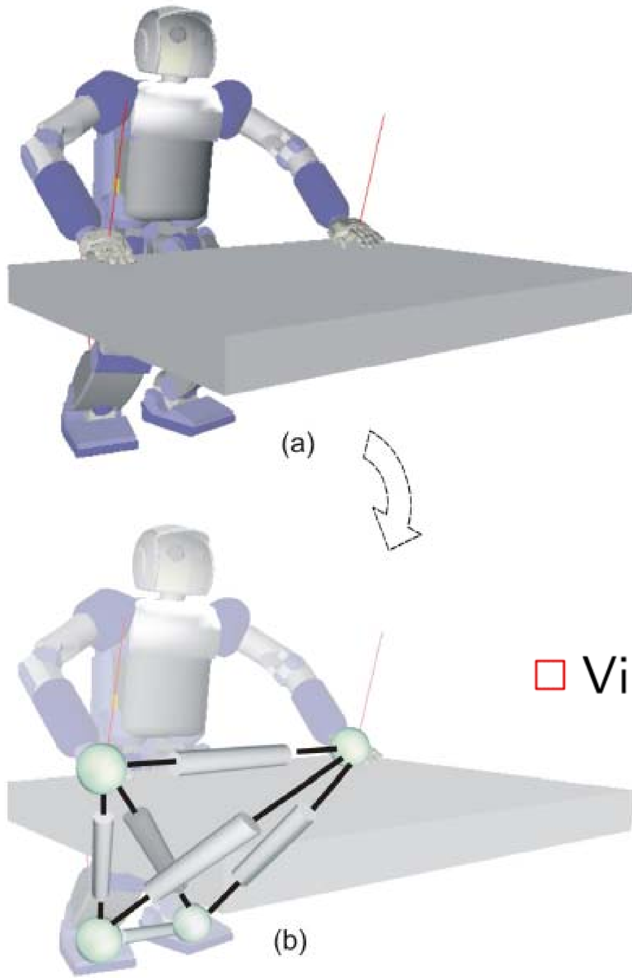


(b) Contact COPs



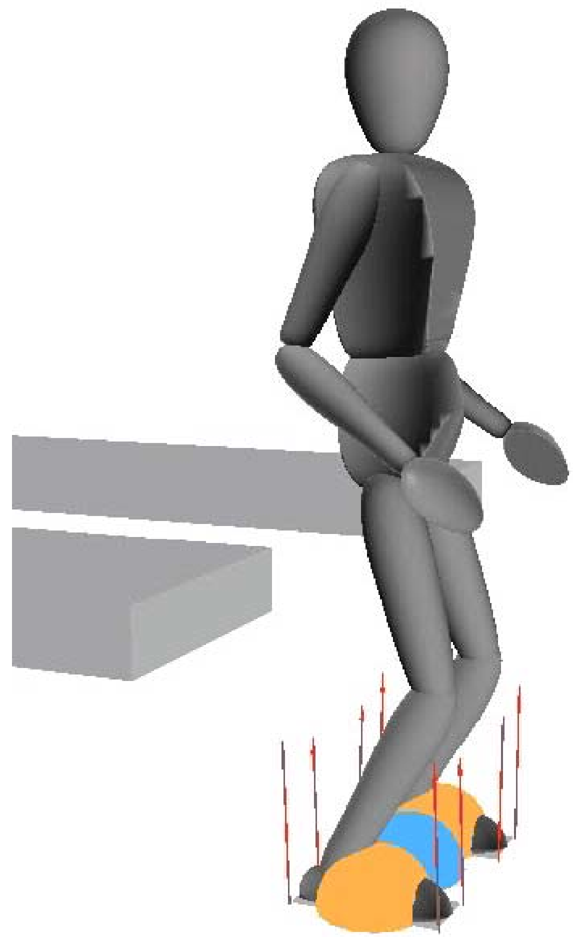
(c) Internal forces

Control of internal forces

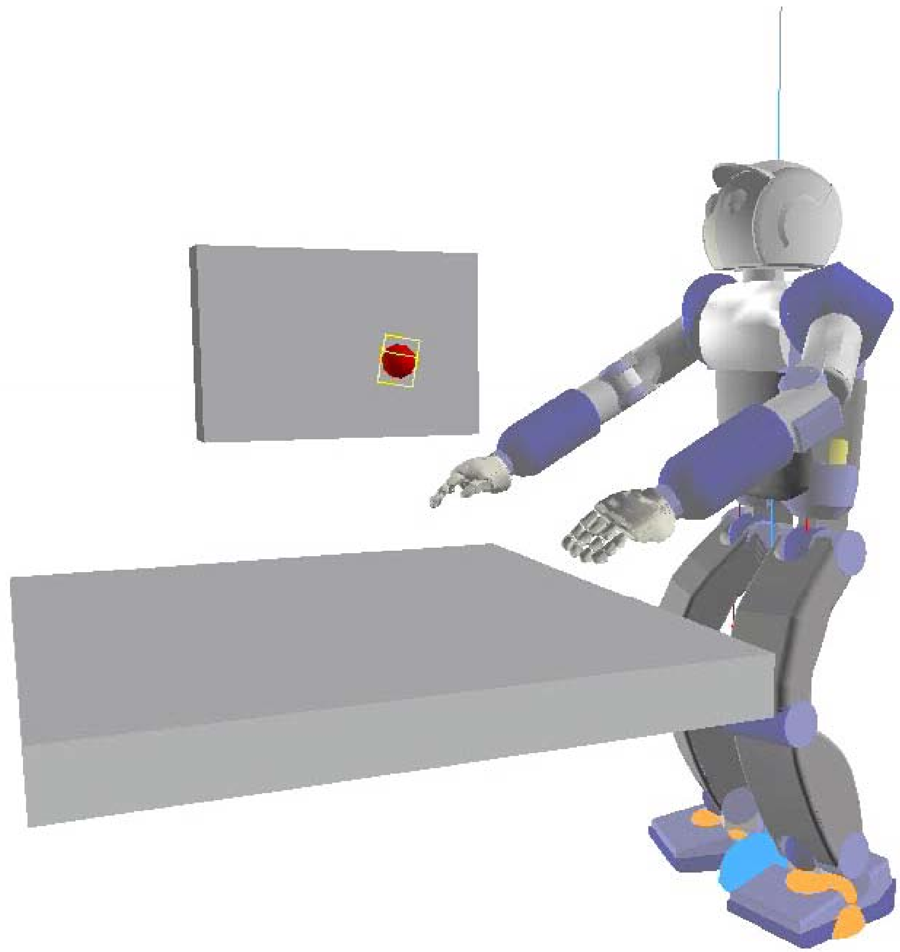


- Virtual linkage model

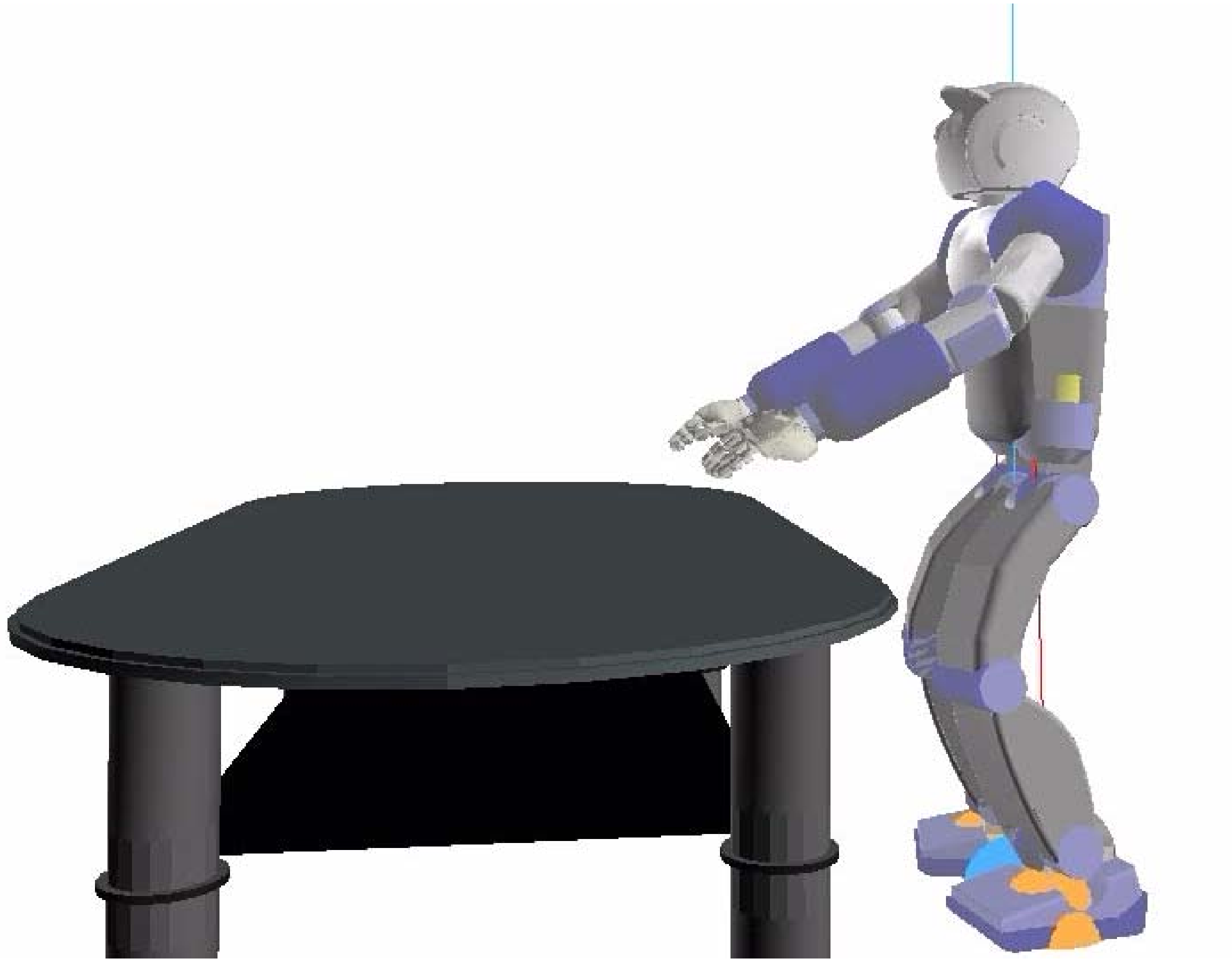
