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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 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
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

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.
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

$$\varepsilon_r = \begin{bmatrix} E_{pos}^T & E_{ori}^T \end{bmatrix}^T$$

- 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

$$\varepsilon_{ori} = R_{Ref} \left( \ln \left( R^{-1}_{Ref} \ R_{Body} \ R_{BodyDes} \right) \right)^{\top}$$

- Orientation error
- Keeps the torso upright
Fourth task

Joints’ limits avoidance

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

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

4 main objectives
ZMP regulation

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

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
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

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

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

Task formalism

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

Robot hardware

Block diagram:
- $q_{\text{imed}}$
- $\text{Torso}\_\text{Roll}_d$
- $\text{ZMP}_d$
- $\text{CoM}_d$
- $P_{rd}$

Context - Human data - Control Scheme - Experiments - Conclusion
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**

This demonstrator is useful for **whole body motion control**.
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
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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