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Pattern Generation and Control of Humanoid Robots: Towards Human-Like Walking

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Khenchela, November, 21st, 2012
Montpellier

- Montpellier is a city in the south of France
- It is the capital of Languedoc Roussillon region as well as Hérault department
- It is the 8th city in the country

Montpellier
LIRMM Laboratory

✓ Laboratory of Informatics, Robotics and Microelectronics of Montpellier (LIRMM) is a research laboratory supervised by both University Montpellier 2 and the French National Center for Scientific Research (CNRS)

✓ 359 permanent and 80 temporary employees, working together in 3 research units:

- Department of **Computer science**
- Department of **Robotics**
- Department of **Microelectronics**
Robotics department

- The robotics department constitutes one of the vital forces of robotics in France
- It comprised of 30 researchers and lecturer-researchers
- It contains 5 main research teams

- IDH
- DEXTER
- ICAR
- EXPLORE
- DEMAR

LIRMM Laboratory
Robotics department of LIRMM
Robotics department
DEXTER Research team

Medical robotics

Parallel robotics
Robotics department

Facilities
LIRMM in the robotics platforms network in France
Outline of the presentation

Part I  ○ **Context and problem formulation**
  ✓ Humanoid robotics
  ✓ Origin of Humanoid robots
  ✓ Humanoid robots over the years
  ✓ Humanoid robots of today
  ✓ Problem formulation

Part II ○ **Our demonstrators**
  ✓ SHERPA : A two-leg walking robot
  ✓ HOAP3 : A humanoid robot

Part III ○ **Optimal Pattern generation**
  ✓ Related work
  ✓ Proposed solution
  ✓ Simulation results

Part IV ○ **Walking control**
  ✓ Summary of the study
  ✓ Proposed solution
  ✓ Simulation results

Part V  ○ **Towards human-like walking**
  ✓ One basic idea
  ✓ Related work
  ✓ Why human like walking
  ✓ Main steps of our developed study

Part IV ○ **Conclusion**
Part I

Context and problem formulation

- Humanoid robotics
- Origin of humanoid robots
- Humanoid robots over the years
- Humanoid robots of today
- Problem formulation
Some features of a Humanoid Robot

The characteristics features of a humanoid Robot include:

- Autonomous learning
- Avoiding harmful situations to people, and itself
- Safe interacting with human beings and the environment
Origin of humanoid robots

In 1921: Karel Capek coined the term *Robot*

In 1941: Isaac Asimov proposed *Three Laws of Robotics*

In 1948: Norbert Wiener formulated the principle of *Cybernetics*

In 1969: Miomir Vukobratovic proposed the theory of *Zero Moment Point (ZMP)*

In 1973: Waseda University (Tokyo) developed *WABOT-1*, which was capable to communicate with a person in Japanese, could do distance and direction measurements using sensors, artificial ears, eyes and as well as an artificial mouth.


Humanoid robots over the years

Honda humanoid robots

Waseda humanoid robots


Towards whole-body

History
Robot Development Process

Humanoid robots of today

ASIMO (Honda)

SDR4 (Sony)

HRP4/HRP4-C (AIST)

Hoap3 (Fujitsu)

Nao (Aldebaran)
Problem formulation

Walking cycle decomposition

Can distinguish:

- 2 main phases: Single support & double support
- 1 transition: impact with ground (instantaneous)

We need to control the robot on the whole cycle

What we need for that?
**Problem formulation**

Static or dynamic walking?