Demo: multi contact support



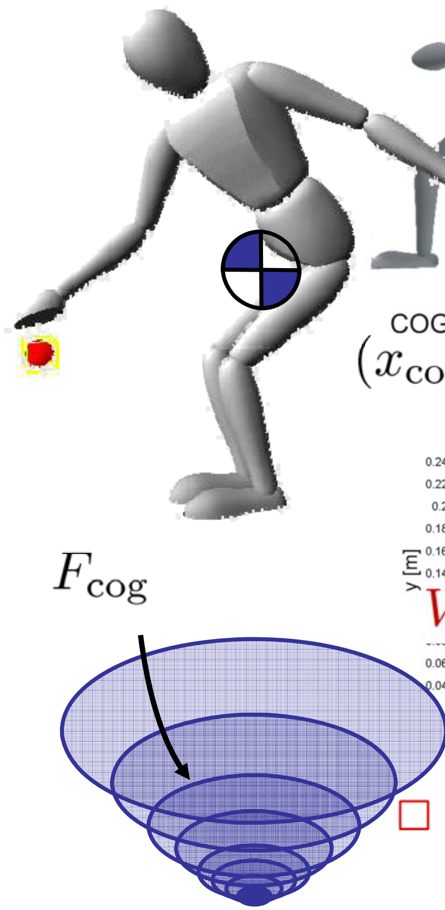
Demo: interactive multi-contact

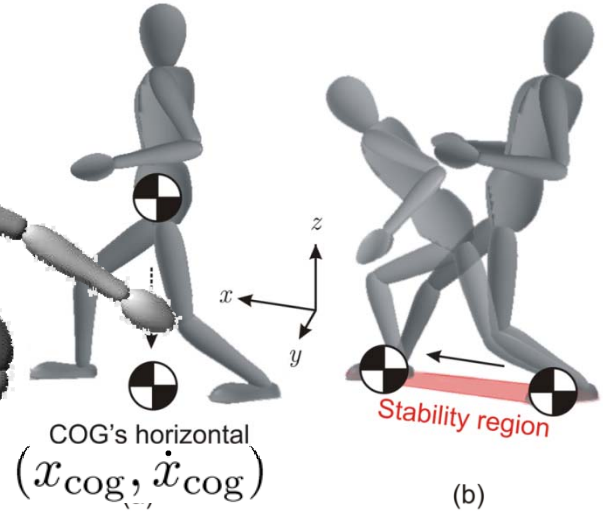


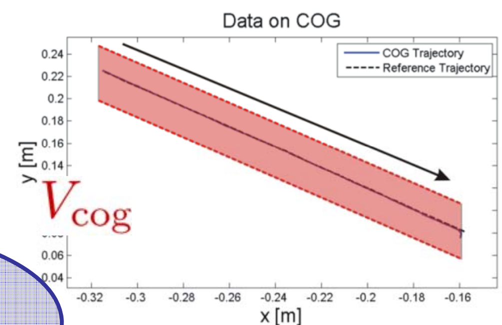
Demo: adaptive multicontact



CoM closed-loop control







- Closed loop control:

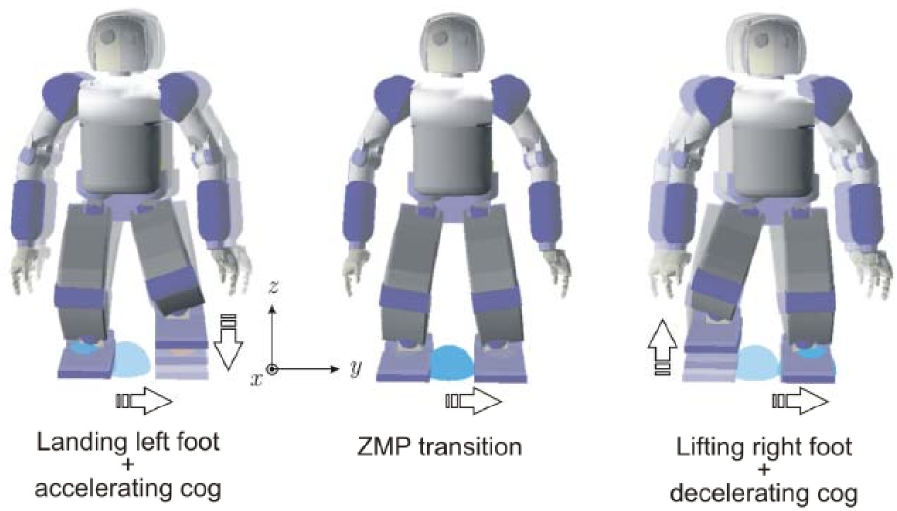
$$\Gamma = J_{\text{cog}}^{*T} F_{\text{cog}}$$

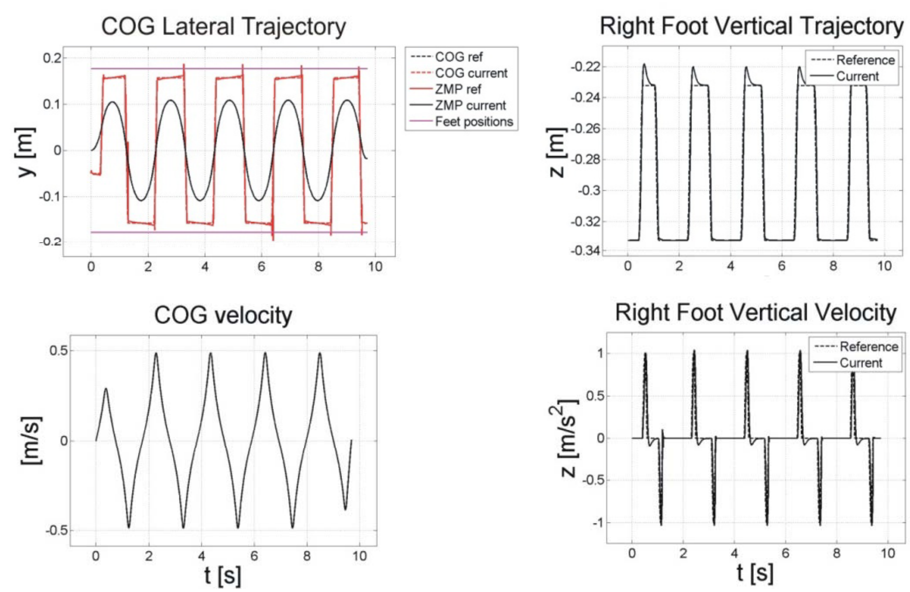
$$J_{\text{cog}} = \frac{1}{M} \sum_i m_i J_{\text{cog}(i)}$$

