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

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Plenary II

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



Ahmed CHEMORI



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LIRMM, CNRS/University of Montpellier 2
161, rue Ada 34095
Montpellier, France

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



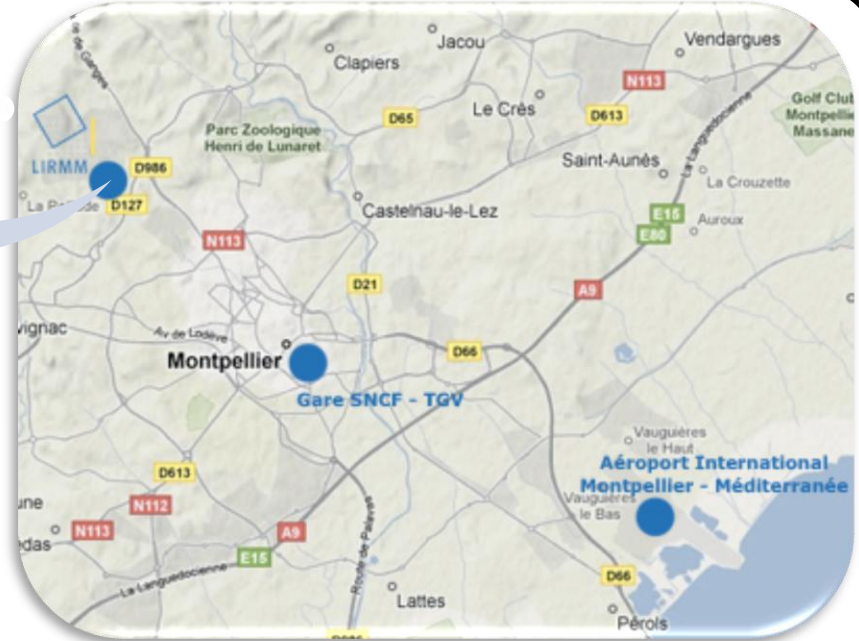
Montpellier



LIRMM Laboratory



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 :

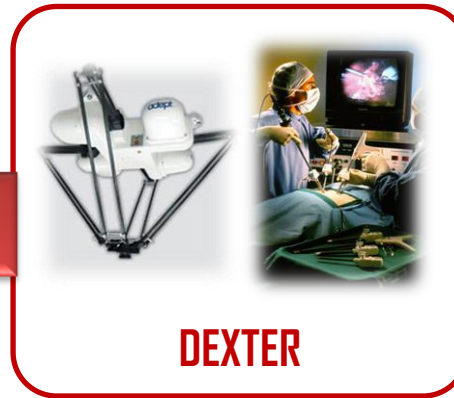
Department of
Computer science

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



Robotics Department

of LIRMM



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)



D. COMPANY
(MC UM2)



S. KRUT
(CR CNRS)



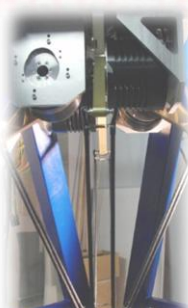
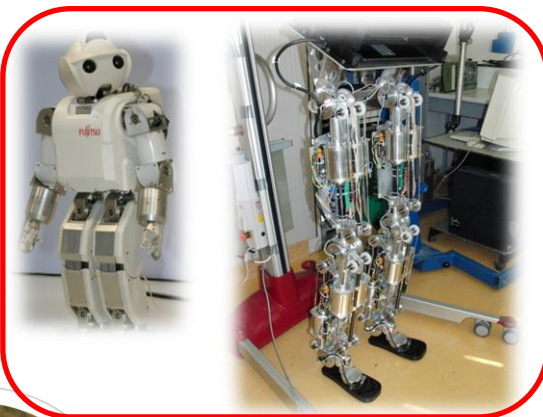
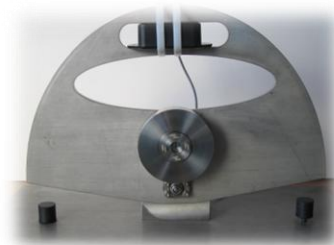
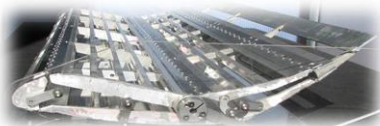
A. CHEMORI
(CR CNRS)



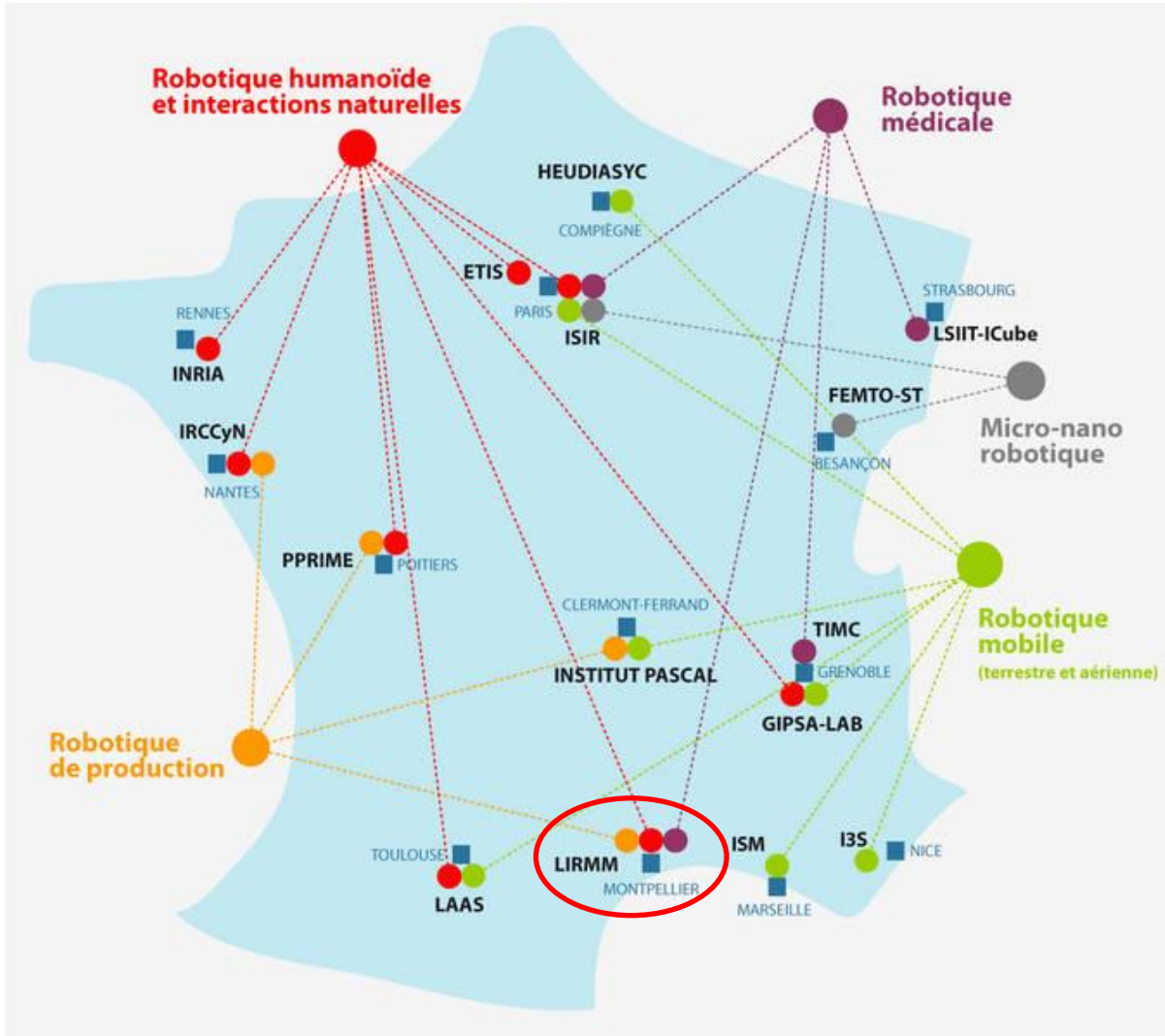
M. GOUTTEFARDE
(CR CNRS)

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

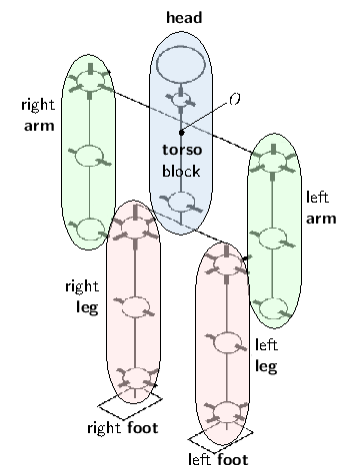
- A **humanoid robot** or an **anthropomorphic robot** is a robot with an overall appearance, based on that of the human body, allowing interaction with made-for-human tools or environments.
- In general humanoid robots have a **torso** with a **head**, **two arms** and **two legs** Some humanoid robots 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 anthropomorphic 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

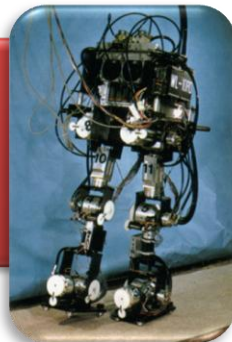
WL-1 (1967)



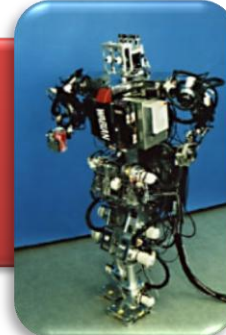
WAP-3 (1971)



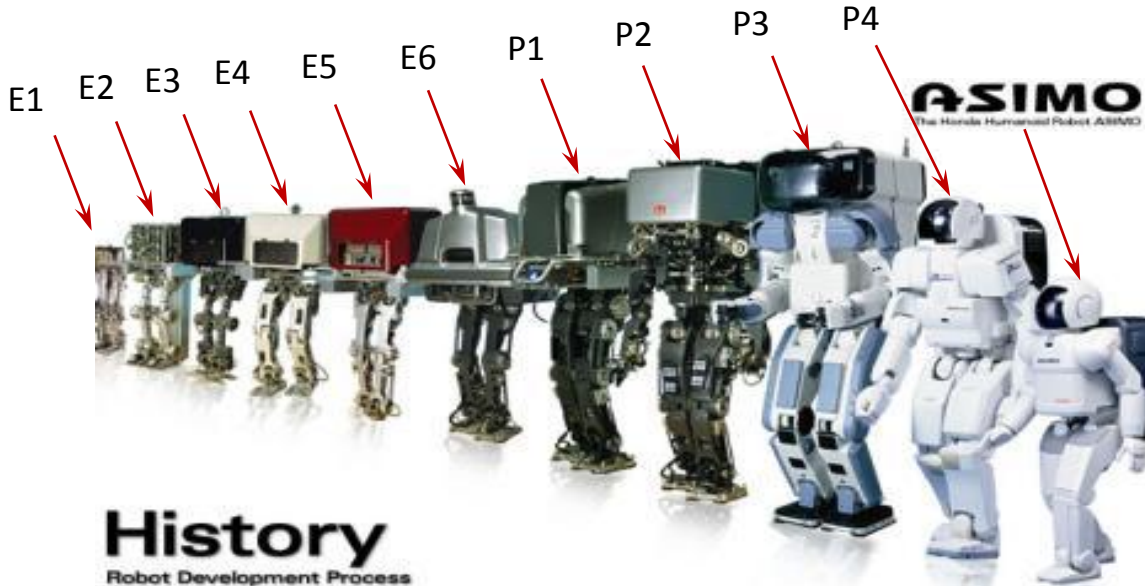
WL-10RD (1984)



WABIAN (1995)



Honda humanoid robots



History
Robot Development Process

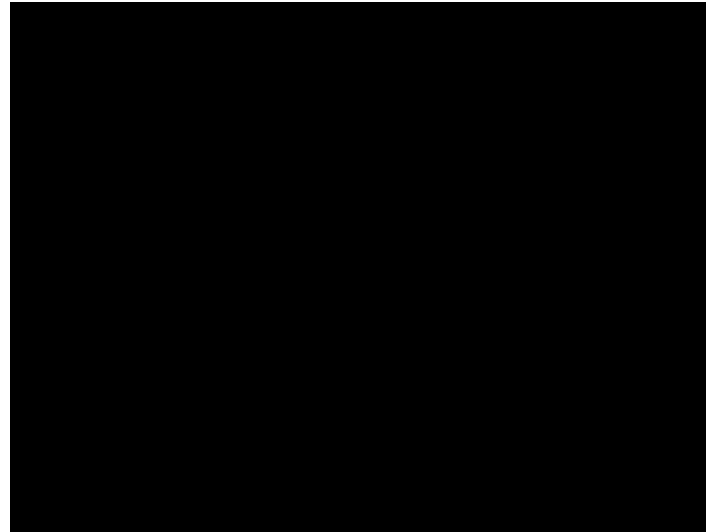
Towards whole-body

Humanoid robots of today



SDR4 (Sony)

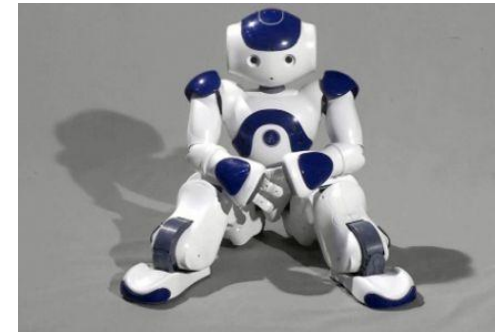
ASIMO (Honda)



HRP4/HRP4-C (AIST)



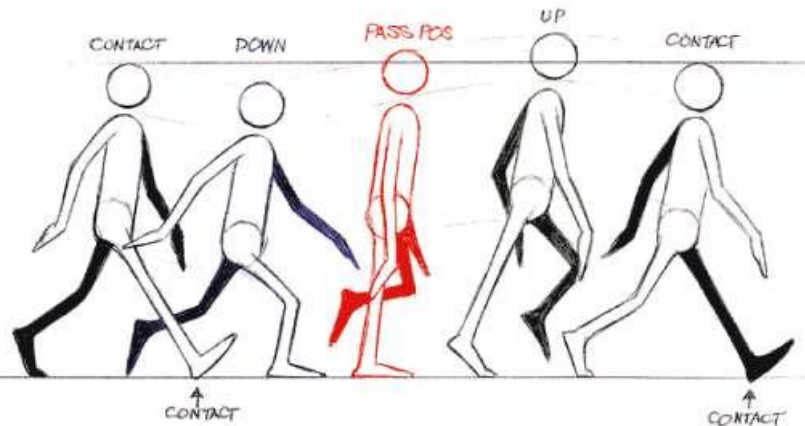
Hoap3 (Fujitsu)



Nao (Aldebaran)

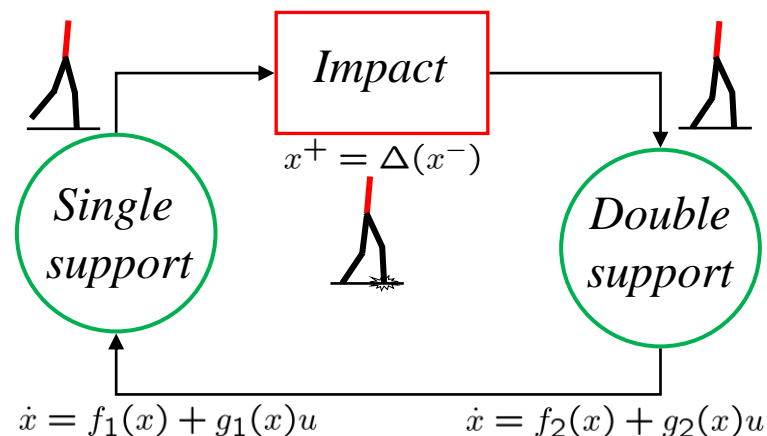
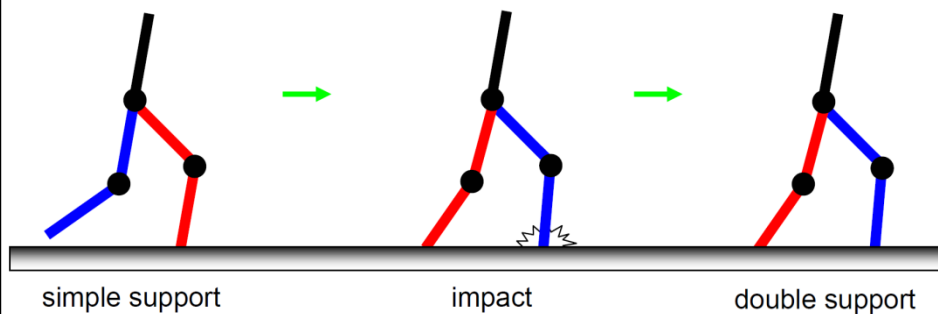
Problem formulation

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

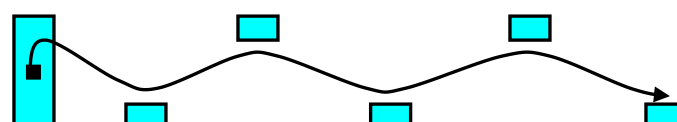
Static or dynamic walking ?

