Human based hybrid kinematic/dynamic whole-body control in humanoid robotics

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Outline of the presentation

- **Context and motivation**
  - ✓ Context
  - ✓ Our main objective
- **Human-data based control schemes**
  - ✓ Motion Capture system
  - ✓ State of art of human-based control
  - ✓ Limitations of human-based control
- **Proposed control scheme**
  - ✓ Basic idea of the proposed control scheme
  - ✓ Prioritized tasks
  - ✓ Tasks definition
  - ✓ ZMP-based nonlinear stabilizer
  - ✓ Summary of the proposed control scheme
- **Real-time experimental results**
  - ✓ Our demonstrator : **HOAP-3 Robot**
  - ✓ **Scenario 1 :** Squat-like motions
  - ✓ **Scenario 2 :** Online adaptation towards slope variation
  - ✓ **Scenario 3 :** Dynamic walking motions
  - ✓ **Scenario 4 :** Toward dynamic walking on irregular ground
- **Conclusion & future work**

Context and motivation

- ✓ Context
- ✓ Our main objective

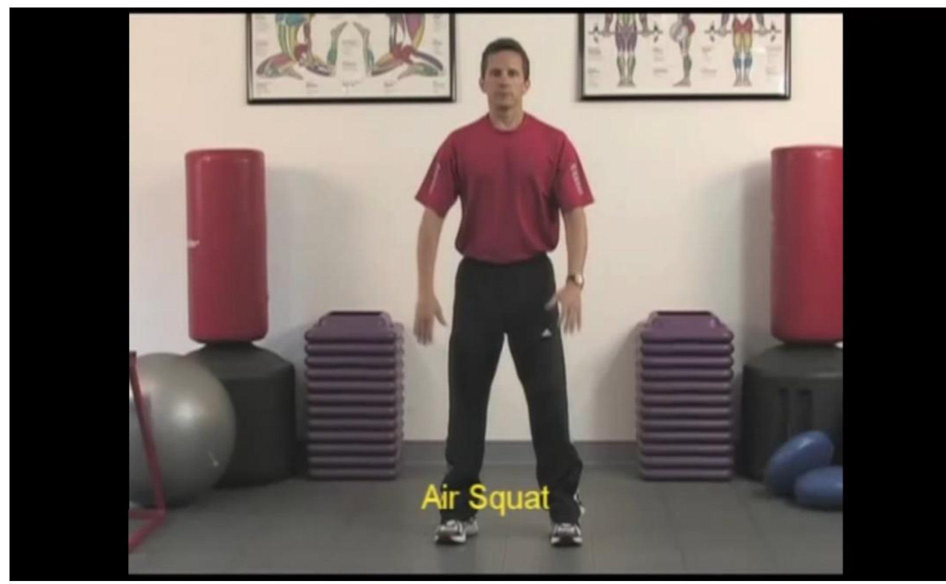
Human whole body motions

Exp 1 : Walking

- ✓ Is one of the main gaits of locomotion
- ✓ Typically slower than running.
- ✓ Alternating the legs
- ✓ Only one foot may leave contact/ground
- ✓ There is also a period of double-support

Exp 2 : Squat

- ✓ It helps building several muscles in legs
- ✓ A cyclic motion
- ✓ Alternating two positions
- ✓ Stand position with extended arms
- ✓ Sit position bent knees



Human versus humanoid walking gaits

A human walking

HRP4 humanoid walking

Our main objective

Reference Trajectories
or
Motion parameters

Issued from human motions

Control scheme

Humanoid robot

Objective : Use of whole body control to perform different tasks
Use of human data in the control scheme
Include the robot's dynamics in the control scheme → dynamic stability

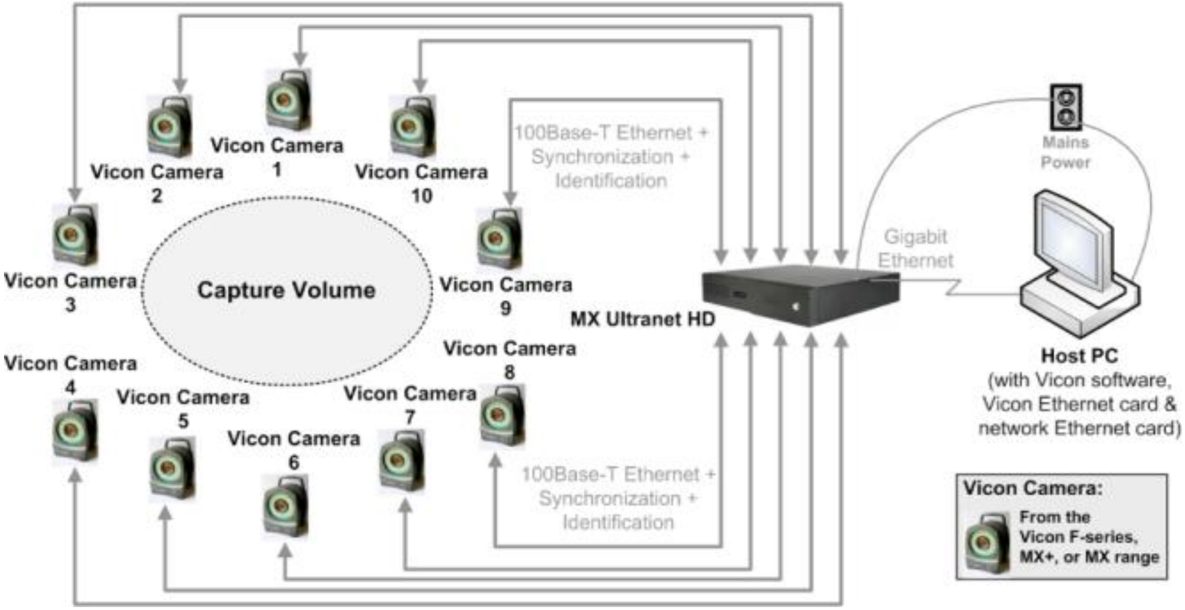
Human-data based control schemes

- ✓ Motion Capture system
- ✓ State of art of human-based control
- ✓ Limitations of human-based control

Motion Capture system

Context: Walking motion analysis project
LABLAB, University of Rome Foro Italico, Pr. Capozzo, Department of Human Movement and Sports Sciences.