$$-K_p \Delta V_{\text{cog}} - K_v \dot{x}_{\text{cog}}$$

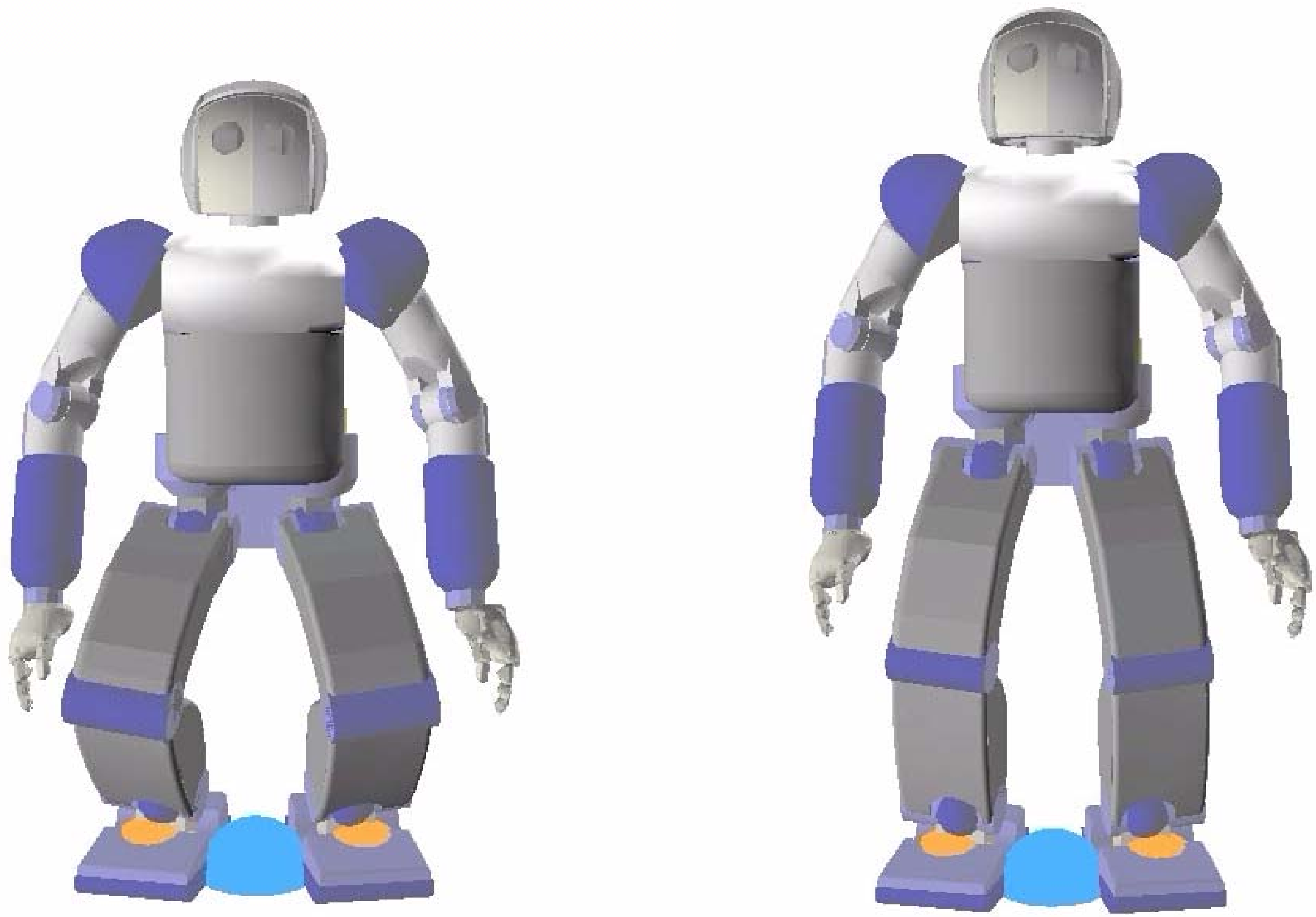
Example: CoM oscillations

Lateral walk: CoM - CoP trajectory planning

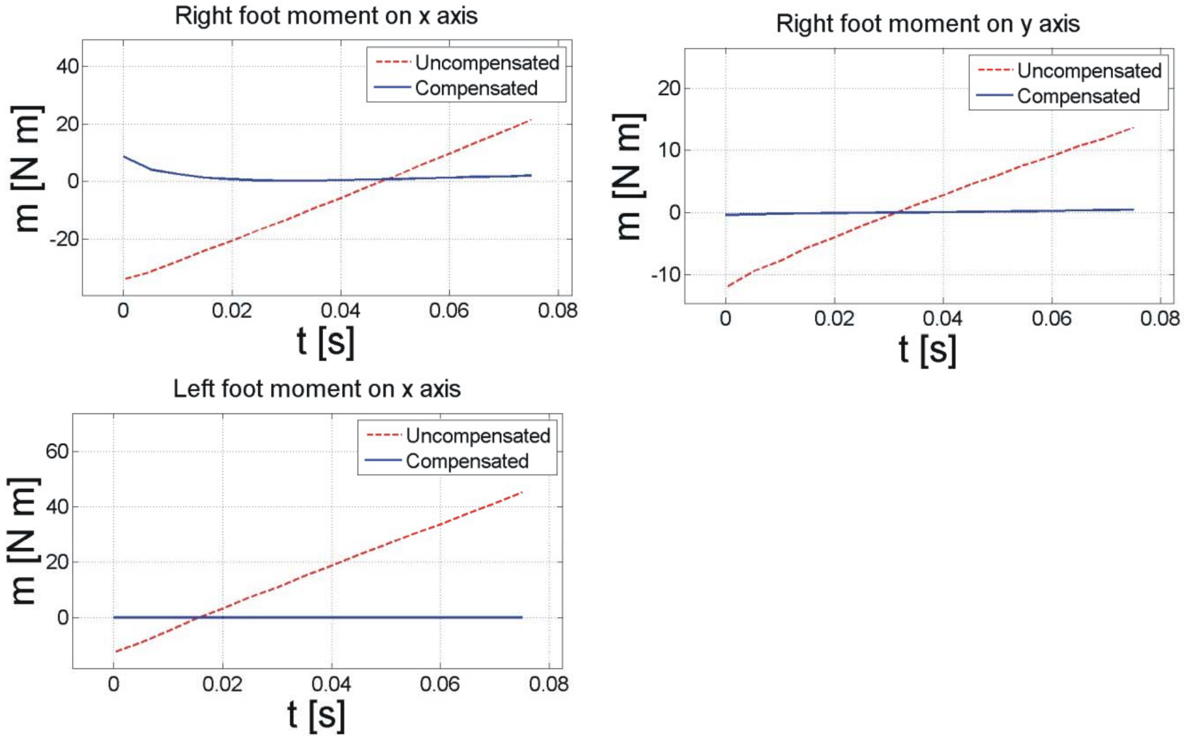




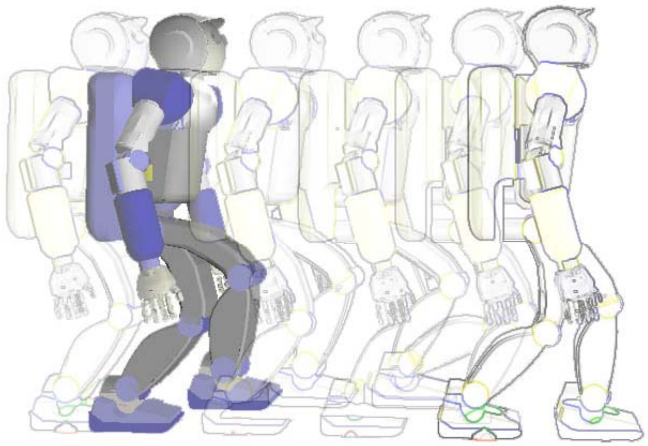
Demo

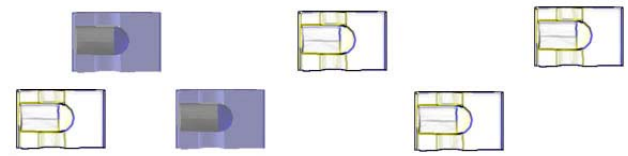