Static walking



Center Of Mass (COM)

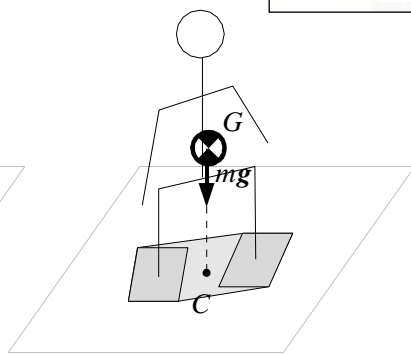
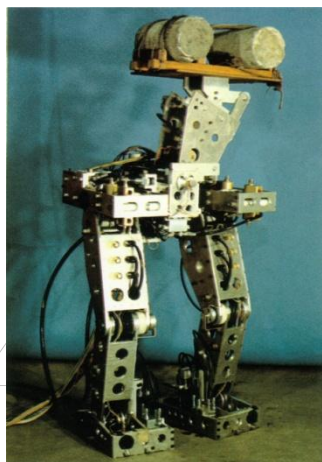
Dynamic walking



Zero Moment Point (ZMP)



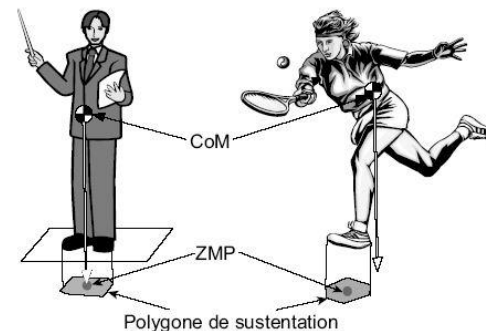
WL-5 (1971)



(b)

Weighting sum of the centers of different bodies

$$OG = \sum M_i G_i$$



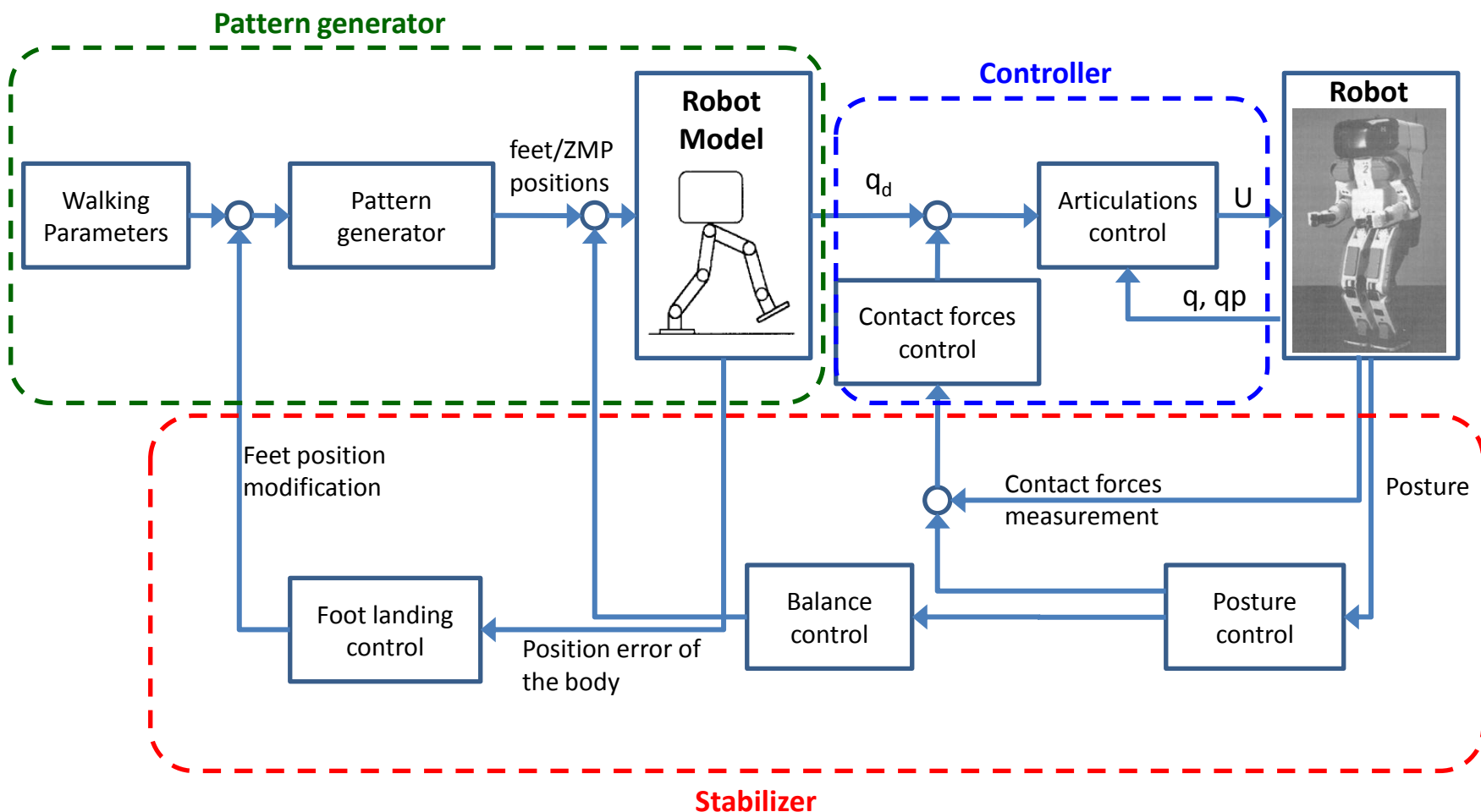
(a) Homme immobile

(b) Homme en mouvement

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

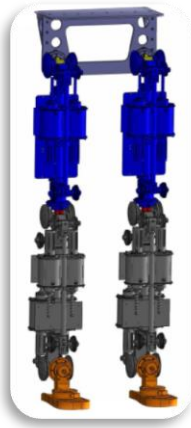


Our demonstrators

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

SHERPA robot : Development steps

Guide de montagne dans l'Himalaya



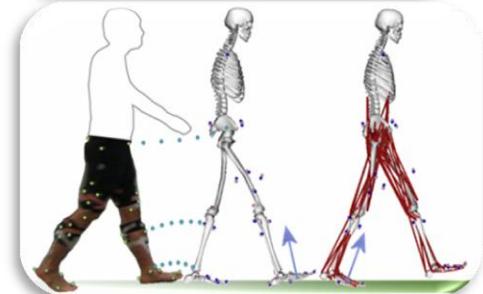
Prototype

Original idea



Mechanical design

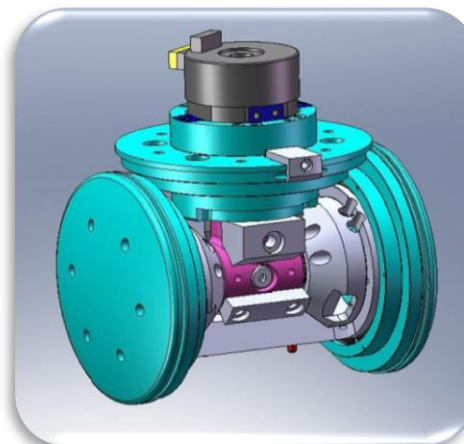
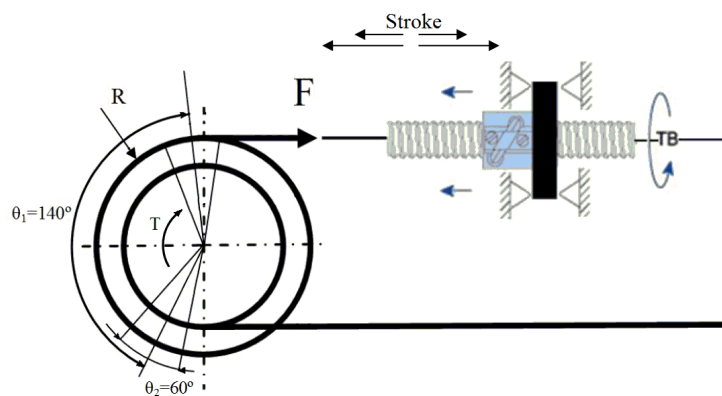
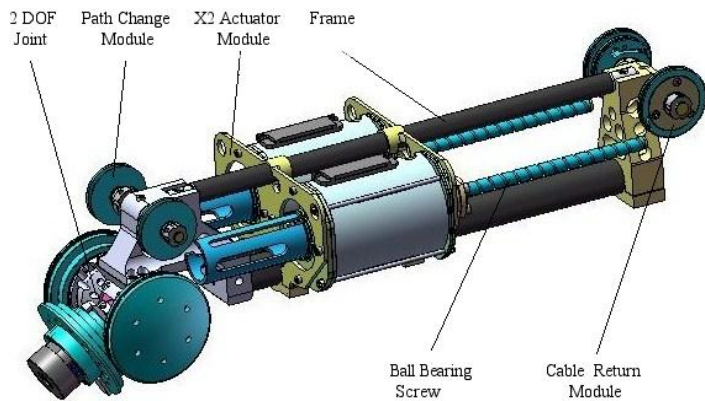
Biomechanical studies



Articulated mechanical structure

- **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

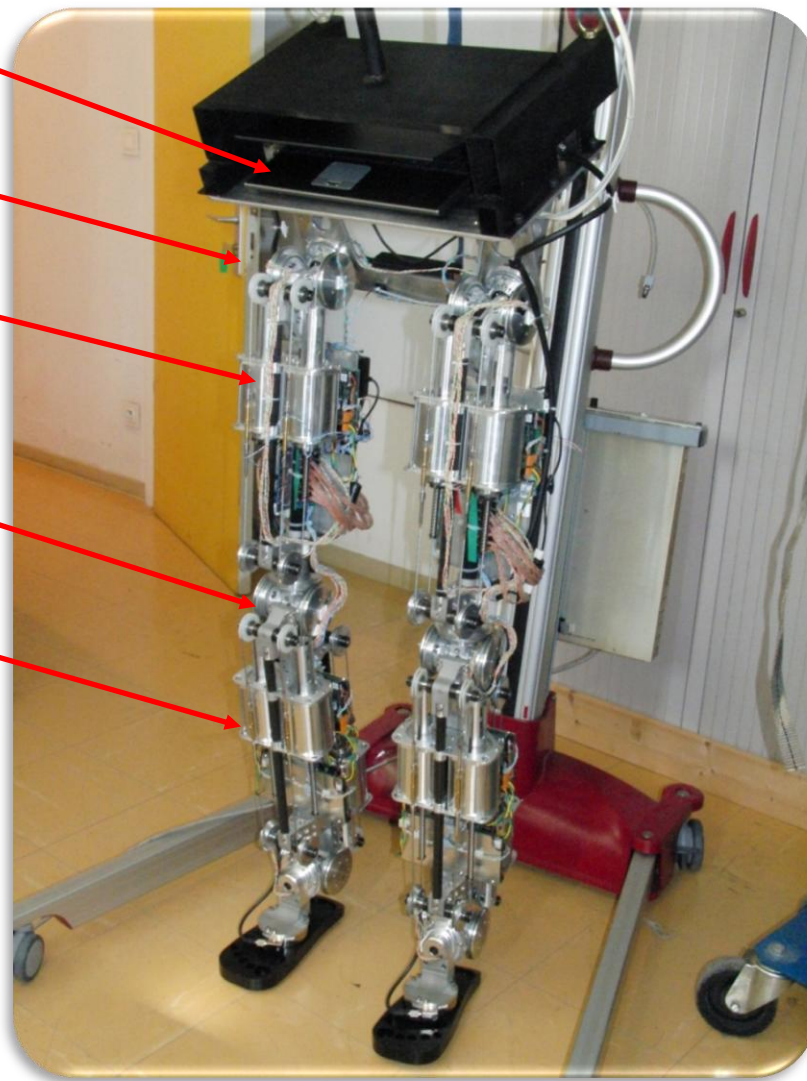
Control PC

Hip

femur

knee

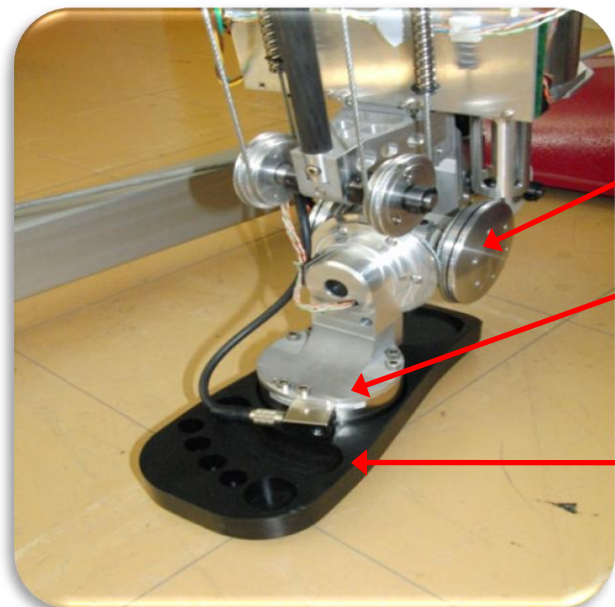
Tibia



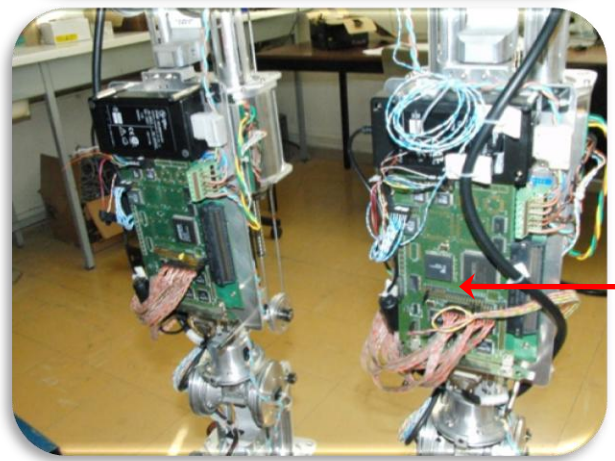
ankle

Force sensor 6-axis

foot



Interface cards



SHERPA robot : First movements

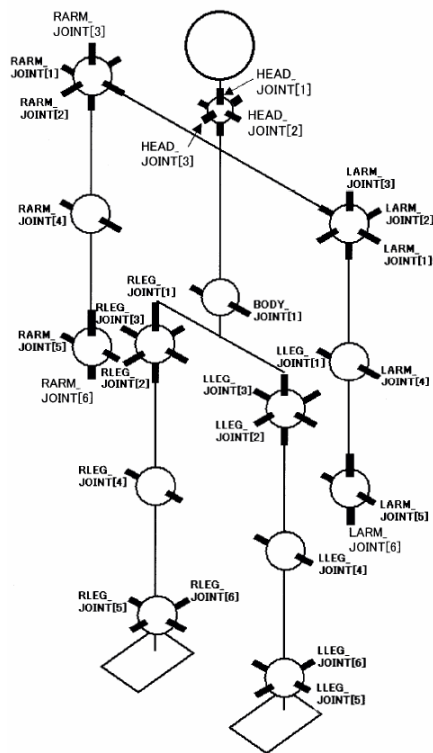


Articulations movements



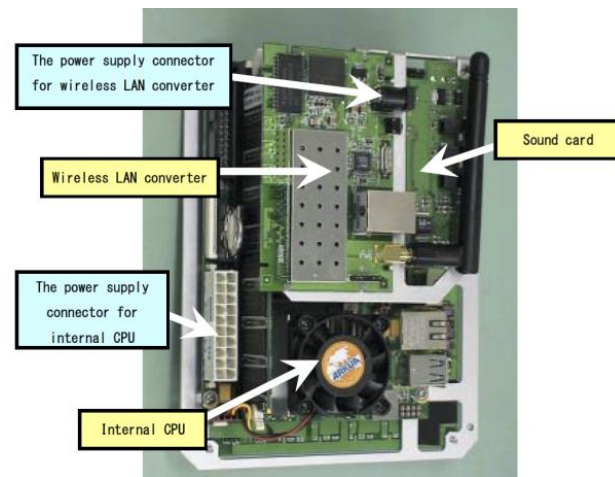
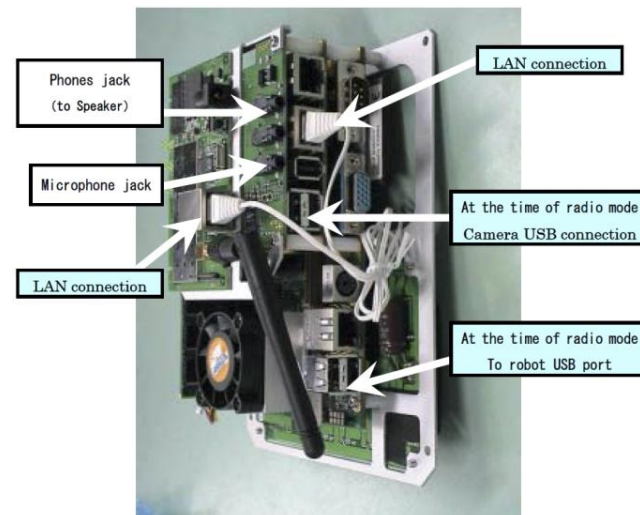
Walking suspended