Equipment : 1 host PC
10 Vicon cameras
3 Forces plates



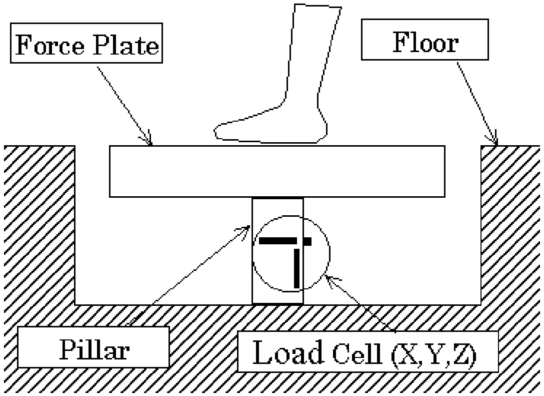
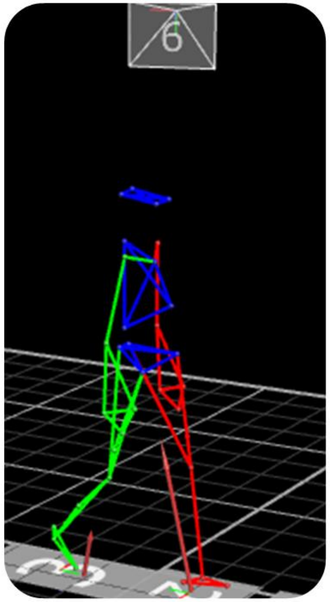


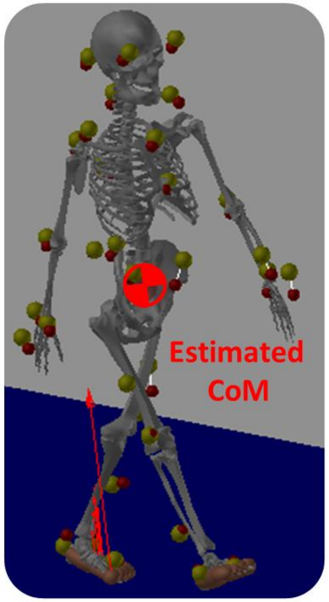
Fig.1 Structure of Force Plate

Motion Capture system

(a)



(b)



(c)

Study: 15 Subjects
Different walking speed
35 markers using Plug-in Gait template
Reconstruction of movement using Vicon Nexus
Estimation of CoM using Lifemod

Related work

Human-Data based schemes with Whole body motion control

Class 1: Offline computation

Motion Primitives
[Nakaoka et al., 2003-2005]
Gait parameter extraction
[Harada et al.,2009]
Scale and optimization
[Suleiman et al., 2008]

Class 2: Online computation

Balance/Tracking controller
[Yamane et al.,2009-2010]
Imitation
[Shaal et al.,1999-2003,
Calderon & Hu 2005]
Human Normalized model
[Montecillo et al.,2010]

Human data based whole body motion control using offline calculation

[Nakaoka et al., 2003, 2005]
Data from human motion capture are used as motion primitives to produce postural imitation (only postural motions, no walking).

[Harada et al., 2009]
Data from human motion capture are used to find gait's parameters.

[Suleiman et al., 2008]
Data from human motion capture are first scaled to humanoid joint position, then an optimization with constraint is used.

👍 :
Offline computations allows optimized motions

👎 :
Offline computation do not allow reactive motions

Human data based whole body motion control using online calculation

[Schaal, 1999 ; Schaal et al., 2003 ; Calderon & Hu, 2005]
Data from human motion capture are used to feed a learning system to produce accurate movement primitives.

[Yamane & Hodgins, 2009 ; Yamane et al., 2010]
Two controllers are used in this application.
First controller : a balance controller.
Second controller : joint space trajectory tracking

[Montecillo-Puente et al., 2010]
Data from human motion capture are performed in real time to produce postural imitation (postural motion, no walking).

:
Reactive motions using feedback from sensors

:
No walking motions are reproduced

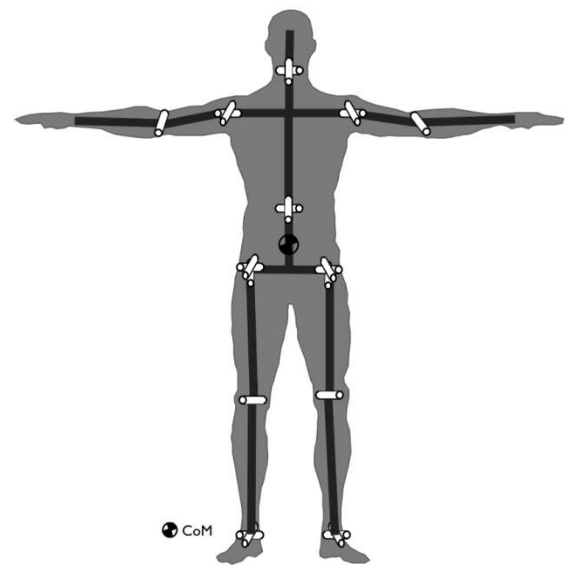
Proposed control scheme

- ✓ Basic idea of the proposed control scheme
- ✓ Prioritized tasks
- ✓ Tasks definition
- ✓ ZMP-based nonlinear stabilizer
- ✓ Summary of the proposed control scheme

Basic idea of the proposed control scheme

Reference motion : from human motion capture

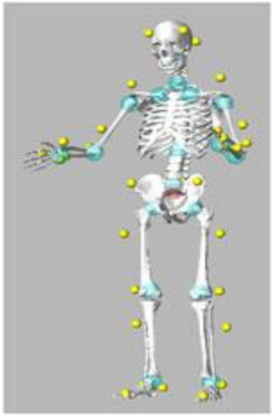
Differences:
Flexible/Rigid
Different DoF
Different Power
Contacts
Similarities:
CoM
Feet cycle



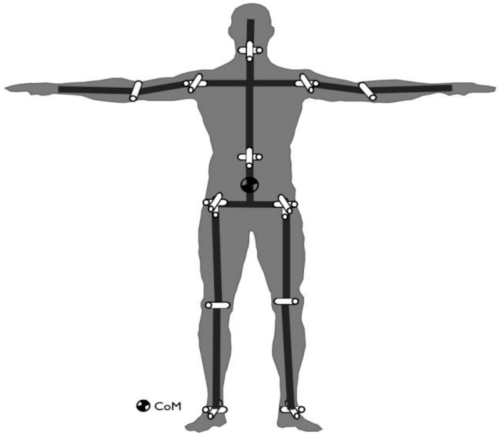
Reduced set of human data:

Relative feet pose (6) + CoM (3) → Articular trajectories (22)

Basic idea of the proposed control scheme



P_{rd} & CoM_d



Basic idea: Task-priority formalism [Nakamura, 1987]

How : Two tasks

- Relative feet position tracking.
- CoM trajectory tracking.

Advantages:

Continuous control framework:

No decomposition into distinct phases, one control law.

Brief overview on task formalism

- ✓ Task formalism is used to control a robot for tracking several objectives
- ✓ In the operational space
- ✓ Use the high redundancy of robots
- ✓ Concept initially proposed by [Nakamura 1987] and [Siciliano 1991]

- ✓ The task formalism has been used recently in humanoid robotics
- ✓ In [Sentis et al 2006] for multi-contact dynamic motions
- ✓ In [Mansard 2009] has generalized the formalism by using the addition and removal of tasks during the control execution

- ✓ In the literature, several tasks are needed to produce stable whole-body motions
- ✓ In this work, the proposed architecture is focused on only 4 main tasks
  - Task 1 :The relative feet position and orientation tracking,
  - Task 2 : CoM position tracking with nonlinear ZMP regulation,
  - Task 3 : Body orientation and the
  - Task 4 : Joints' limits avoidance

