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

Ahmed Chemori

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Plenary II

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

LIRMM Laboratory

LIRMM

- ✓ 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 :

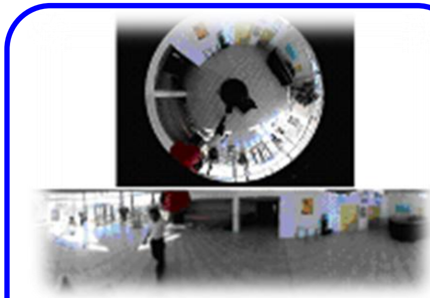
Department of **Computer science**	Department of **Robotics**	Department of **Microelectronics**

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

Robotics Department

Of LIRMM

EXPLORE

DEMAR

LIRMM Laboratory

Robotics department

DEXTER Research team


E. DOMBRE
(DR CNRS)


P. POIGNET
(PR UM2)


N. ZEMITI
(MC UM2)


C. LIU
(CR CNRS)

Medical robotics


F. PIERROT
(DR CNRS)


O. COMPANY
(MC UM2)


S. KRUT
(CR CNRS)


A. CHEMORI
(CR CNRS)


M. GOUTTEFARDE
(CR CNRS)

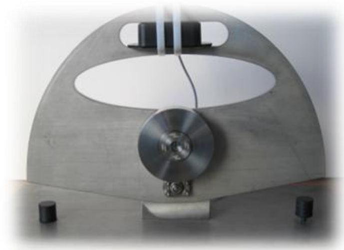
Parallel robotics

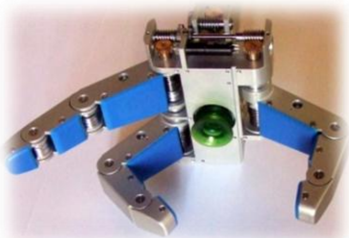
Robotics department

Facilities





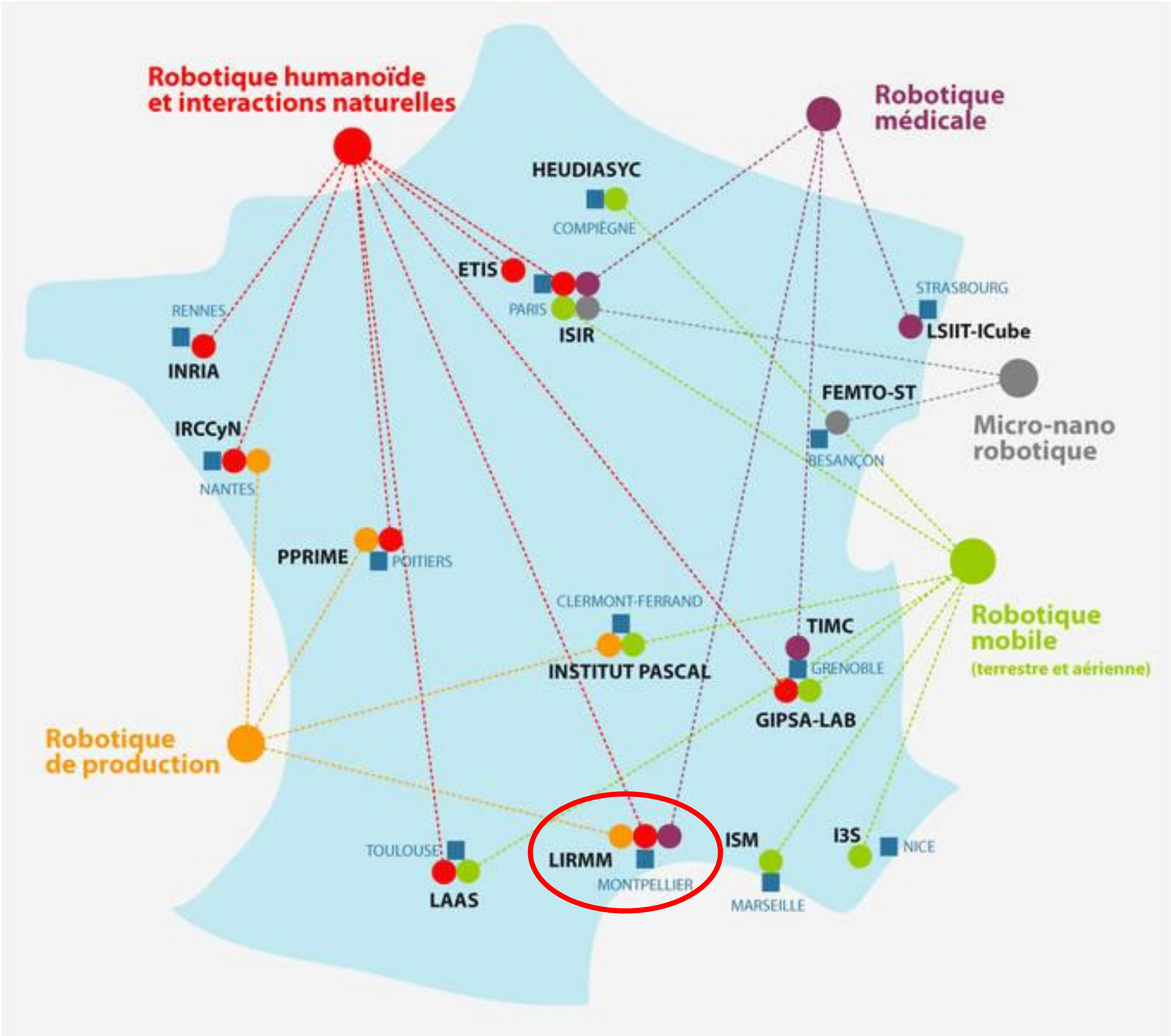






LIRMM in the robotics platforms network in France



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

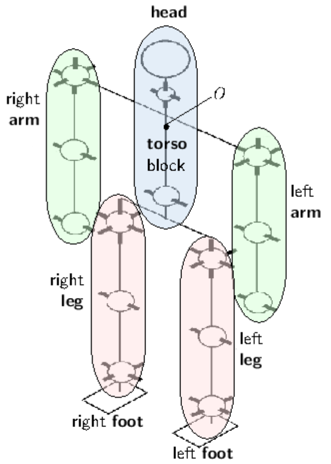
Humanoid robotics

- A **humanoid robot** or an **anthropomorphic robot** is a robot with an overall appearance, based on that of the human body, allowing interaction with made-for-human tools or environments.
- In general humanoid robots have a **torso** with a **head**, **two arms** and **two legs** Some humanoid robots may also have a 'face', with 'eyes' and 'mouth'
- **Androids** are humanoid robots built to aesthetically resemble a human

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

In 20th century (end) many robots have been proposed : ***Greenman*** in 1983, ***WABOT-2*** in 1984, ***WHL-11*** in 1985, the musician robot- ***WASUBOT*** in 1985, series of seven biped robots called ***E0-E6*** by Honda in 1986, the full scale anthromorphic robot- ***MANNY*** in 1989, with 42 degrees of freedom, Honda's ***P1** through **P3*** in 1993, ***HADALY*** and ***WABIAN*** in 1995, ***SAIKA*** in 1996 and ***ASIMO*** by Honda in 2000.

In 21st Century, further additions were done by Sony's ***QRIO*** in 2001, ***HOAP*** and ***ACTROID*** in 2003, ***PERSIA*** and ***KHR-1*** in 2004, ***PKD** android* and ***WAKAMARU*** in 2005, ***TOPIO*** in 2007, ***Justin***, ***KT-X*** and ***NEXI*** in 2008, ***SURALP*** in 2009, ***Robonaut-2***, ***SURENA-II*** and ***HRP-4C*** in 2010

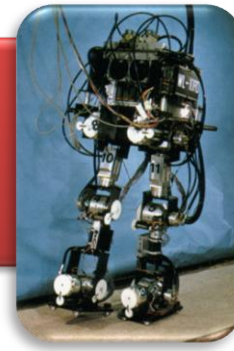
Humanoid robots over the years

Waseda humanoid robots

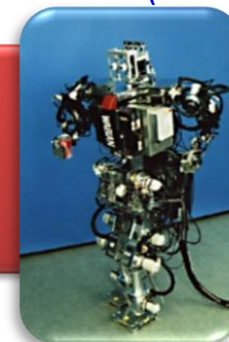
WL-1 (1967)

WAP-3 (1971)

WL-10RD (1984)

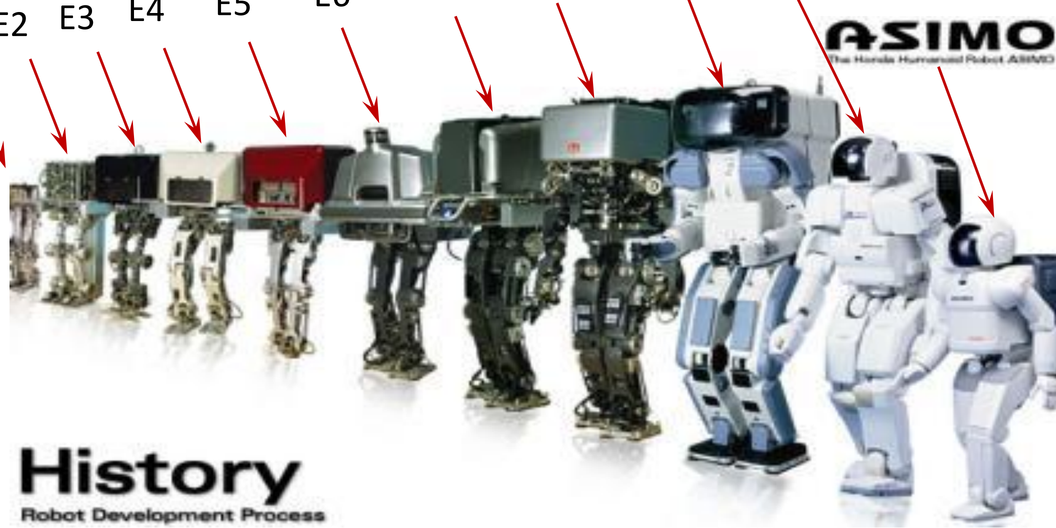


WABIAN (1995)



Honda humanoid robots

E1 E2 E3 E4 E5 E6 P1 P2 P3 P4



Towards whole-body

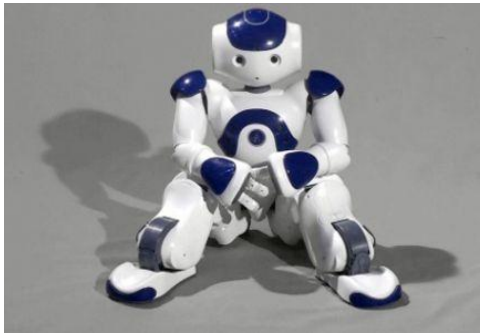
Humanoid robots of today

SDR4 (Sony)

ASIMO (Honda)

HRP4/HRP4-C (AIST)

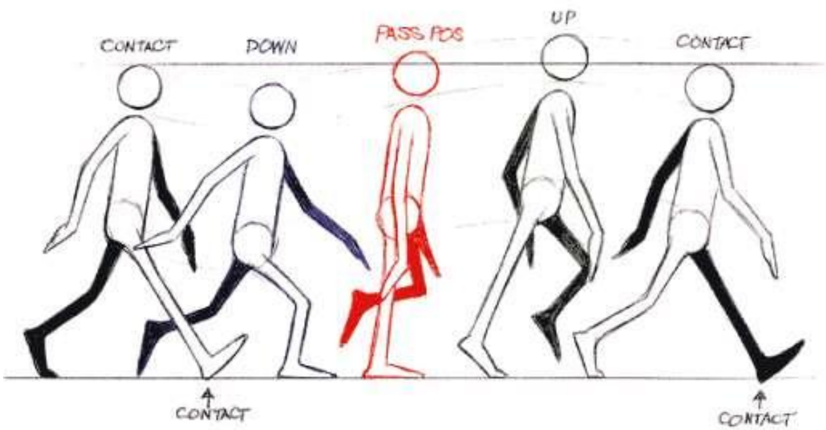
Hoap3 (Fujitsu)



Nao (Aldebaran)

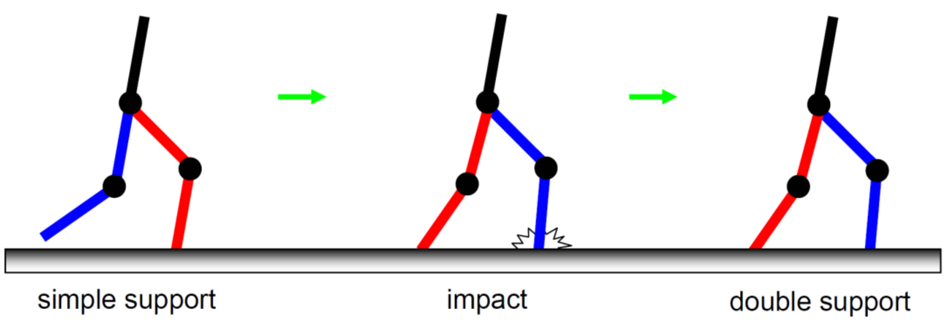
Problem formulation

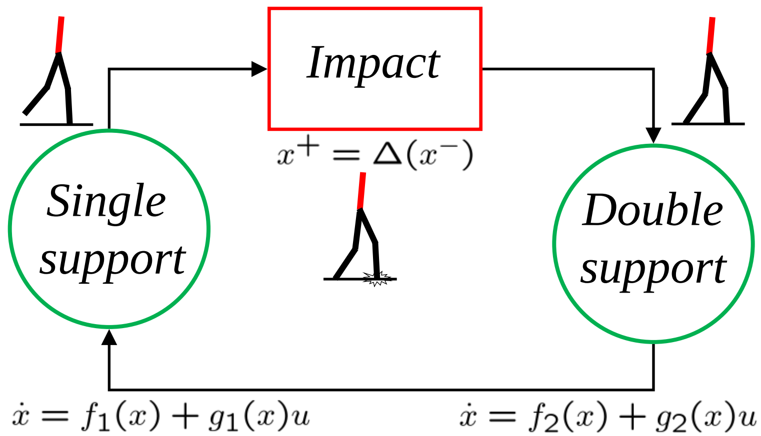
Walking cycle decomposition



Can distinguish :

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





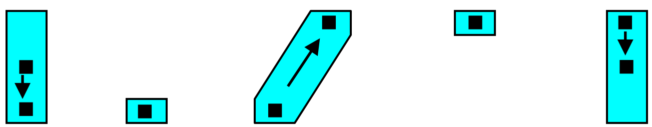
We need to control the robot on the whole cycle

What we need for that ?

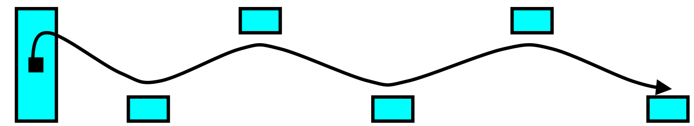
Problem formulation

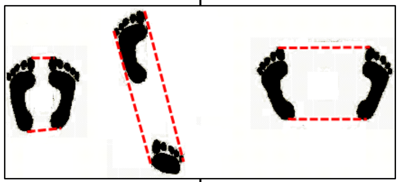
Static or dynamic walking ?

Static walking



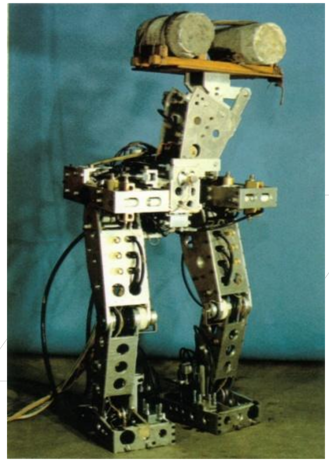
Dynamic walking

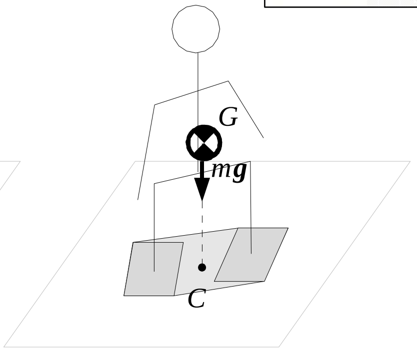




Center Of Mass (COM)

WL-5 (1971)



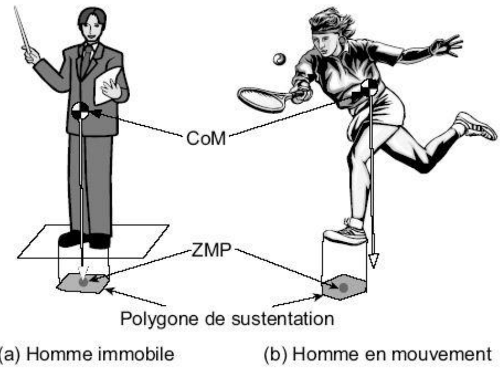


(b)