**Static walking**
- Center Of Mass (COM)
- Weighting sum of the centers of different bodies

\[ OG = \sum M_i G_i \]

**Dynamic walking**
- Zero Moment Point (ZMP)
- Point with respect to which dynamic reaction forces at the contact does not produce any moment in the horizontal direction

\[ ZMP(t) = f(q, \dot{q}, \ddot{q}, f_e(t)) \]
Two related problems

Two problems to be resolved:
Pattern generation and control design for walking
Part III

Our demonstrators

✓ **SHERPA**: A two-leg walking robot
✓ **HOAP 3**: A humanoid robot
SHERPA robot: Development steps

- **dof**: 18 (6dof/leg) + 6 dof (position/orientation)
  - 3 rotations (hip)
  - 1 rotation (knee)
  - 2 rotations (ankle)

- **Actuation**: 3 modules / leg
  - For each module:
    - 2 AC brushless motors
    - Cable differential joints
    - Transparent actuation (low inertia & backdrivable)

**Prototype**

**Original idea**

**Mechanical design**

**Articulated mechanical structure**

**Biomechanical studies**

- **Guide de montagne dans l'Himalaya**

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SHERPA robot: Actuation

Context

Demonstrators

P. Generation

Walking

T. H. Walking

Conclusion

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SHERPA robot: Experimental setup

Control PC

Hip

femur

knee

Tibia

ankle

Force sensor
6-axis

foot

Interface cards

Context

Demonstrators

P. Generation

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Conclusion

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SHERPA robot: First movements

Articulations movements

Walking suspended
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
- At the time of radio mode: To robot USB port
- The power supply connector for wireless LAN converter
- Wireless LAN converter
- The power supply connector for internal CPU
- Sound card
- Internal CPU
HOAP3: Actuators and sensors

This demonstrator is useful for whole body control

- Distance sensor
- USB Cameras
- Posture sensor
  - 3-axis acc sensor
  - Angular velocity sensor (gyro)
- Joint sensors
- 28 actuators
  - (21 DC, 7 Stepper)
- Force sensors
  - (4/foot)
- Grip sensors

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HOAP3: Operating modes

System configuration in cable mode

System configuration in radio mode

Context

Demonstrators

P. Generation

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Conclusion
Part IV

Optimal pattern generation

✓ Related work
✓ Proposed solution
Related work

Pattern generators

Simplified models
- LIPM
  - [Kajita et al. 2001]
  - [Hong et al. 2009]
  - [Tang et al. 2007]
  - [Ferreira et al. 2009]
  - [Lee, 2007]
- 2MLIPM
  - [Albert et al. 2002]
- 3MLIPM
  - [Takenaka et al. 2009]

Biomechanics
- [Bruneau et al. 1998]
  - Motion capture
  - [Harada, 2009]
  - [Kim et al. 2009]
  - [Takano et al. 2007]

Oscillators
- Van Der Pol
  - [Katoh et al. 1984]
  - Sinusoidal
  - [Zhao et al. 2008]
    - FFT
    - [Yamaguchi et al. 2008]

B-Splines functions
- [Huang et al. 1999]

Others
- Polynomial functions
  - [Zaier et al. 2007]
- Neural networks
  - [Yang et al. 2007]

Our proposed solution is within this class
Summary of the proposed solution

Objective

Design and development of a pattern generator for stable dynamic walking

Assumptions

- A1: Walking on a horizontal ground without obstacles
- A2: walking cycle (SS+impact phases), no DS phase

Method & application

- Method 1: B-Spline functions with control points
- Method 2: B-Spline functions with boundary conditions & interpolated points
- Application: Walking robot SHERPA
Block-diagram of the proposed solution

- Feet Placement
- B-Spline Functions
- Swing foot Trajectory
- Hip's Trajectory
- Feet Positions
- I.K
- COM computation
- Whole model
- Simplified Model
- COM
- Reference trajectories
- Parameters of stability
- Simplified ZMP
- Real ZMP

B-Spline with boundary conditions & interpolated points
Simulation results

- Integration of the proposed solution in a simulator
- Simulation results without optimization
- Trajectories optimization
- Simulation results with optimization
Integration of the proposed solution in a simulator

Walking parameters

Curves visualization

Trajectories computation

User help

Animation make movie

Visualization footprints & CoM

Context

Demonstrators

P. Generation

Walking

T. H. Walking

Conclusion
Scenario 1: Straight walking without optimization

Articular positions

Articular velocities

Articular accelerations

Feet trajectories

Obtained cyclic trajectories
Scenario 1: Stability evaluation without optimization