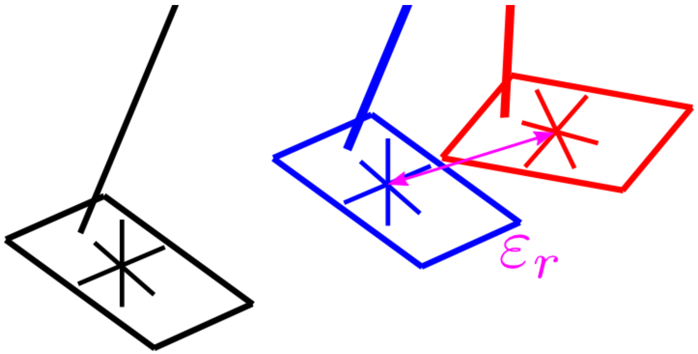
Tasks definition

First task

Feet relative-pose

$$\varepsilon_r = [E_{pos}^T \;\; E_{ori}^T]^T$$

- ✓ Position and orientation error
- ✓ Place one foot / the other one
- ✓ Manage the feet walking cycle



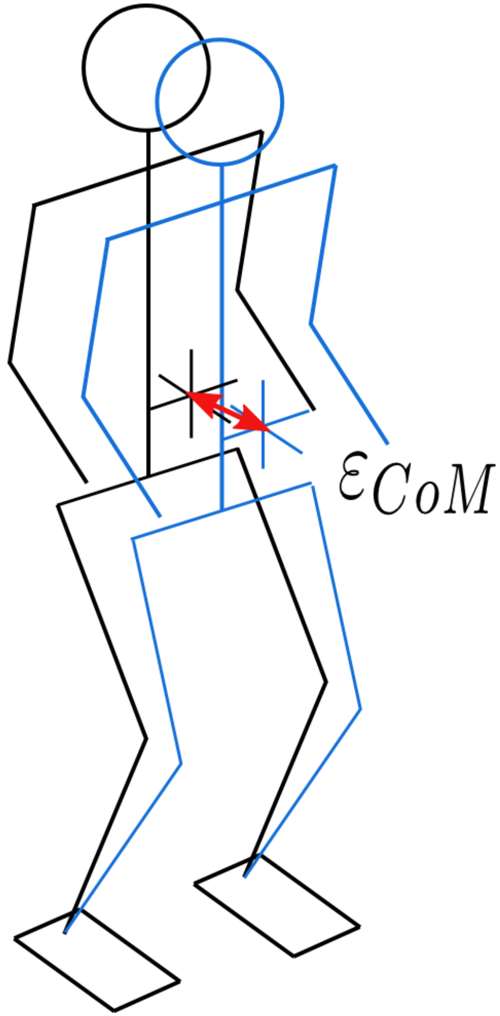
Tasks definition

Second task

Center of Mass position

$$\varepsilon_{CoM} = CoM_d - CoM$$

- ✓ Position error
- ✓ Place the CoM
- ✓ To follow a specific trajectory



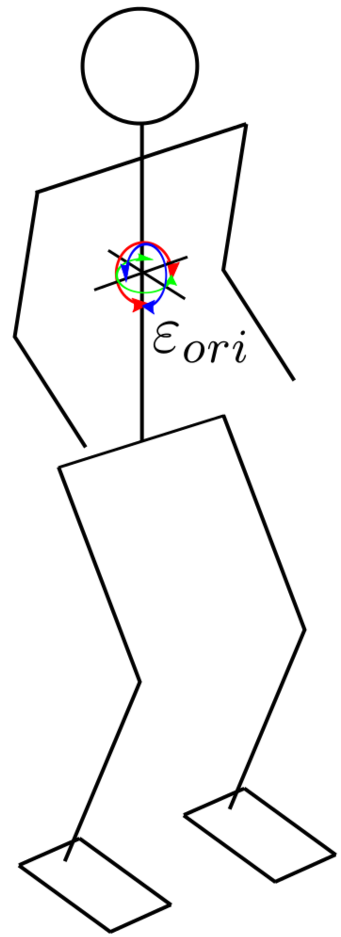
Tasks definition

Third task

Body orientation

$$\varepsilon_{ori} = R_{Ref} \, (\ln(R_{Ref}^{-1} \, R_{Body} \, R_{BodyDes}))^{\vee}$$