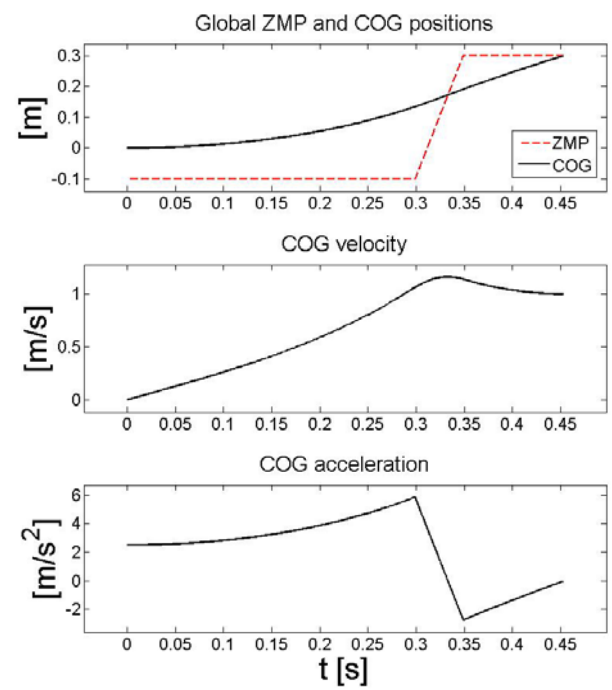
Results: centers of pressure

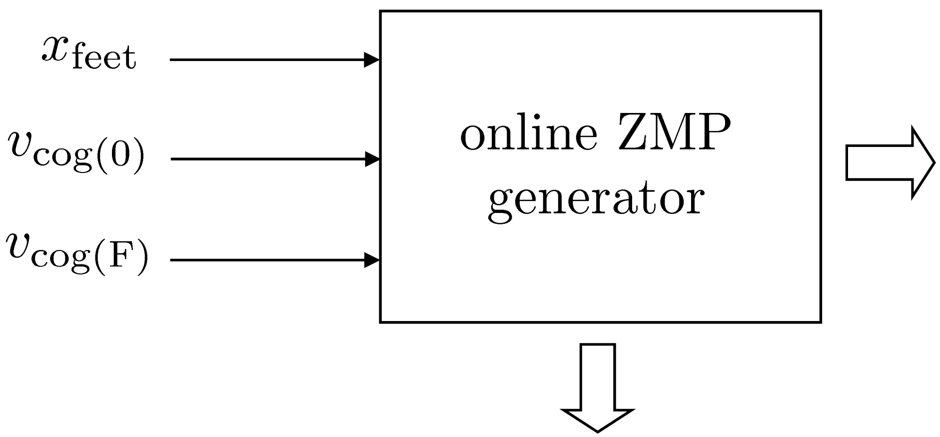


Specifications





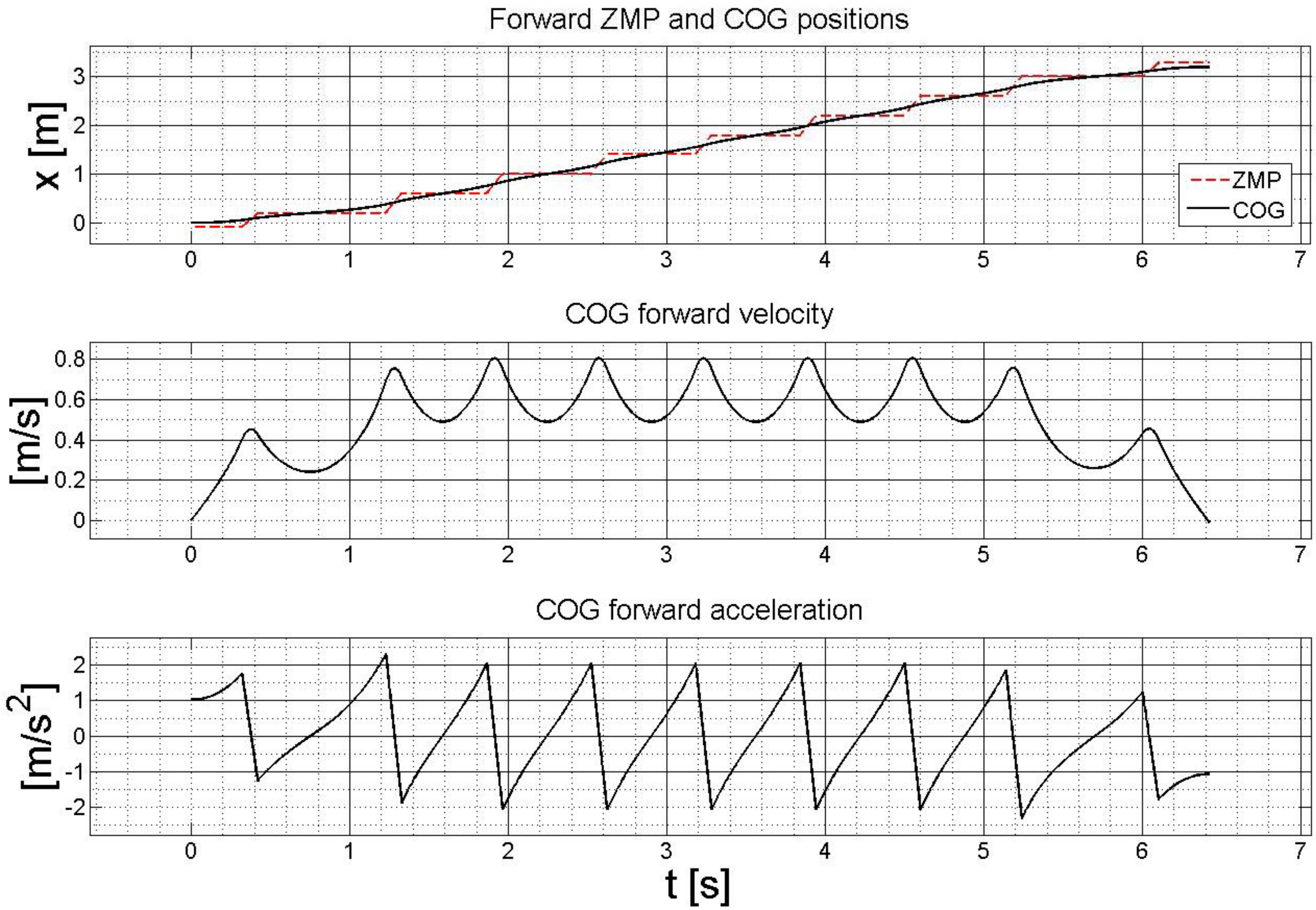




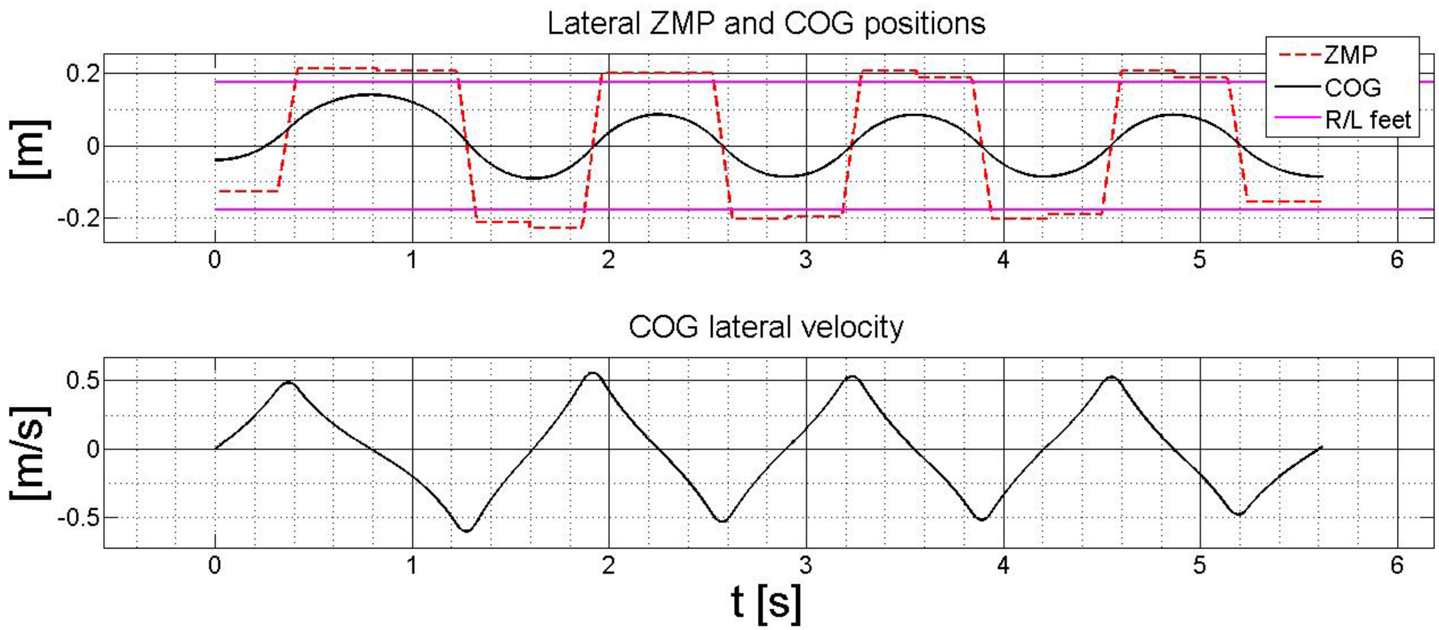
$$LZM_x = G_x - \frac{f_{rx}}{f_{rz}}\left(G_z - LZM_z\right)$$