S1: Straight walking

- ZMP, COM et footprints

S2: Walking with change of direction

- ZMP, COM and footprints

S1: ZMP is inside of the support polygon → Stable walking

S2: ZMP is outside of the support polygon → Unstable walking
Objective: Improve the stability of dynamic walking

Proposed solution: Optimization with respect to ZMP

\[
\begin{bmatrix}
\hat{x}_i \\
\hat{y}_i
\end{bmatrix} = \text{Arg} \min_{x_i \ y_i} J = \text{Arg} \min_{x_i \ y_i} \max \sum Q_x (zmp_x - zmp_{xd})^2 + Q_y (zmp_y - zmp_{yd})^2
\]

\( zmp_x, \ zmp_y \) : Coordinates of ZMP position

\( zmp_{xd}, \ zmp_{yd} \) : Desired ZMP position

\( Q_x, \ Q_y \) : Weighting coefficients
Scenario 2: Straight walking with optimization

M2: Without optimization

ZMP, COM, and footprints

M2: With optimization

ZMP, COM, and footprints

With optimization: ZMP is inside of the support polygon ➞ Stable walking
ZMP is more concentrated ➞ Stability improved
GUI Animation
Part V

Walking control

- Summary of the study
- Proposed solution
- Simulation results
Summary of the study

Objective

Design of controllers for stable dynamic walking in humanoid robotics

Assumptions

- **A1:** Walking on a horizontal ground without obstacles
- **A2:** Walking cycle (SS+impact phases), no DS phase (except at the beginning)

Method & application

- Method: **Dynamic control**
- Walking stability: **ZMP-based stabilizer**
- Application: **Walking robot SHERPA**
Block-diagram of the proposed solution

- **Trajectories Generation**
  - $CoM_{d}$
  - $CoM_{aux}$
- **IKM**
  - $q_d$, $\dot{q}_d$, $\ddot{q}_d$
- **Dynamic controller**
  - $u$
- **Stabilizer**
  - $\lambda$
- **3D foot/ground contact model**
  - $q$, $\dot{q}$

**SHERPA Robot**
Simulation results

- 14 steps walking scenario
- Starting from rest
- Variable (increasing) walking speed

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>dt</td>
<td>sampling time</td>
<td>$1 \times 10^{-2}$ sec</td>
</tr>
<tr>
<td>dt$\times$ NL</td>
<td>previewing period</td>
<td>1.6 sec</td>
</tr>
<tr>
<td>$H_{pend}$</td>
<td>inverted pendulum height</td>
<td>0.66 m</td>
</tr>
<tr>
<td>$N_{pas}$</td>
<td>number of steps</td>
<td>14 steps</td>
</tr>
<tr>
<td>$L_{pas}$</td>
<td>step length</td>
<td>0.2 m</td>
</tr>
<tr>
<td>$T_{pas}$</td>
<td>step duration</td>
<td>0.6 sec</td>
</tr>
<tr>
<td>$K_p$</td>
<td>position gain</td>
<td>500 sec$^{-2}$</td>
</tr>
<tr>
<td>$K_v$</td>
<td>velocity gain</td>
<td>50 sec$^{-1}$</td>
</tr>
<tr>
<td>k</td>
<td>stiffness coefficient</td>
<td>$35 \times 10^4$ N.m$^{-1}$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>damping coefficient</td>
<td>$6 \times 10^6$ N.sec.m$^{-2}$</td>
</tr>
</tbody>
</table>
Simulation results

Joint positions of first leg

Joint positions of second leg
Simulation results

Torques of first leg

Torques of second leg
Simulation results

**Contact forces**

- Right foot forces [N]
- Left foot forces [N]
- Sum of foot forces [N]

**ZMP tracking**

- ZMP_y [m]
- ZMP_x [m]
- ZMP error [m]

**Context**

- T. H. Walking
- Demonstrators
- P. Generation
- ICEECA 2012 - khenchela, Algeria

**Conclusion**

Speaker: A. Chemori (LIRMM, CNRS – Univ. Montpellier 2, France)
Part VI

Towards human-like walking

(for whole body control)