Weighting sum of the centers of different bodies

$$OG = \sum M_i G_i$$

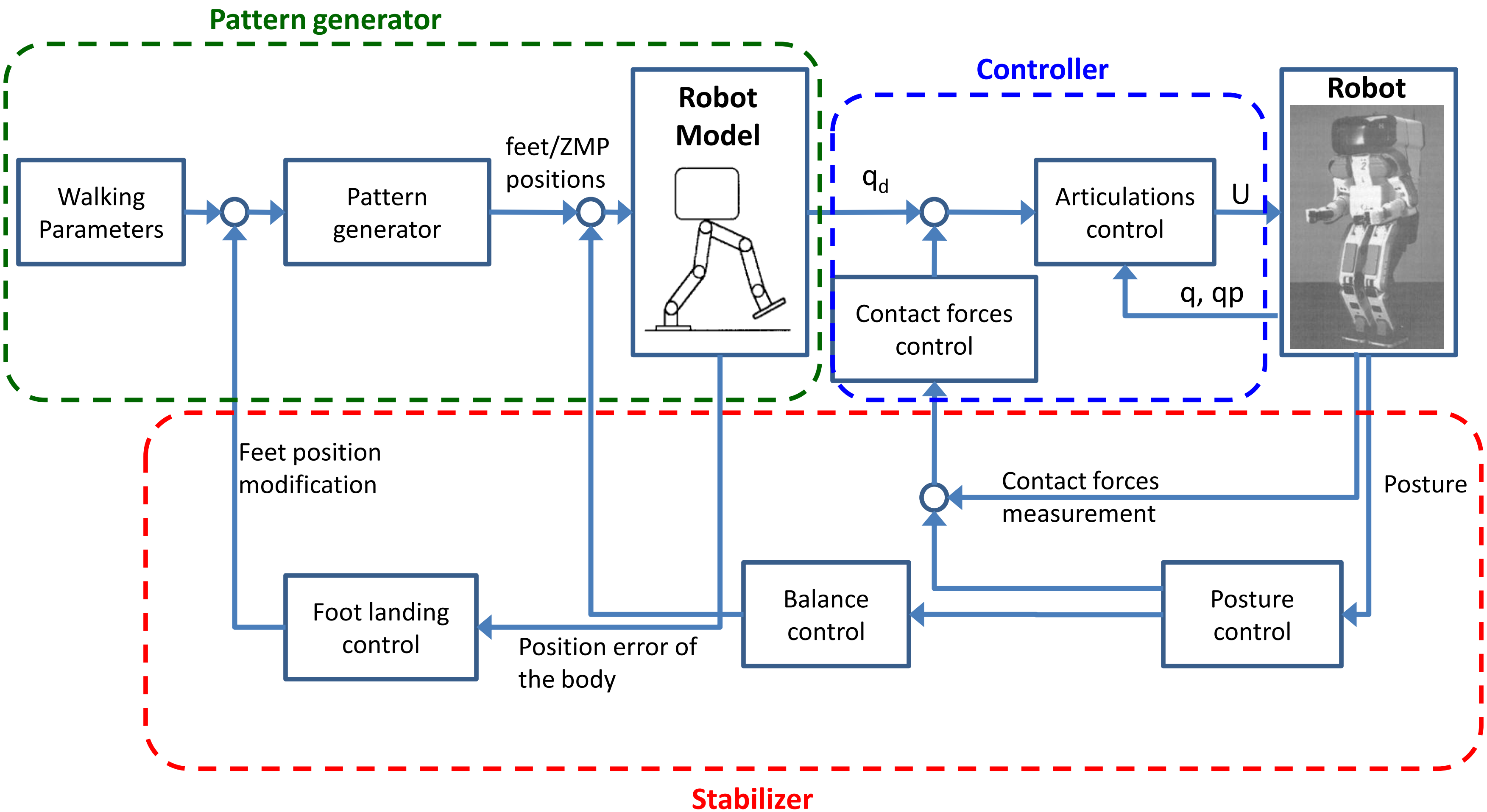
Zero Moment Point (ZMP)



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 :

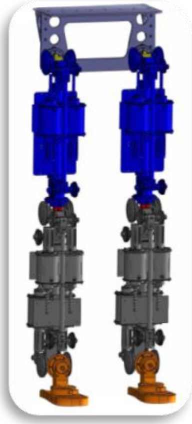
Pattern generation and control design for walking

Part III

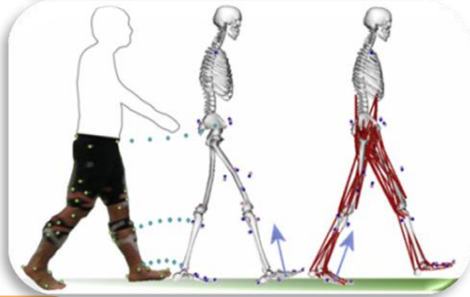
Our demonstrators

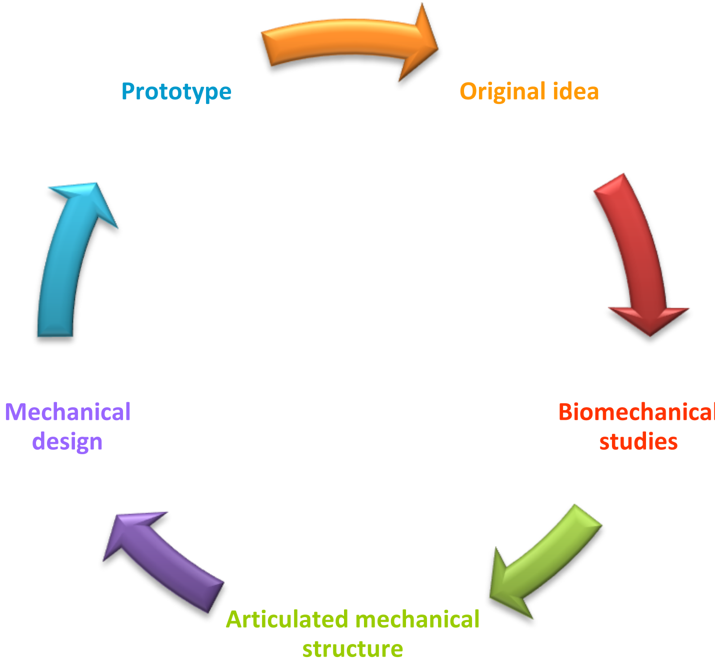
- ✓ **SHERPA :** A two-leg walking robot
- ✓ **HOAP 3 :** A humanoid robot

SHERPA robot : Development steps



Guide de montagne dans l'Himalaya



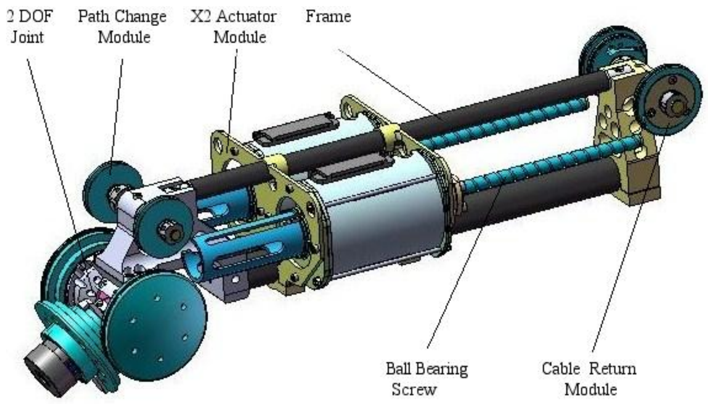


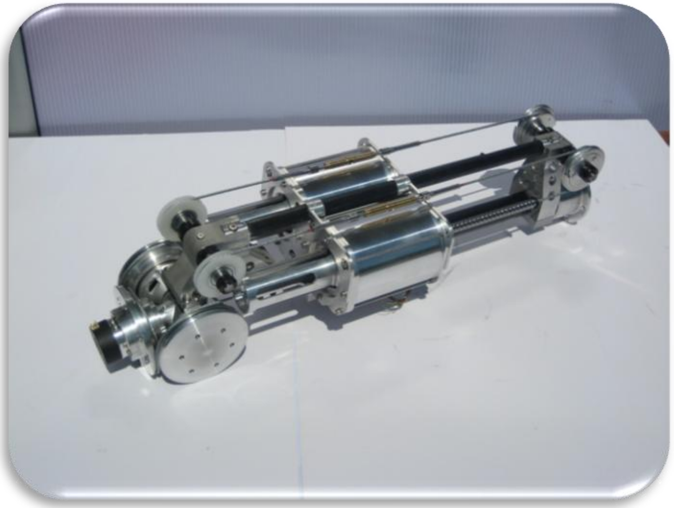
- **dof** : 18 (6dof/leg) + 6 dof (position/orientation)
  - ✓ 3 rotations (hip)
  - ✓ 1 rotation (knee)
  - ✓ 2 rotations (ankle)
- **Actuation** : 3 modules / leg

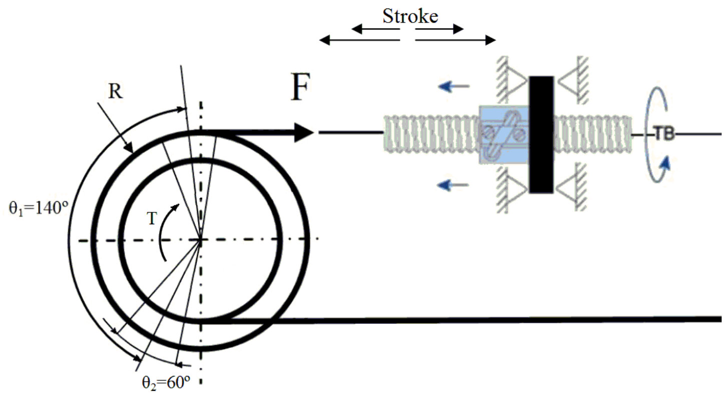
  For each module :
  - ✓ 2 AC brushless motors
  - ✓ Cable differential joints

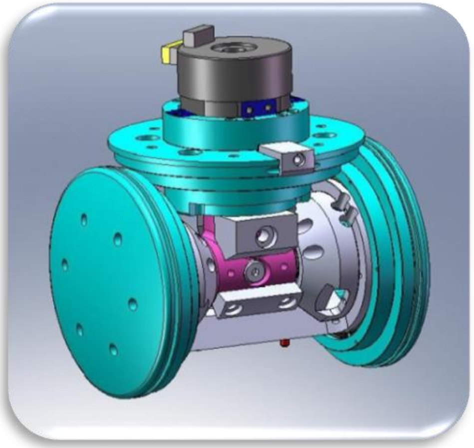
  Transparent actuation (low inertia & backdrivable)

SHERPA robot : Actuation

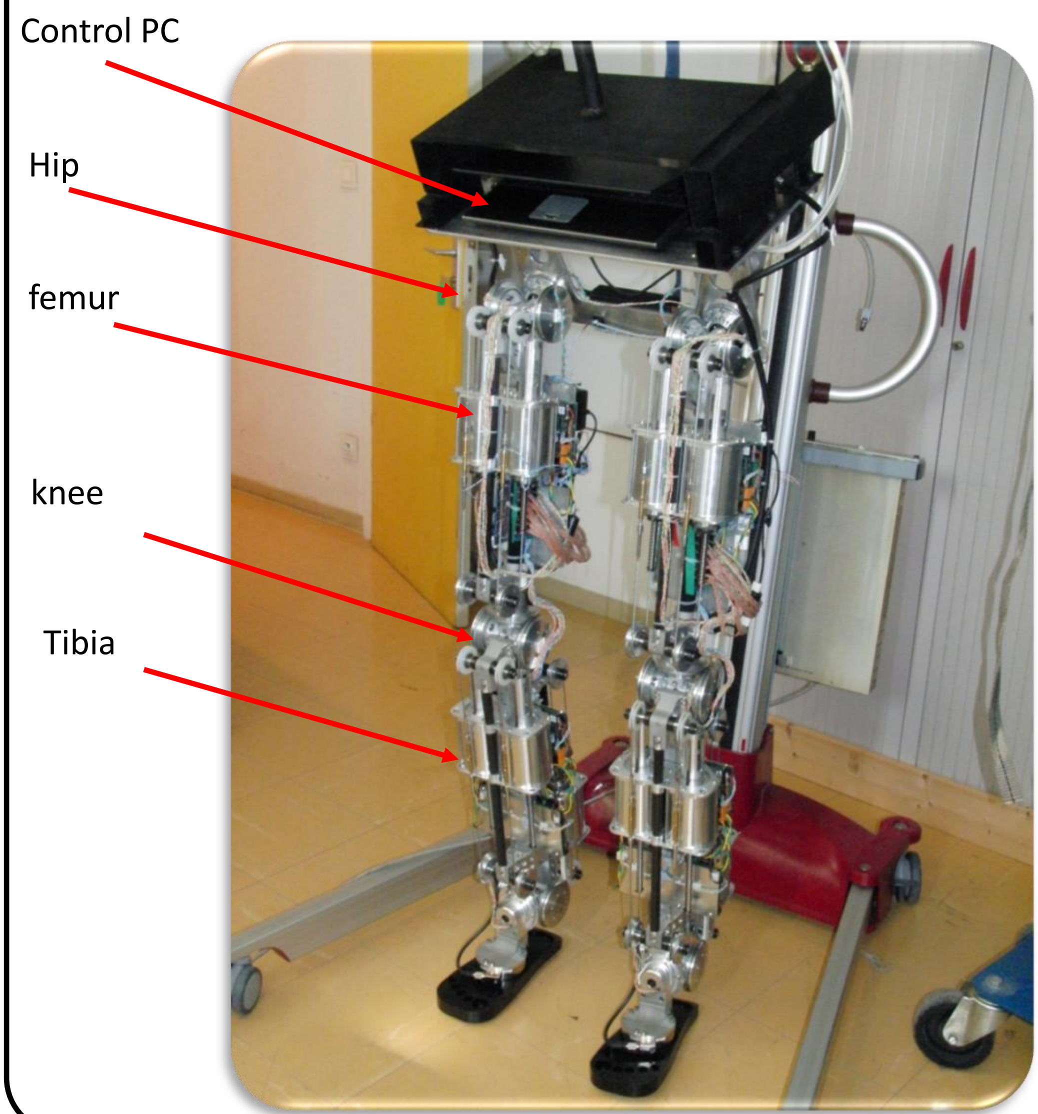


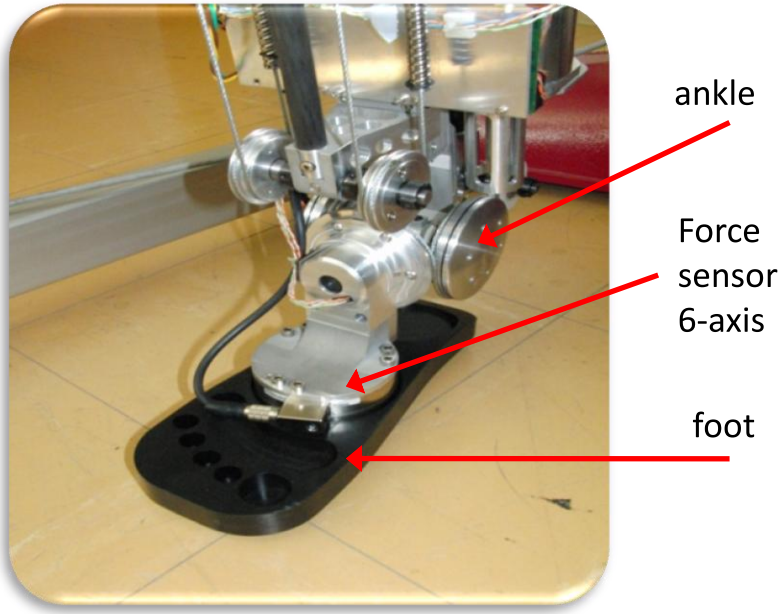


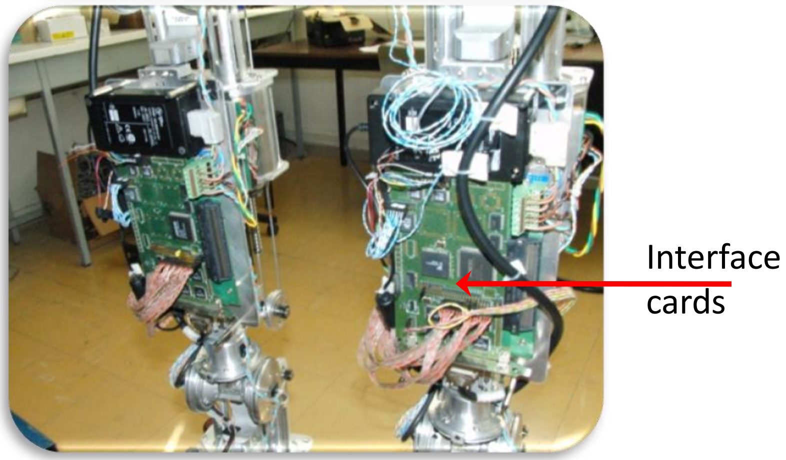




SHERPA robot : Experimental setup





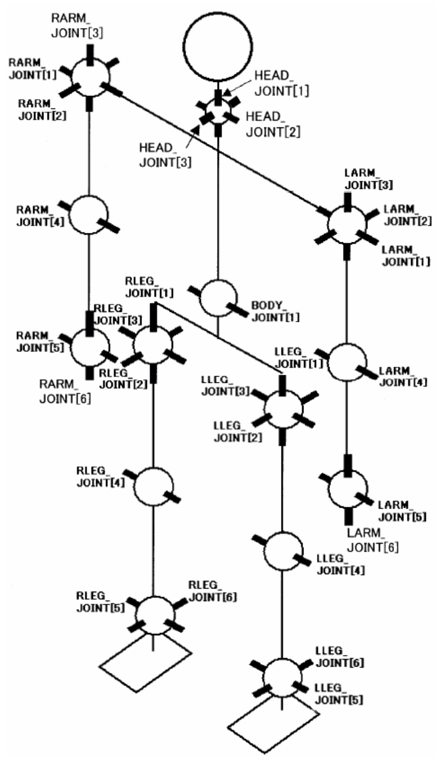


SHERPA robot : First movements

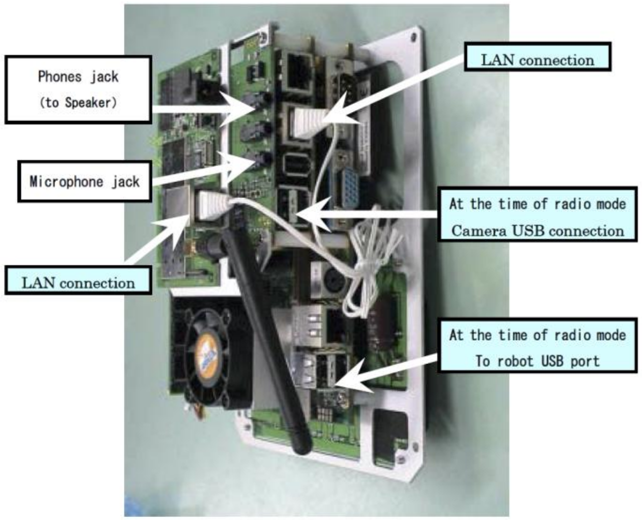
Articulations movements

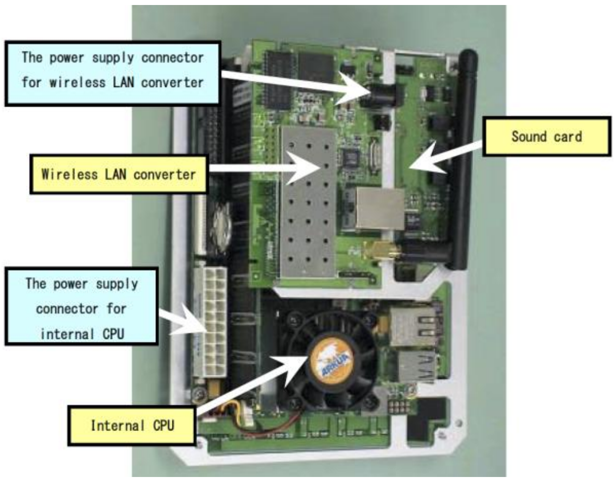
Walking suspended

HOAP3 : Architecture



Electronic boards inside





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

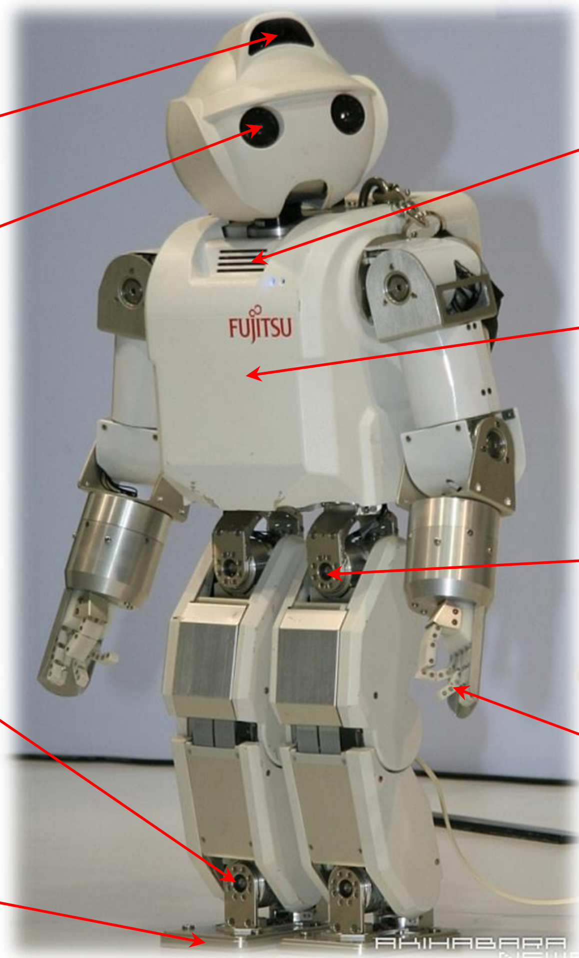
HOAP3 : Actuators and sensors

Distance sensor

USB Cameras

Speaker

Posture sensor
3-axis acc sensor
Angular velocity sensor (gyro)