HOAP3 : Architecture

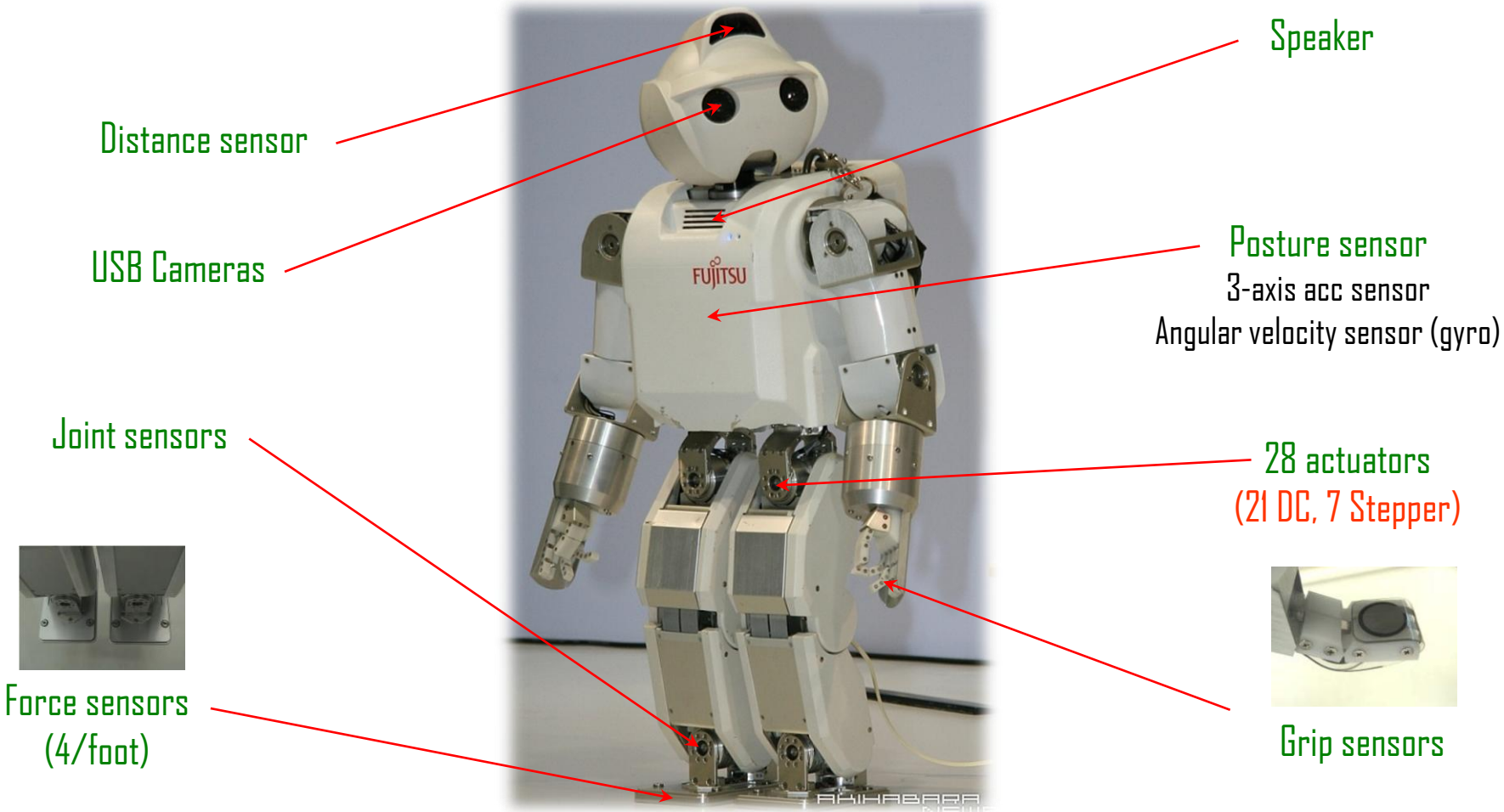


28 dof : 6 dof/leg - 6dof/arm - 3dof/head - 1dof/body

Electronic boards inside



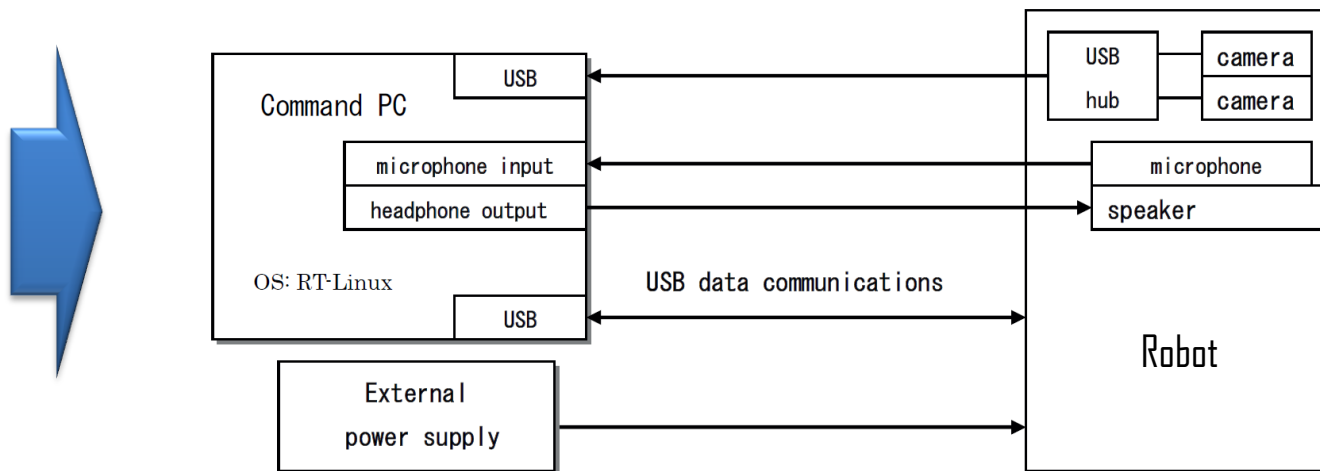
HOAP3 : Actuators and sensors



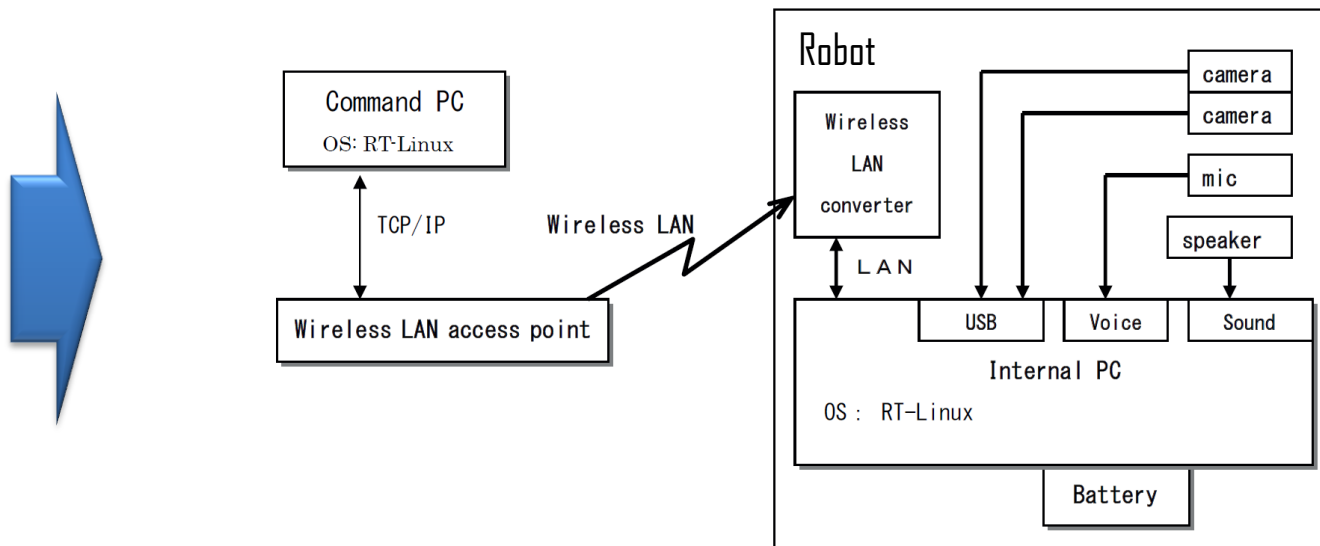
This demonstrator is useful for **whole body control**

HOAP3 : Operating modes

System configuration in cable mode



System configuration in radio mode



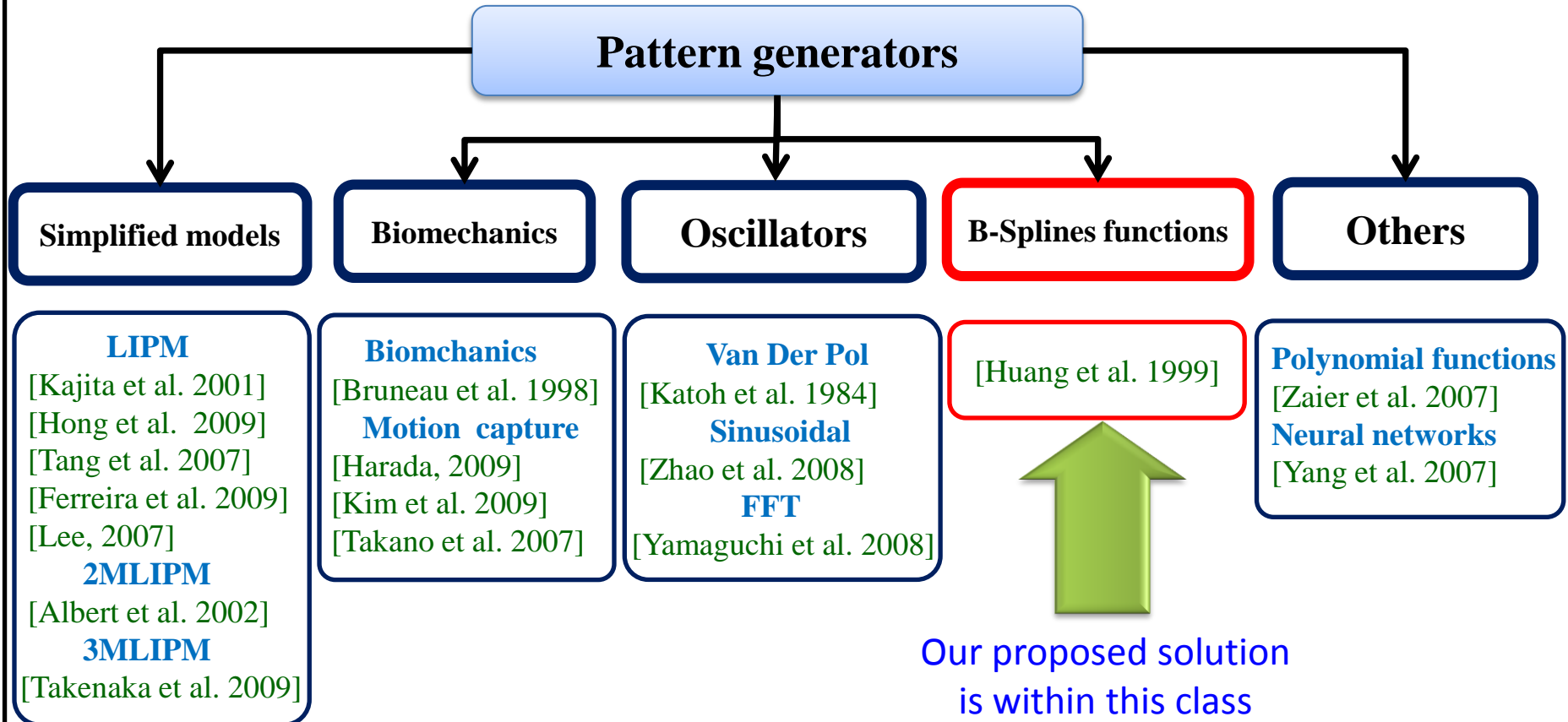
Part IV



Optimal pattern generation

- ✓ Related work
- ✓ Proposed solution

Related work



Summary of the proposed solution

Objective

Design and development of a pattern generator for stable dynamic walking

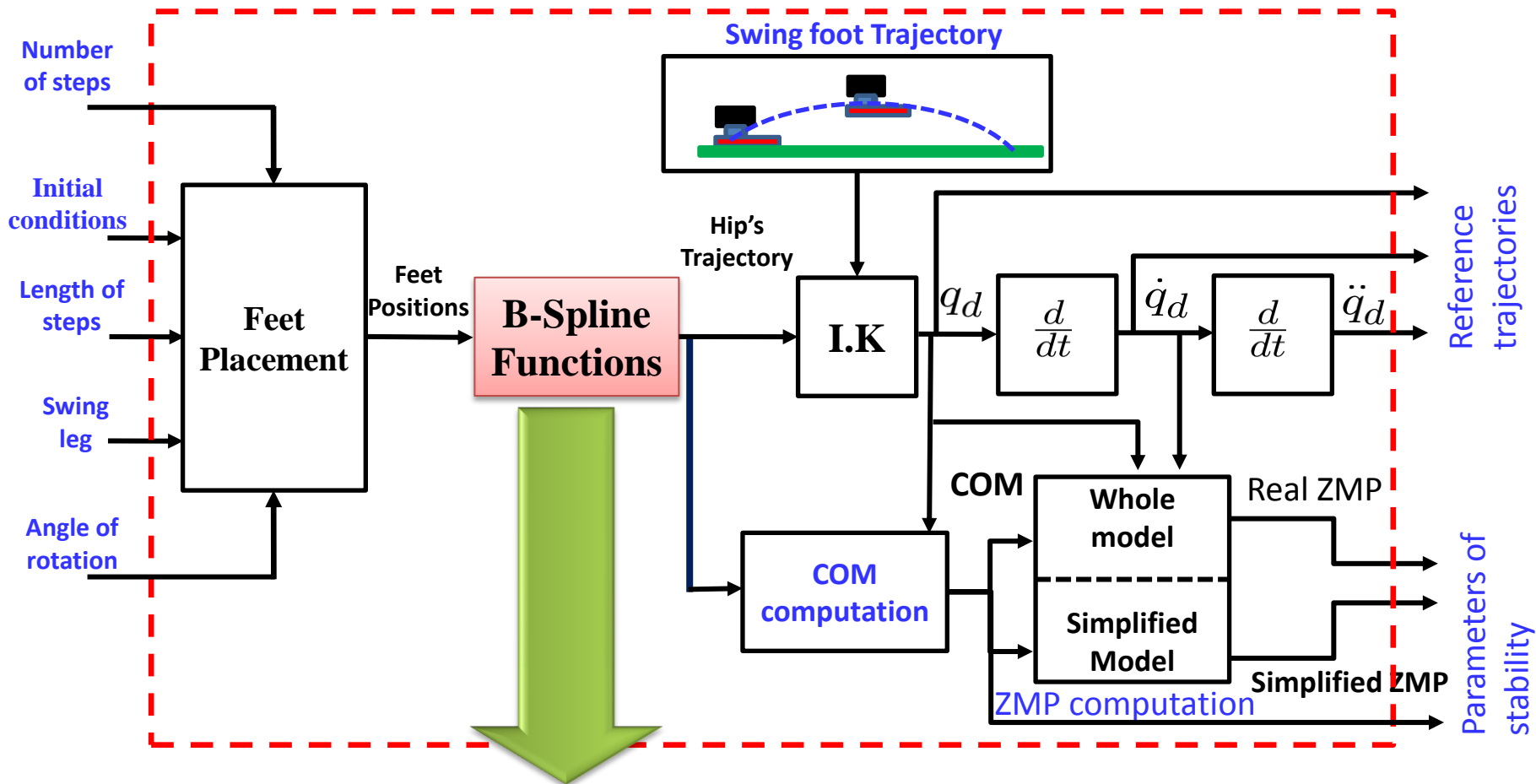
Assumptions

- **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

The screenshot shows the 'GENERATION DE TRAJECTOIRES HUMANOIDE' software interface. The window title is 'GENERATION DE TRAJECTOIRES HUMANOIDE (Stage M2 - LIRMM)'. The menu bar includes File, Edit, View, Insert, Tools, Desktop, Window, and Help. The interface is divided into several sections:

- Walking parameters:** Located on the left, it includes 'Nombre de pas (Np)' set to 1, 'Choix de direction', and 'Choix de Theta'.
- Début de marche:** Located in the top center, it has radio buttons for 'Distinct' (selected) and 'Joint'.
- Allure Arret:** Located in the top center, it has radio buttons for 'NON' (selected) and 'OUI'.
- Pied de Vol:** Located in the top center, it has radio buttons for 'Droit' (selected) and 'Gauche'.
- Choix de B-Spline:** Located in the top center, it has radio buttons for 'Méthode 1', 'Méthode 2' (selected), 'Sans optimisation', and 'Avec optimisation'.
- Trajectoire:** Located on the right, it includes buttons for 'Optimisation', 'Génération', and 'Effacer'.
- Visualisation de l'animation:** Located on the right, it includes buttons for 'Animation' and 'Video'.
- User help:** Located on the right, it includes buttons for 'Aide' and 'Fermer'.
- Curves visualization:** Located on the left, it lists 'Position', 'vitesse', 'Accélération', 'COM', 'ZMP', and 'Trajectoir Pied'.

The central plot shows a 2D trajectory with a yellow shaded area representing the foot's path. The plot axes range from -0.3 to 0.5 on the x-axis and -0.5 to 0.5 on the y-axis. A small 3D animation window is visible in the bottom right corner.

Walking parameters

User help

Trajectories computation

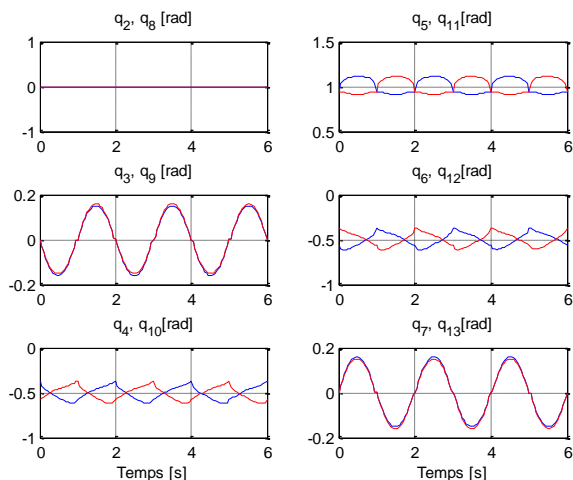
Curves visualization

Animation make movie

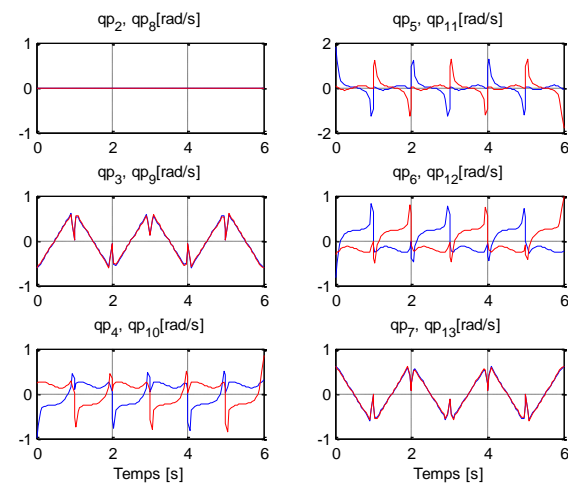
Visualization footprints & CoM

Scenario 1 : Straight walking without optimization

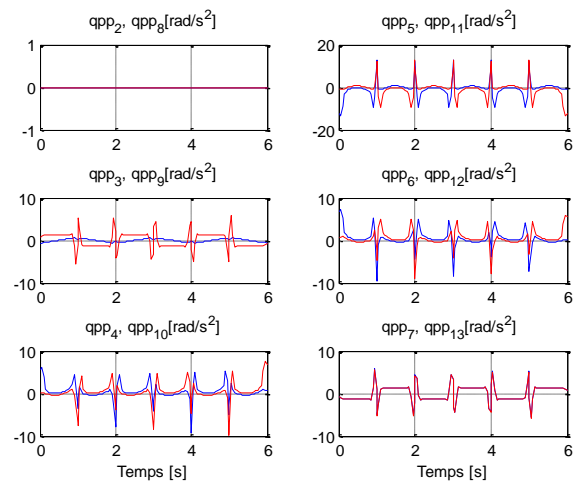
Articular positions



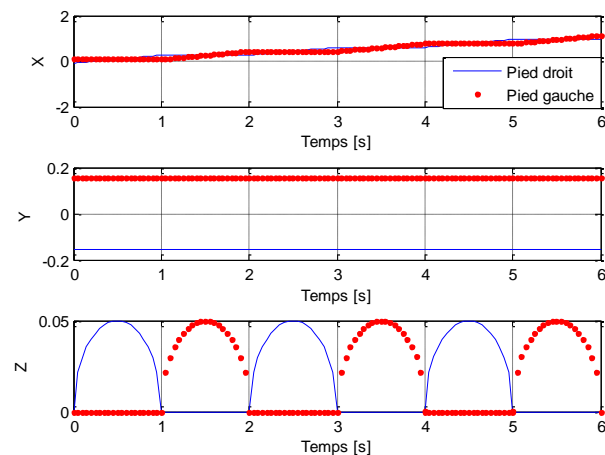
Articular velocities



Articular accelerations



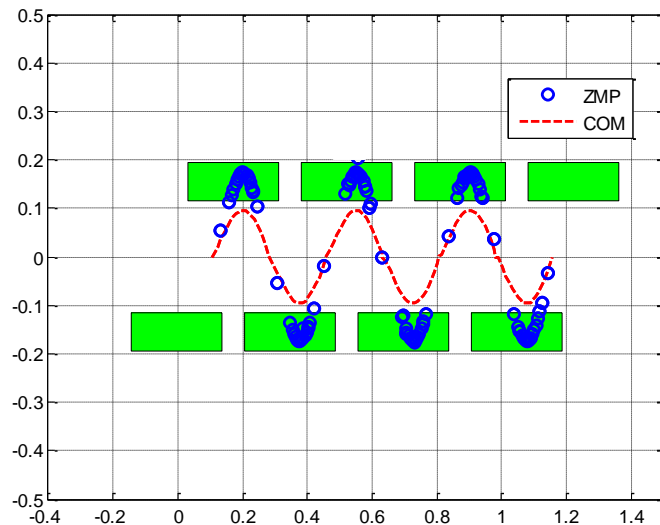
Feet trajectories



Obtained cyclic trajectories

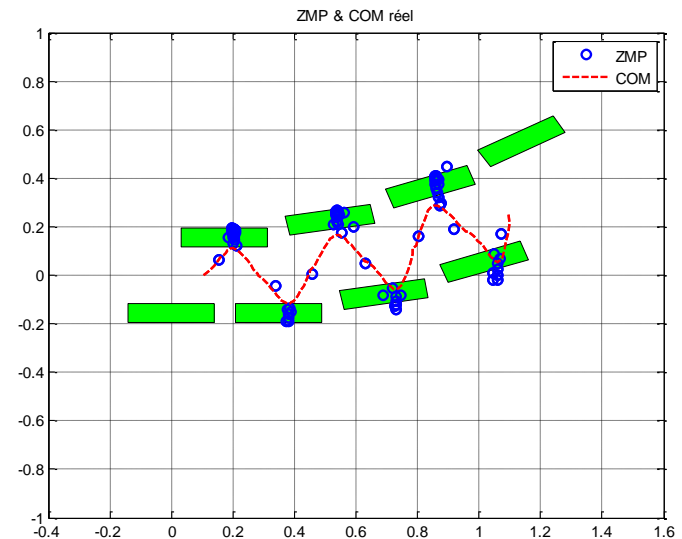
Scenario 1 : Stability evaluation without optimization