- ✓ Orientation error
- ✓ Keeps the torso upright



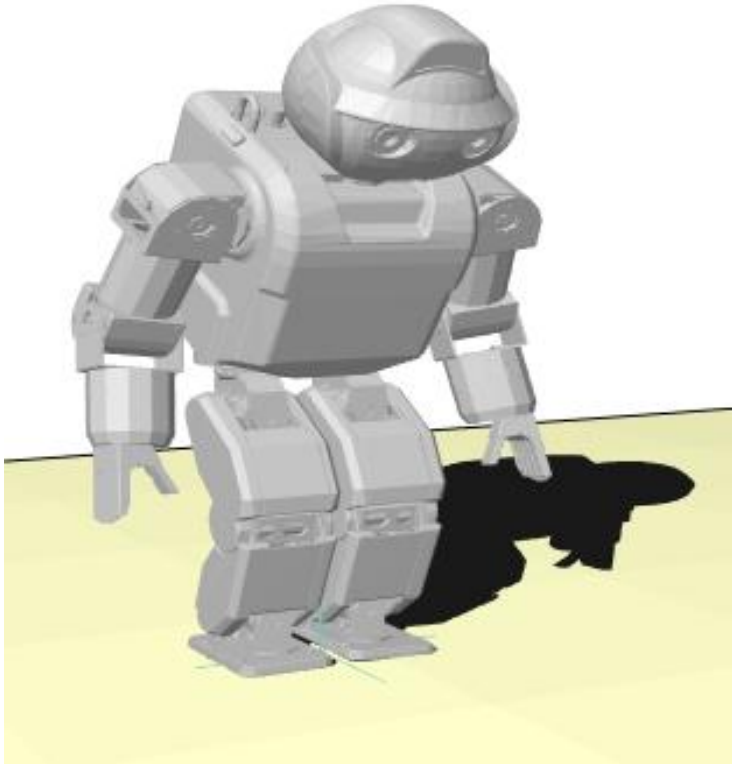
Tasks definition

Fourth task

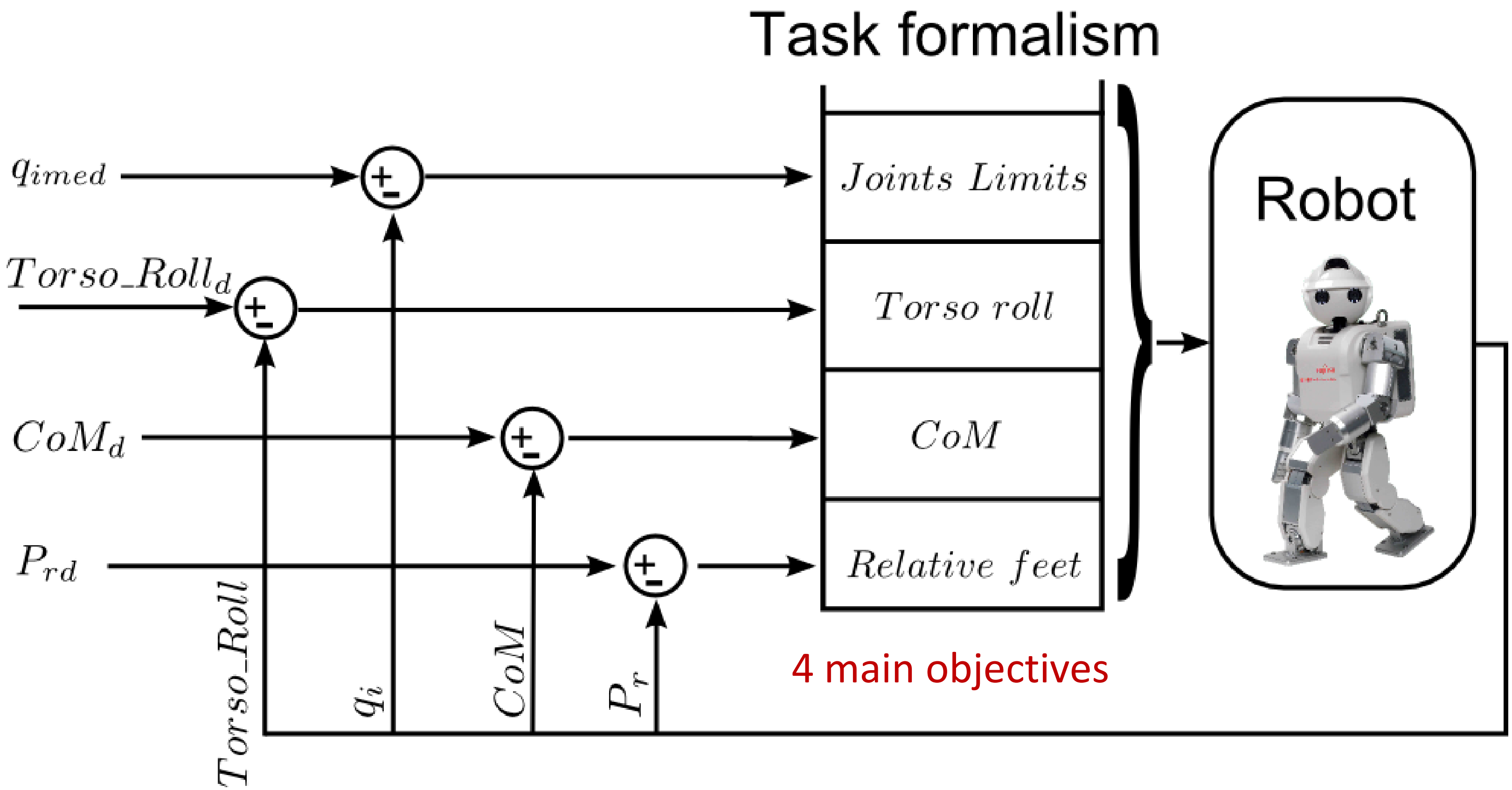
Joints' limits avoidance

$$\varepsilon_{q_i} = \frac{2\ (q_i - q_{imed})}{(q_{imax} - q_{imin})^2}$$

- ✓ Attractive potential fields
- ✓ Define a comfort position



Brief overview on task formalism



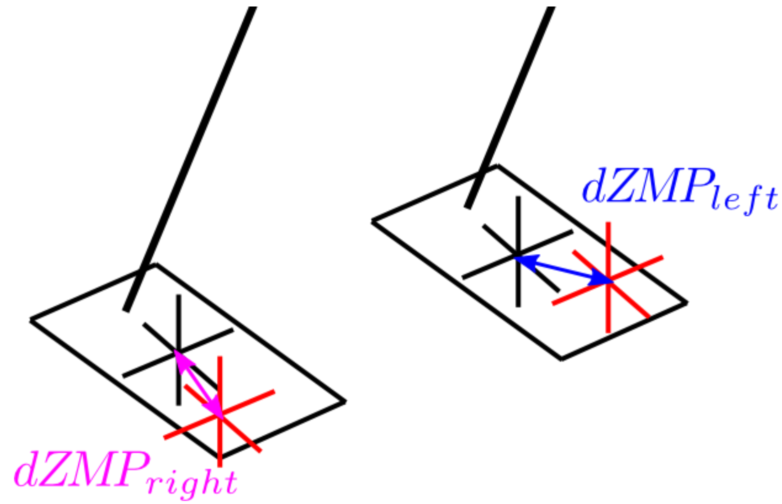
Tasks definition

ZMP regulation

$$\varepsilon_{ZMP} = \alpha \; dZMP_{left} + (1-\alpha) \; dZMP_{right}$$

Feedback based ZMP regulation

- ✓ Weighted distribution
- ✓ Dynamic feedback



Tasks definition

Nonlinear PID

$$u_{ZMP} = k_p(\varepsilon_{ZMP})\varepsilon_{ZMP} + k_d(\varepsilon_{ZMP})\dot{\varepsilon_{ZMP}} + k_i \int \varepsilon_{ZMP}$$

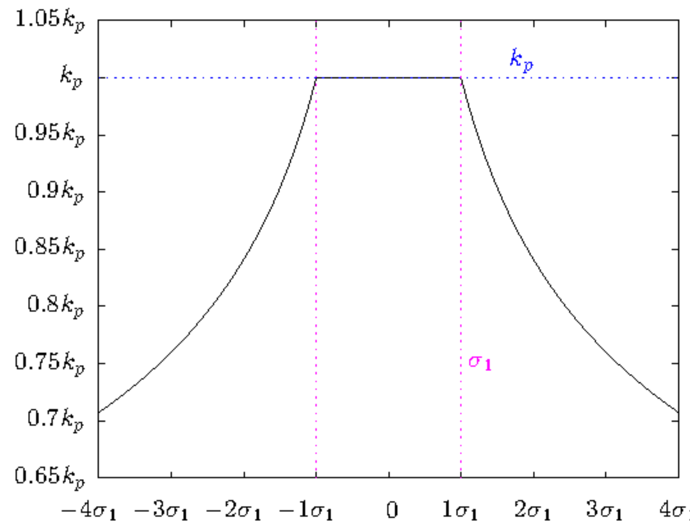
Nonlinear proportional gain

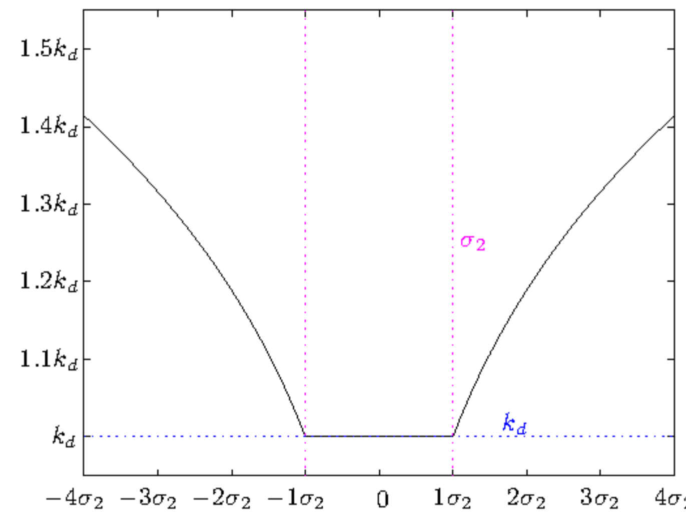
$$k_p(\varepsilon_{ZMP}) = \begin{cases} k_p|\varepsilon_{ZMP}|^{\alpha_1 - 1}, & |\varepsilon_{ZMP}| > \delta_1, \\ k_p\delta_1^{\alpha_1 - 1}, & |\varepsilon_{ZMP}| \leqslant \delta_1. \end{cases}$$

