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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 data Control Scheme Experiments Conclusion
Human versus humanoid walking gaits

A human walking  HRP4 humanoid walking
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 $\rightarrow$ dynamic stability
Human-data based control schemes

- Motion Capture system
- State of art of human-based control
- Limitations of human-based control
**Human data**

**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
Human data

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

Motion Capture system

(a) 
(b) 
(c)
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
  [Schaal 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
Reference motion: from human motion capture

Basic idea of the proposed control scheme

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

**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
  o Task 1: The relative feet position and orientation tracking,
  o Task 2: CoM position tracking with nonlinear ZMP regulation,
  o Task 3: Body orientation and the
  o Task 4: Joints’ limits avoidance
First task

Feet relative-pose

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

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

Center of Mass position

\[ \varepsilon_{CoM} = CoM_d - CoM \]

- Position error
- Place the CoM
- To follow a specific trajectory
Third task

Body orientation

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

- Orientation error
- Keeps the torso upright
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

Task formalism

4 main objectives

Context
Human data
Control Scheme
Experiments
Conclusion

Speaker: D. GALDEANO (LIRMM / UM2, France)

HLR 2014 (Heidelberg, Germany)
Tasks definition

ZMP regulation

\[ \varepsilon_{ZMP} = \alpha \text{dZMP}_{left} + (1 - \alpha) \text{dZMP}_{right} \]

Feedback based ZMP regulation

- Weighted distribution
- Dynamic feedback
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

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

Nonlinear derivative gain

\[ k_d(\varepsilon_{ZMP}) = \begin{cases} 
    k_d|\varepsilon_{ZMP}|^{\alpha_2 - 1}, & |\varepsilon_{ZMP}| > \delta_2, \\
    k_d\delta_2^{\alpha_2 - 1}, & |\varepsilon_{ZMP}| \leq \delta_2.
\end{cases} \]

Faster response with favorable damping
**Spherical projection**

\[
\begin{aligned}
\varepsilon_{SPX} &= h_{CoM} \sin \left( \frac{u_{ZMPX}}{h_{CoM}} \right), \\
\varepsilon_{SPY} &= h_{CoM} \sin \left( \frac{u_{ZMPY}}{h_{CoM}} \right), \\
\varepsilon_{SPZ} &= h_{CoM} \cos \left( \frac{u_{ZMPX}}{2h_{CoM}} + \frac{u_{ZMPY}}{2h_{CoM}} - 1 \right).
\end{aligned}
\]

**ZMP regulation in the COM workspace**

\[\varepsilon_{CoM\&ZMP} = \varepsilon_{CoM} + \varepsilon_{SP}\]

**Body orientation adjustment**

\[
\begin{aligned}
\varepsilon_{ori\_sp}(r) &= \varepsilon_{ori}(r) + \arctan2(u_{ZMP}(y), h_{CoM}), \\
\varepsilon_{ori\_sp}(p) &= \varepsilon_{ori}(p) + \arctan2(u_{ZMP}(x), h_{CoM}), \\
\varepsilon_{ori\_sp}(y) &= \varepsilon_{ori}(y).
\end{aligned}
\]

**Adaptation toward large ZMP correction**
Block diagram of the proposed control scheme

Task formalism

\[ q_{\text{imed}} \]
\[ \text{Torso Roll}_d \]
\[ \text{ZMP}_d \]
\[ \text{CoM}_d \]
\[ P_{rd} \]
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

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

CoM and ZMP evolution

![Graph showing CoM and ZMP evolution](image)
Application of the proposed control scheme

Scenario 3

Dynamic walking motions

✔ B-spline based reference trajectories

✔ ZMP stabilizer improves stability margins

✔ Stable dynamic walking

CoM

LFoot

RFoot
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*

![Diagram showing the application of the proposed control scheme](image)
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
www.lirmm.fr/~galdeano/

David Galdeano

Research activities

My work:
First work:
Design an optimal ZMP based pattern generator for stable dynamic walking.

The proposed method is based on a Three-Mass Linear Inverted Pendulum Model (3MLIPM), used as a simplified dynamics of the biped robot. The 3MLIPM simplifies the biped robot as a three point masses and two-link system. A ZMP based criterion is then used in an optimization problem whose solution gives the best values of the model's parameters w.r.t. dynamic walking stability.

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