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

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Khenchela, November, 21st, 2012
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 8\(^{th}\) city in the country
✓ 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
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:

1. **IDH**
2. **DEXTER**
3. **ICAR**
4. **EXPLORE**
5. **DEMAR**

These research teams are part of the Robotics Department of LIRMM Laboratory.
Robotics department
DEXTER Research team

Medical robotics

Parallel robotics

ICEECA 2012 - khenchela, Algeria

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


Context | Demonstrators | P. Generation | Walking | T. H. Walking | Conclusion
Humanoid robots over the years

Context

Demonstrators

P. Generation

Walking

T. H. Walking

Conclusion

Honda humanoid robots

Waseda humanoid robots

WL-1 (1967)

WAP-3 (1971)

WL-10RD (1984)

WABIAN (1995)

Towards whole-body
Humanoid robots of today

Context

Demonstrators

P. Generation

Walking

T. H. Walking

Conclusion

SDR4 (Sony)

ASIMO (Honda)

HRP4/HRP4-C (AIST)

Hoap3 (Fujitsu)

Nao (Aldebaran)
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)

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

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

Weighting sum of the centers of different bodies

\[ OG = \sum M_i G_i \]
Two related problems

Pattern generator

Walking Parameters → Pattern generator

Pattern generator → feet/ZMP positions

feet/ZMP positions → Robot Model

Robot Model → q_d

q_d → Articulations control

Articulations control → U

U → Contact forces control

Contact forces control → q, qp

q, qp → Contact forces measurement

Contact forces measurement → Posture

Posture → Position error of the body

Position error of the body → Balance control

Balance control → Foot landing control

Foot landing control → Feet position modification

Feet position modification → Feet position modification

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)

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**Guide de montagne dans l’Himalaya**

- **Prototype**
- **Original idea**
- **Mechanical design**
- **Articulated mechanical structure**
- **Biomechanical studies**

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**Context**

P. Generation  Walking  T. H. Walking  Conclusion
SHERPA robot: Actuation

Context

Demonstrators

P. Generation

Walking

T. H. Walking

Conclusion

ICEECA 2012 - khenchela, Algeria

Speaker: A. Chemori (LIRMM, CNRS – Univ. Montpellier 2, France)
SHERPA robot: Experimental setup

Control PC

Hip

femur

knee

Tibia

ankle

Force sensor 6-axis

foot

Interface cards

Context

P. Generation

Walking

T. H. Walking

Conclusion

ICEECA 2012 - khenchela, Algeria

Speaker: A. Chemori (LIRMM, CNRS – Univ. Montpellier 2, France)
SHERPA robot: First movements

Articulations movements

Walking suspended
HOAP3: Architecture

28 dof: 6 dof/leg - 6dof/arm - 3dof/head - 1dof/body
HOAP3: Actuators and sensors

This demonstrator is useful for whole body control.
HOAP3: Operating modes

**System configuration in cable mode**
- Command PC
  - USB
  - microphone input
  - headphone output
- OS: RT-Linux
- External power supply
- USB data communications
- Robot
  - USB hub
  - camera hub
  - microphone
  - speaker

**System configuration in radio mode**
- Command PC
  - OS: RT-Linux
  - TCP/IP
  - Wireless LAN
- Wireless LAN access point
- Robot
  - Wireless LAN converter
  - LAN
  - USB
  - Voice
  - Sound
  - Internal PC
    - USB
    - Battery
  - Camera
  - Mic
  - Speaker
  - Sound
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
  - Biomachanics
    - [Bruneau et al. 1998]
    - Motion capture
      - [Harada, 2009]
      - [Kim et al. 2009]
      - [Takano et al. 2007]
  - Van Der Pol
    - [Katoh et al. 1984]
    - Sinusoidal
      - [Zhao et al. 2008]
    - FFT
      - [Yamaguchi et al. 2008]

- Oscillators

- 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+imact 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
B-Spline with boundary conditions & interpolated points

Number of steps
Initial conditions
Length of steps
Swing leg
Angle of rotation

Feet Placement

Feet Positions

B-Spline Functions

Swing foot Trajectory

Hip's Trajectory

IK

q_d

\frac{dq}{dt}

\frac{dq}{dt}

\frac{d^2q}{dt^2}

COM

COM computation

Whole model

Simplified Model

ZMP computation

Real ZMP

Simplified ZMP

Reference trajectories

Parameters of stability

Context

Demonstrators

P. Generation

Walking

T. H. Walking

Conclusion

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Speaker: A. Chemori (LIRMM, CNRS – Univ. Montpellier 2, France)
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**
  - Nombre de pas (Np)
  - Choix de direction