✓ One basic idea
✓ Related work
✓ Why human-like walking?
✓ Main steps of our study
One basic idea

Pattern generator

Walking Parameters
Pattern generator
Feet position modification
Foot landing control

feet/ZMP positions

Robot Model

Controller

Robot

Robot Model

Contact forces control

U

q, qp

Contact forces measurement

Posture control

Posture

Balance control

Position error of the body

Human walking data

Pattern generator

Controller

One basic idea

Context
Demonstrators
P. Generation
Walking
T. H. Walking
Conclusion

ICEECA 2012 - khenchela, Algeria

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Related work

Whole body motion control

Task-based schemes
- Objective function [Ligueois, 1977]
- Task priority based redundancy control [Siciliano et al., 1991; Nakamura et al., 1987]
- Stack of task [Mansard, 2007]

Human-Data based schemes
- Class 1: Online computation
  - Balance/Tracking controller [Yamane et al., 2009-2010]
  - Imitation [Shaal et al., 1999-2003; Calderon & Hu, 2005]
- Class 2: Offline computation
  - Motion Primitives [Nakaoka et al., 2003-2005]
  - Gait parameter extraction [Harada et al., 2009]
  - Scale and optimization [Suleiman et al., 2008]

Human Normalized model [Montecillo et al., 2010]
Why human like-walking?

Human walking *versus* humanoid walking

Objective: Study of the influence of the upper limbs (torso & arms) on dynamic stability and energy consumption during walking
Main steps of our study

Step 1
• Simulator development

Step 2
• Human walking study ⇒ Gather human walking data

Step 3
• Pattern generator design (based on human walking data)

Step 4
• Control architecture (controller + stabilizer)

Step 5
• Implementation on a humanoid robot (HOAP3)
Developed simulator for whole-body control

- Summary of the simulator characteristics
- View GUI of the simulator
- Whole body proposed model
Summary of the simulator main characteristics

- Includes whole-body models of different robots
- Examples: SHERPA robot, Whole-body proposed model, Hydroid, Hoap3
- Easy extensions \(\Rightarrow\) add other models
- Takes into account both robot dynamics and contact dynamics
- Two contact models: compliant / rigid
- Has a graphical interface (OpenGL) \(\Rightarrow\) Show the movements of the robot
- Written in C++ language (use GSL open source library)
- Modular approach
View of the GUI of the simulator

20 dof whole body model

Hoap 3 robot model (28 dof)

And others …
Whole body proposed model

Modeling and simulation

- 3D model.
- 20 DoF (6/Leg, 2/torso, 3/arm).
- Forward kinematics.
- Inverse kinematics.
- Dynamic model.
- Contact model.
- Link in tree representation allows easy modification.
- Modular approach allows to switch between different models.
Preliminary tests on the simulator

Scenario 1: Squat task

Scenario 2: Whole body balance

Scenario 3: Arms balance

Scenario 3: Torso & arms balance
Human walking study

- Human walking
- Motion capture system
Human walking

Including:
✓ Human Locomotion
✓ Kinematics & kinetics of human walking
✓ Energy & muscle activity during walking
✓ Simulation of Walking
✓ … etc

How we can acquire data on human walking?
Motion capture system

Plug-in-Gait Marker Placement
**Context:** A joint French-Italian project → LIRMM (France) / LABLAB (Italy)

**Objective:** Human walking analysis → Effects of upper limbs on human walking

**Equipments:**
- 1 host PC
- 10 VICON cameras
- 3 Forces plates

---

**Motion capture system**

![Diagram of motion capture system with VICON cameras and force plates](image)

**Context:**

- A joint French-Italian project
- LIRMM (France) / LABLAB (Italy)

**Objective:**

- Human walking analysis
- Effects of upper limbs on human walking

**Equipments:**

- 1 host PC
- 10 VICON cameras
- 3 Forces plates

---

**Fig.1 Structure of Force Plate**
Motion capture system

Is the process of recording movement, and translate that movement to a digital model

Study:
- 15 Subjects walking at different speeds
- 35 markers using Plug-in Gait template (a)
- Reconstruction of movement using Vicon Nexus (b)
- Estimation of CoM using Lifemod (c)
Pattern generator design

- Basic idea of the proposed solution
- Proposed human data base pattern generator
- Simulation results
Basic idea of the proposed solution

What happen if we apply directly human data to the humanoid robot?

