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

David Galdeano, Ahmed Chemori, Sébastien Krut, Philippe Fraisse

Laboratory of Informatics, Robotics and Microelectronics of Montpellier
LIRMM, University of Montpellier 2 - CNRS
161, rue Ada 34095
Montpellier, France
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
  [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
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
  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

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

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

Center of Mass position

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

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

Body orientation

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

- Orientation error
- Keeps the torso upright
Fourth task

Joints’ limits avoidance

\[ \varepsilon q_i = \frac{2(q_i - q_{med})}{(q_{max} - q_{min})^2} \]

- 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

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

Faster response with favorable damping
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

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

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

Task formalism

- $q_{\text{imed}}$
- $Torso_{Roll_d}$
- $ZMP_d$
- $CoM_d$
- $P_{rd}$

- 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

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

Electronic boards inside:
- LAN connection
- Microphone jack
- At the time of radio mode: Camera USB connection
- At the time of radio mode: To robot USB port
- The power supply connector for wireless LAN converter
- Wireless LAN converter
- Sound card
- 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**
**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

CoM

LFoot

RFoot
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
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.

David GALDEANO

Galdeano@lirmm.fr

Ph.D.
LIRMM – UMR CNRS/UM2 N° 5506
161, Rue Ada 34095, Montpellier
Tel : 04.67.41.85.62
Fax : 04.67.41.85.00