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



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

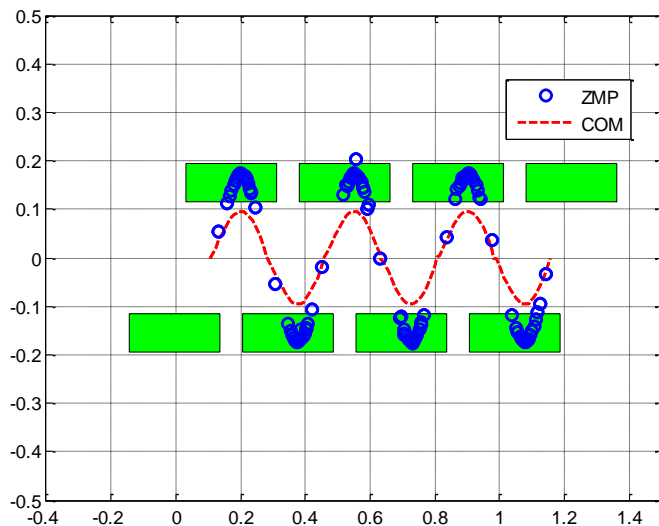
zmp_x, zmp_y : Coordinates of ZMP position

zmp_{xd}, zmp_{yd} : Desired ZMP position

Q_x, Q_y : Weighting coefficients

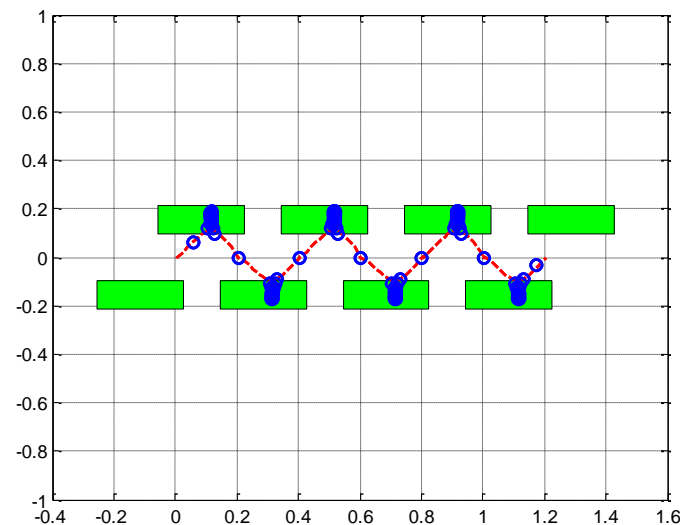
Scenario 2 : Straight walking with optimization

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

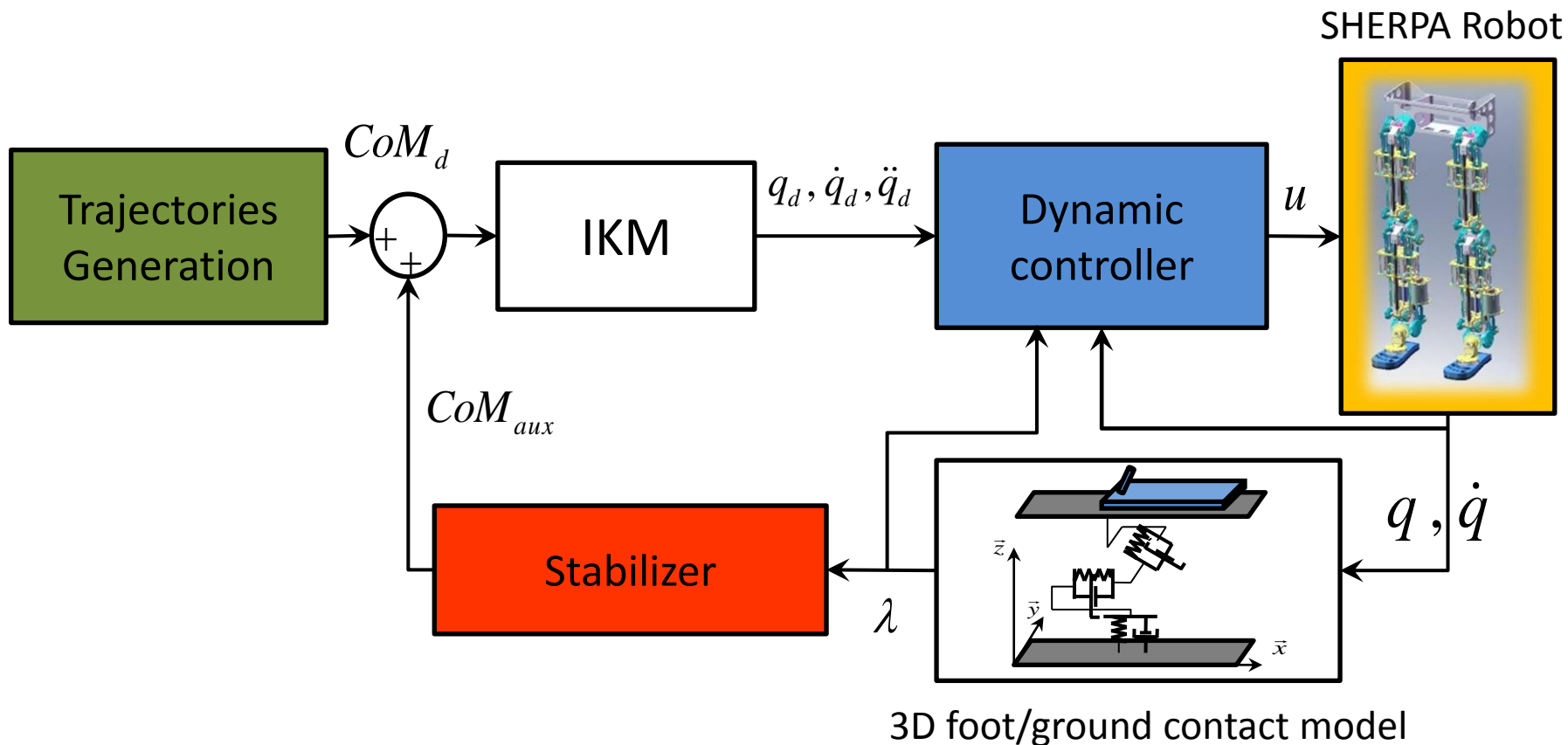
Assumptions

- **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

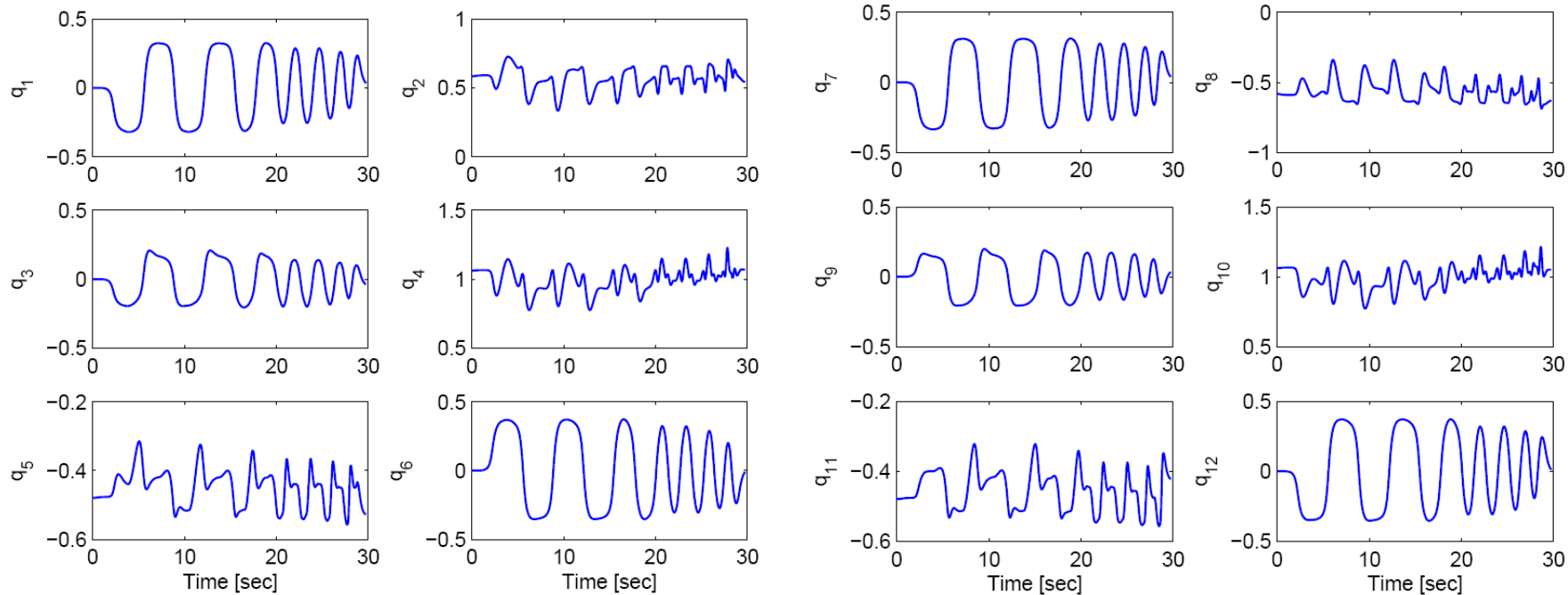


Simulation results

- ✓ 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	$35e^4 \text{ N.m}^{-1}$
μ	damping coefficient	$6e^6 \text{ N.sec.m}^2$

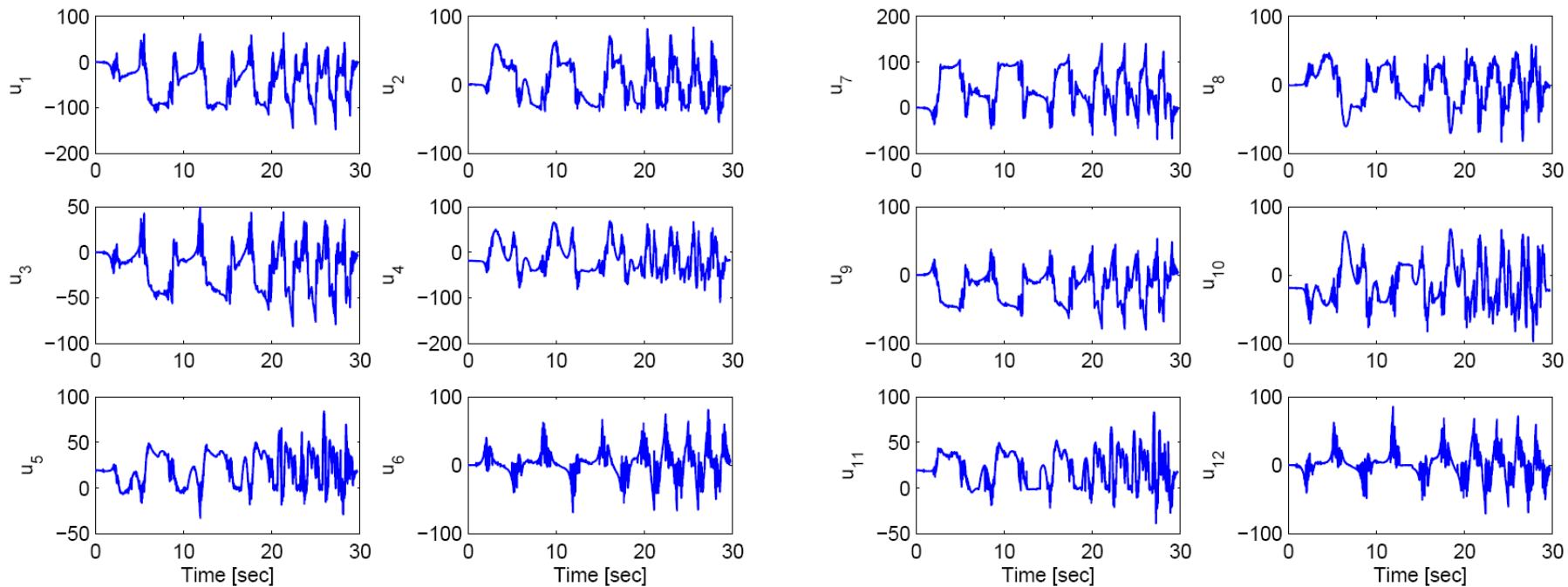
Simulation results



Joint positions of first leg

Joint positions of second leg

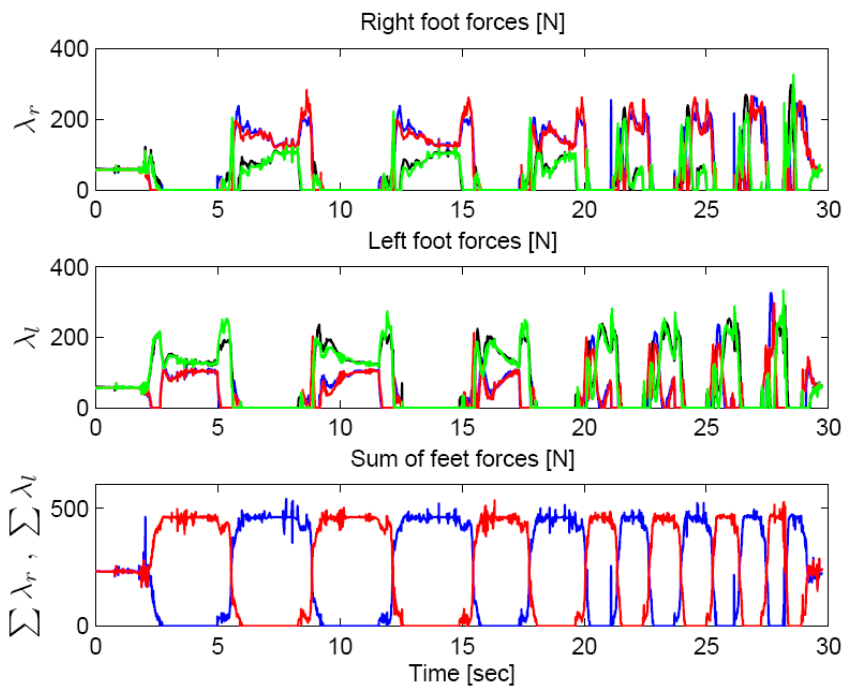
Simulation results



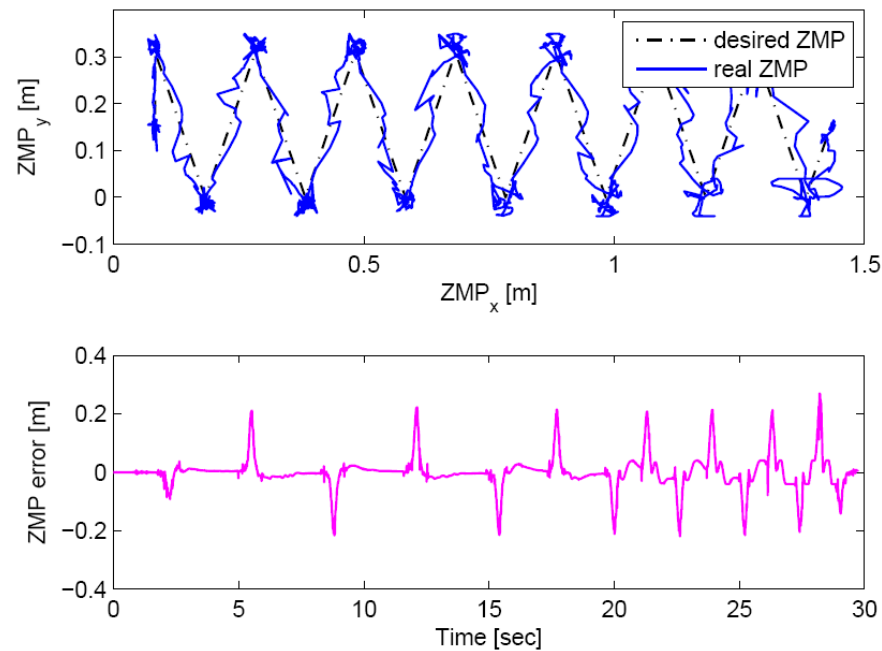
Torques of first leg

Torques of second leg

Simulation results



Contact forces



ZMP tracking

Part VI

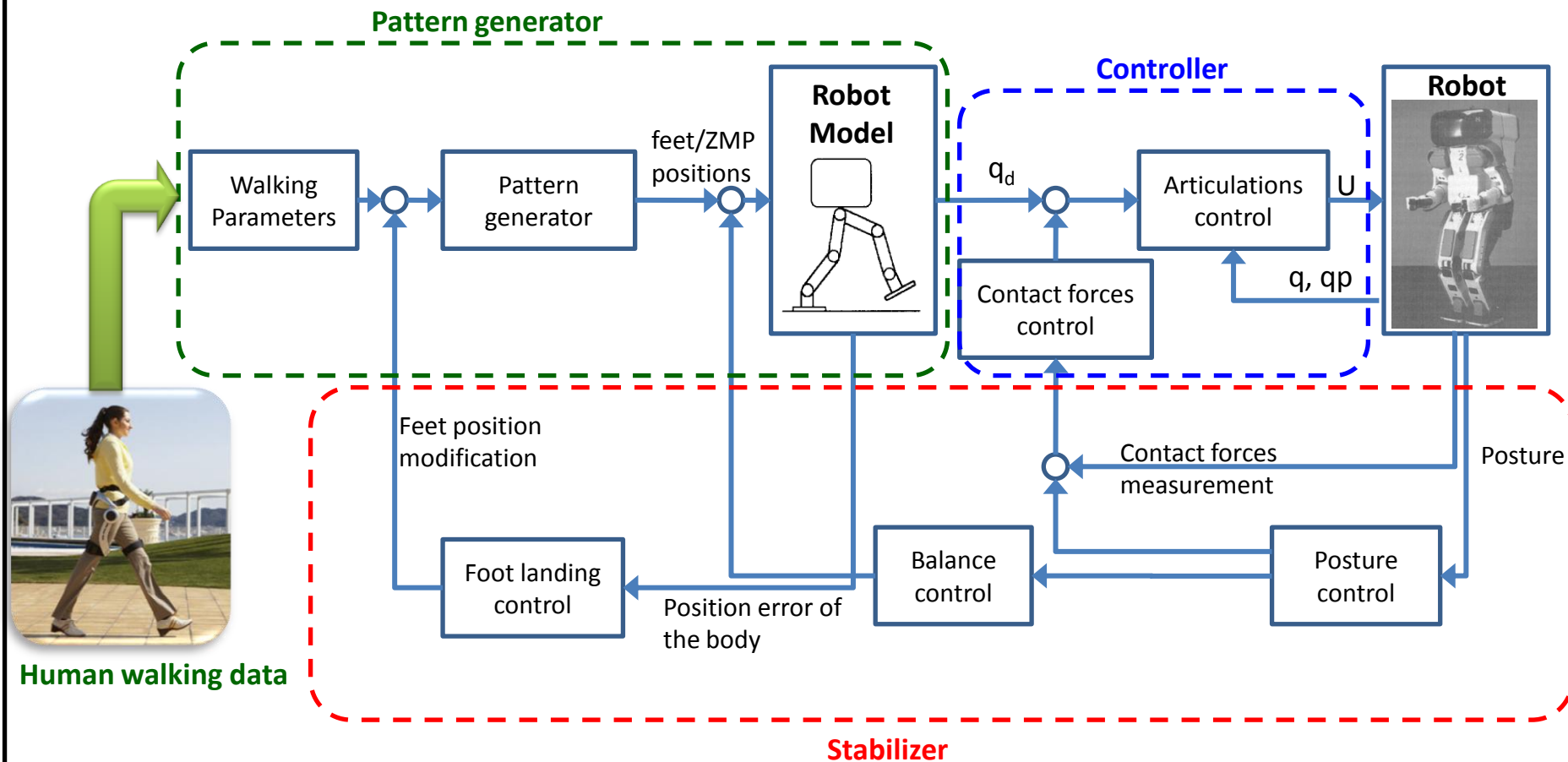
Towards human-like walking

(for whole body control)