Joint sensors

28 actuators
(21 DC, 7 Stepper)

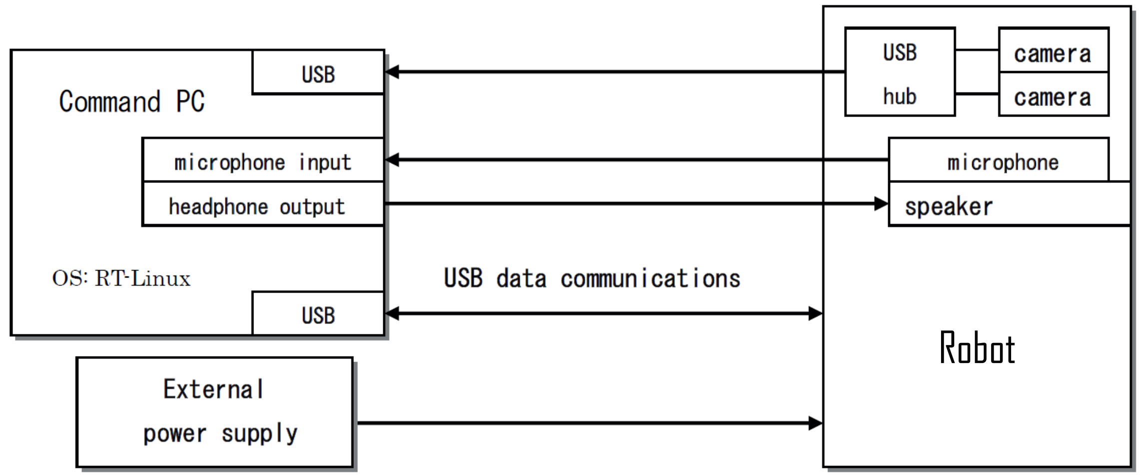
Force sensors
(4/foot)

Grip sensors

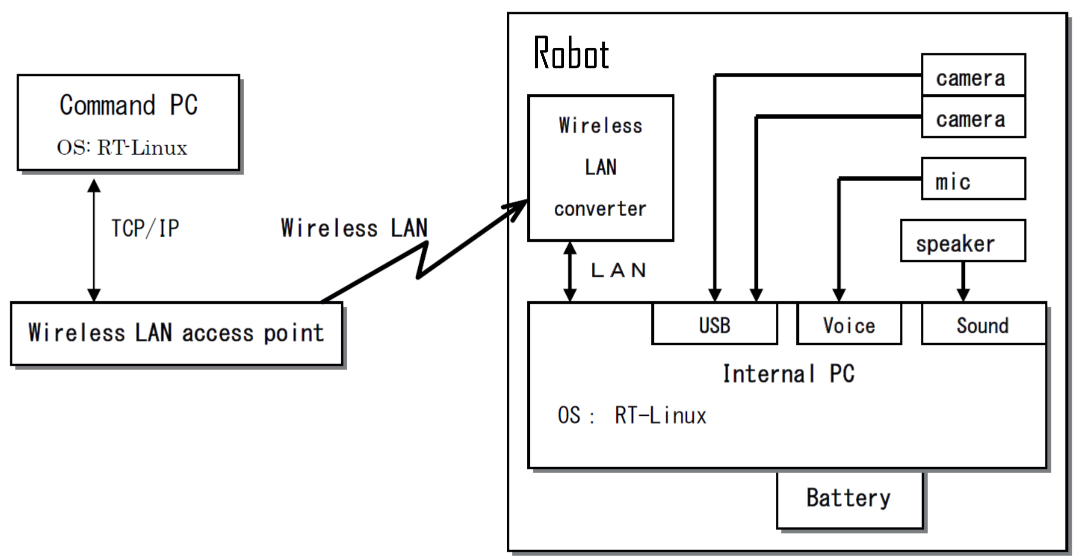
This demonstrator is useful for whole body control

HOAP3 : Operating modes

System configuration in cable mode



System configuration in radio mode



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

Biomchanics
[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]

Our proposed solution is within this class

Others

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

Summary of the proposed solution

Objective

Design and development of a pattern generator for stable dynamic walking

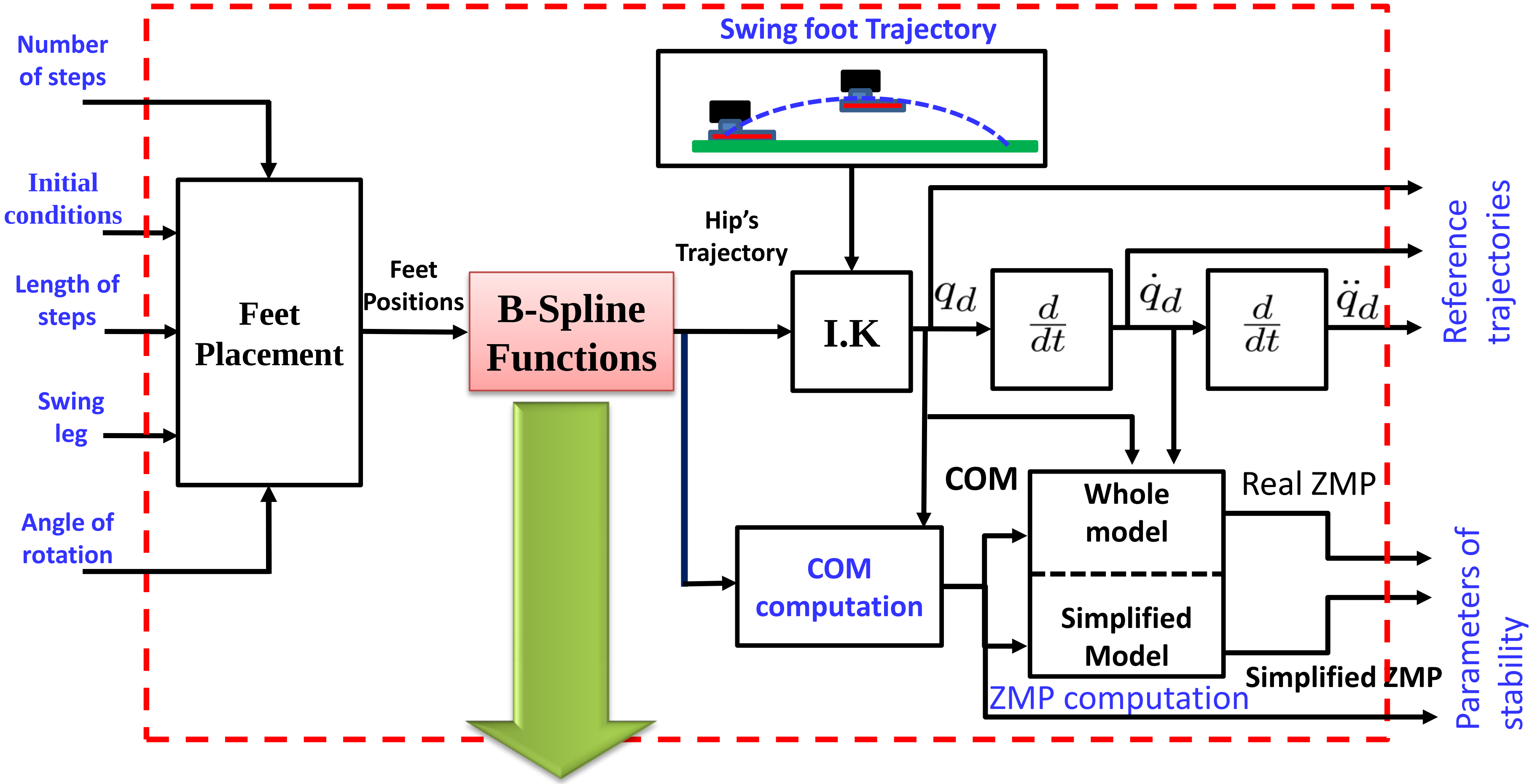
Assumptions

- **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**

Block-diagram of the proposed solution



B-Spline with boundary conditions & interpolated points

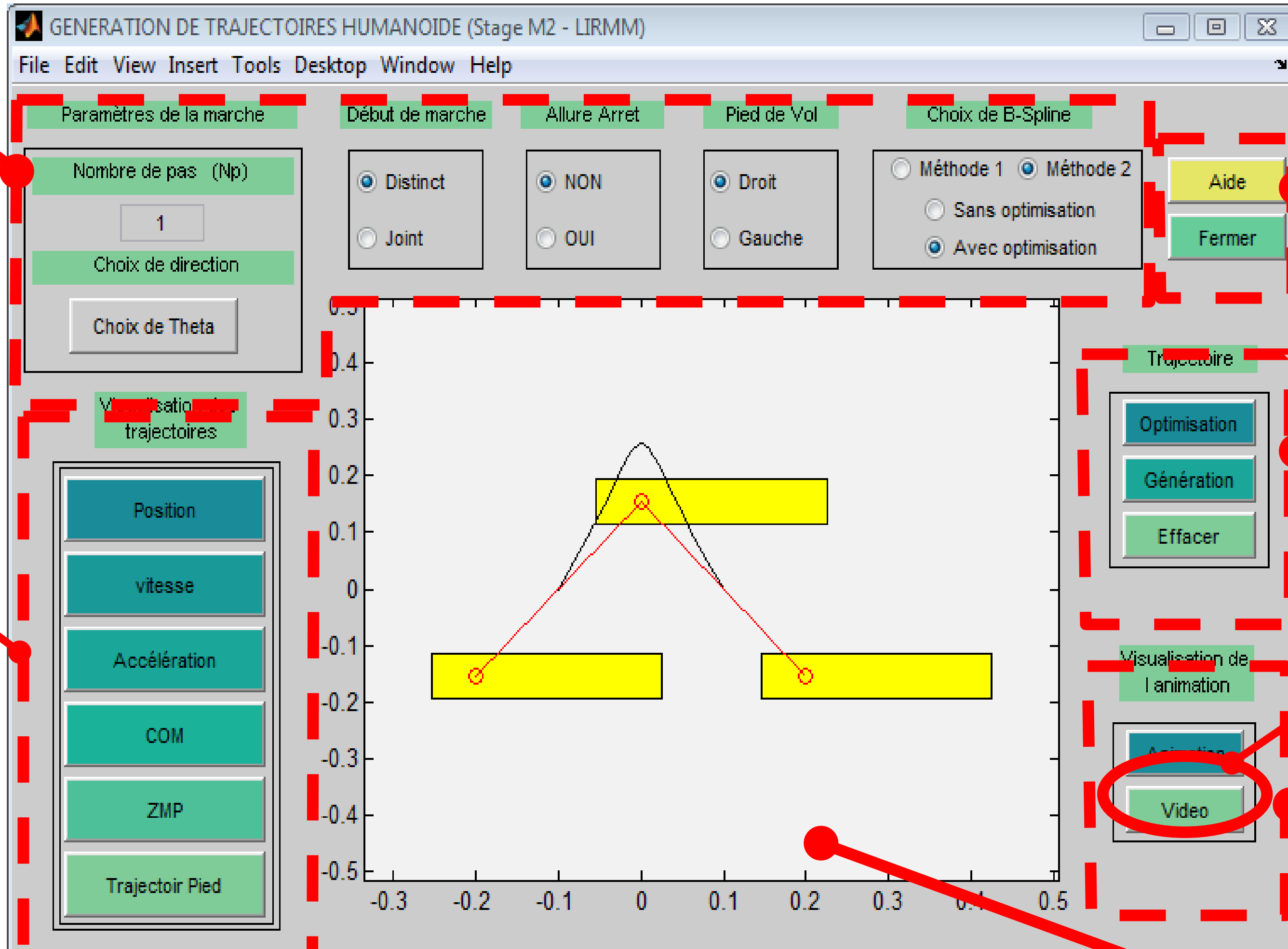
Simulation results

- ✓ 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

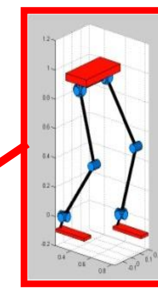
Walking parameters

Curves visualization



User help

Trajectories computation

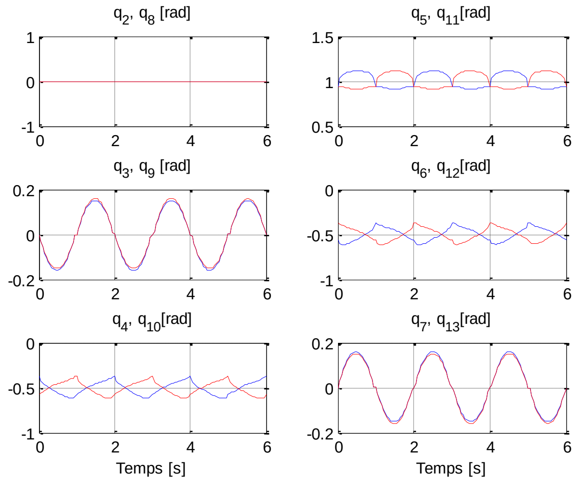


Animation make movie

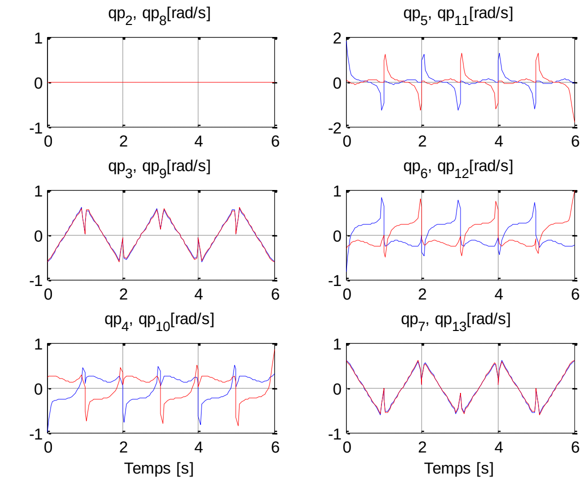
Visualization footprints & CoM

Scenario 1 : Straight walking without optimization

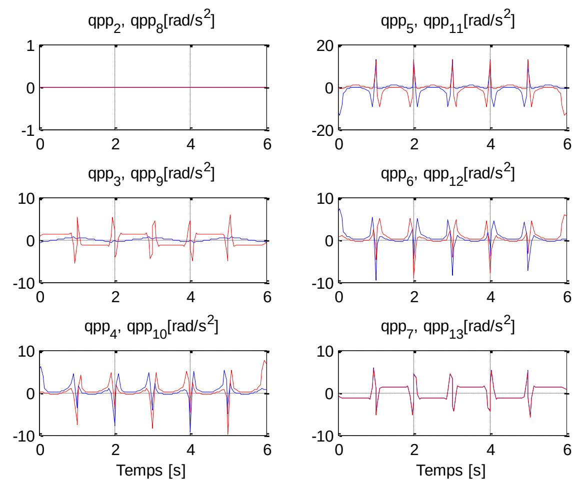
Articular positions



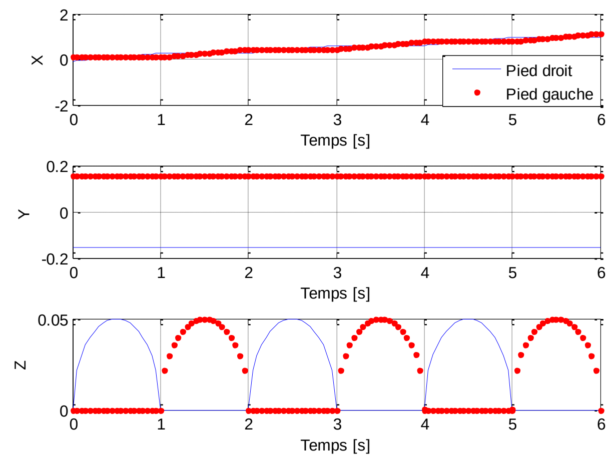
Articular velocities



Articular accelerations



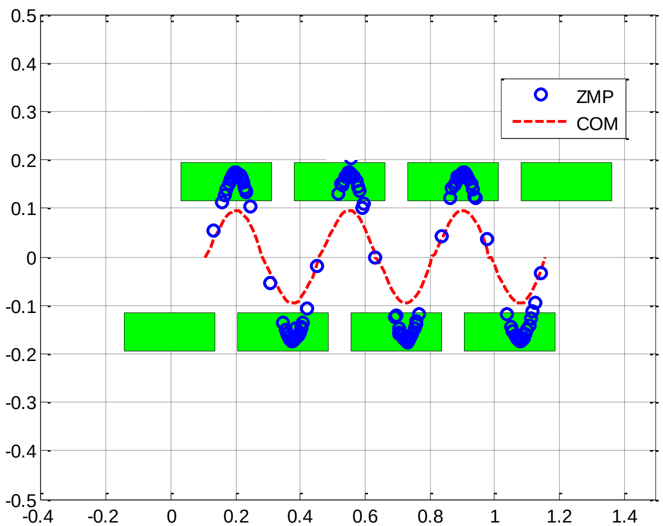
Feet trajectories



Obtained cyclic trajectories

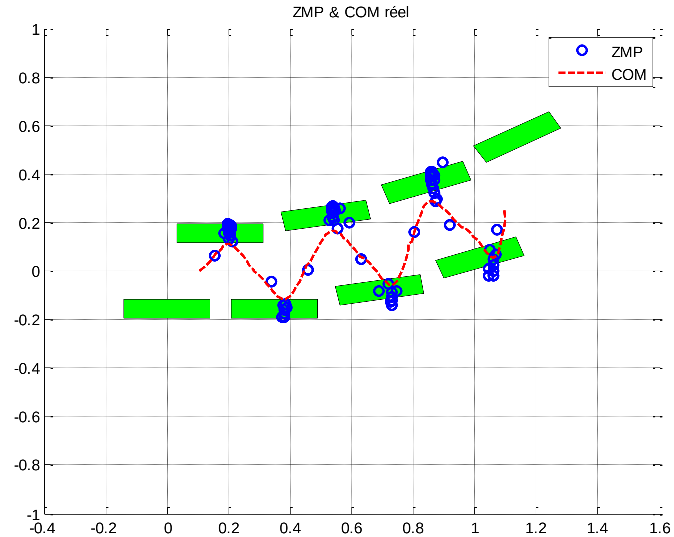
Scenario 1 : Stability evaluation without optimization