$$LZM_y = G_y - \frac{f_{ry}}{f_{rz}}\left(G_z - LZM_z\right)$$

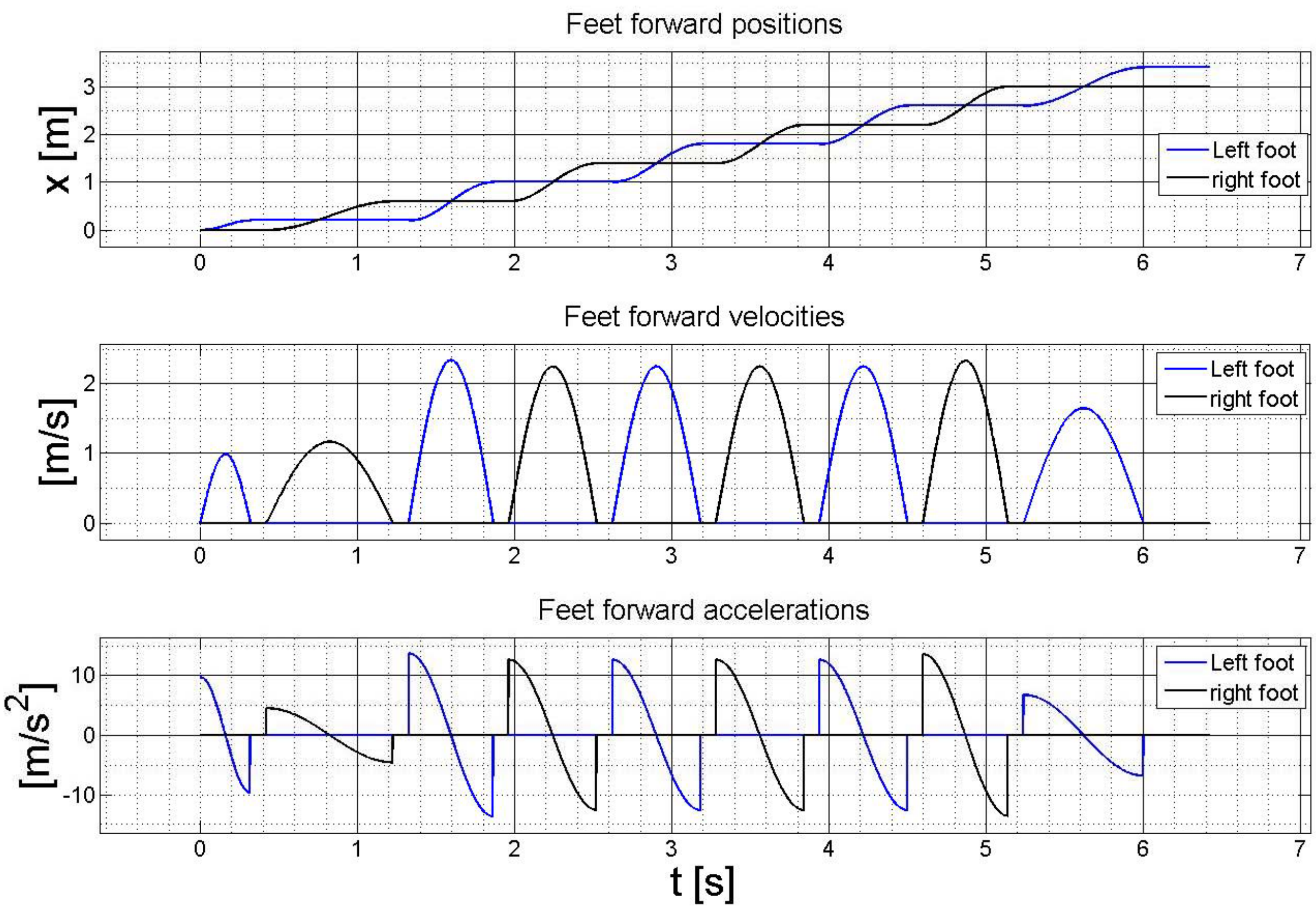
Multiple steps: forward trajectories



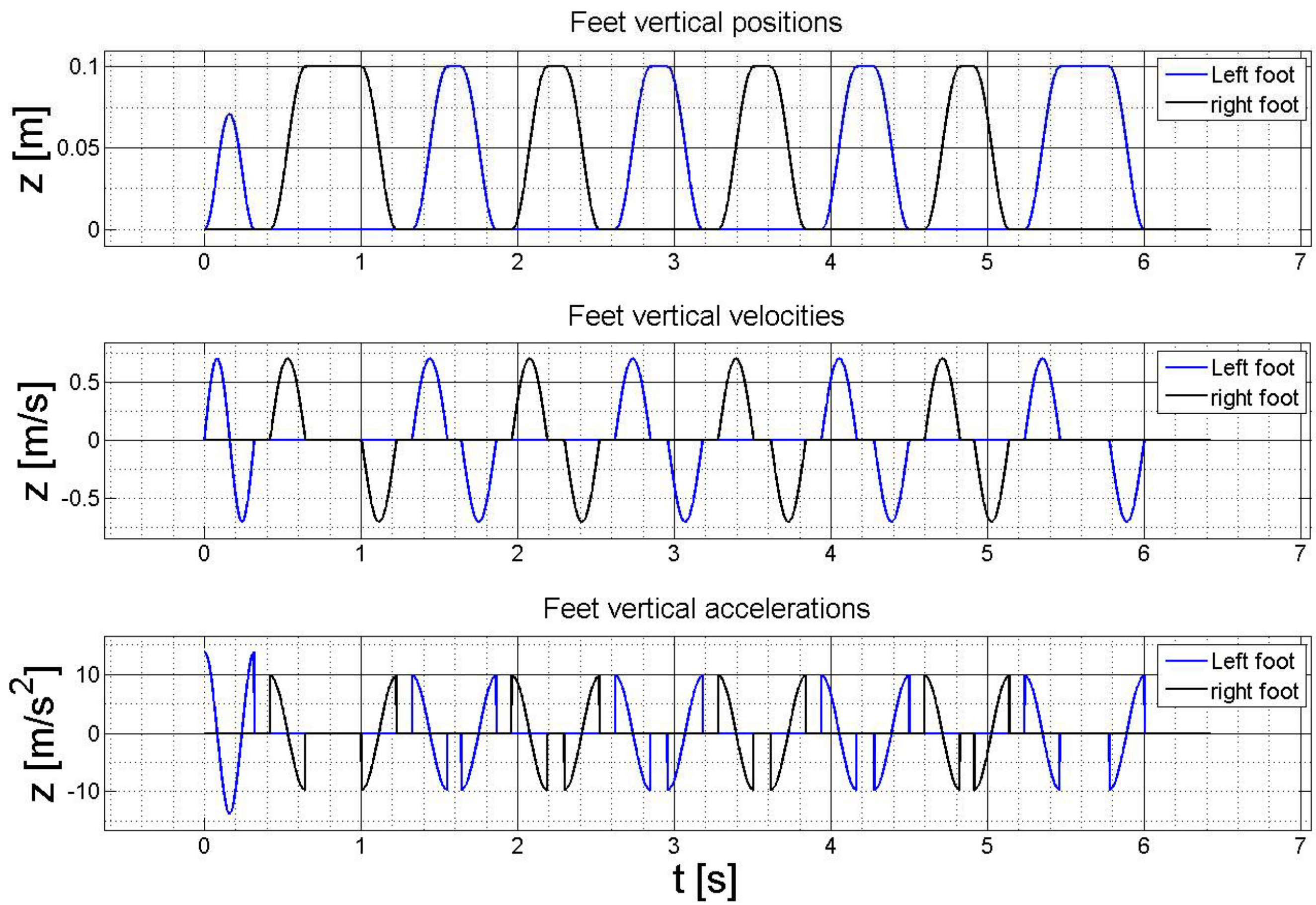