- **Curves visualization**
  - Position
  - vitesse
  - Accélération
  - COM
  - ZMP
  - Trajectoire Pied

- **Trajectories computation**

- **User help**
  - Aide
  - Fermer

- **Animation**
  - Optimisation
  - Génération
  - Effacer
  - Visualisation de l'animation
  - Animation
  - Video

- **Visualization footprints & CoM**

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

- **S1**: ZMP is inside of the support polygon
  - Stable walking

- **S2**: ZMP is outside of the support polygon
  - Unstable walking

**S2**: Walking with change of direction

- **S1**: ZMP and COM et footprints
- **S2**: ZMP, COM and footprints
Objective: Improve the stability of dynamic walking

Proposed solution: Optimization with respect to ZMP

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

\(zmp_x, zmp_y\) : 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

M2: With optimization

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

Context

Demonstrators

P. Generation

Walking

T. H. Walking

Conclusion

Trajectories Generation

$CoM_d$

IKM

$CoM_{aux}$

Stabilizer

Dynamic controller

SHERPA Robot

3D foot/ground contact model

$u$

$q, \dot{q}$

$\dot{q}, \ddot{q}, \dddot{q}$

$\lambda$

$\lambda$

$\lambda$

$\lambda$

$\lambda$

$\lambda$

$\lambda$

$\lambda$

$\lambda$

$\lambda$

$\lambda$

$\lambda$

$\lambda$

$\lambda$

$\lambda$

$\lambda$

$\lambda$
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

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Simulation results

Contact forces

ZMP tracking
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

Walking Parameters

Pattern generator

Pattern generator

feet/ZMP positions

Robot Model

Articulations control

Contact forces control

Contact forces measurement

Posture control

Posture

Position error of the body

Foot landing control

Feet position modification

Human walking data

Walking

Pattern generator

Controller

Robot

Stabilizer

Contact forces control

Balance control

Posture control

Contact forces measurement

U

q, qp

q_d

Robot

Robot

Robot

Controller

Pattern generator

Walking Parameters

Human walking data
Related work

Whole body motion control

Task-based schemes
- Objective function
  - [Ligeois, 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 ⇒ add other models

- Takes into account both robot dynamics and contact dynamics

- Two contact models: compliant / rigid

- Has a graphical interface (OpenGL) ⇒ 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

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![Diagram of motion capture system]

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**Conclusion**

Demonstrators

P. Generation

Walking

T. H. Walking

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**Speaker:** A. Chemori  
(LIRMM, CNRS – Univ. Montpellier 2, France)
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 → unstable waking!

Proposed solution:

- Upper body
- Lower body
- 3D-LIPM
- 22 dof

SS: DS

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Proposed human data based pattern generator

Humanoid Robot

Upper-body Human Data

Lower-body Joints Data

Motion Capture System

Captured Data Analysis

Transitions instants DS/SS

Feet Trajectory Generator Based on B-Splines

Desired ZMP

3D Linear Inverted Pendulum Model

Inverse Kinematics

Walking

Proposed human data based pattern generator

Context

Demonstrators

P. Generation

Walking

T. H. Walking

Conclusion
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

![Diagrams showing simulation results](image-url)
Simulation results

Context

Demonstrators

P. Generation

Walking

T. H. Walking

Conclusion

Simulation results for different parts of the body:
- Right Arm
- Left Arm
- Right Leg
- Left Leg
- Spine

Graphs showing angle over time (rad) for different segments.
Control architecture design

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

Motion Capture

\[ P_{rd} \]

\[ CoM_d \]

Control scheme

Walking

Conclusion
Block-diagram of the proposed control architecture

First task

\[ P_r \quad J_r^+ \quad FKM_r \quad \varepsilon_q \quad K_p \quad u \]

Second task

\[ COM_d \quad \varepsilon_{COM} \quad J_{COM} \quad \tilde{J}_{COM}^+ \quad (I - J_r^+J_r) \]

Null space projection

FKM_{COM}
Extended version of the proposed control architecture
(With ZMP regulation)
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 ➔ B-spline based generator
- **Second study**: Walking control ➔ 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 ➔ continuous)
  - Implementation

**Future work**: Final walking control implementation on Hoap 3 robot

Real-time implementation on a humanoid robot: HRP4