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**

Trajectories optimization

Objective : **Improve the stability of dynamic waling**

Proposed solution : **Optimization with respect to ZMP**

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

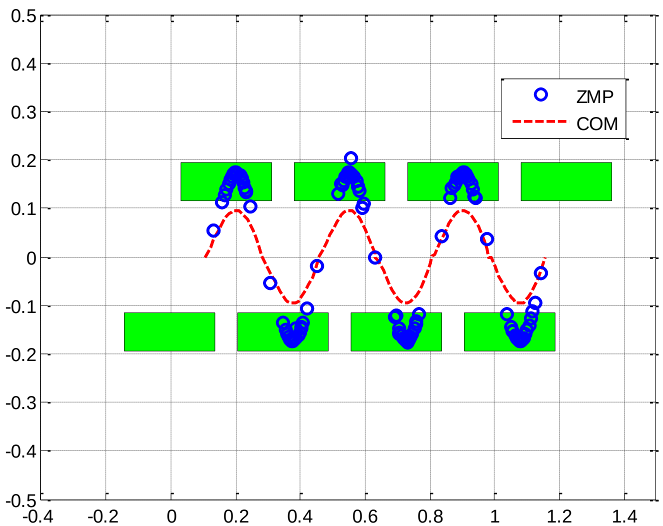
$zmp_x, \; zmp_y$: Coordinates of ZMP position

$zmp_{xd}, \; zmp_{yd}$: Desired ZMP position

$Q_x, \; Q_y$: Weighting coefficients

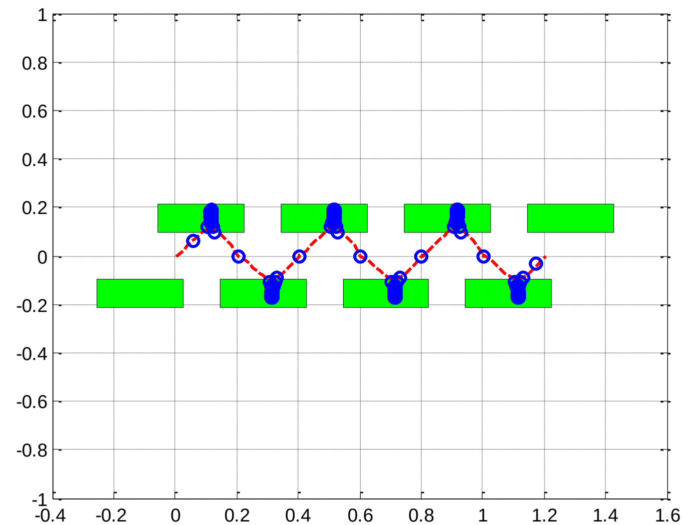
Scenario 2 : Straight walking with optimization

M2 : Without optimization



ZMP, COM et 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

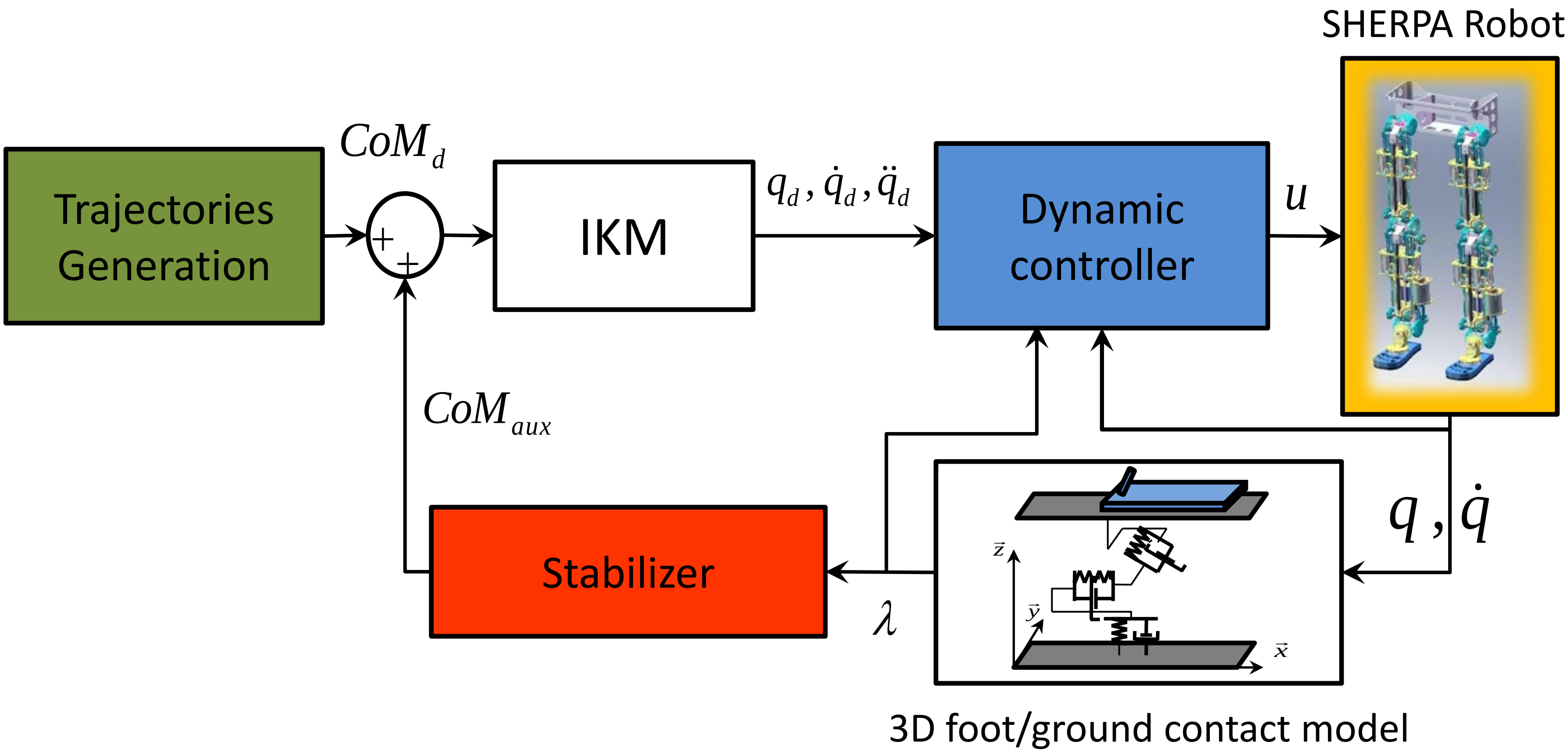
Assumptions

- **A1**: Walking on a horizontal ground without obstacles
- **A2**: walking cycle (SS+imact 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

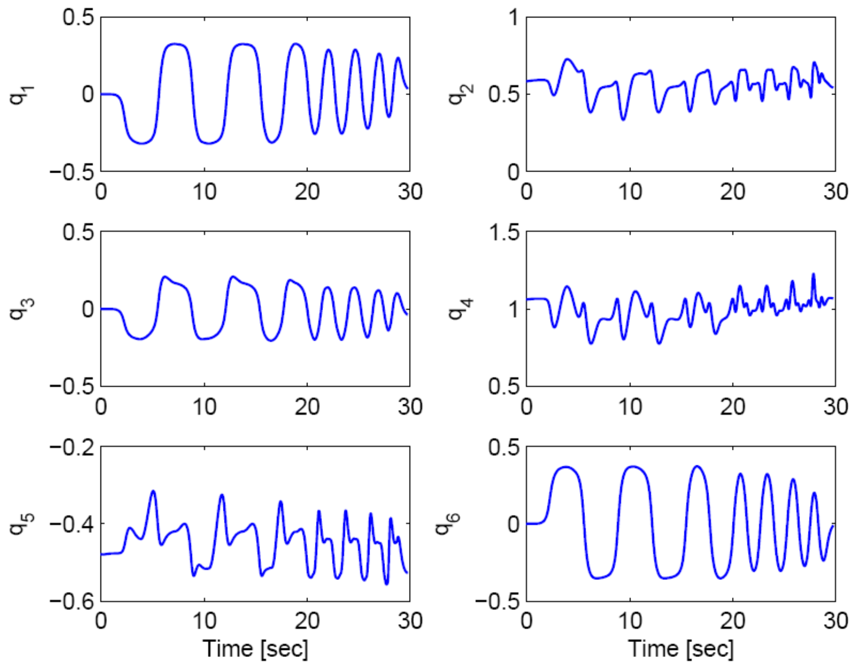


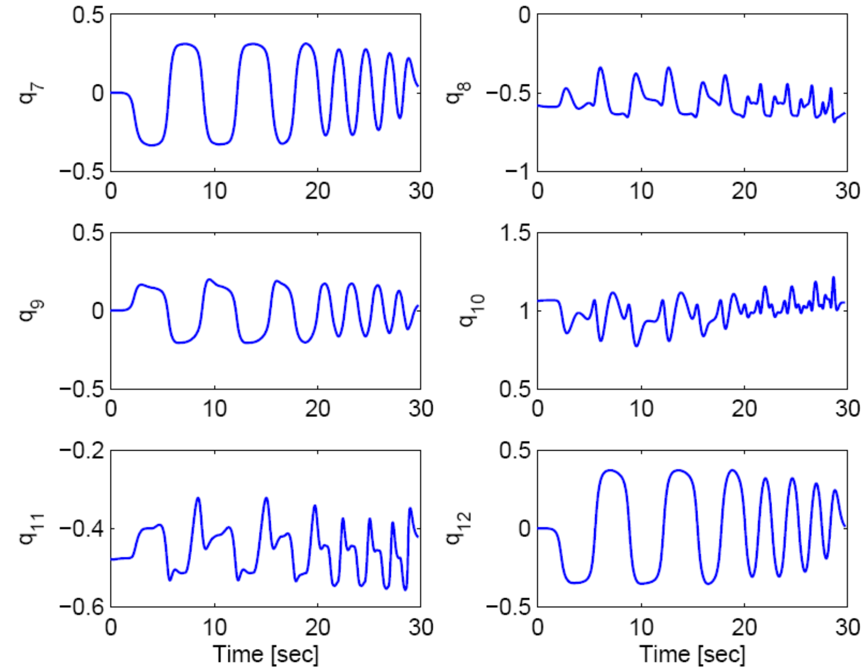
Simulation results

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

Parameter	Description	Value
dt	sampling time	$1e^{-2}$ sec
dt× NL	previewing period	1.6 sec
H_{pend}	inverted pendulum height	0.66 m
N_{pas}	number of steps	14 steps
L_{pas}	step length	0.2 m
T_{pas}	step duration	0.6 sec
K_p	position gain	500 sec^{-2}
K_v	velocity gain	50 sec^{-1}
k	stiffness coefficient	$35e^4$ $N.m^{-1}$
μ	damping coefficient	$6e^6$ $N.sec.m^2$