Multiple steps: lateral trajectories



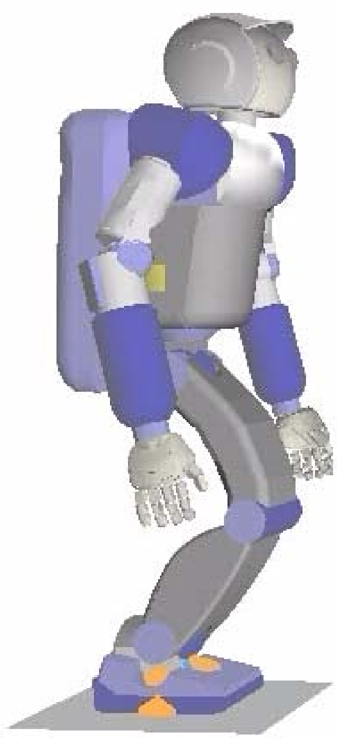
Multiple steps: forward feet trajectories



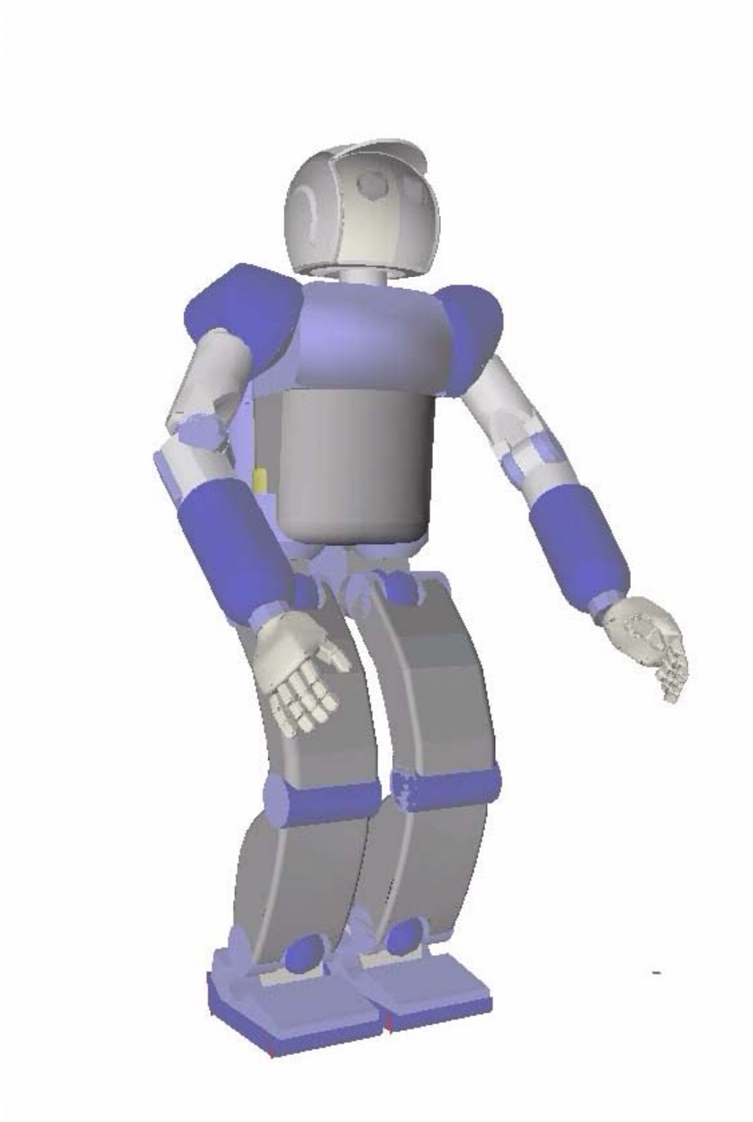
Multiple steps: vertical feet trajectories