Nonlinear derivative gain

$$k_d(\dot{\varepsilon_{ZMP}}) = \begin{cases} k_d|\dot{\varepsilon_{ZMP}}|^{\alpha_2 - 1}, & |\dot{\varepsilon_{ZMP}}| > \delta_2, \\ k_d\delta_2^{\alpha_2 - 1}, & |\dot{\varepsilon_{ZMP}}| \leqslant \delta_2. \end{cases}$$

Faster response with favorable damping





Tasks definition

Spherical projection

$$\varepsilon_{SPX} = h_{CoM}\sin\left(\frac{u_{ZMPX}}{h_{CoM}}\right),$$
$$\varepsilon_{SPY} = h_{CoM}\sin\left(\frac{u_{ZMPY}}{h_{CoM}}\right),$$
$$\varepsilon_{SPZ} = h_{CoM}\cos\left(\frac{u_{ZMPX}}{2h_{CoM}}+\frac{u_{ZMPY}}{2h_{CoM}}-1\right).$$

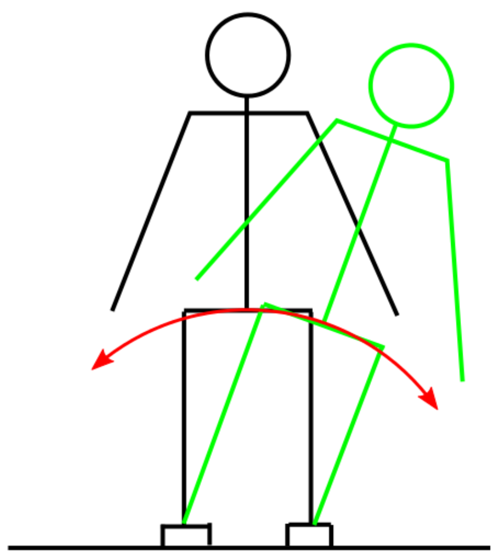
ZMP regulation in the COM workspace

$$\varepsilon_{CoM\&ZMP} = \varepsilon_{CoM} + \varepsilon_{SP}$$

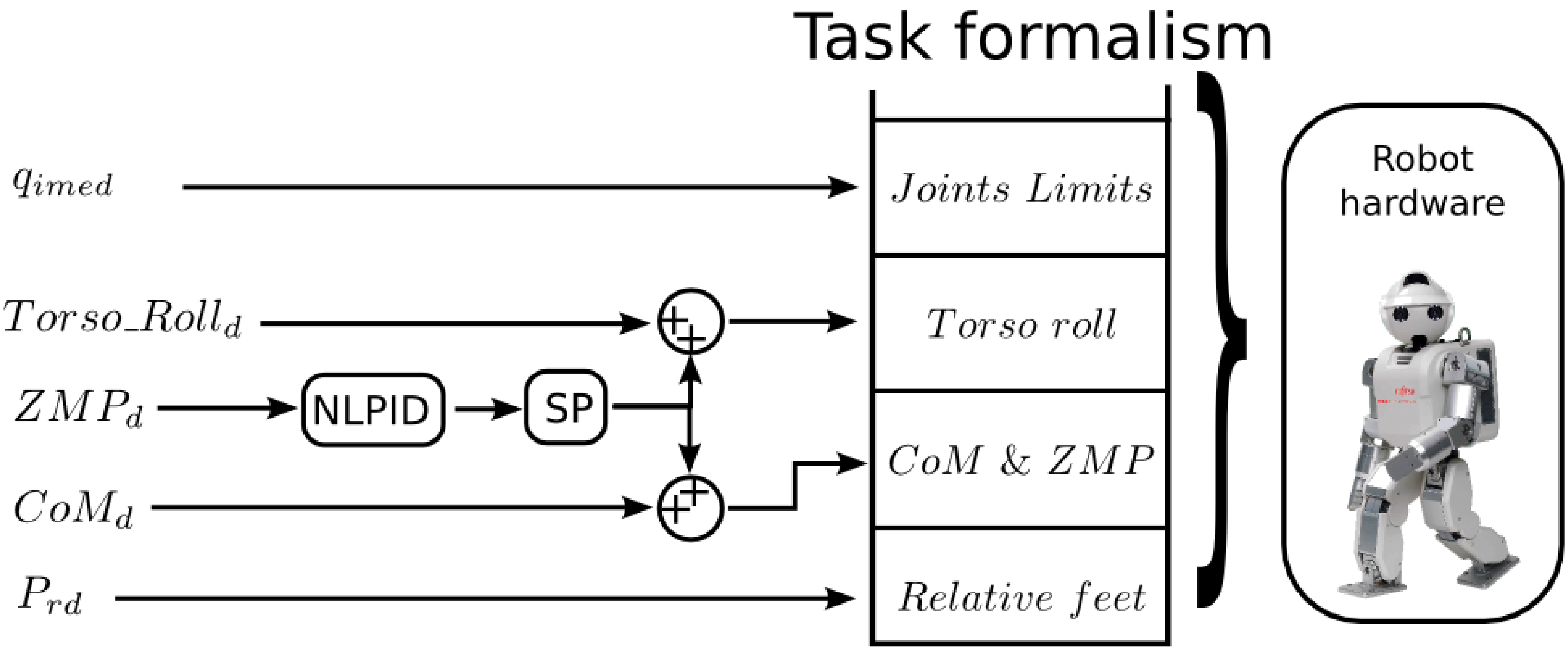
Body orientation adjustment

$$\begin{aligned}\varepsilon_{ori\_sp}(r) &= \varepsilon_{ori}(r) + \mathrm{atan2}(u_{ZMP}(y), h_{CoM}),\\ \varepsilon_{ori\_sp}(p) &= \varepsilon_{ori}(p) + \mathrm{atan2}(u_{ZMP}(x), h_{CoM}),\\ \varepsilon_{ori\_sp}(y) &= \varepsilon_{ori}(y).\end{aligned}$$

Adaptation toward large ZMP correction



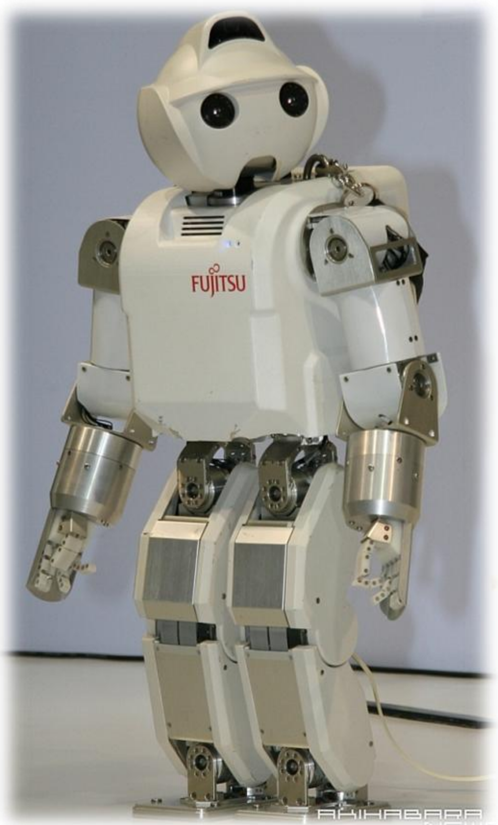
Block diagram of the proposed control scheme