Simulation results

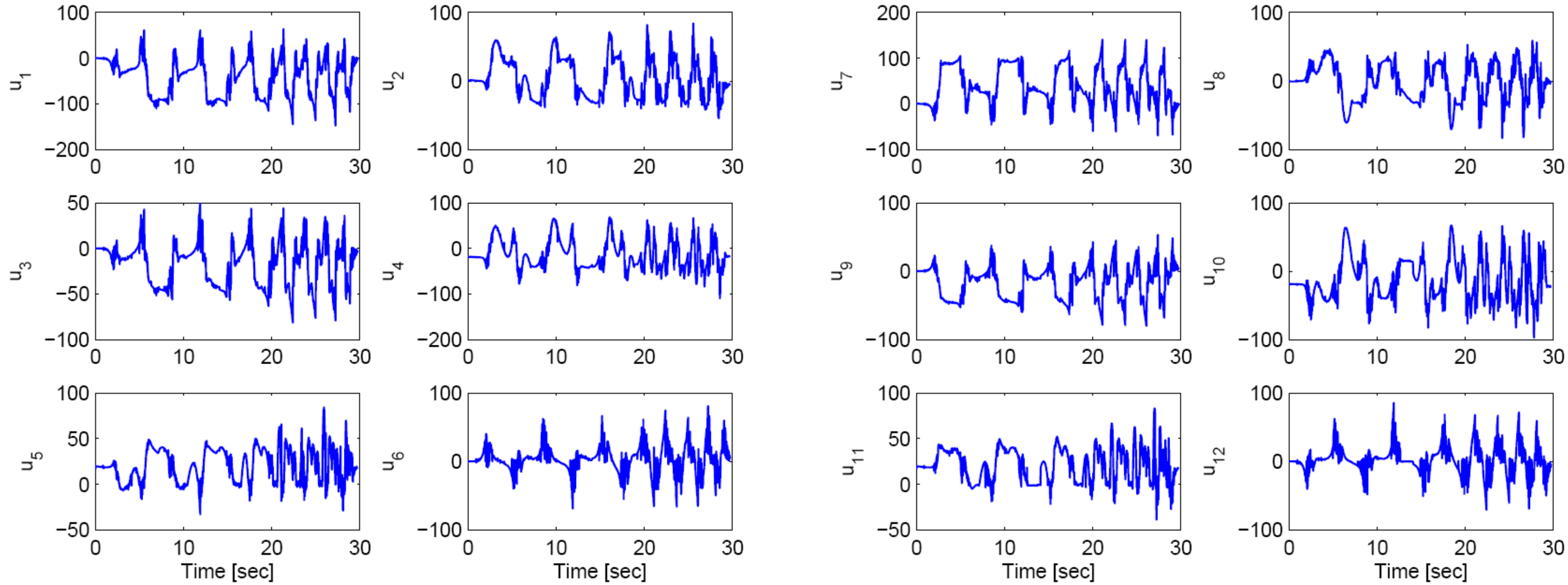




Joint positions of first leg

Joint positions of second leg

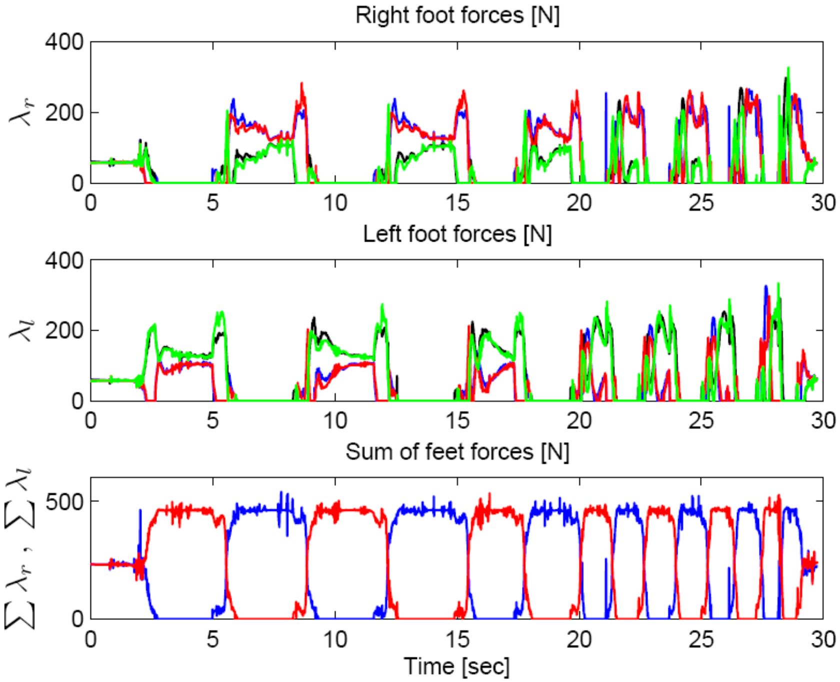
Simulation results

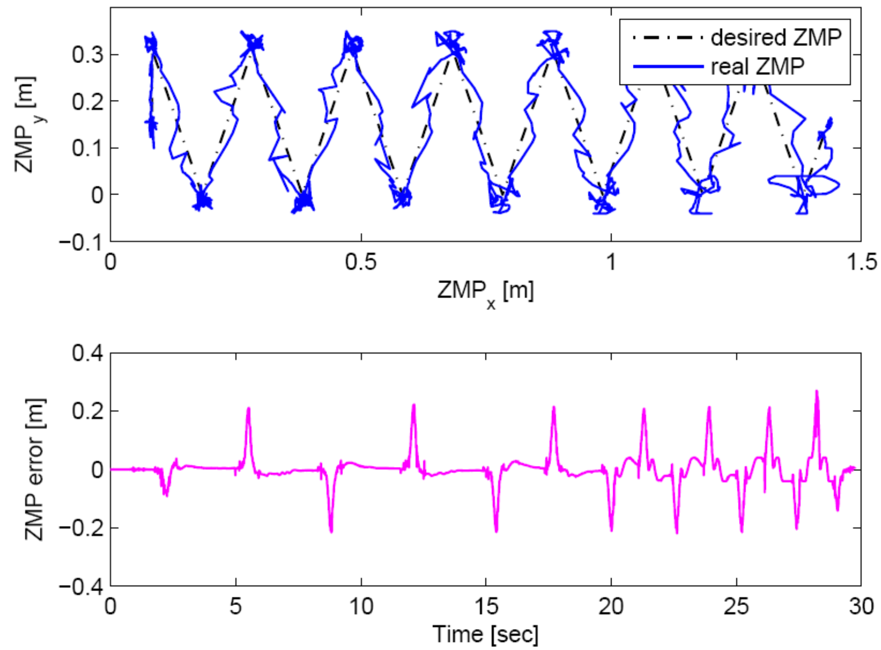


Torques of first leg

Torques of second leg

Simulation results





Contact forces

ZMP tracking

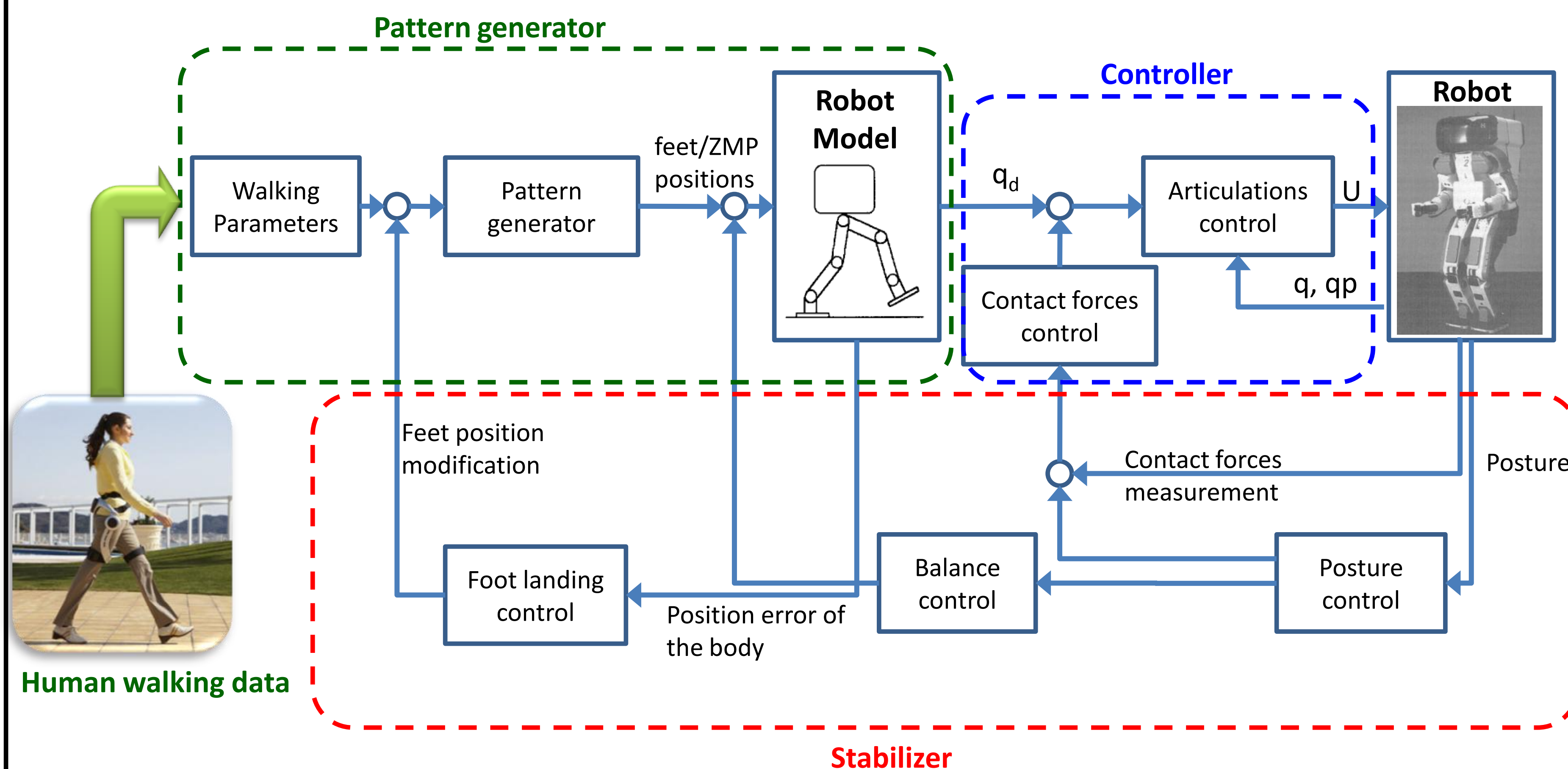
Part VI

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



Related work

Whole body motion control

- Task-based schemes
  - Objective function [Liegeois, 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

step1
- 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)

Step 1

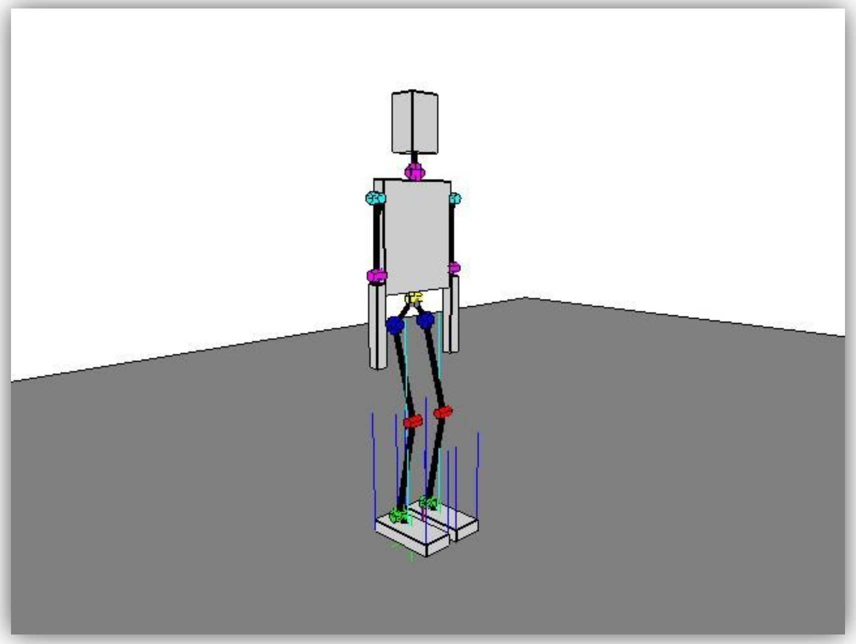
Developed simulator for whole-body control

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

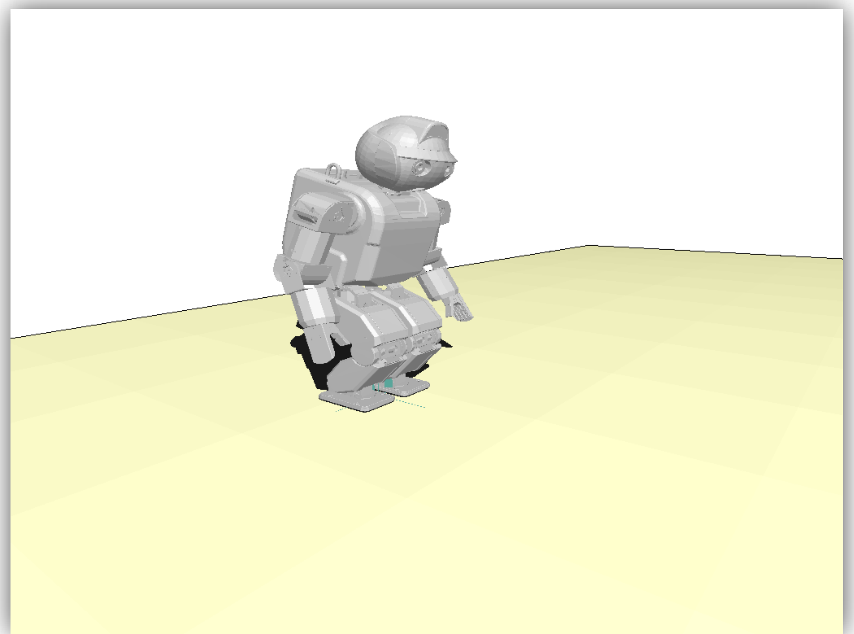
Summary of the simulator main characteristics

- 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



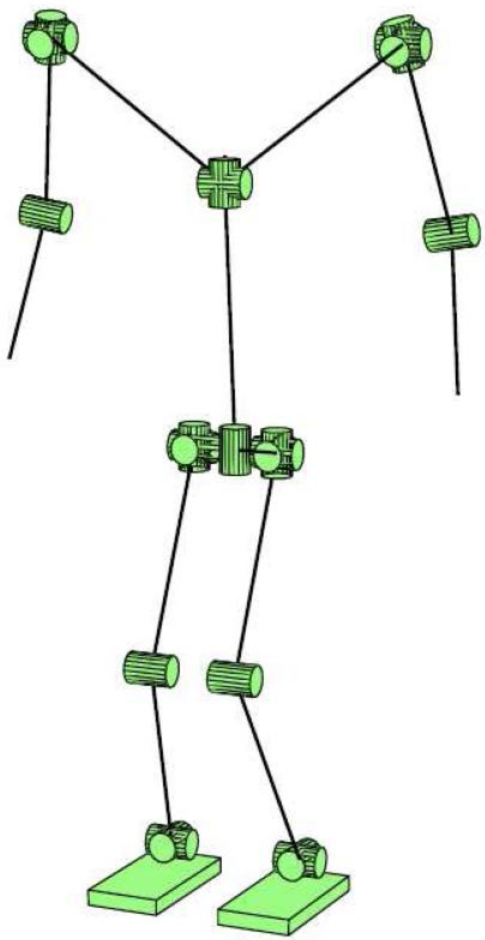
20 dof whole body model



Hoap 3 robot model (28 dof)

And others …

Whole body proposed model

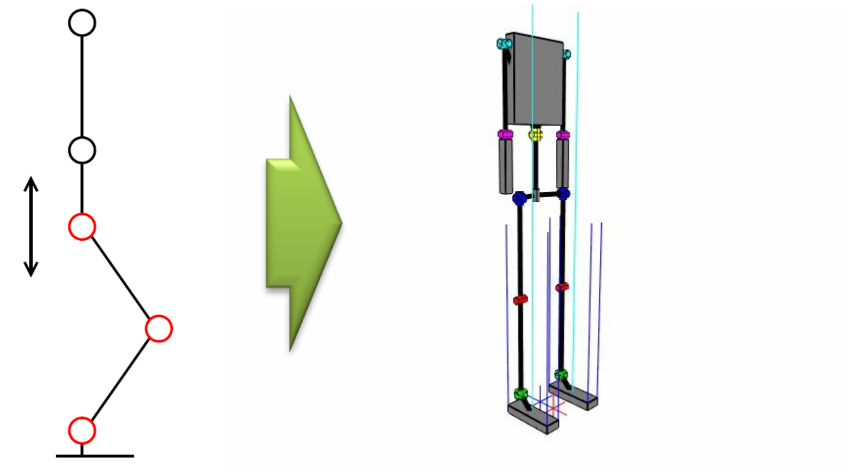


Modeling and simulation

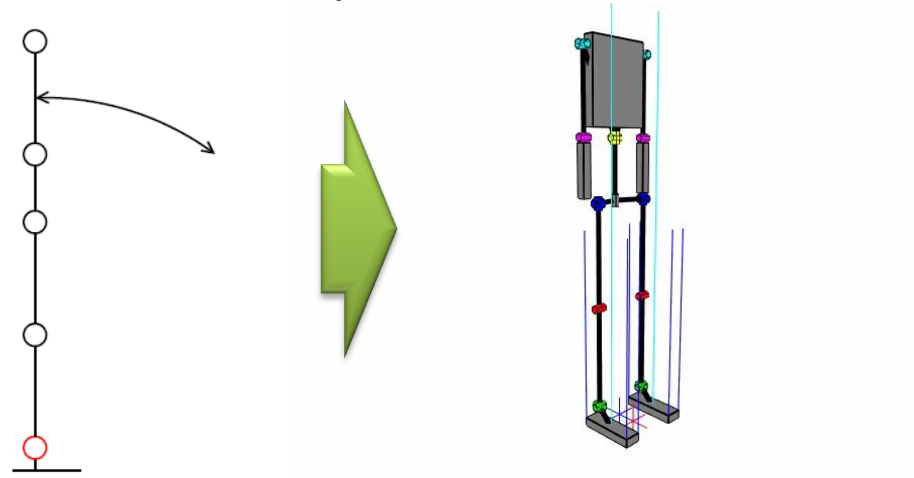
- 3D model.
- 20 DoF (6/Leg,2/torso,3/arm).
- Forward kinematics.
- Inverse kinematics.
- Dynamic model.
- Contact model.
- Link in tree representation allows easy modification.
- Modular approach allows to switch between different models.

