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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
Our main objective

Reference Trajectories
or
Motion parameters
Issued from human motions

Control scheme

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
Motion Capture system

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

(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
  [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

Reduced set of human data:
Relative feet pose (6) + CoM (3) → Articular trajectories (22)

Differences:
- Flexible/Rigid
- Different DoF
- Different Power
- Contacts

Similarities:
- CoM
- Feet cycle
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

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

- 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

\[ \varepsilon_{ori} = R_{Ref} \left( \ln(R_{Ref}^{-1} R_{Body} R_{BodyDes}) \right)^{\top} \]

- Orientation error
- Keeps the torso upright
Fourth task

Joints’ limits avoidance

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

- 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)
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

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

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

\[ \varepsilon_{ori\_sp}(r) = \varepsilon_{ori}(r) + \text{atan2}(u_{ZMP}(y), h_{CoM}), \]
\[ \varepsilon_{ori\_sp}(p) = \varepsilon_{ori}(p) + \text{atan2}(u_{ZMP}(x), h_{CoM}), \]
\[ \varepsilon_{ori\_sp}(y) = \varepsilon_{ori}(y). \]

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

\[ q_{\text{imed}} \rightarrow Joints \text{ Limits} \]
\[ Torso_{Roll_d} \rightarrow Torso \text{ roll} \]
\[ ZMP_d \rightarrow \text{CoM} \& ZMP \]
\[ CoM_d \rightarrow \text{Relative feet} \]
\[ P_{rd} \]
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 - 6dof/arm - 3dof/head - 1dof/body

**Electronic boards inside**

- The power supply connector for wireless LAN converter
- Sound card
- Internal CPU
- Wireless LAN converter
- The power supply connector for internal CPU
- At the time of radio mode To robot USB port
- At the time of radio mode Camera USB connection
- Microphone jack
- LAN connection
- Phones jack (to Speaker)
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
Scenario 3

Dynamic walking motions

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

Application of the proposed control scheme
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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