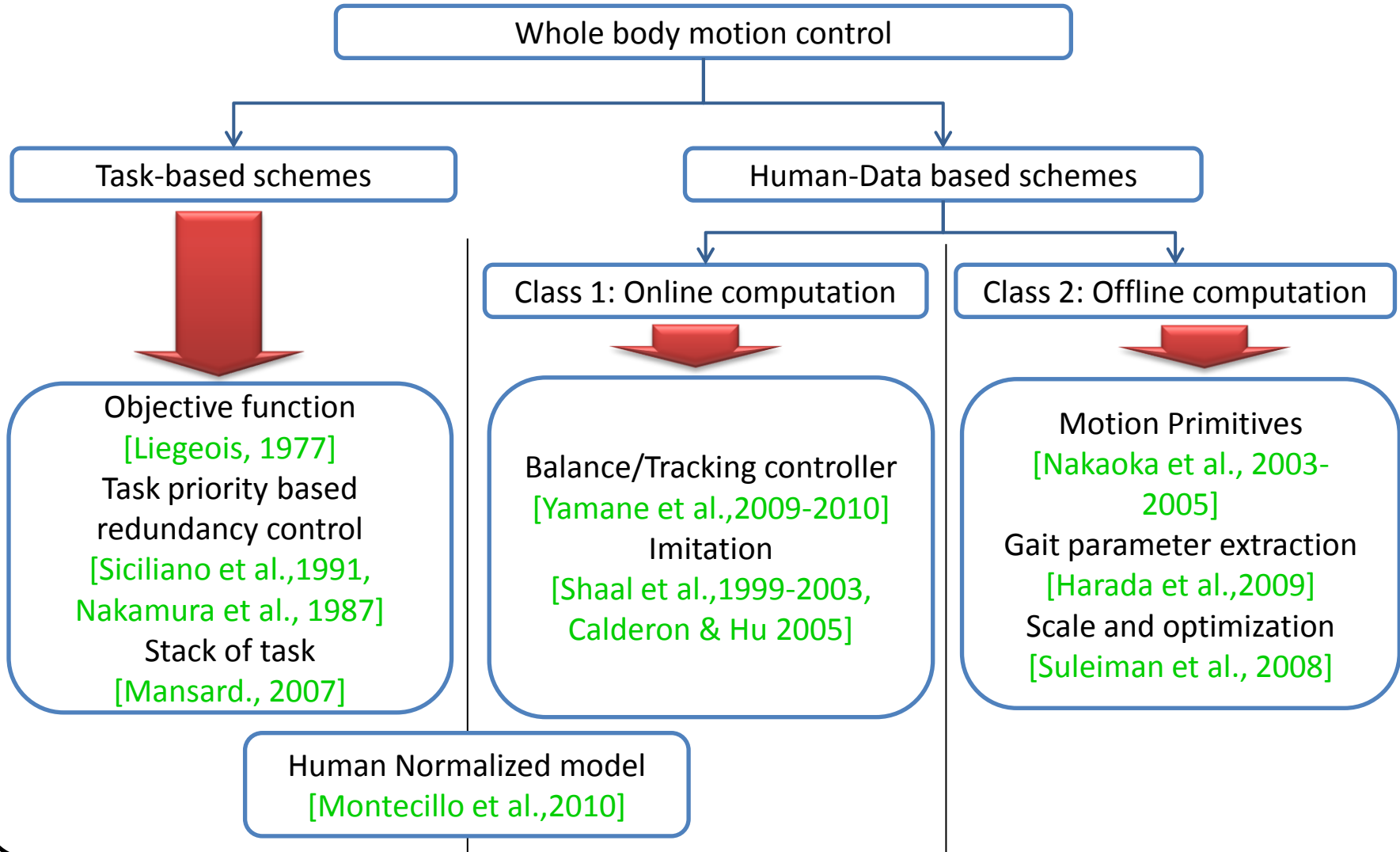


- ✓ One basic idea
- ✓ Related work
- ✓ Why human-like walking?
- ✓ Main steps of our study

One basic idea



Related work



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 \Rightarrow 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

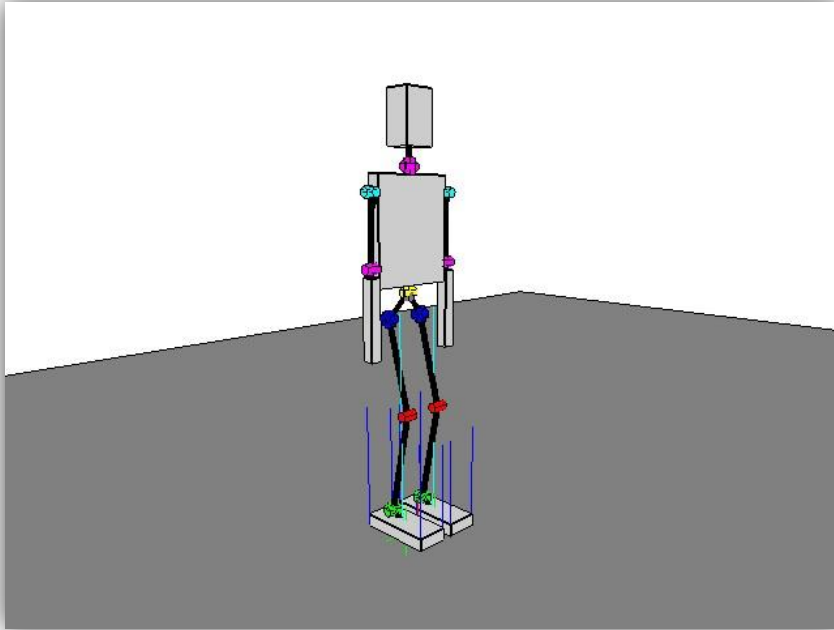
Developed simulator for whole-body control

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

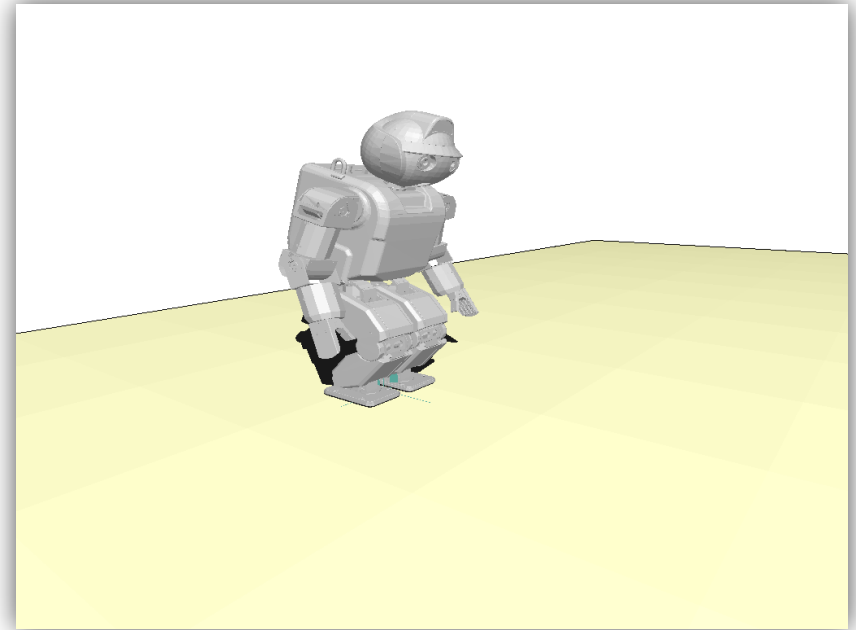
Summary of the simulator main characteristics

- 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



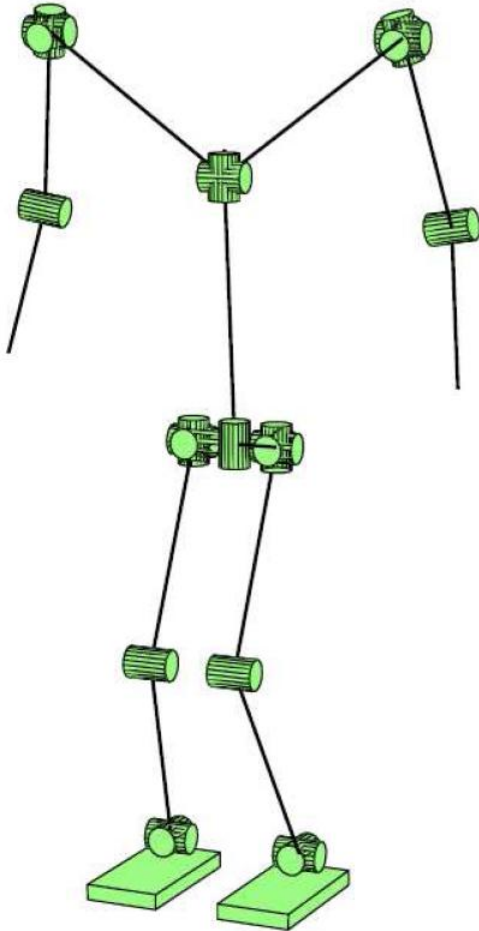
20 dof whole body model



Hoap 3 robot model (28 dof)

And others ...

Whole body proposed model

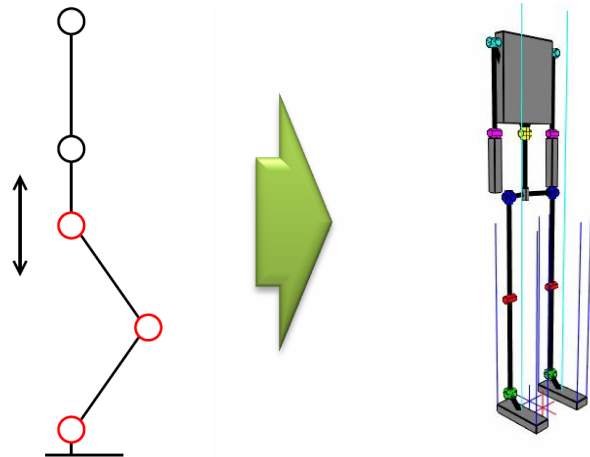


Modeling and simulation

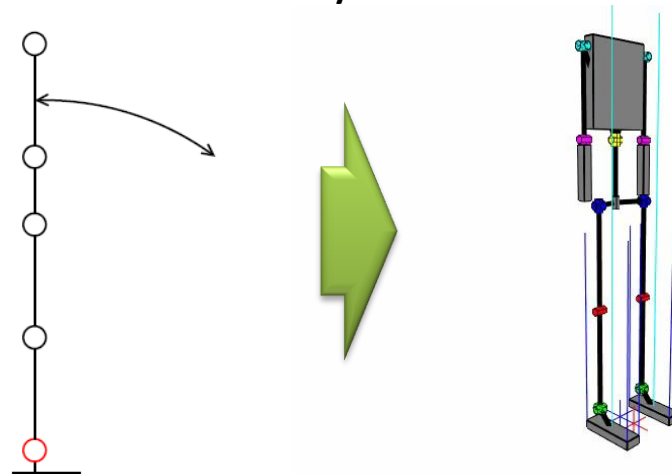
- 3D model.
- 20 DoF (6/Leg, 2/torso, 3/arm).
- Forward kinematics.
- Inverse kinematics.
- Dynamic model.
- Contact model.
- Link in tree representation allows easy modification.
- Modular approach allows to switch between different models.

Preliminary tests on the simulator

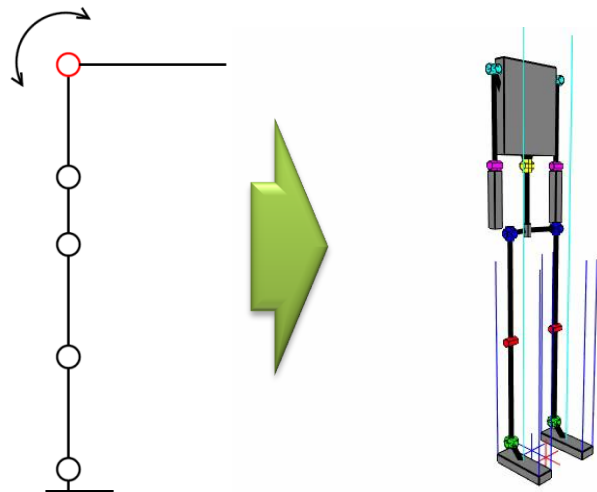
Scenario 1: Squat task



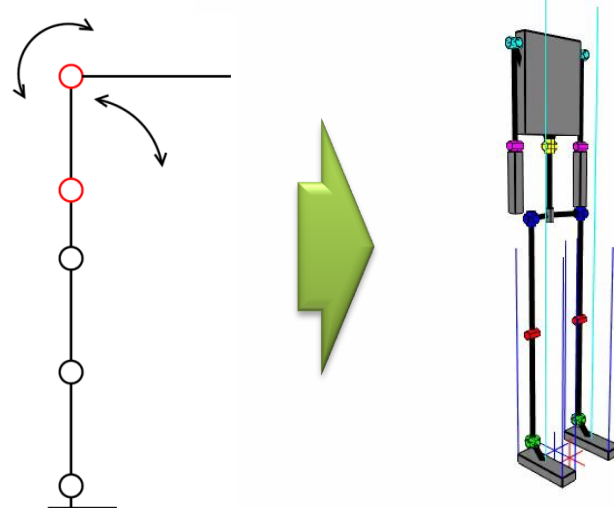
Scenario 2: Whole body balance



Scenario 3: Arms balance



Scenario 3: Torso & arms balance

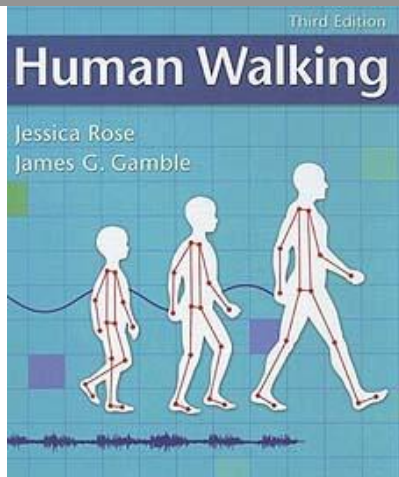
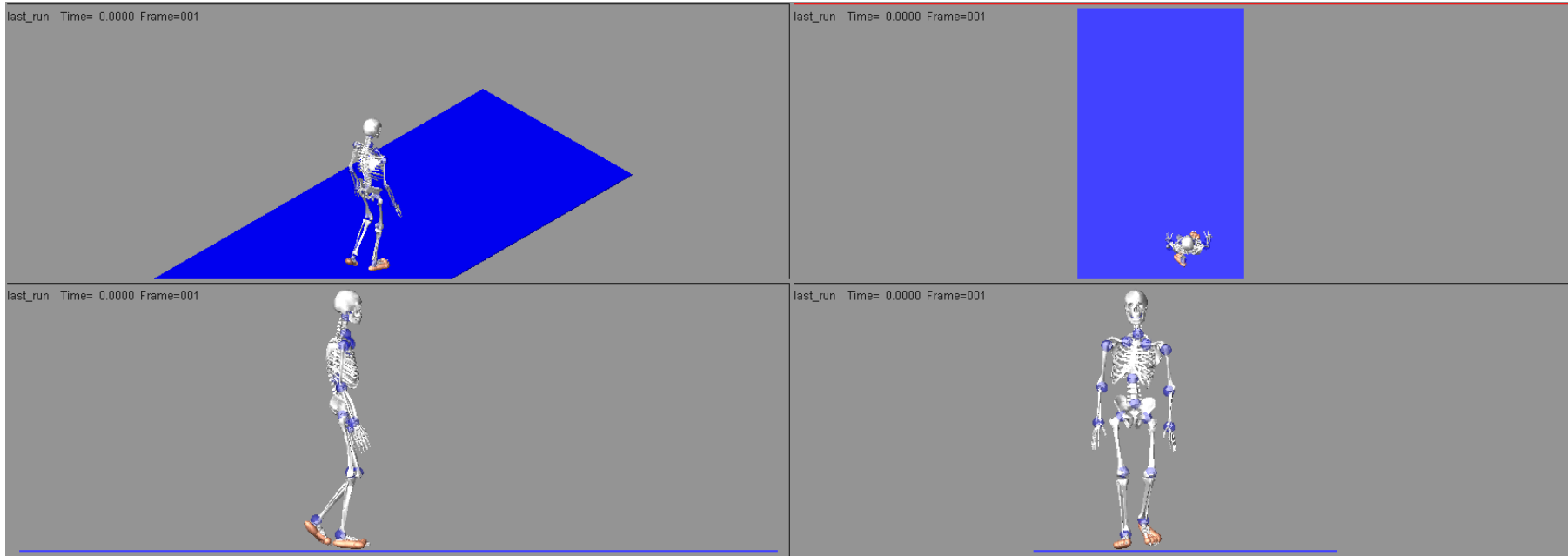