Preliminary tests on the simulator

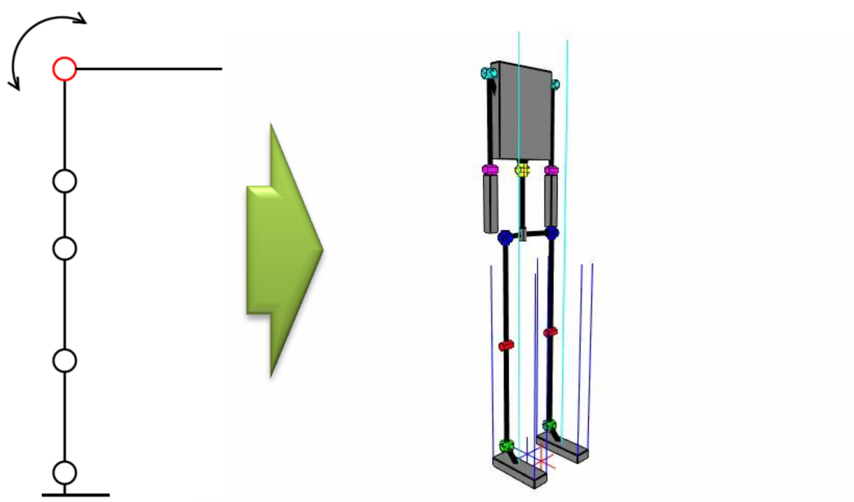
Scenario 1: **Squat task**



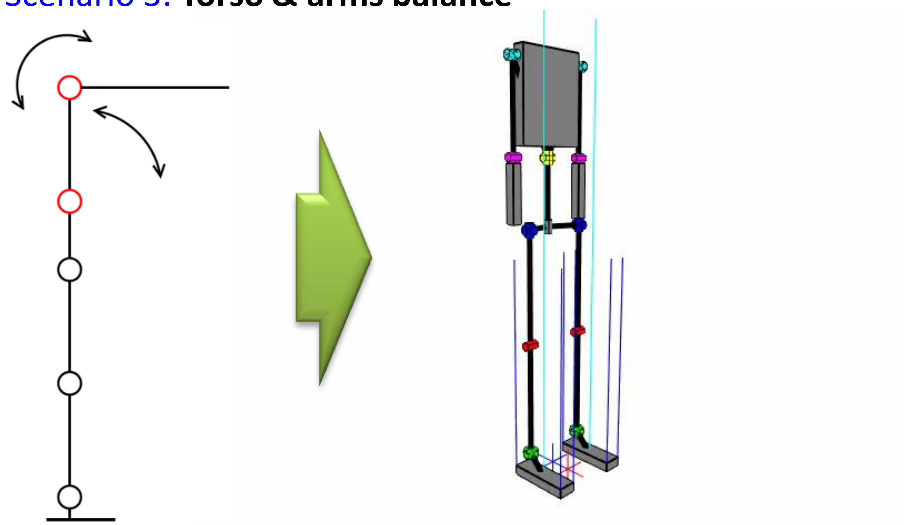
Scenario 2: **Whole body balance**



Scenario 3: **Arms balance**



Scenario 3: **Torso & arms balance**

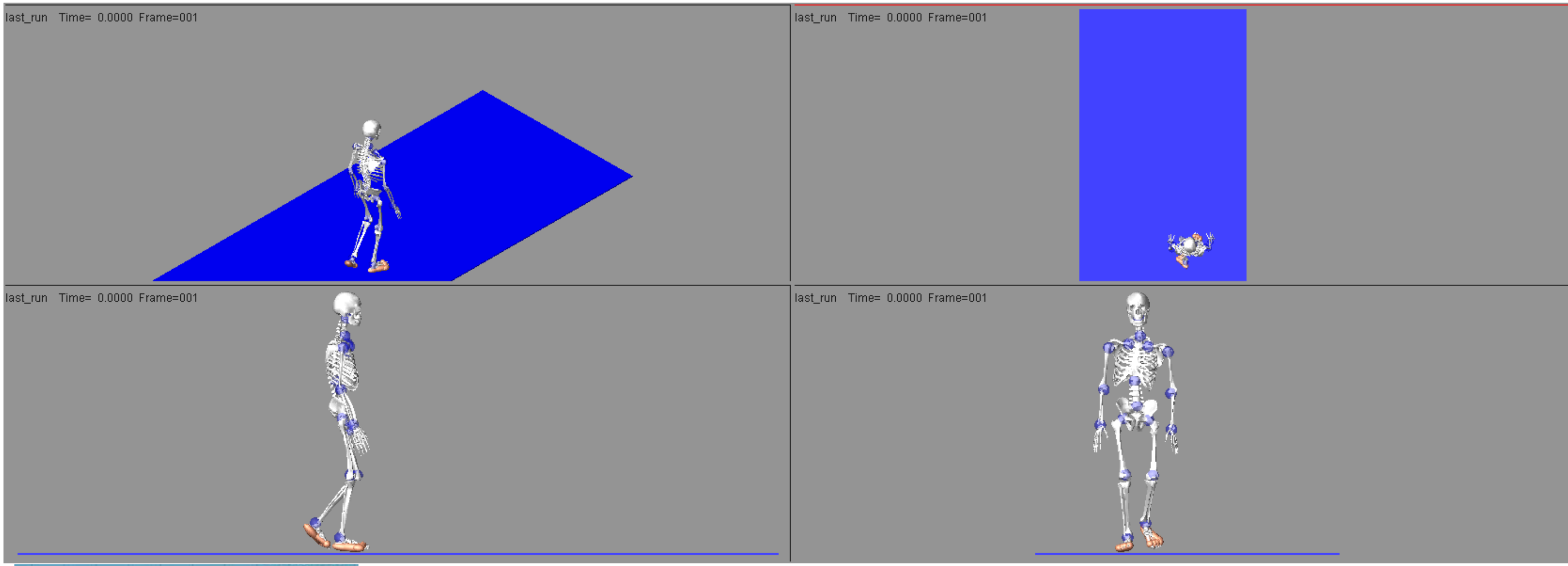


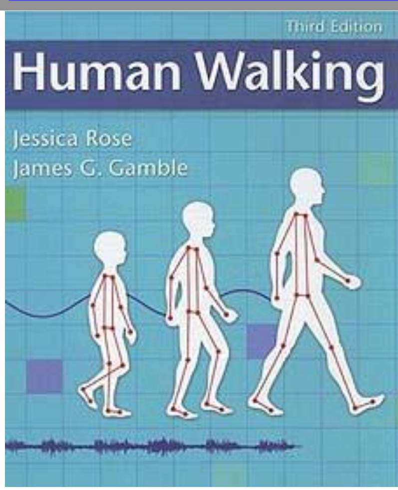
Step 2

Human walking study

- ✓ Human walking
- ✓ Motion capture system

Human walking



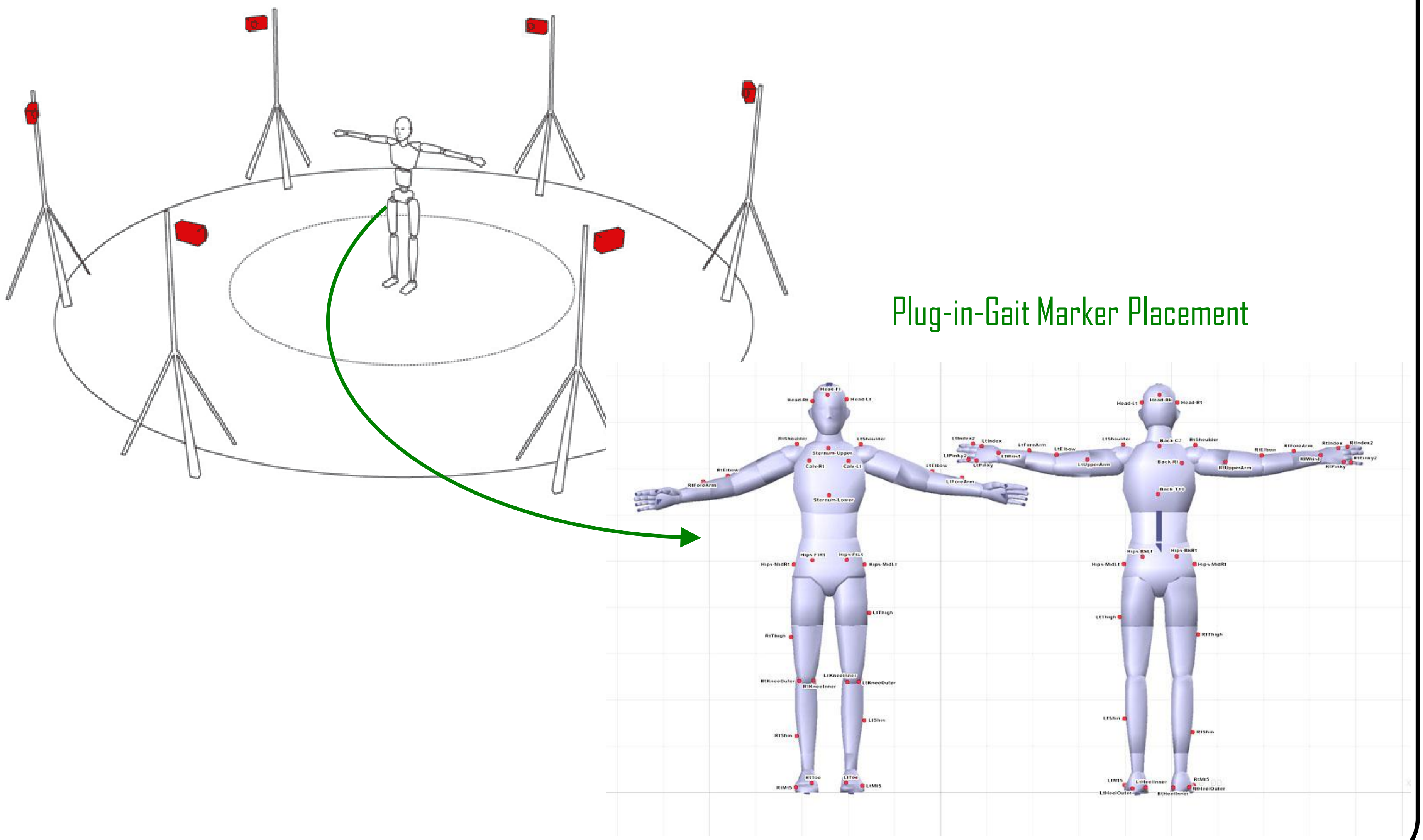


Including :

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

How we can acquire data on human walking ?

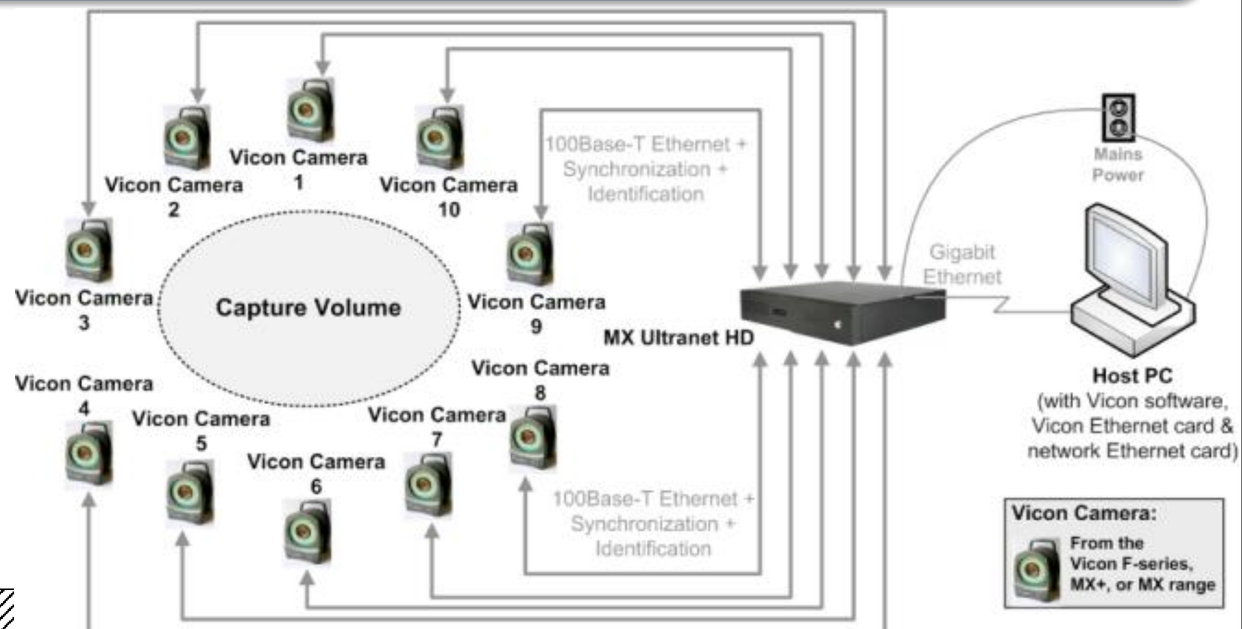
Motion capture system



Motion capture system

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



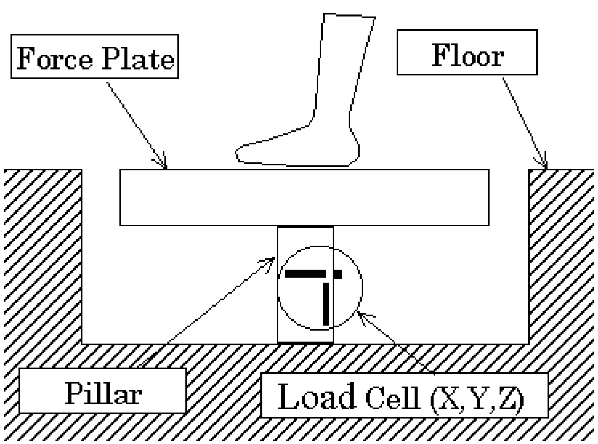


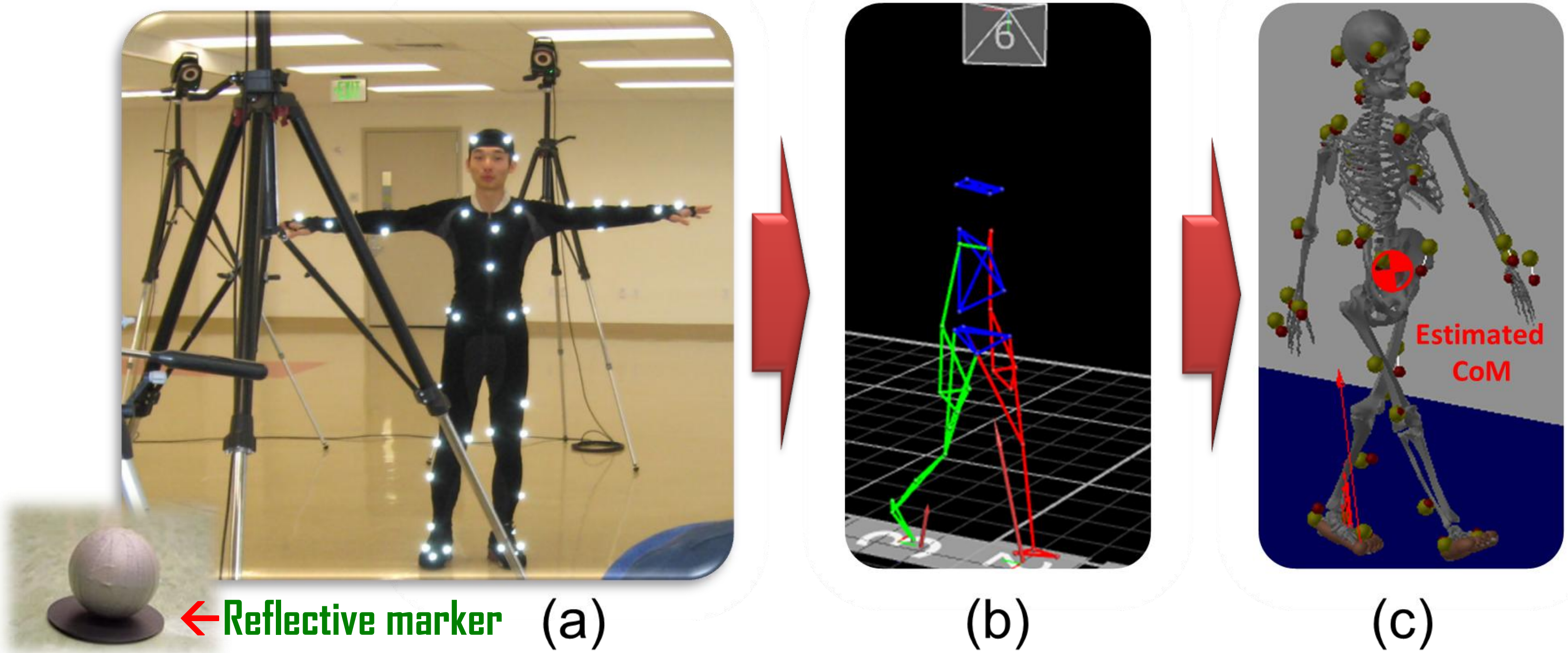
Fig.1 Structure of Force Plate

Force plate

VICON Camera

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)

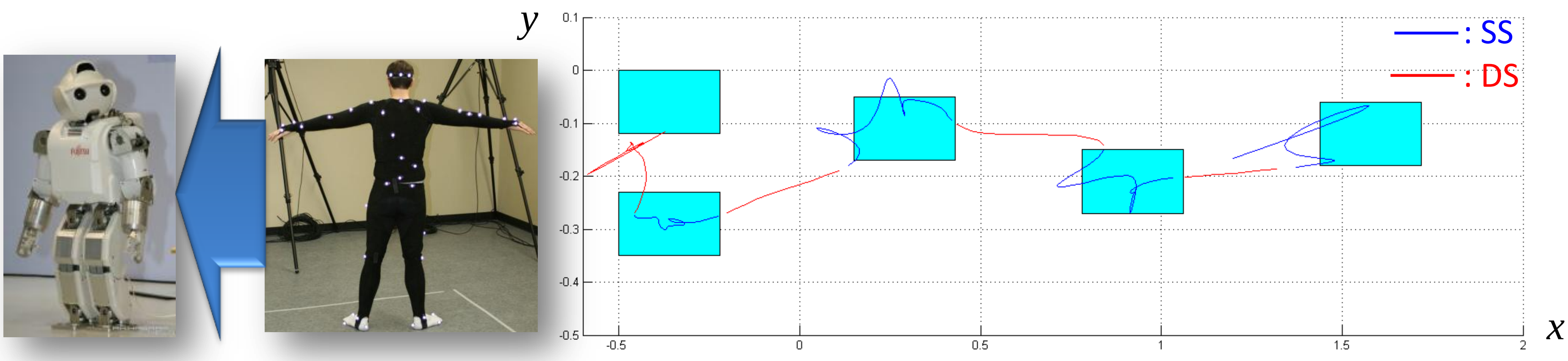
Step 3

Pattern generator design

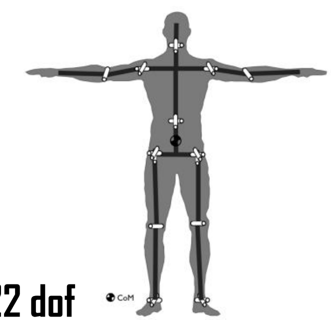
- ✓ Basic idea of the proposed solution
- ✓ Proposed human data base pattern generator
- ✓ Simulation results

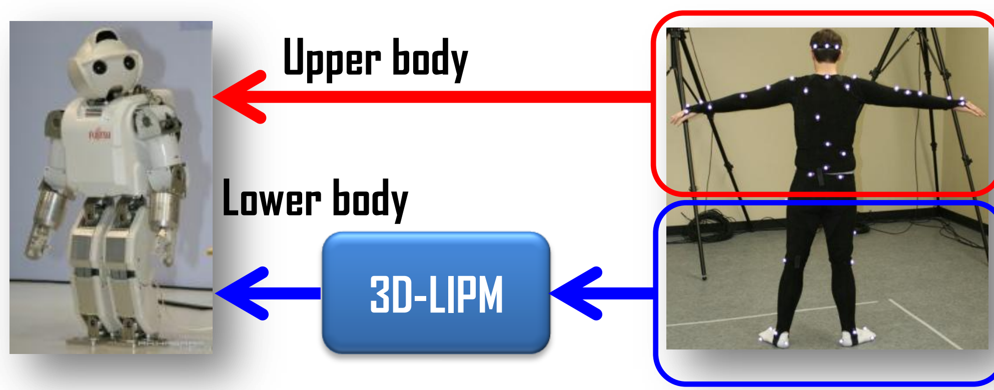
Basic idea of the proposed solution

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

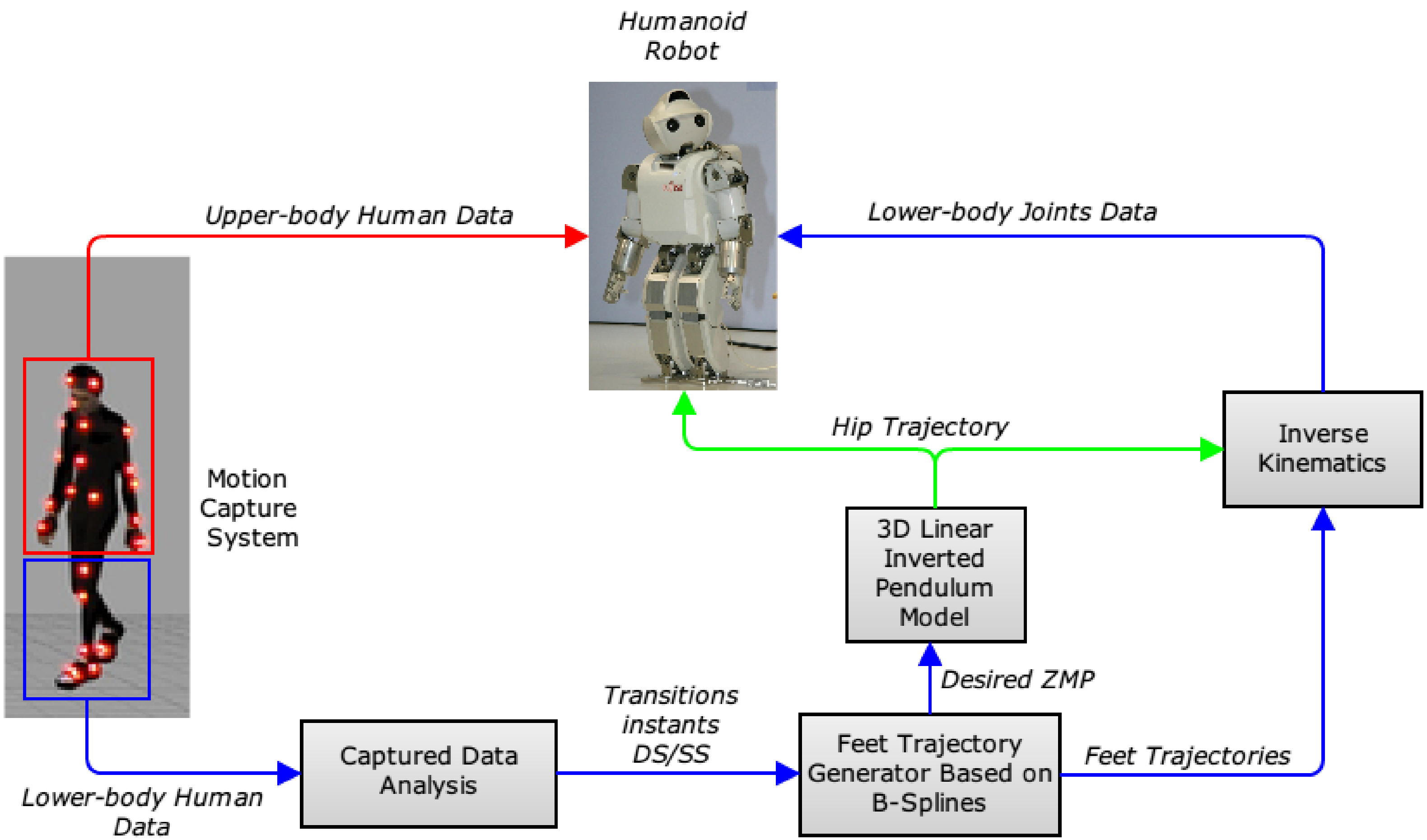


- ZMP is outside the polygon of support → unstable waking !
- **Proposed solution :**