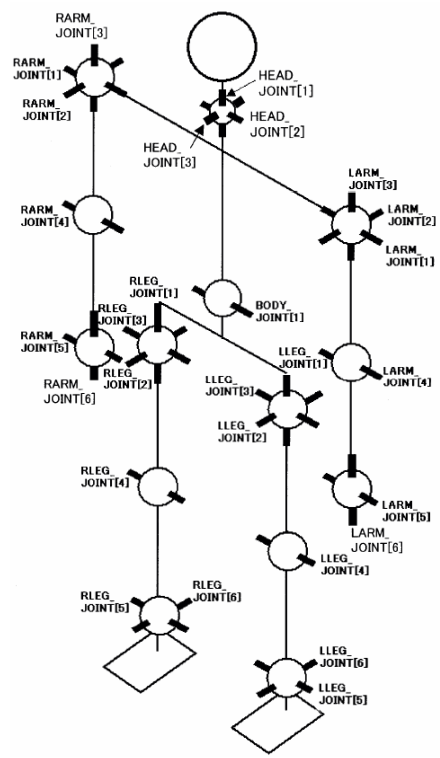


Real-time experimental results

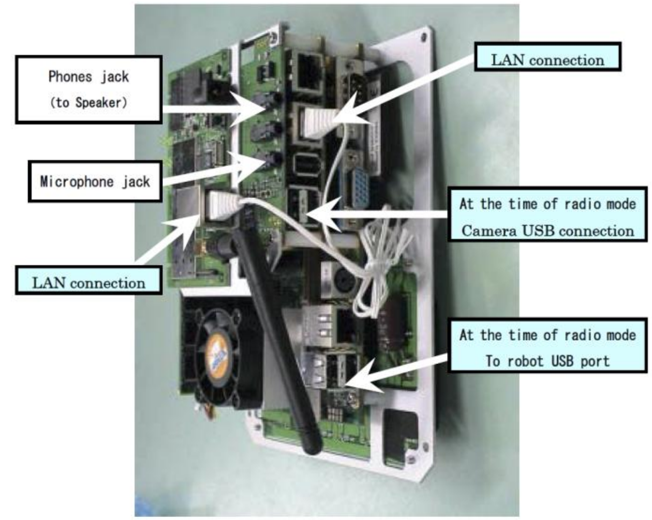
- ✓ Our demonstrator : HOAP-3 Robot
- ✓ Scenario 1 : Squat-like motions
- ✓ Scenario 2 : Online adaptation towards slope variation
- ✓ Scenario 3 : Dynamic walking motions
- ✓ Scenario 4 : Toward dynamic walking on irregular ground

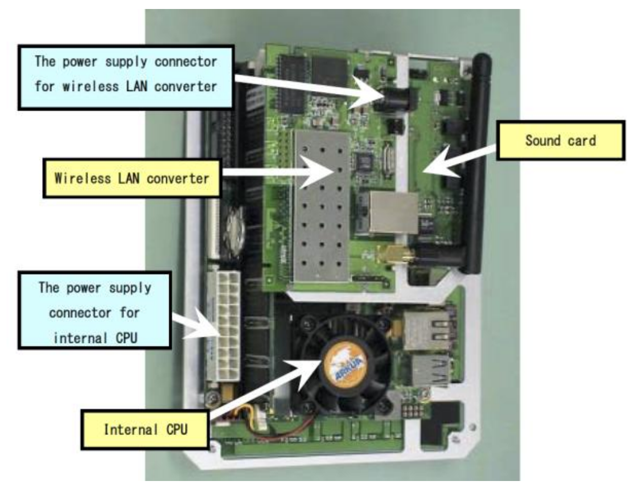
HOAP3 : Architecture





Electronic boards inside





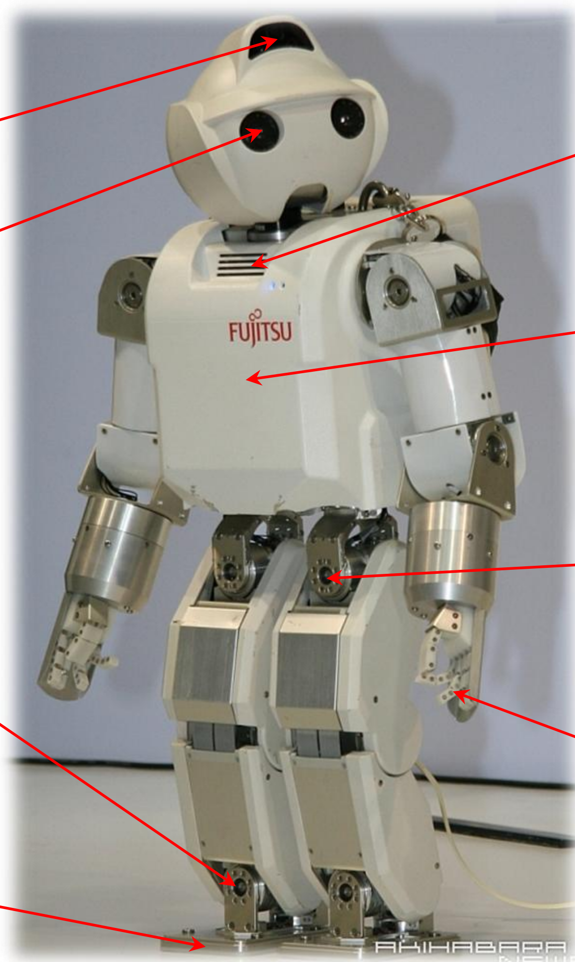
28 dof : 6 dof/**leg** - 6dof/**arm** - 3dof/**head** - 1dof/**body**

HOAP3 : Actuators and sensors

Distance sensor

USB Cameras

Speaker



Posture sensor
3-axis acc sensor
Angular velocity sensor (gyro)

Joint sensors

28 actuators
(21 DC, 7 Stepper)

Force sensors
(4/foot)