Step 2

Human walking study

- ✓ Human walking
- ✓ Motion capture system

Human walking

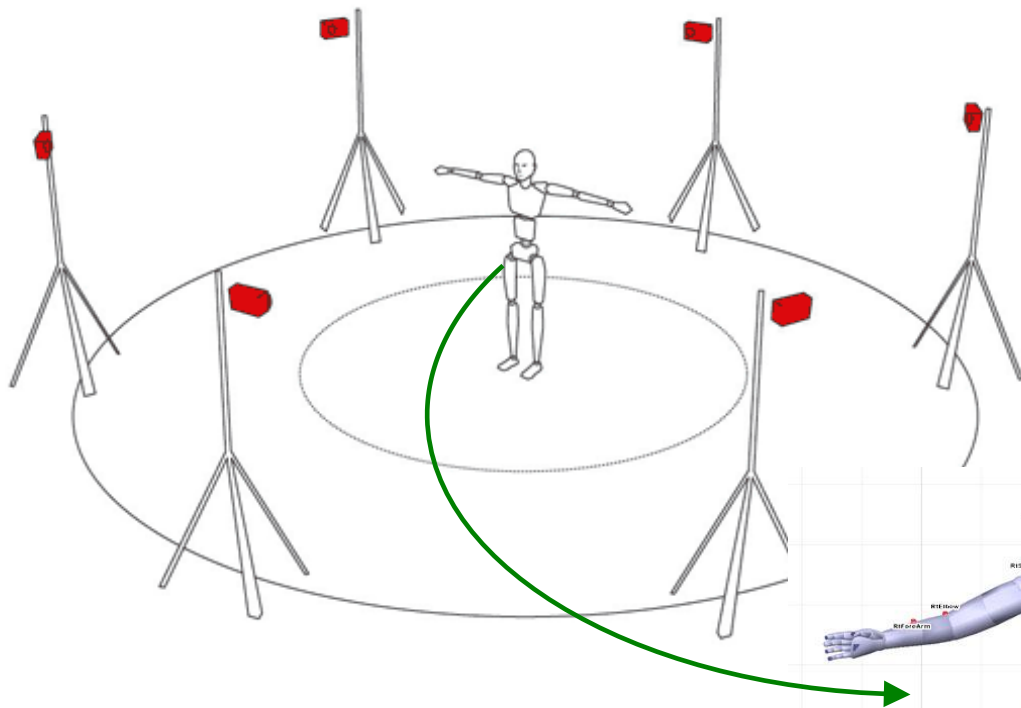


Including :

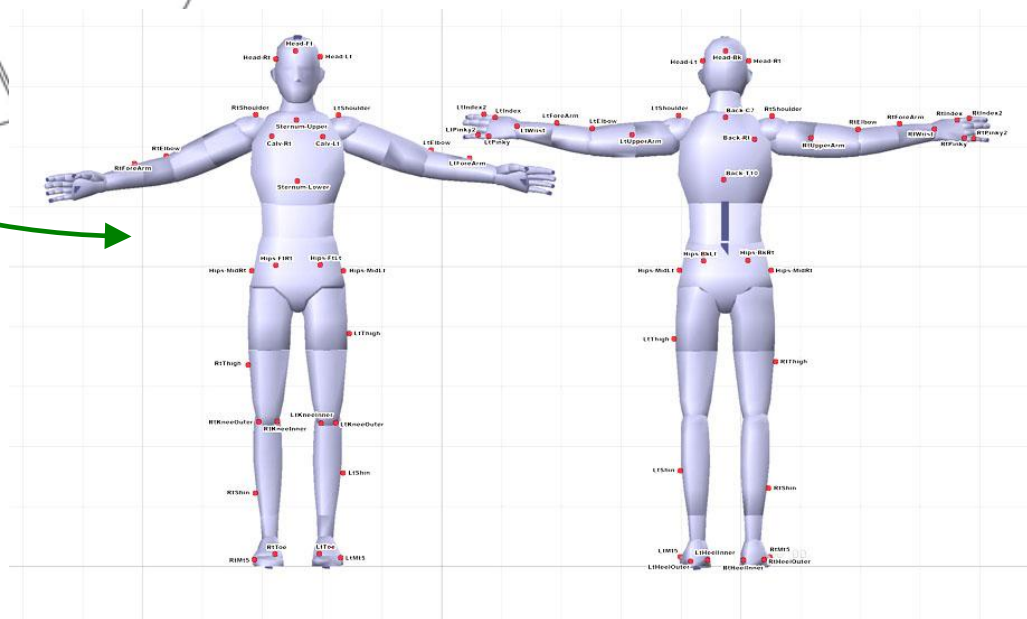
- ✓ Human Locomotion
- ✓ Kinematics & kinetics of human walking
- ✓ Energy & muscle activity during walking
- ✓ Simulation of Walking
- ✓ ... etc

How we can acquire data on human walking ?

Motion capture system



Plug-in-Gait Marker Placement



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

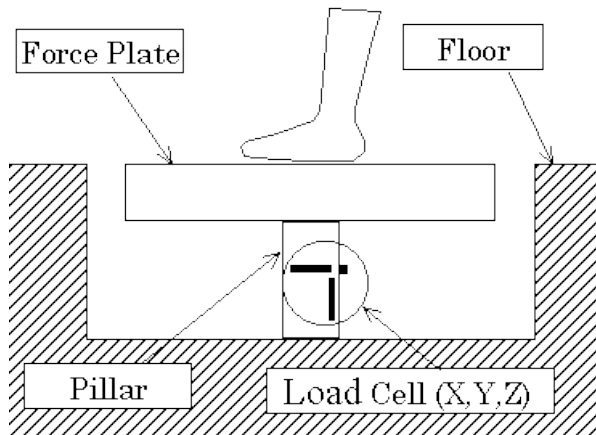
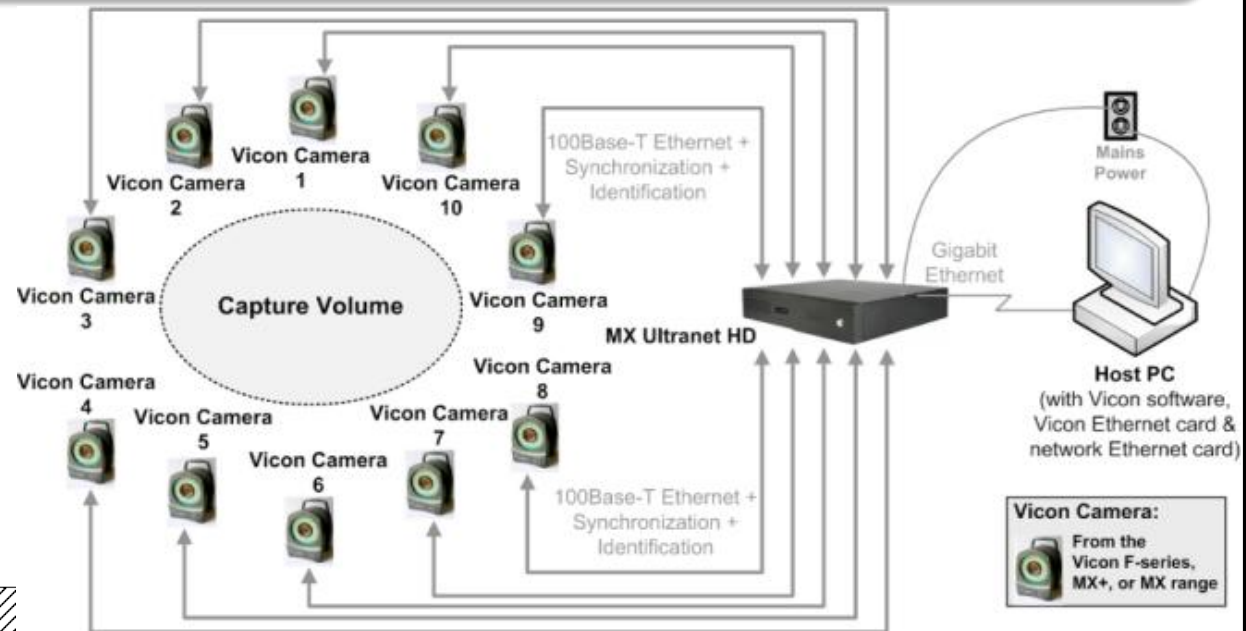


Fig.1 Structure of Force Plate

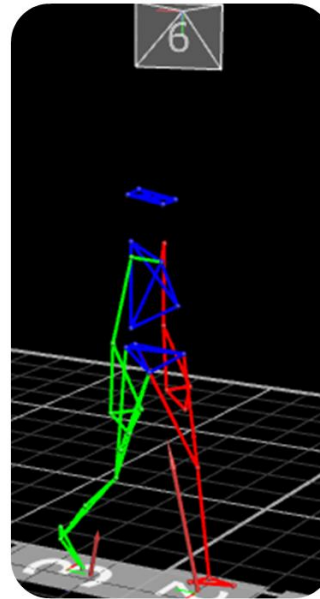


Motion capture system

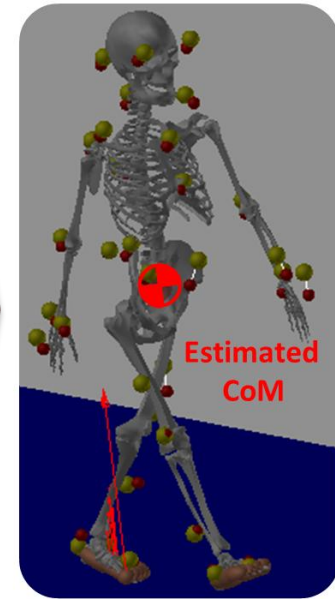
Is the process of recording movement, and translate that movement to a digital model



← Reflective marker (a)



(b)



(c)

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)

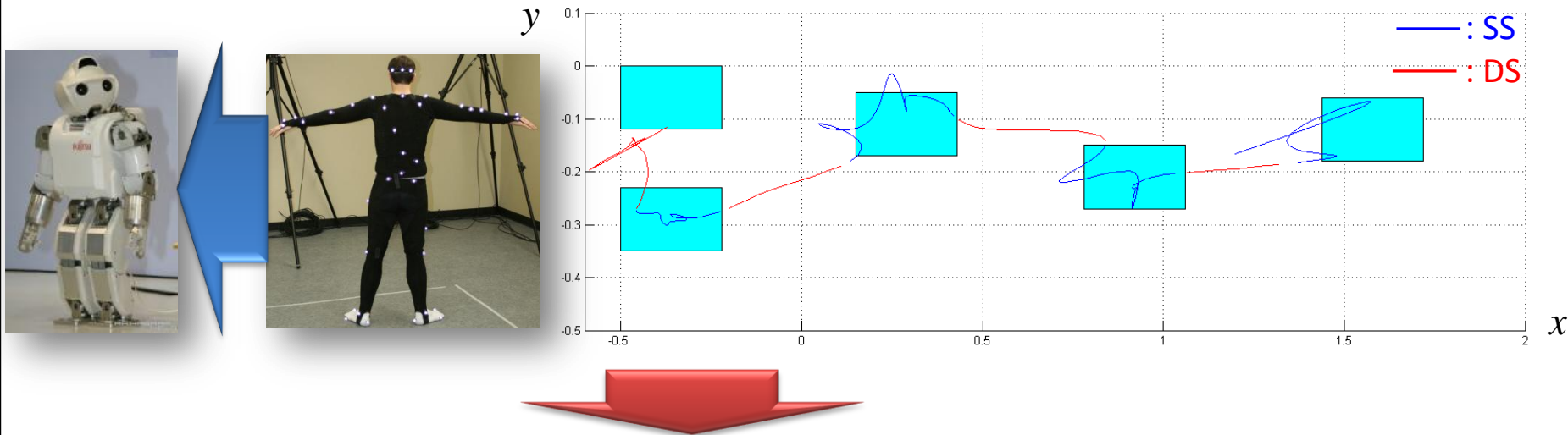
Step 3

Pattern generator design

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

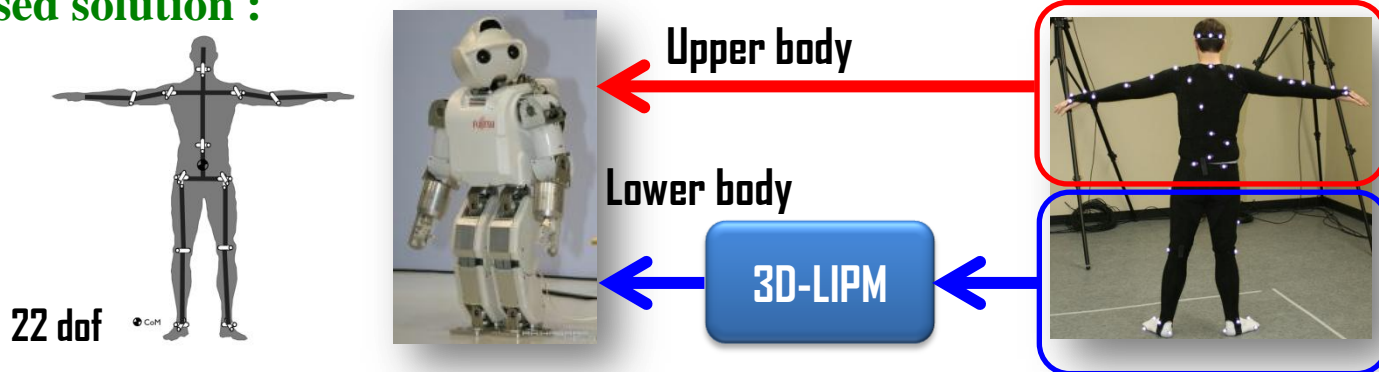
Basic idea of the proposed solution

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

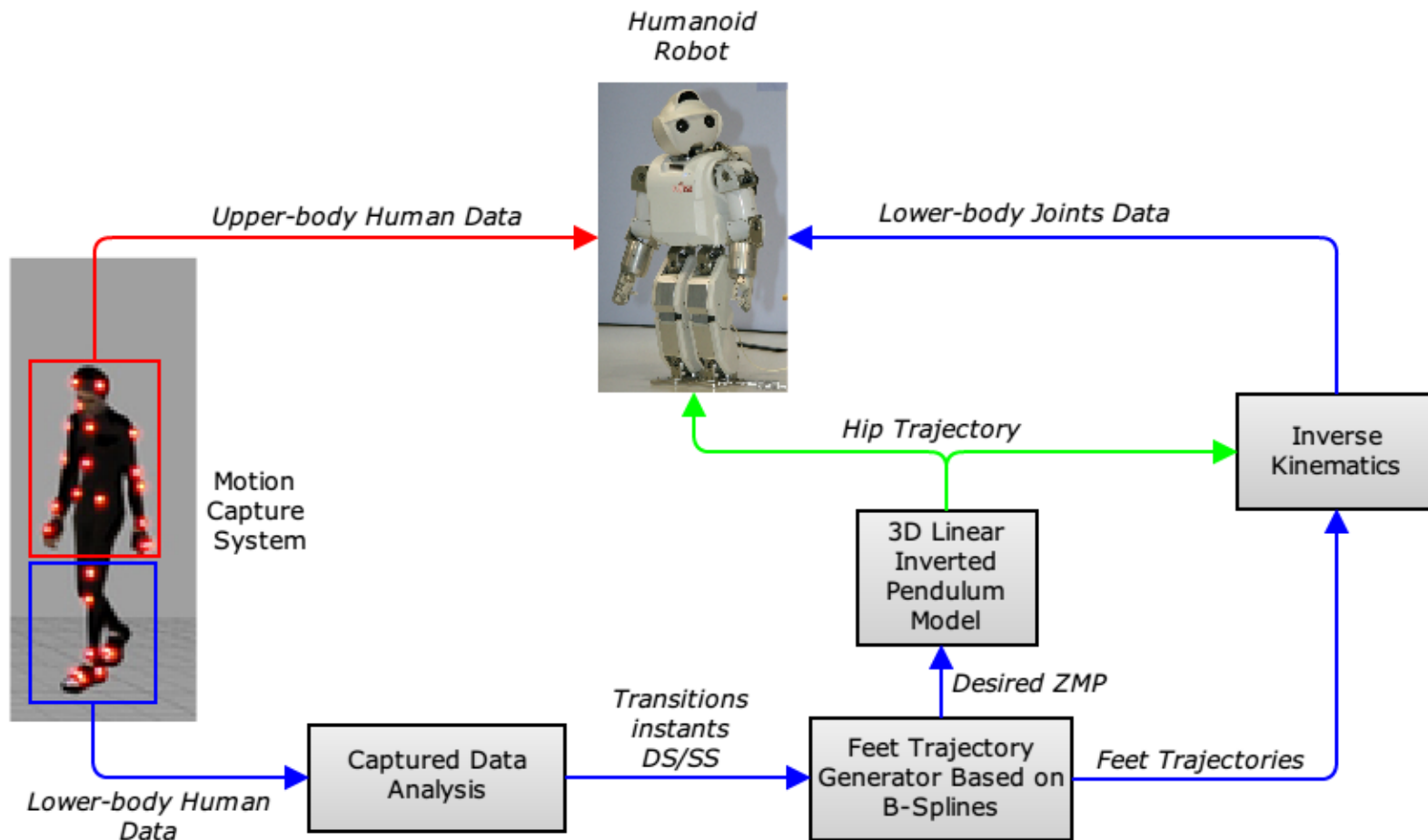


- ZMP is outside the polygon of support \rightarrow **unstable** walking !