22 dof

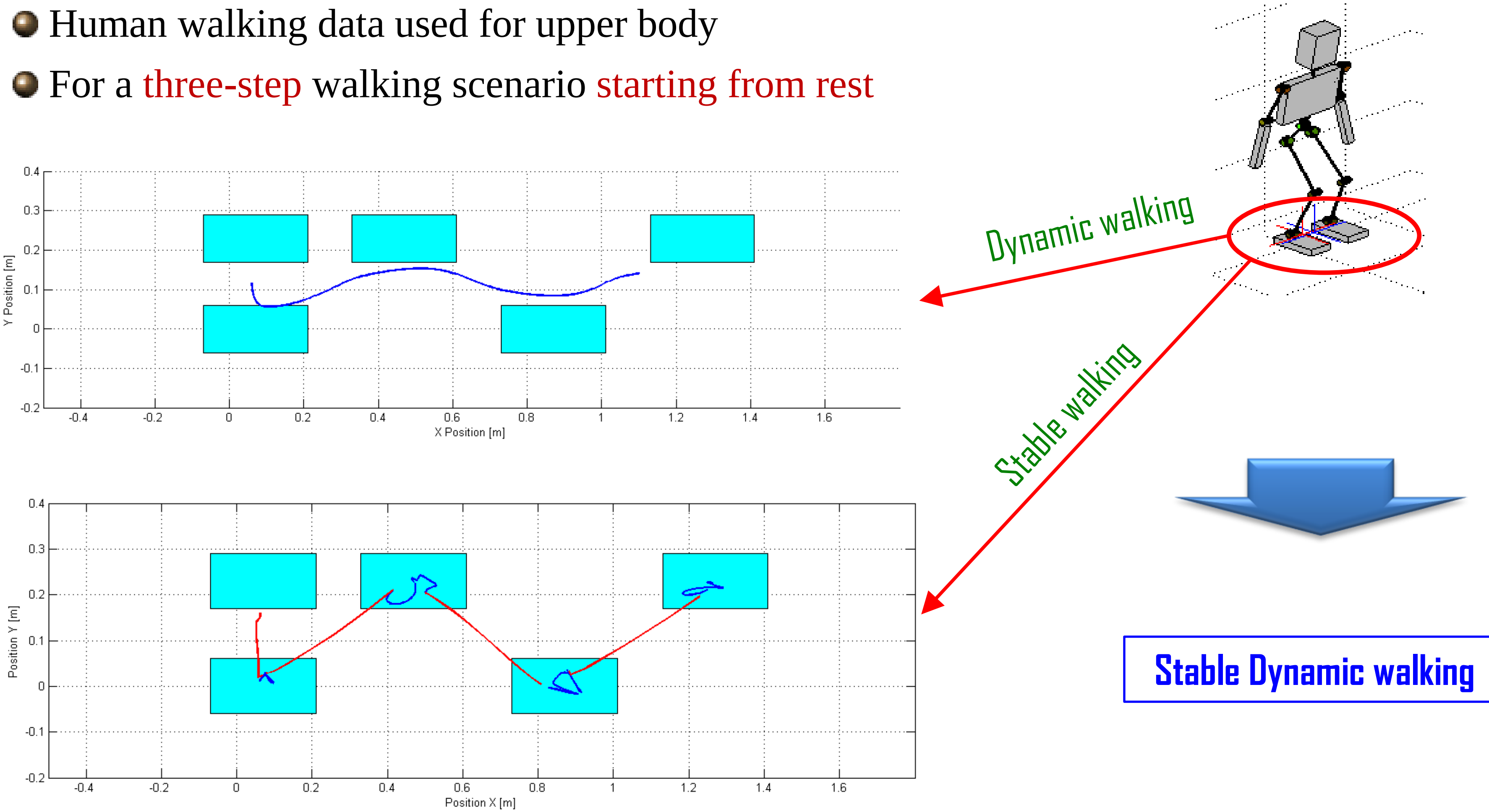


Proposed human data based pattern generator



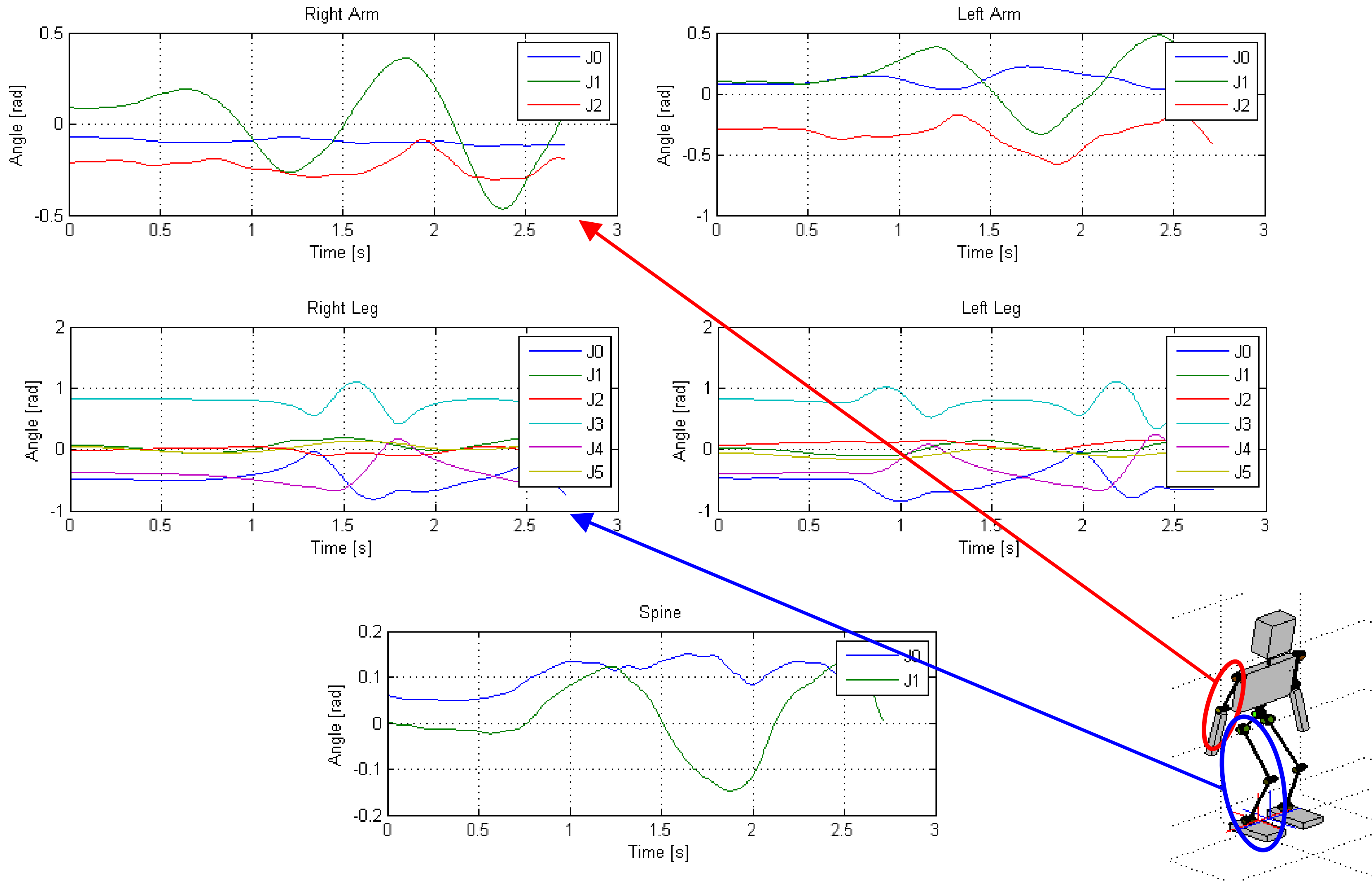
Simulation results

- 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



Stable Dynamic walking

Simulation results

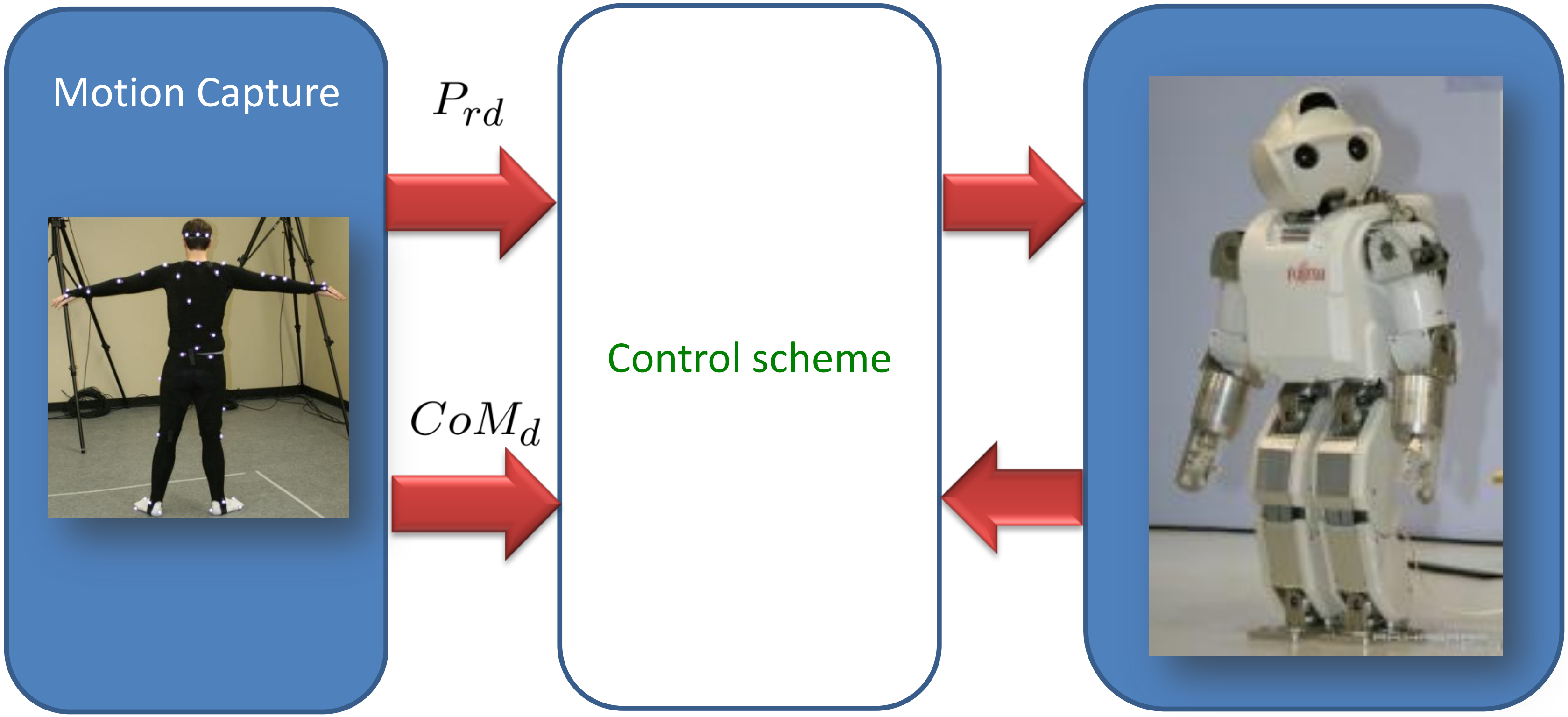


Step 4

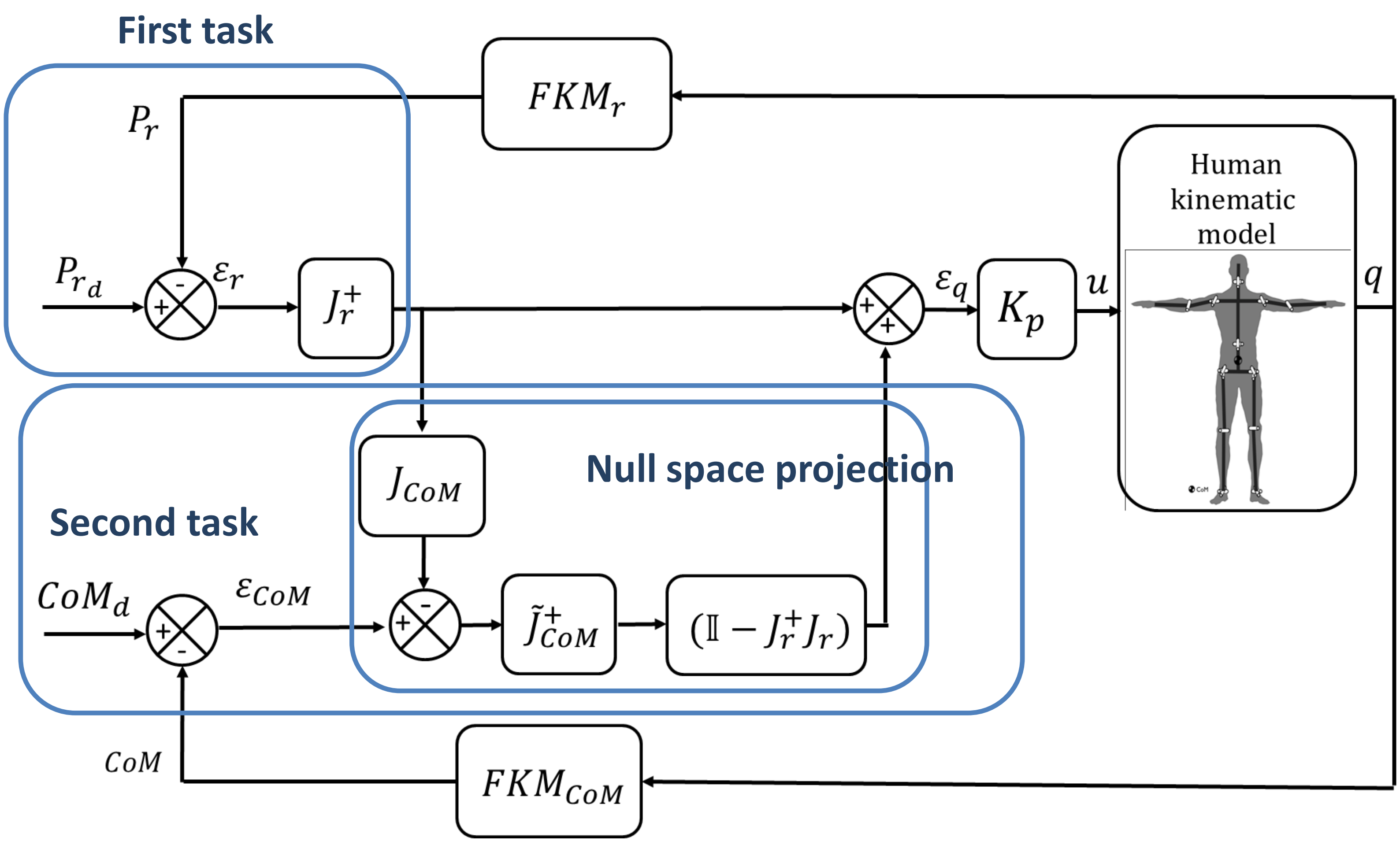
Control architecture design

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

Basic idea of the proposed control scheme

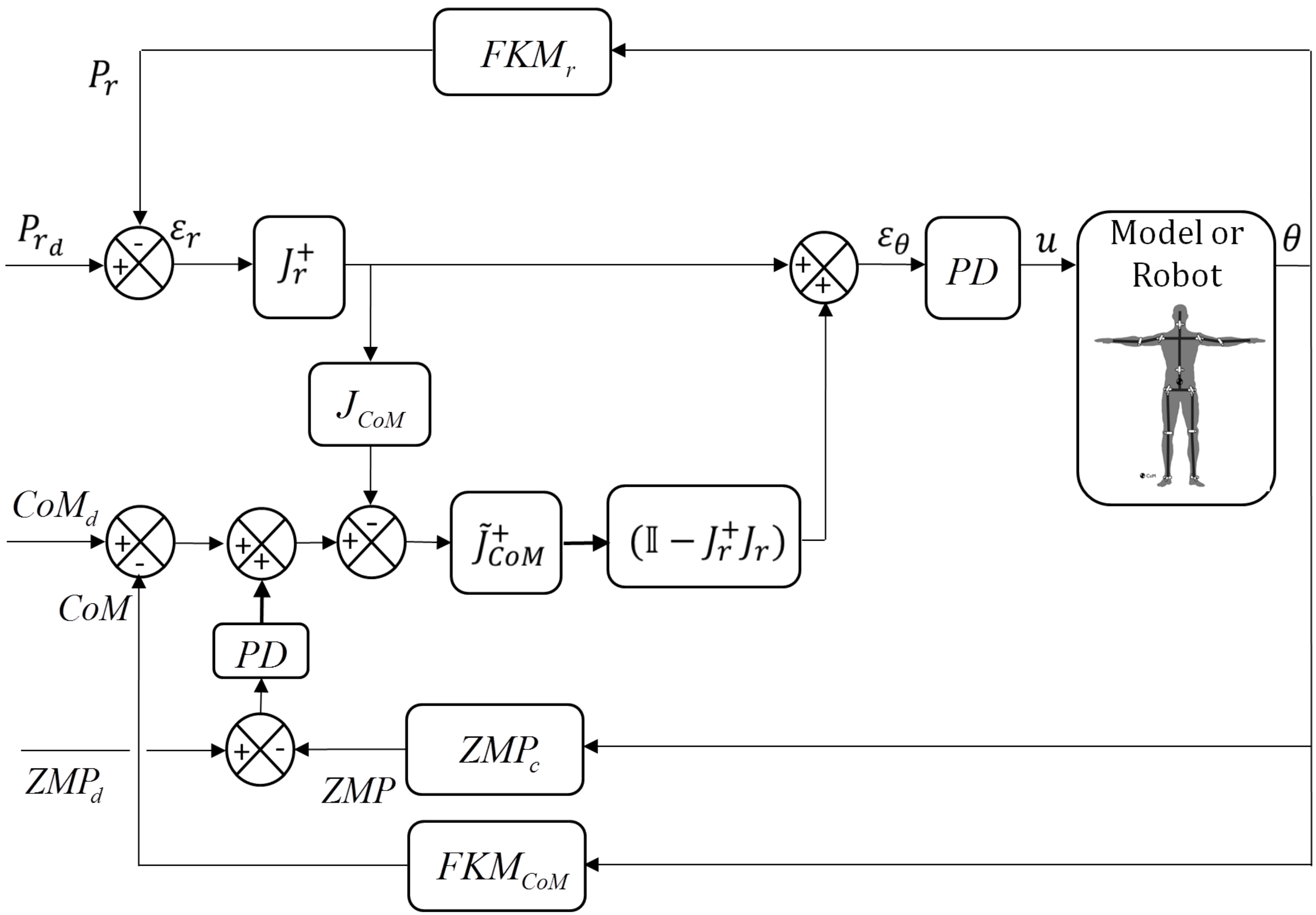


Block-diagram of the proposed control architecture



Extended version of the proposed control architecture

(With ZMP regulation)