- ZMP is outside the polygon of support $\rightarrow$ unstable waking!

Proposed solution:

- 22 dof

Upper body

Lower body

3D-LIPM
Proposed human data based pattern generator

Context

Demonstrators

P. Generation

Walking

T. H. Walking

Conclusion

Upper-body Human Data

Lower-body Joints Data

Humanoid Robot

Motion Capture System

Lower-body Human Data Analysis

Captured Data Analysis

Transitions instants DS/SS

Feet Trajectory Generator Based on B-Splines

3D Linear Inverted Pendulum Model

Inverse Kinematics

Hip Trajectory

Desired ZMP

Feet Trajectories
Simulation results

• Proposed pattern generator was implemented in the robot simulator
• Human walking data used for upper body
• For a three-step walking scenario starting from rest
Control architecture design

- Basic idea of the proposed control architecture
- Block-diagram
- Extended version
Basic idea of the proposed control scheme

- Motion Capture
- Control scheme
- P \(_{rd}\)
- CoM\(_{d}\)
- T. H. Walking
Block-diagram of the proposed control architecture

First task

\[ P_r \]

\[ J_r^+ \]

\[ FKM_r \]

Second task

\[ J_{COM} \]

Null space projection

\[ \tilde{J}_{COM}^+ \]

\[ (I - J_r^+ J_r) \]

Context

Demonstrators

P. Generation

Walking

T. H. Walking

Conclusion
Extended version of the proposed control architecture
(With ZMP regulation)

\[ P_r \]

\[ P_{rd} \]

\[ J_r^+ \]

\[ J_{CoM} \]

\[ \tilde{J}_{CoM}^+ \]

\[ (I - J_r^+ J_r) \]

\[ \varepsilon_{\theta} \]

\[ PD \]

\[ u \]

\[ \theta \]

\[ CoM_d \]

\[ CoM \]

\[ \varepsilon_{\theta} \]

\[ \theta \]

\[ ZMP_d \]

\[ ZMP \]

\[ ZMP_c \]

\[ FKM_{CoM} \]

\[ FKM_r \]
Implementation on a humanoid robot

Simulation scenarios
✓ Scenario 1: Simple validation of the scheme
✓ Scenario 2: Human data without adaptation
✓ Scenario 3: Human data with CoM scaling
✓ Scenario 4: Squat motion

Real-time experimental scenarios
✓ Scenario 1: ZMP control
✓ Scenario 2: Squat motion
Simulation scenario 1: First validation of the scheme
Simulation scenario 2: Human data without adaptation

Reconstructed human movement

Application of the proposed scheme

Simulation of the proposed control scheme
Use of human data without any adaptation
Simulation scenario 3: Human data with CoM scaling

Reconstructed human movement

Application of the proposed scheme

Simulation of the proposed control scheme
Use of human data with scaling of the CoM trajectories
Simulation scenario 4: Squat motion
Experimental scenario 1: ZMP control with external disturbance
Experimental scenario 2: Squat motion
Part V

Conclusion
Context : Pattern generation and control in humanoid robotics

Three main studies :

- **First study**: Pattern generation $\rightarrow$ B-spline based generator
- **Second study**: Walking control $\rightarrow$ Walking control architecture with stabilizer
- **Third study**: Towards human-like walking (whole body control) in 5 steps
  - ✓ Simulation development
  - ✓ Human walking study
  - ✓ Pattern generator design
  - ✓ Control architecture design (no phase decomposition $\rightarrow$ continuous)
  - ✓ Implementation

Future work : Final walking control implementation on Hoap 3 robot

Real-time implementation on a humanoid robot : HRP4