Grip sensors

This demonstrator is useful for whole body motion control

Application of the proposed control scheme

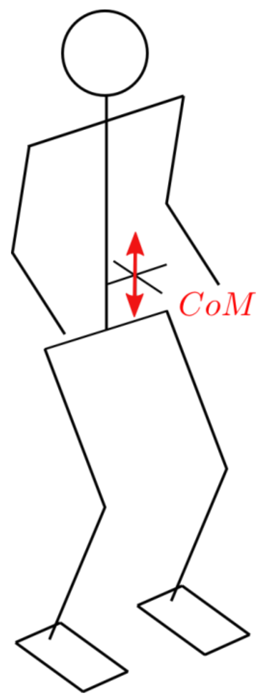
Scenario 1

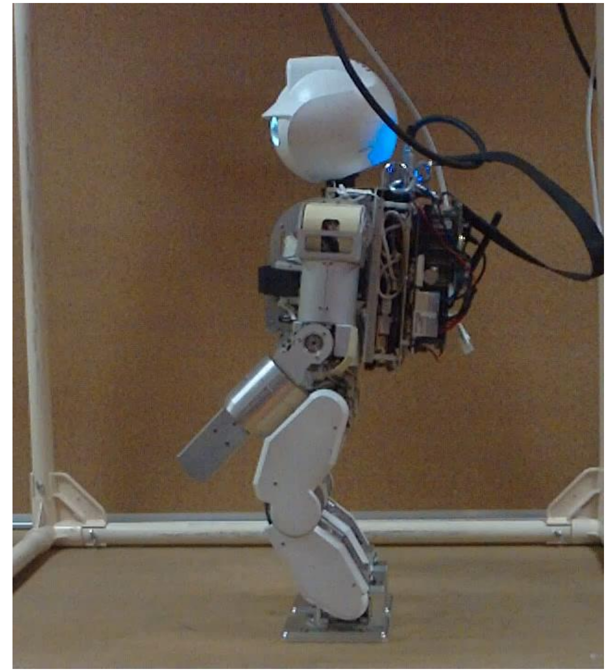
Squat task

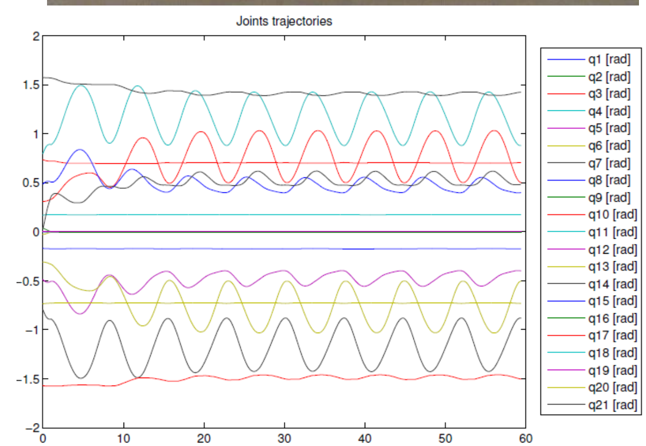
✓ *No feet movement*

✓ *Only CoM moves*

✓ *Up and down*





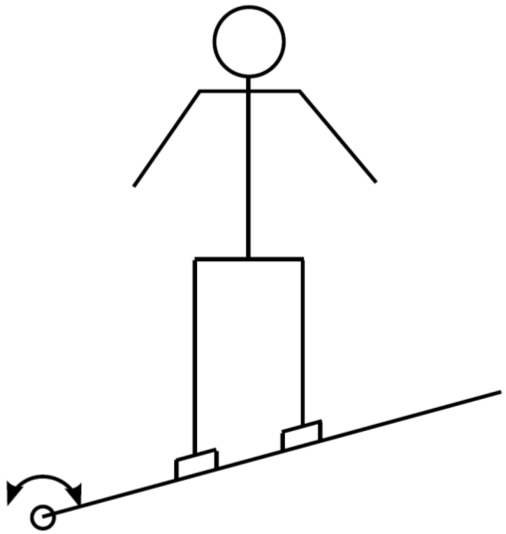


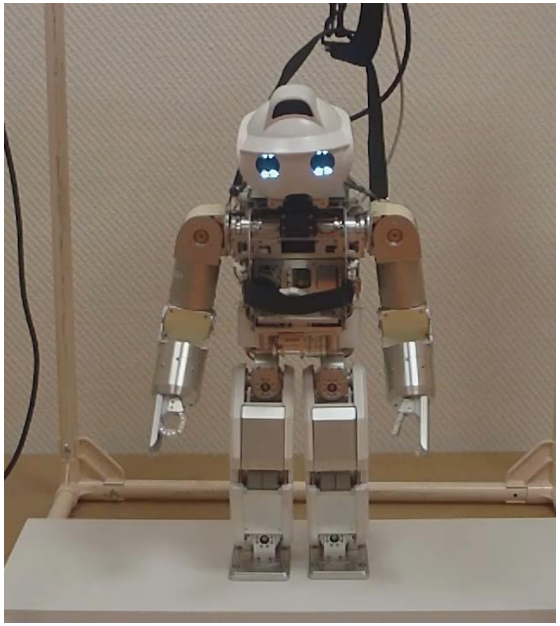
Application of the proposed control scheme

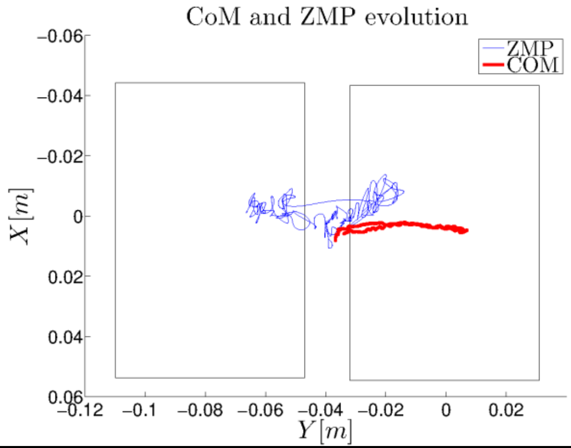
Scenario 2

Online adaptation towards slope variation

- ✓ *No feet movement*
- ✓ *No CoM movement*
- ✓ *Ground inclination variation*
- ✓ *Only ZMP regulation*





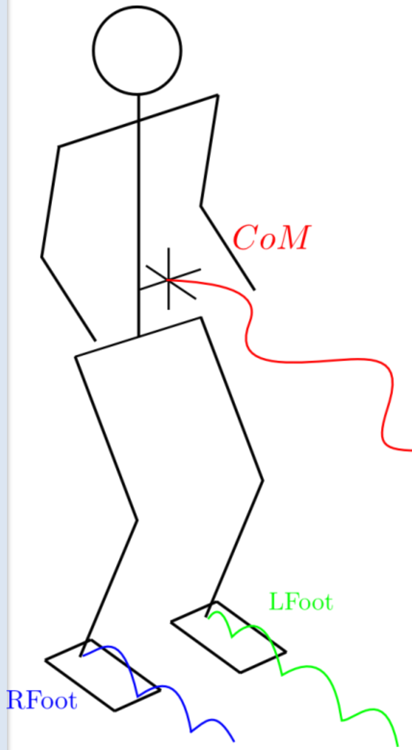


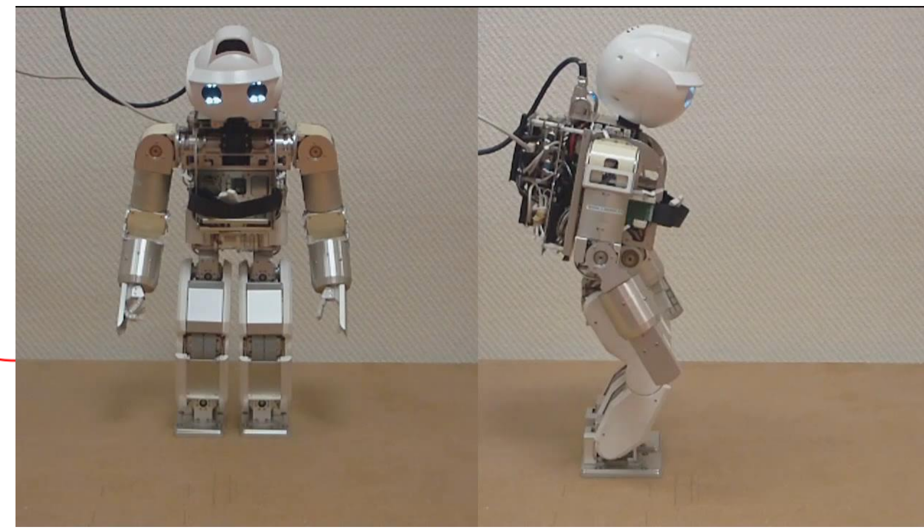
Application of the proposed control scheme

