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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
**Context**

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 → dynamic stability
Human-data based control schemes

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

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**Motion Capture system**

**Fig. 1: Structure of Force Plate**
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
  [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
Data from human motion capture are used to feed a learning system to produce accurate movement primitives.

Two controllers are used in this application. First controller: a balance controller. Second controller: joint space trajectory tracking.

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

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
First task

Feet relative-pose

\[ \varepsilon_r = [E^{T}_{pos} \ E^{T}_{ori}]^T \]

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

Center of Mass position

\[ \varepsilon_{CoM} = C_{oM_d} - C_{oM} \]

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

Body orientation

\[ \varepsilon_{ori} = \mathbf{R}_{Ref} \ (\ln(\mathbf{R}_{Ref}^{-1} \ \mathbf{R}_{Body} \ \mathbf{R}_{BodyDes}))^{\top} \]

- Orientation error
- Keeps the torso upright
Fourth task

Joints’ limits avoidance

\[ \varepsilon q_i = \frac{2 (q_i - q_{im})}{(q_{imax} - q_{imin})^2} \]

✓ Attractive potential fields
✓ Define a comfort position
Brief overview on task formalism

Task formalism

4 main objectives
ZMP regulation

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

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
**Tasks definition**

**Spherical projection**

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

ZMP regulation in the COM workspace

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

Body orientation adjustment

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

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

Task formalism

- $q_{med}$
- $Torso_{Roll_d}$
- $ZMP_d$
- $CoM_d$
- $P_{rd}$

Joints Limits
- Torso roll
- CoM & ZMP
- Relative feet

Robot hardware
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

**Context**

**Human data**

**Control Scheme**

**Experiments**

**Conclusion**

**HOAP3**:

**Architecture**

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

**Electronic boards inside**

- LAN connection
- Microphone jack
- At the time of radio mode
  - Camera USB connection
  - To robot USB port
- The power supply connector for wireless LAN converter
- Sound card
- Wireless LAN converter
- The power supply connector for internal CPU
- Internal CPU
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

CoM
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

![Graph of CoM and ZMP evolution](image)
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

Application of the proposed control scheme
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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