Step 5

Implementation on a humanoid robot

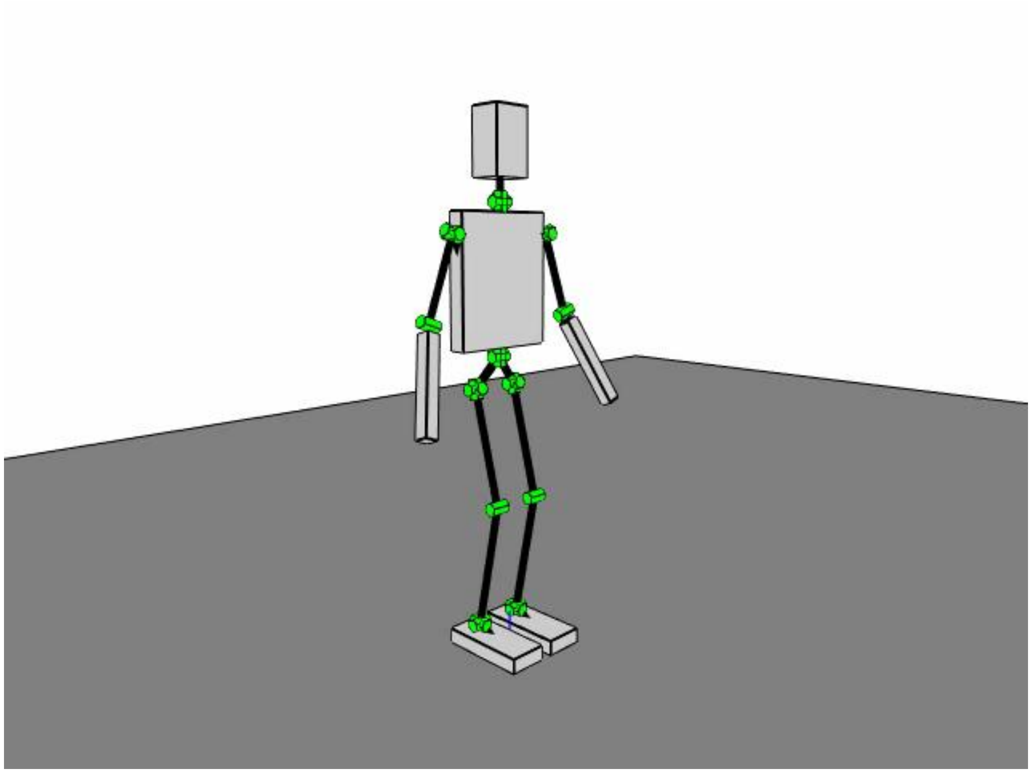
Simulation scenarios

- ✓ 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

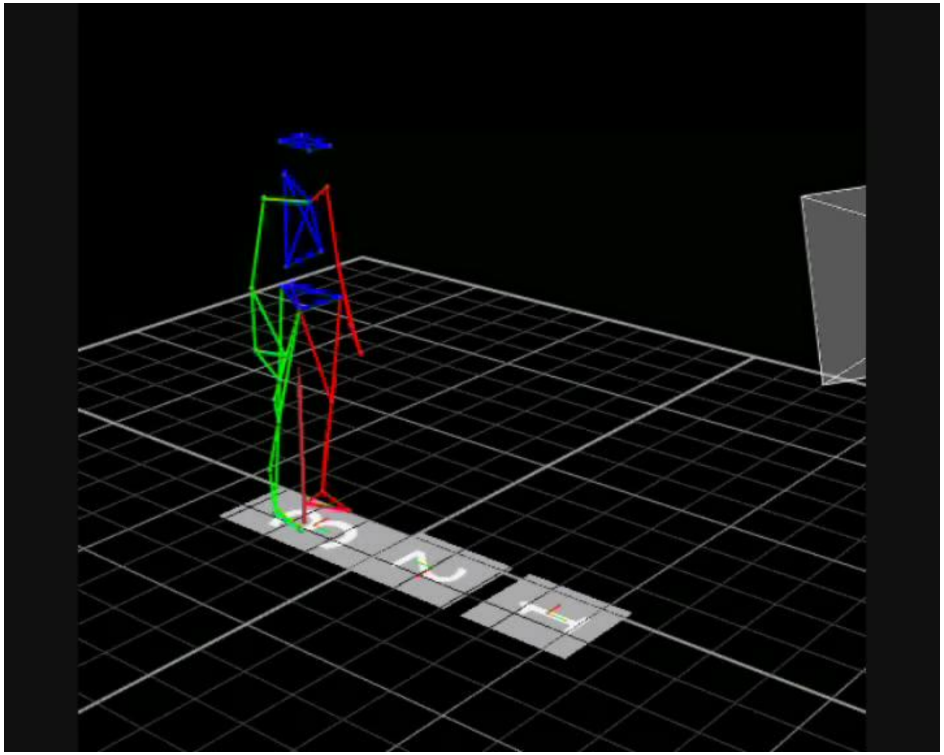
- ✓ Scenario 1 : ZMP control
- ✓ Scenario 2 : Squat motion

Simulation scenario 1 : First validation of the scheme

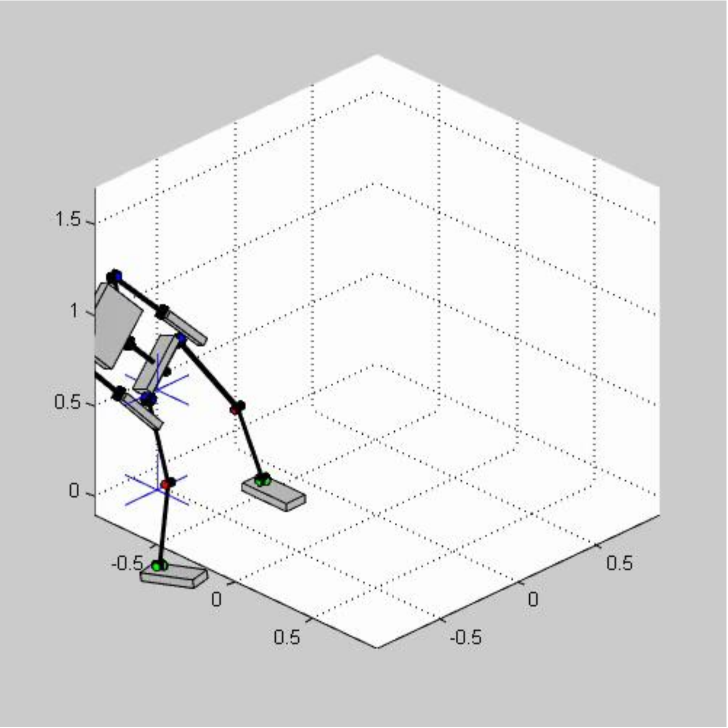


Simulation scenario 2 : Human data without adaptation

Reconstructed human movement



Application of the proposed scheme

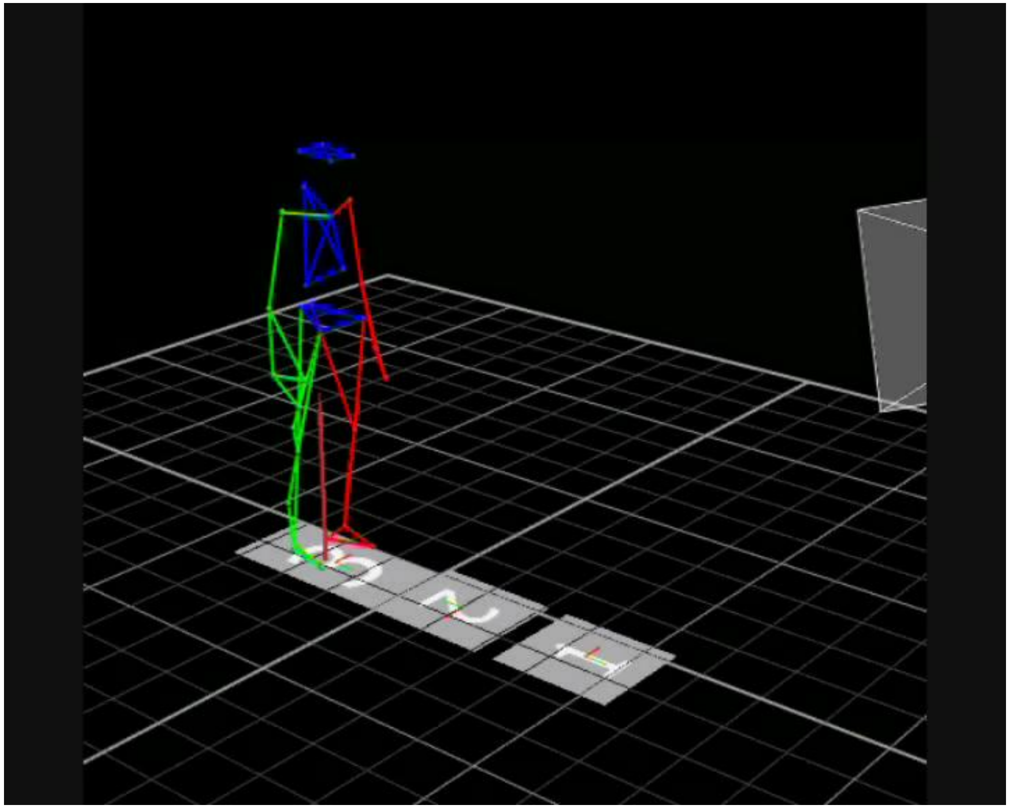


Simulation of the proposed control scheme

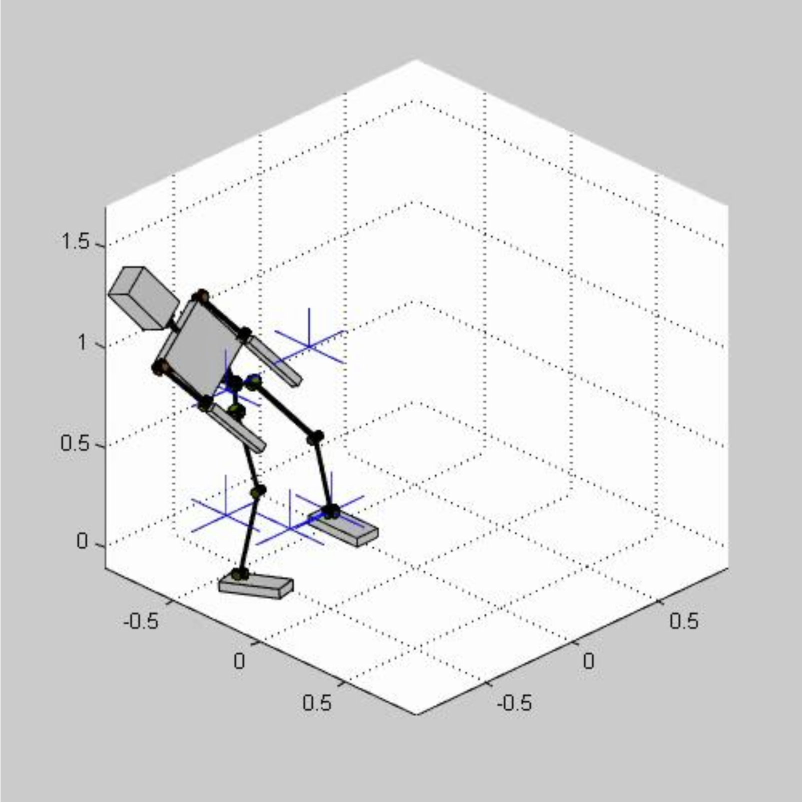
Use of human data without any adaptation

Simulation scenario 3 : Human data with CoM scaling

Reconstructed human movement



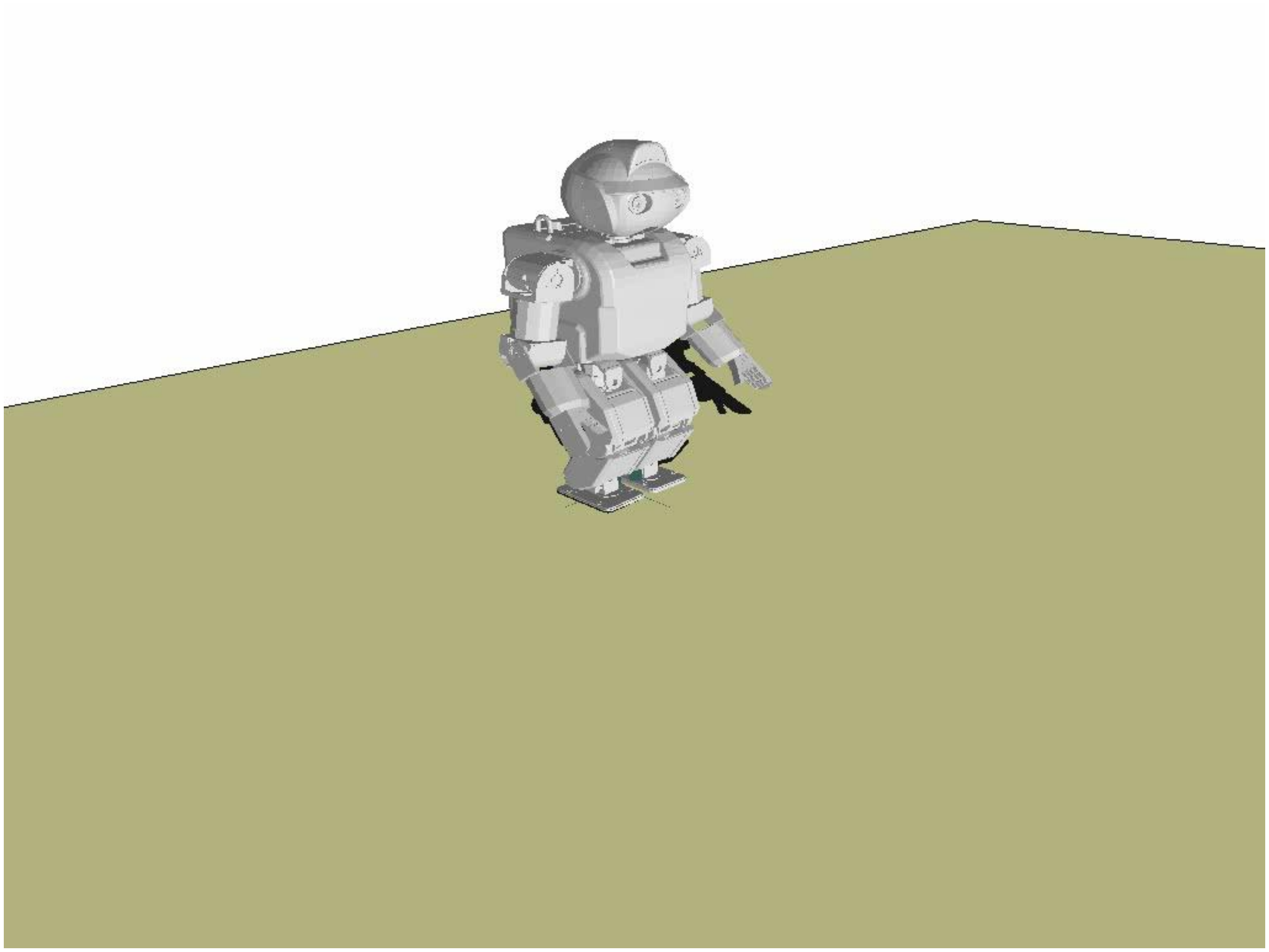
Application of the proposed scheme



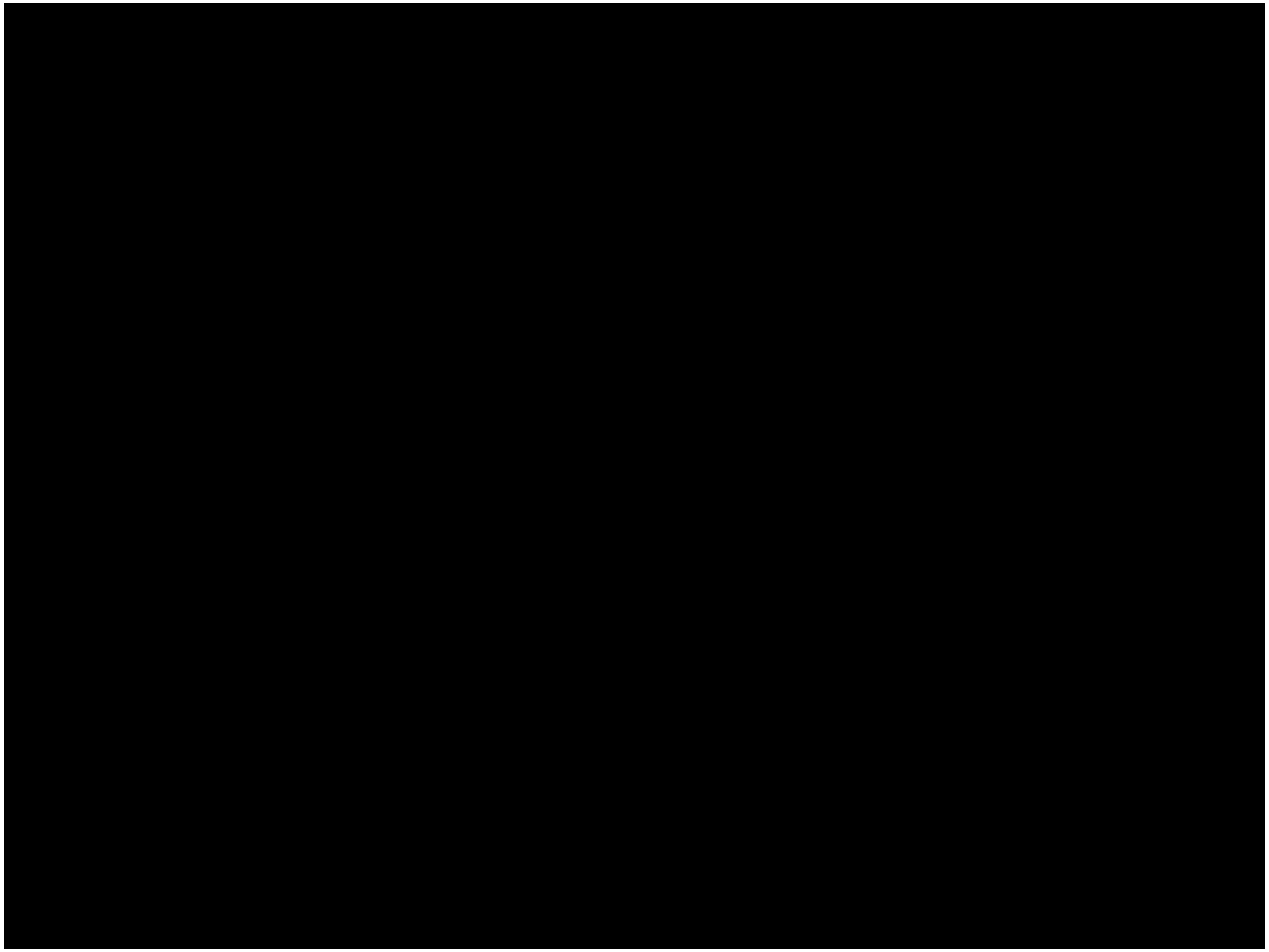
Simulation of the proposed control scheme

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