- Proposed solution :**

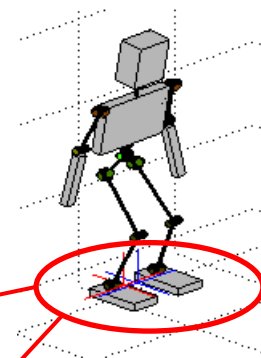
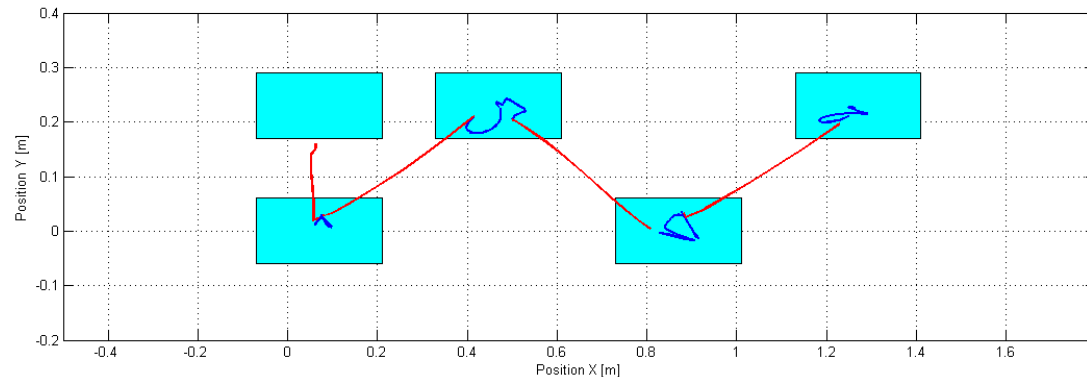
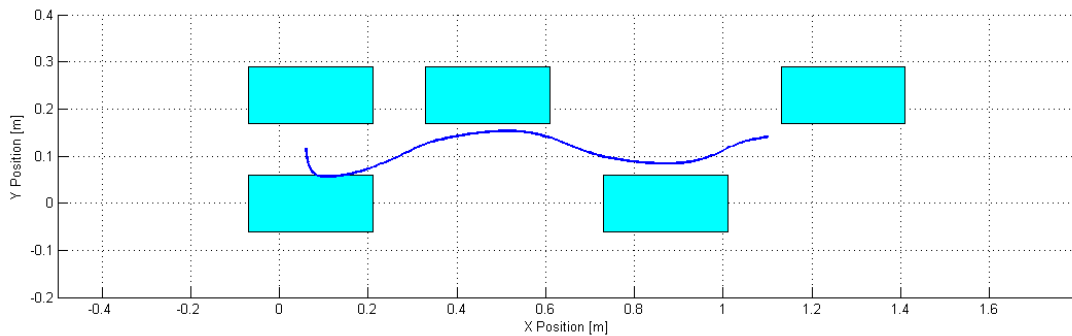


Proposed human data based pattern generator



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**



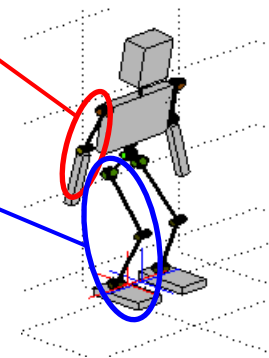
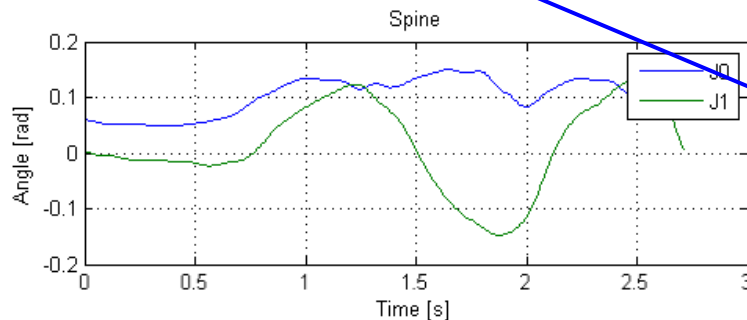
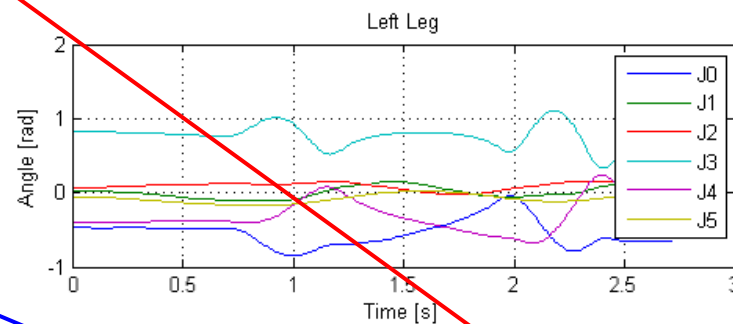
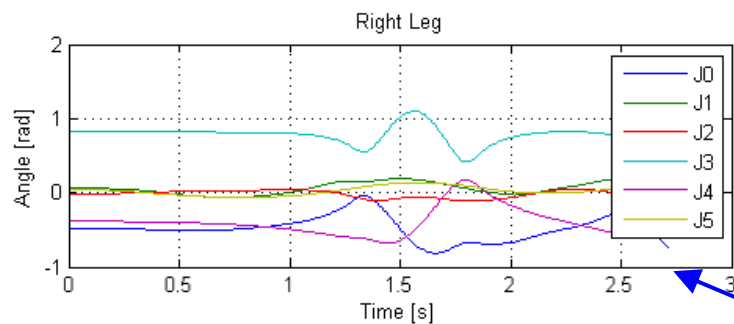
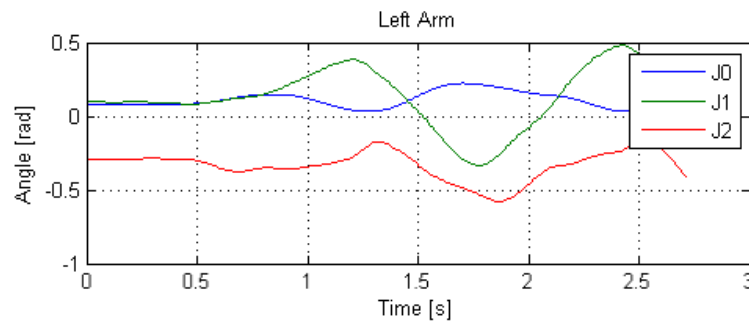
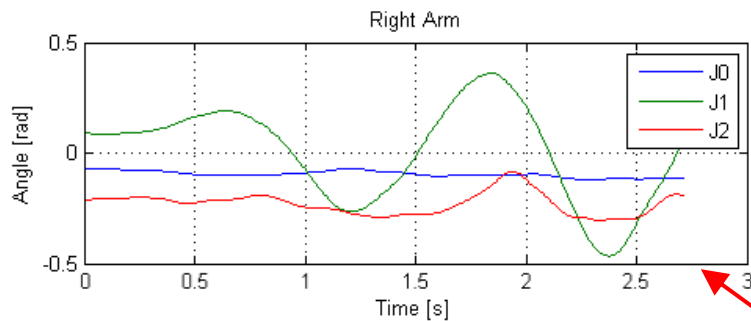
Dynamic walking

Stable walking



Stable Dynamic walking

Simulation results

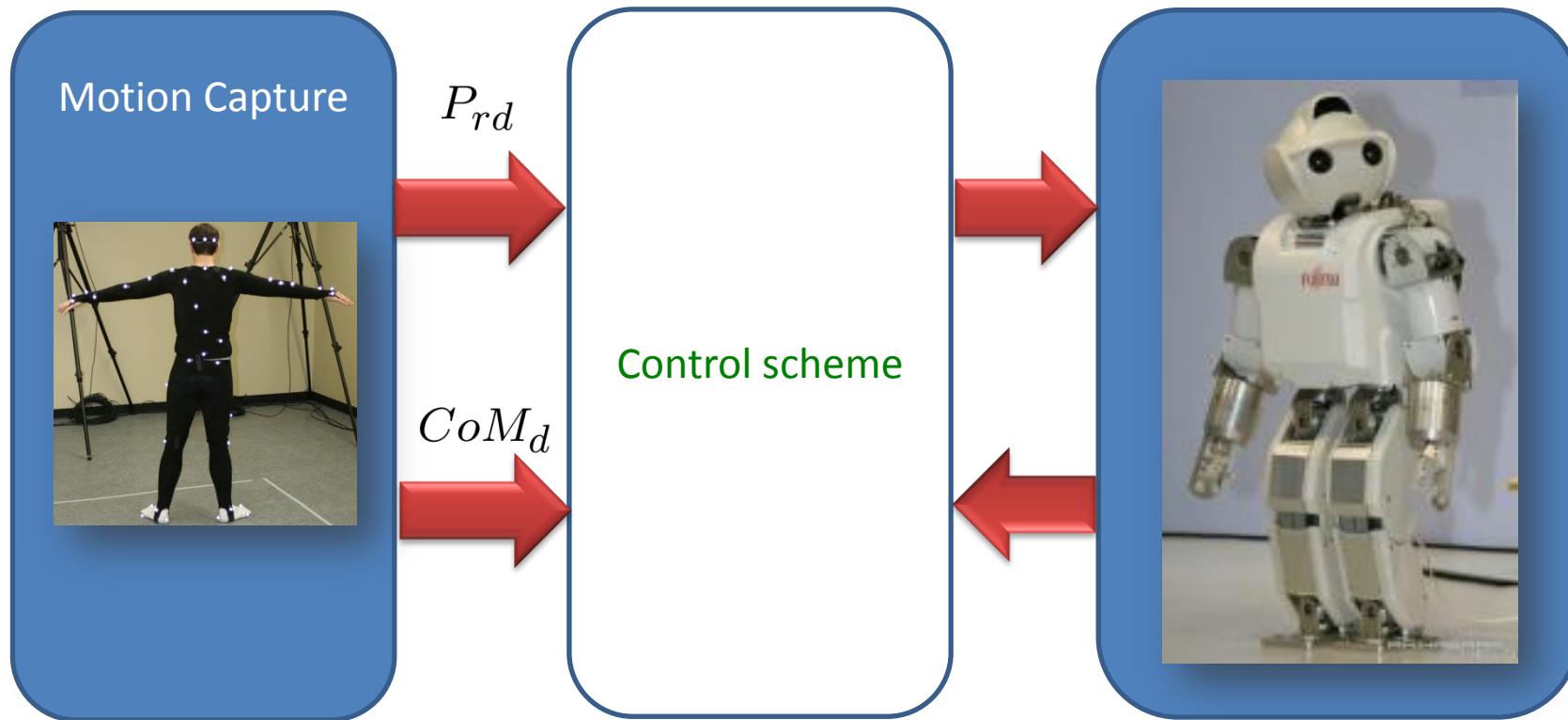


Step 4

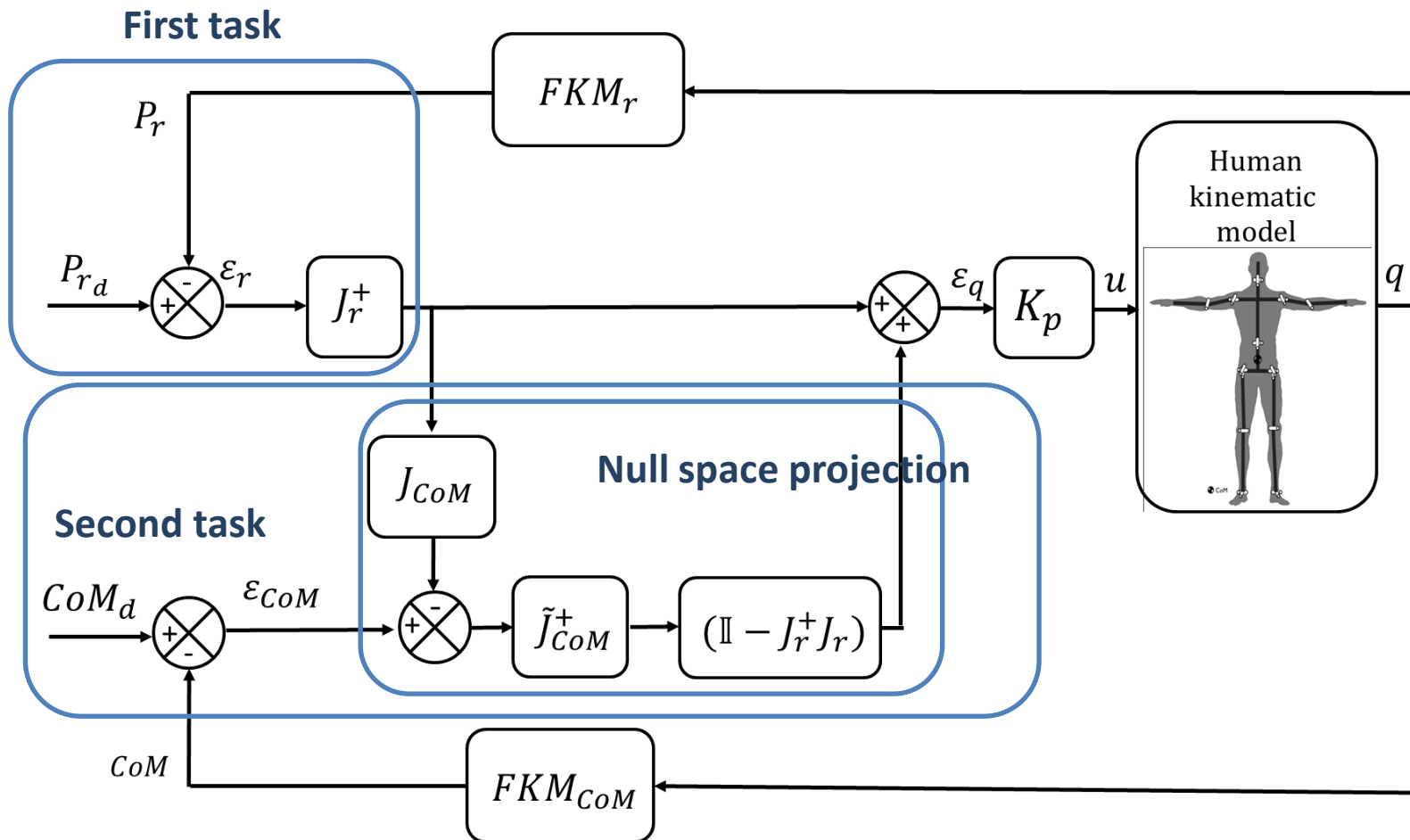
Control architecture design

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

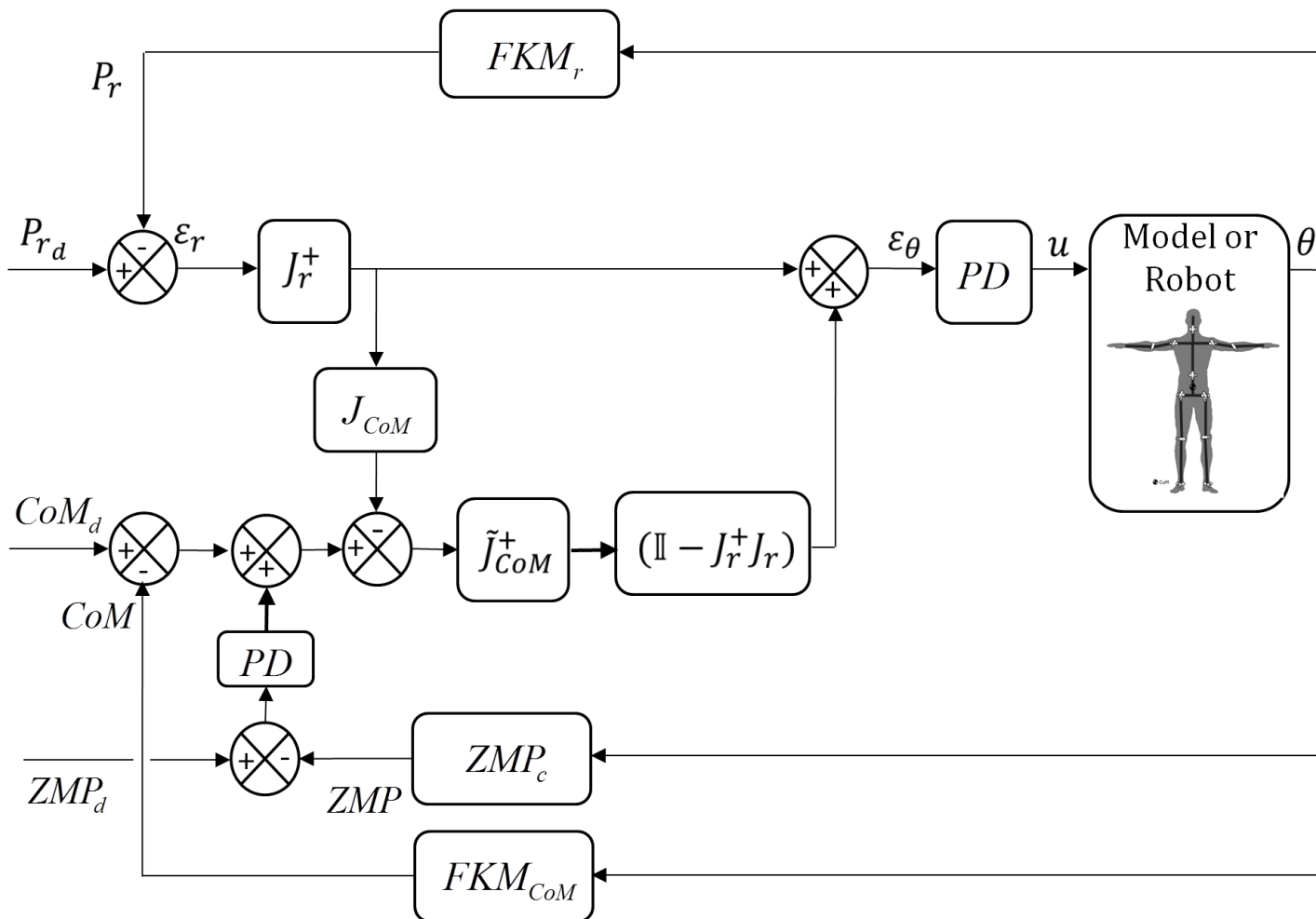
Basic idea of the proposed control scheme



Block-diagram of the proposed control architecture



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



Step 5

Implementation on a humanoid robot

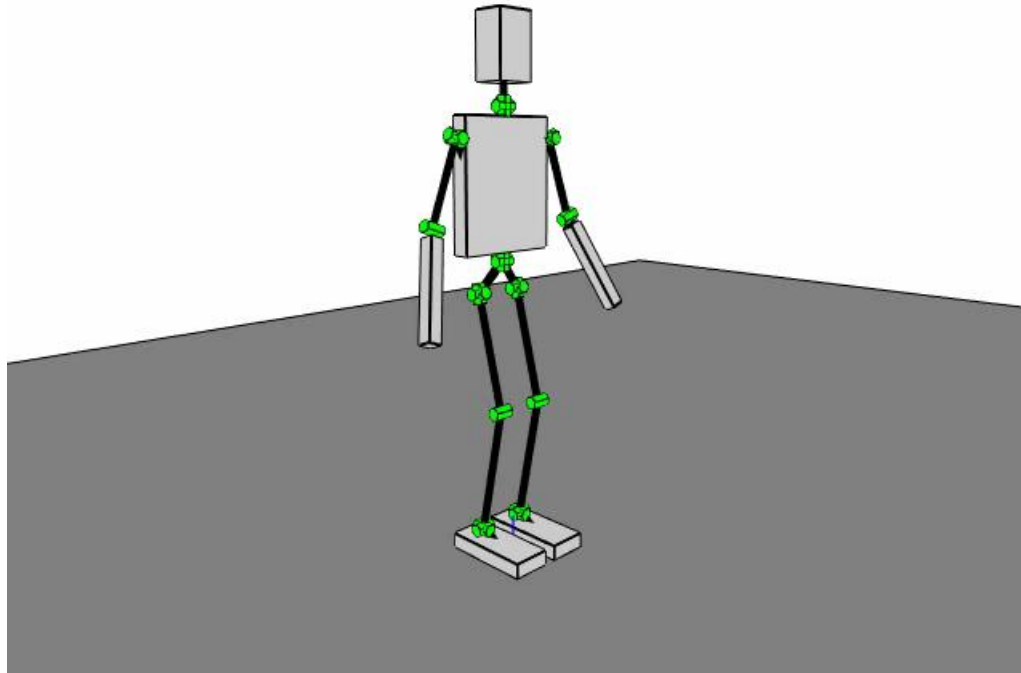
Simulation scenarios

- ✓ 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

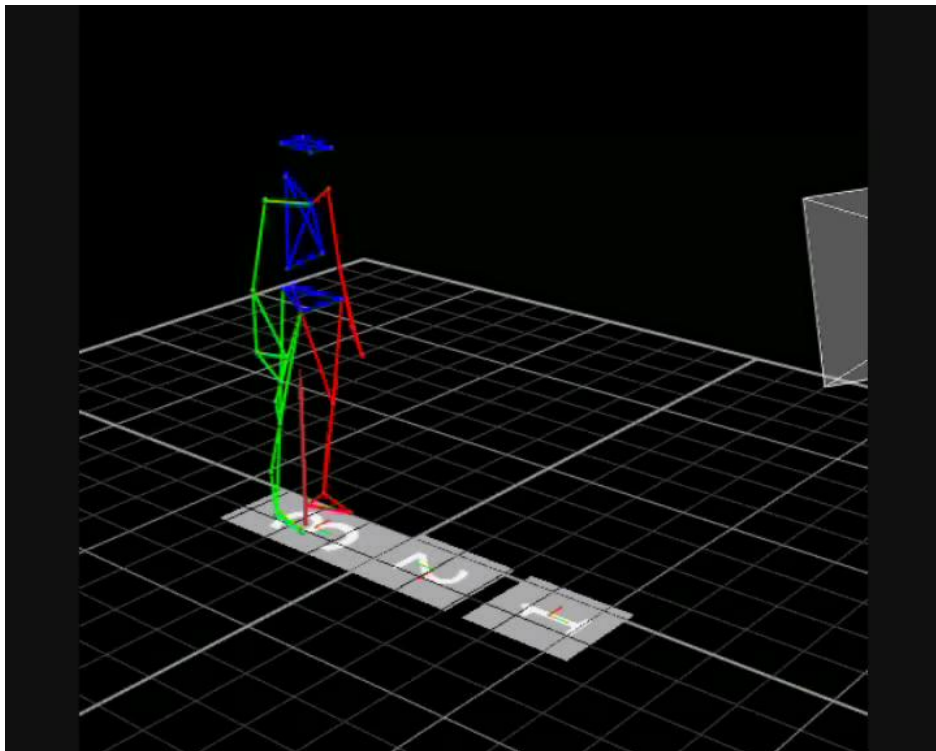
- ✓ Scenario 1 : ZMP control
- ✓ Scenario 2 : Squat motion