Scenario 3

Dynamic walking motions

- ✓ *B-spline based reference trajectories*
- ✓ *ZMP stabilizer improves stability margins*
- ✓ *Stable dynamic walking*



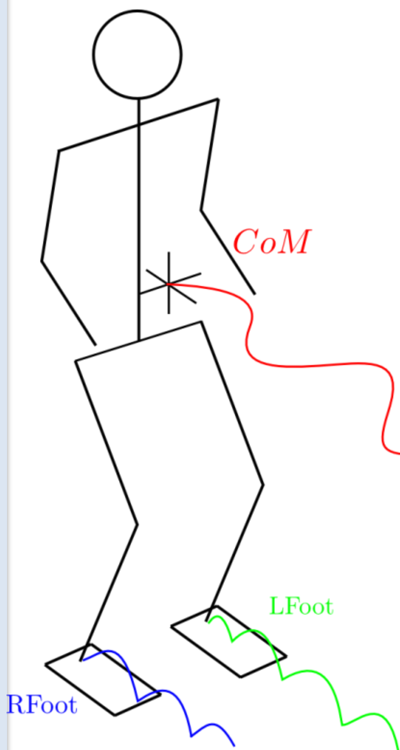


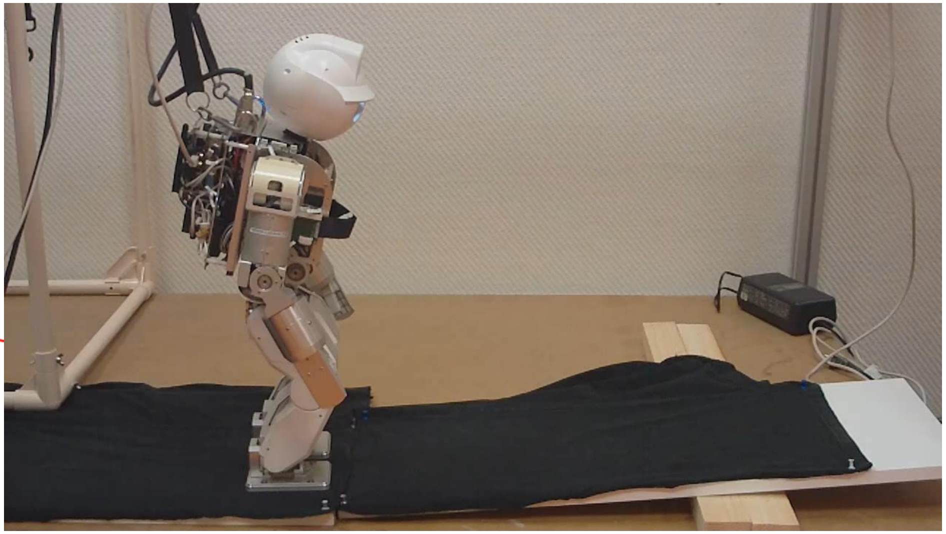
Application of the proposed control scheme

Scenario 4

Toward dynamic walking on irregular ground

- ✓ *Feet cycle and CoM motions from nominal case*
- ✓ *Online adaptation to ground inclination*





Conclusion & future work

- ✓ Conclusion
- ✓ Future work

Conclusion & future work

Addressed problem: Whole-body motion control with dynamic stability

Proposed Solution: Task based whole-body control

(i) the CoM with a nonlinear ZMP regulation,
(ii) the relative pose of robot's feet,
(iii) the body orientation and
(iv) joint's limit avoidance

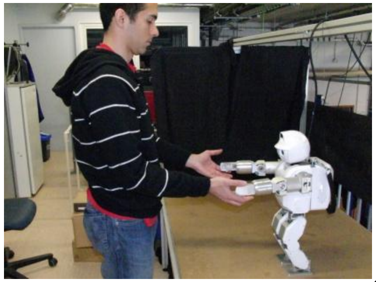
Validation: Real-time experiments on HOAP-3 humanoid robot

Advantages of the proposed solution :

- ✓ Whole body motion
- ✓ Continuous control framework
- ✓ Natural and smooth motions

Future work : Validation for more complex tasks

- ✓ Interaction with human
- ✓ Use of human data
- ✓ Improve the ZMP regulation
- ✓ Experiments on HRP4 robot



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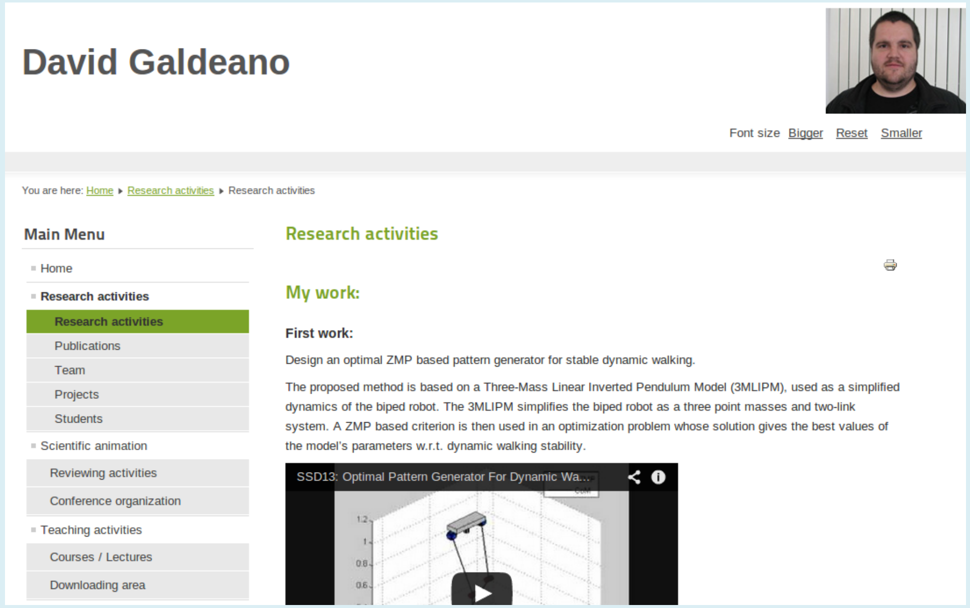

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