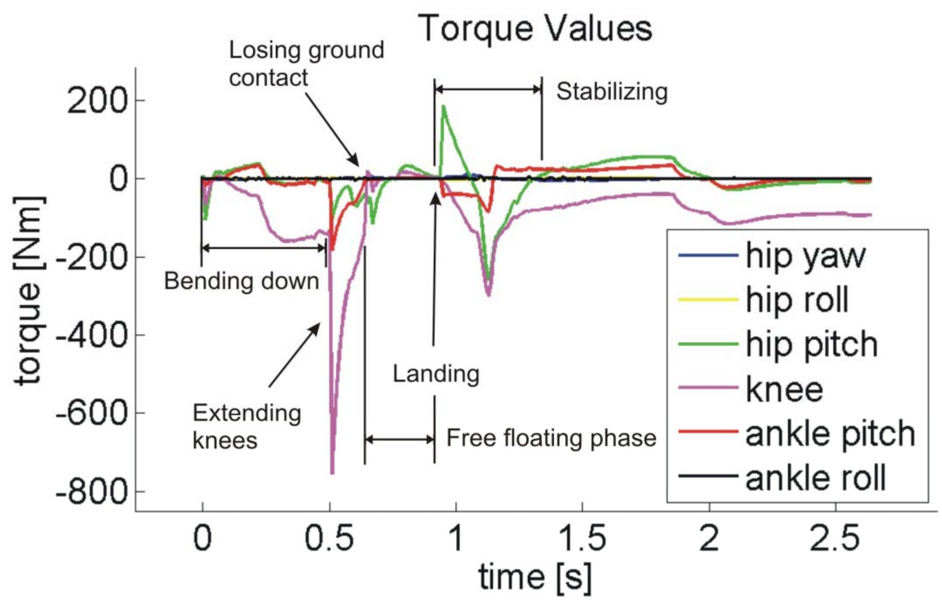


Validation: forward walk

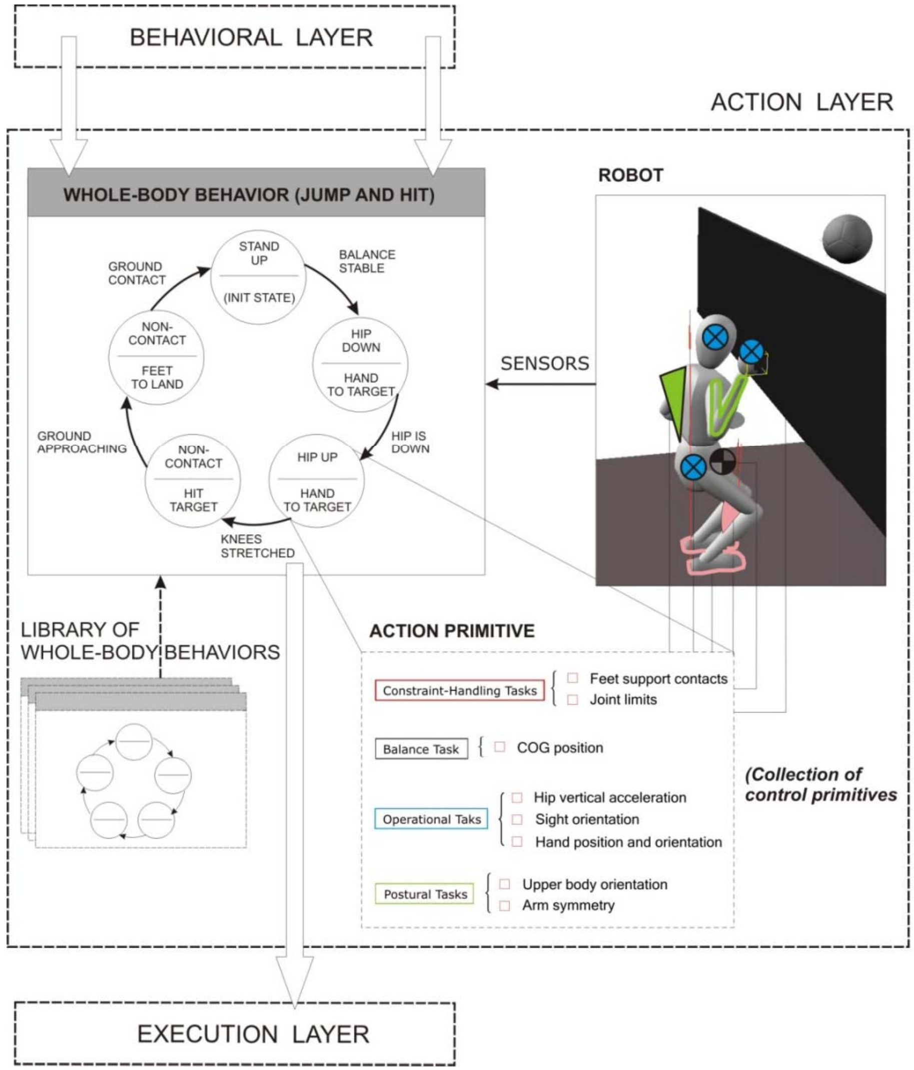


Movements in mid air





Sequencing



BEHAVIORAL LAYER
ACTION LAYER
WHOLE-BODY BEHAVIOR (JUMP AND HIT)
STAND UP
(INIT STATE)
BALANCE STABLE
HIP DOWN
HAND TO TARGET
HIP IS DOWN
HIP UP
HAND TO TARGET
KNEES STRETCHED
NON-CONTACT
HIT TARGET
GROUND APPROACHING
NON-CONTACT
FEET TO LAND
GROUND CONTACT
ROBOT
SENSORS
LIBRARY OF WHOLE-BODY BEHAVIORS
ACTION PRIMITIVE
Constraint-Handling Tasks
Feet support contacts
Joint limits
Balance Task
COG position
Operational Taks
Hip vertical acceleration
Sight orientation
Hand position and orientation
Postural Tasks
Upper body orientation
Arm symmetry
(Collection of control primitives
EXECUTION LAYER

The End