Simulation scenario 1 : First validation of the scheme

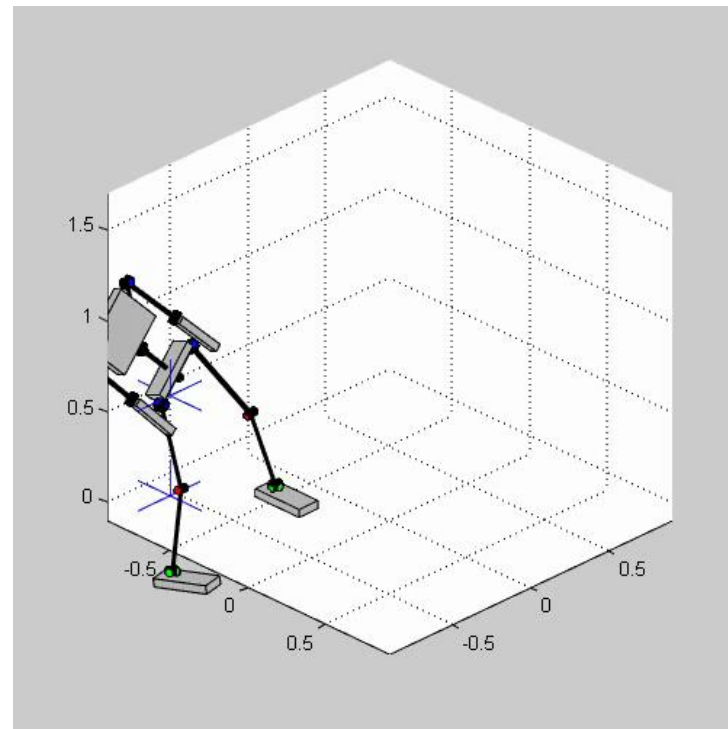


Simulation scenario 2 : Human data without adaptation

Reconstructed human movement



Application of the proposed scheme

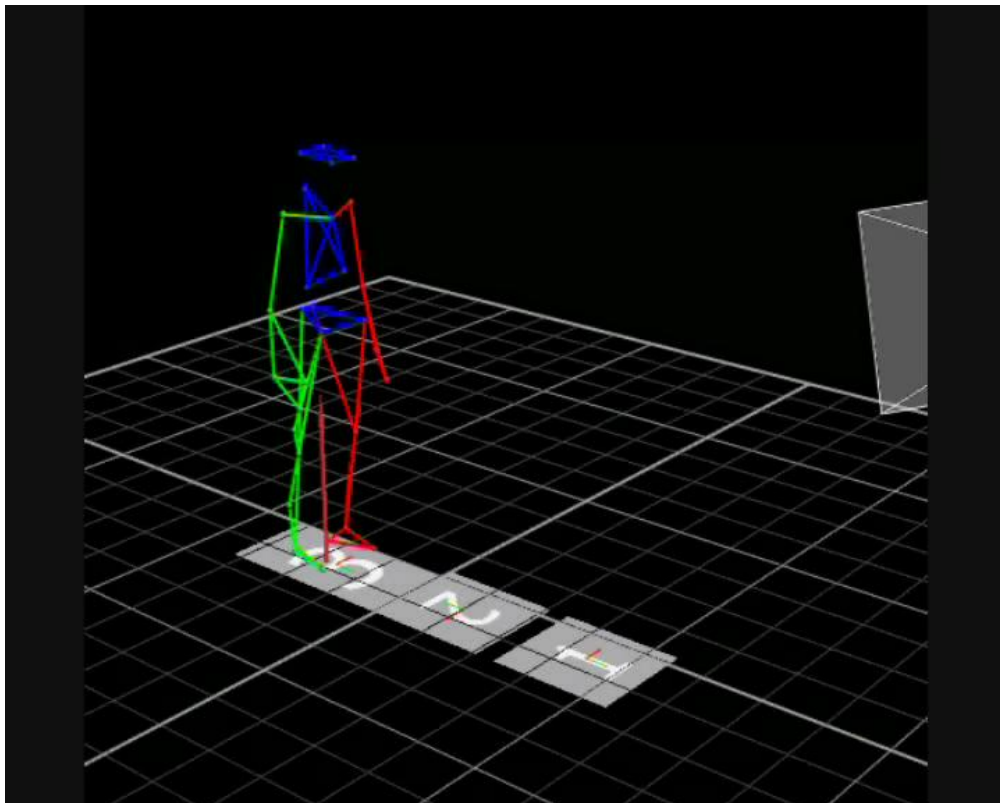


Simulation of the proposed control scheme

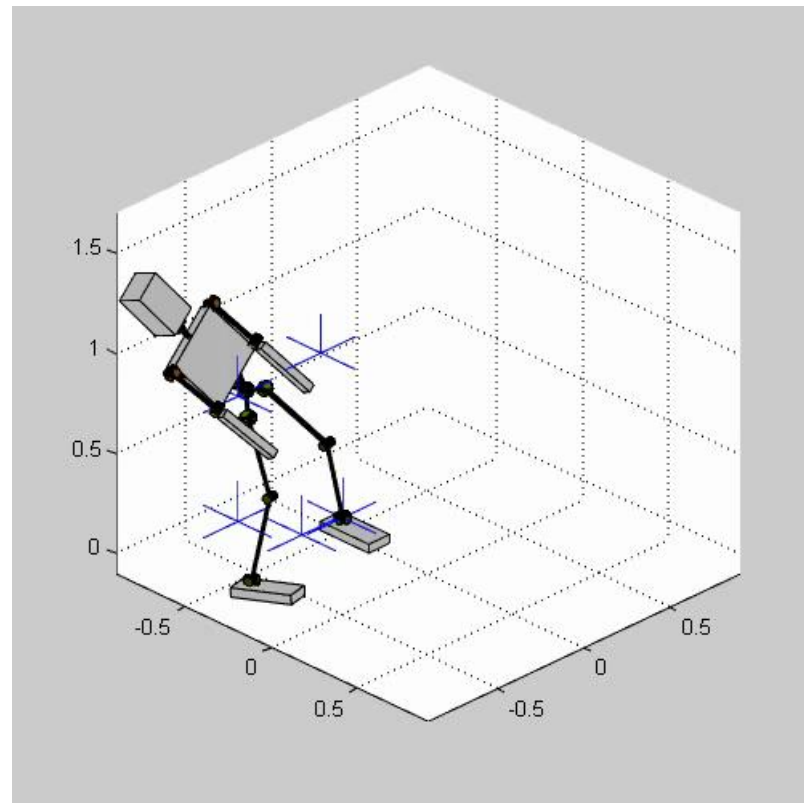
Use of human data without any adaptation

Simulation scenario 3 : Human data with CoM scaling

Reconstructed human movement



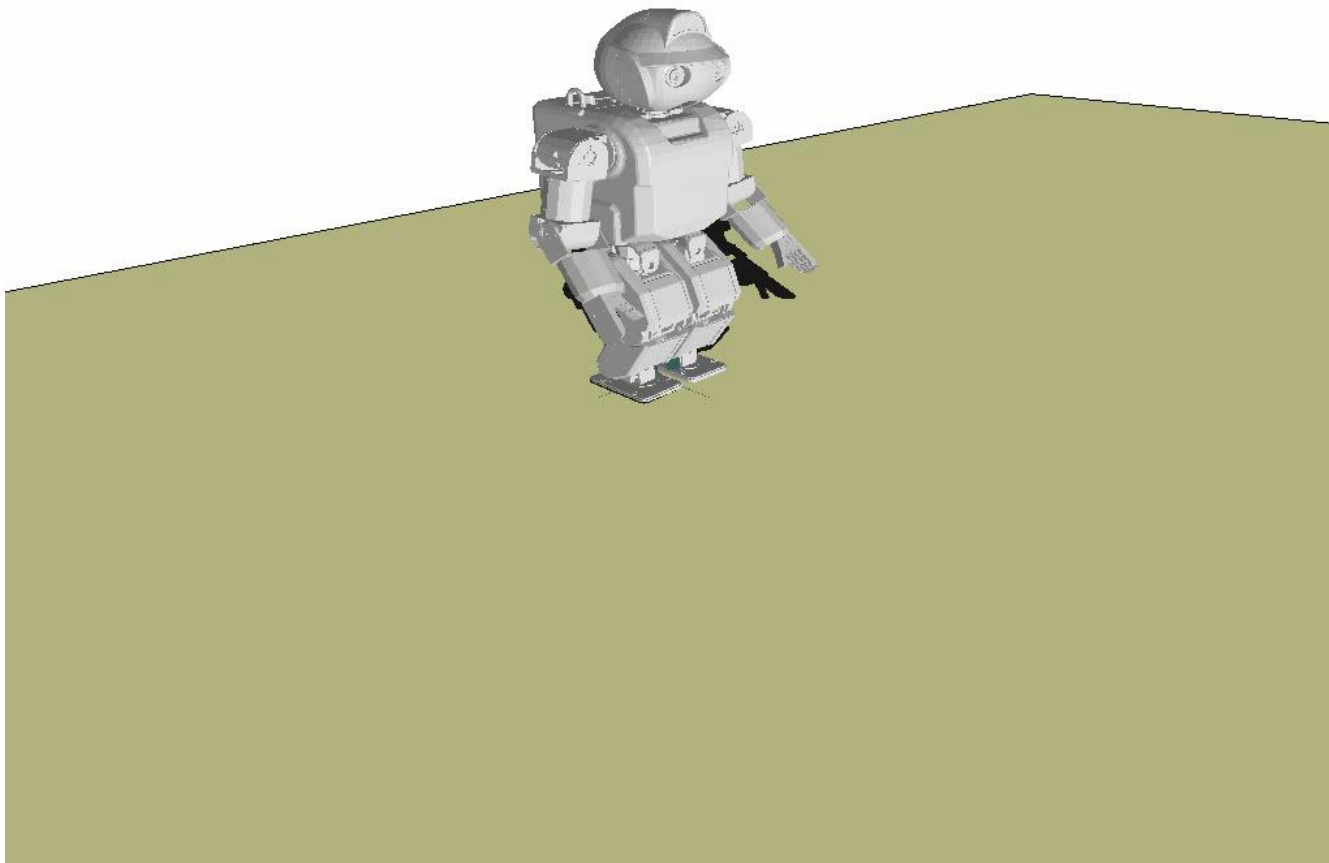
Application of the proposed scheme



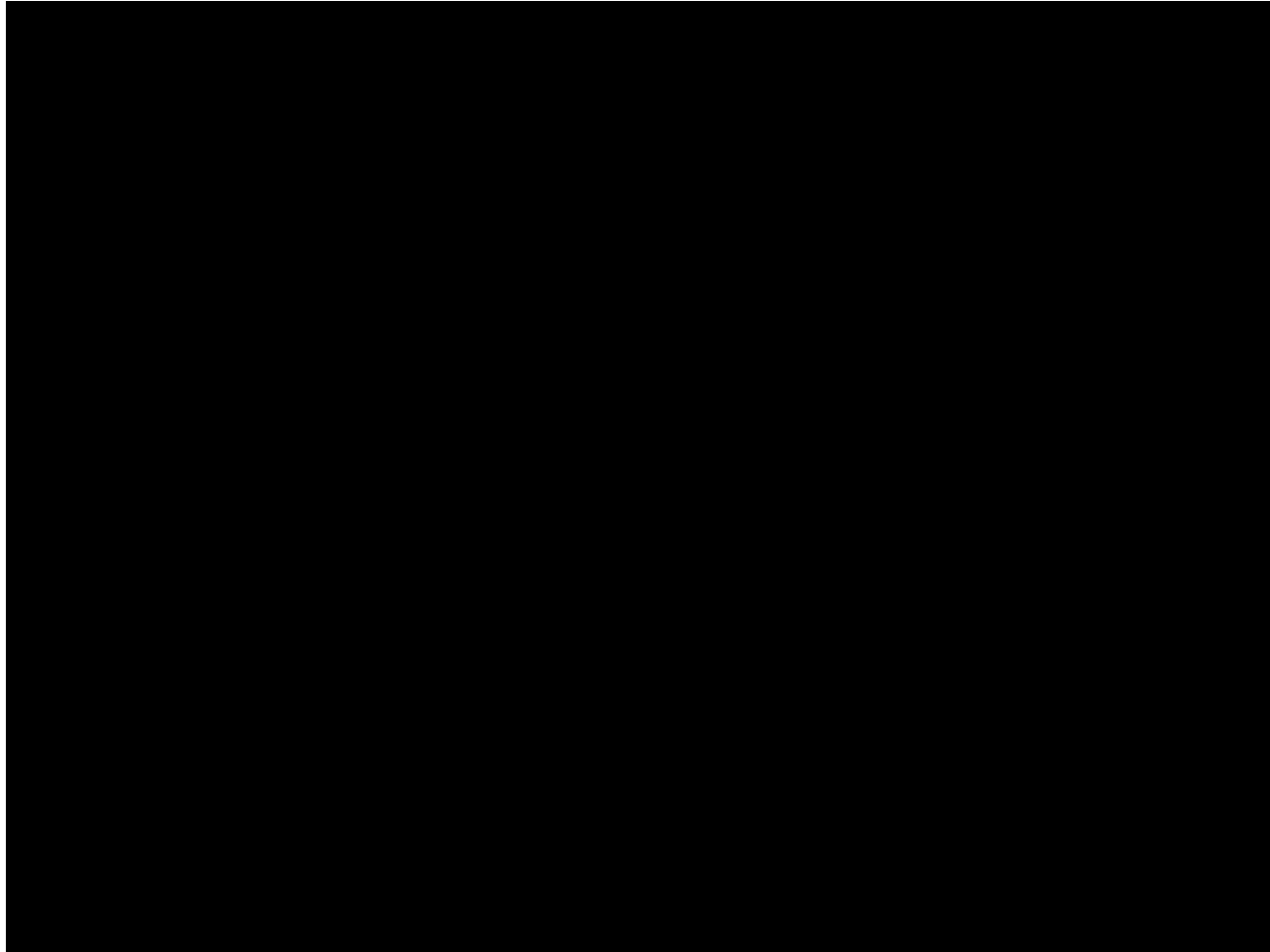
Simulation of the proposed control scheme

Use of human data with scaling of the CoM trajectories

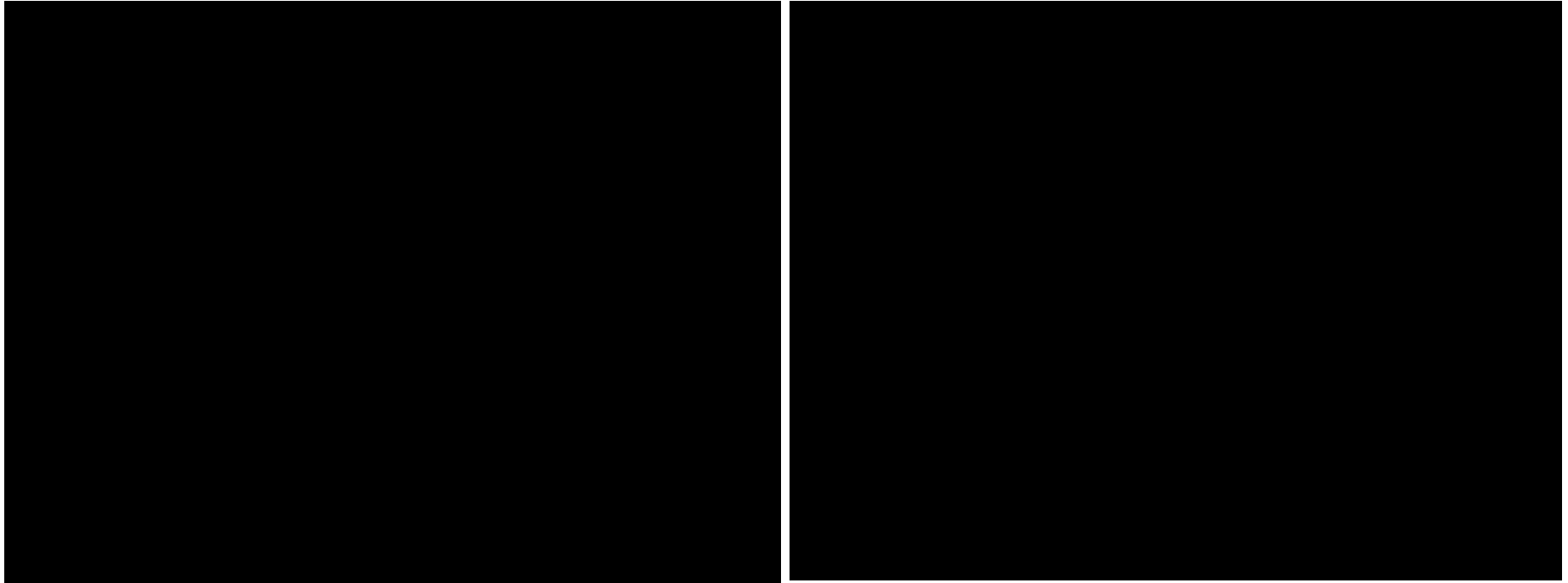
Simulation scenario 4 : Squat motion



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](#)

