Optimal Pattern Generator Based on a Three-Mass Linear Inverted Pendulum Model for Dynamic Walking

David Galdeano, Ahmed Chemori, Sébastien Krut

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Outline

Stability indicators

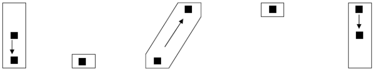
Definition

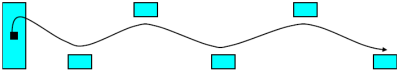
A stability indicator is a mathematical criterion that can characterize the stability margins of a walking robot from the current state of the robot.

Walking mode

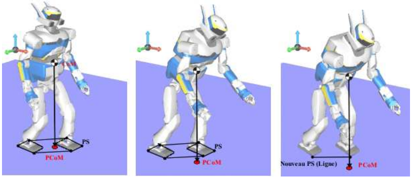
Statically stable walk
Indicator : CoM

Dynamically stable walk
Indicators : ZMP, CoP, FRI...





Center of Mass (CoM)



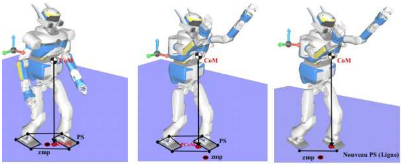
Projection of the CoM relative to the support polygon [Nunez, 2008]

CoM is the mean location of all masses of the robot links

$$OG = \sum m_i OG_i$$

Static stability criterion

Zero Moment Point (ZMP)



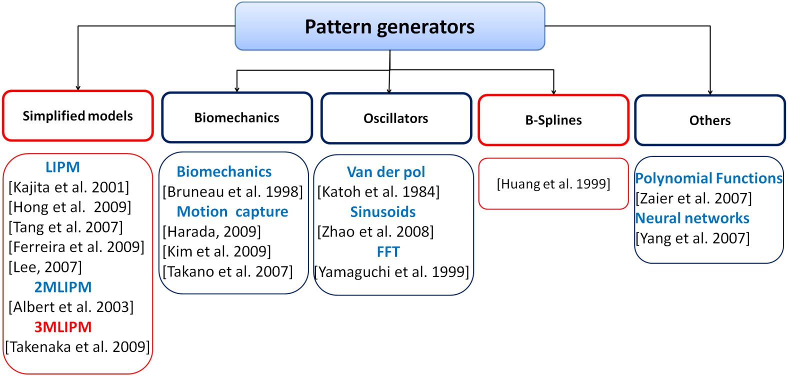
Projection of the ZMP relative to the support polygon [Nunez, 2008]

ZMP is the point where the vertical reaction force intersects the ground

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

Dynamic stability criterion

State of art on walking pattern generators



Motivation

Objective

Design and implementation of a pattern generator for stable dynamic walking

Assumptions

- The ground is flat and without obstacles
- The walking cycle is made of single support and impact phases
- The double support phase is not considered
- The solution use a simplified model of the robot

Method and application

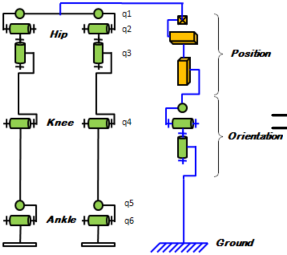
- Model : 3 Masses Linear Inverted Pendulum Model (3MLIPM)
- Application : SHERPA biped robot

Outline

Prototype

SHERPA biped robot

- 7 parts : one waist linked to two legs together articulated with knees and ankles
- 18 degrees of freedom / 12 actuated articulations
- 12 modular transparent actuators (low inertia, low friction and backdrivable)
- Control PC with a real time kernel (RTX)



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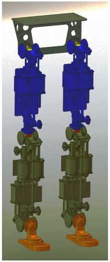

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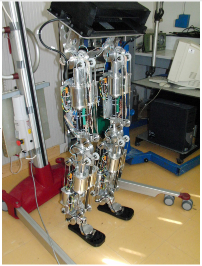
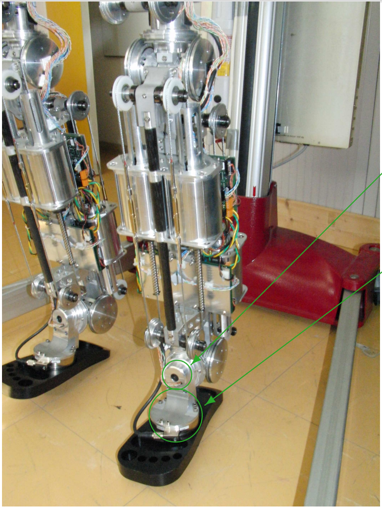


Prototype



Sensor

- 12 Absolute Shaft Encoders (HENGSTLER AD36) to measure articular positions
- 2 six-axis force sensors (ATI-Mini 85) to measure contact forces with ground

HENGSTLER AD36

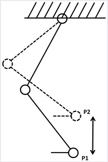
ATI-Mini 85

First movements of the robot

Two motion scenarios are proposed.

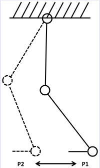
Scenario 1

A swing movement Up and down of the hanged leg



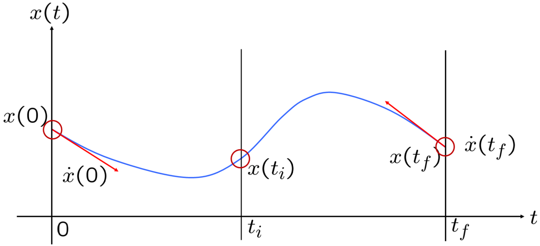
Scenario 2

A swing movement Forward-backward movement of the hanged leg



Reference trajectories generation : based on b-splines functions

B-splines



Objective

Find a trajectory : $T = x(t),\ t \in [0, t_f]$

under a set of constraint : $\begin{cases} x(0) &= x_0 \\ \dot{x}(0) &= \dot{x}_0 \\ x(t_f) &= x_f \\ \dot{x}(t_f) &= \dot{x}_f \\ x(t_i) &= x_i \end{cases}$

Proposed solution

CSAPE algorithm from b-splin toolbox of Matlab software

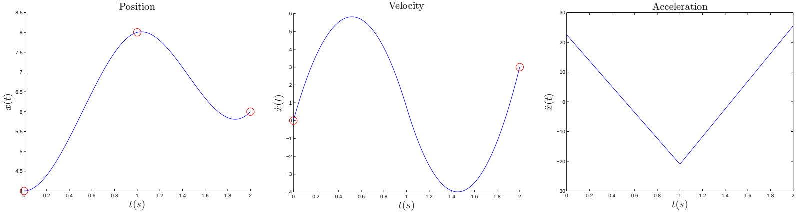
B-splines

Illustration example

Constraints :
$$\begin{cases} x(0) & = & 4 \\ x(1) & = & 8 \\ x(2) & = & 6 \\ \dot{x}(0) & = & 0 \\ \dot{x}(2) & = & 3 \end{cases}$$

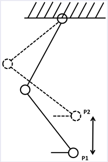
B-splines MATLAB function :
csape([0,1,2], [4,8,6],[1,1],[0,3])
$t_0 = 0,\ t_i = 1,\ t_f = 2$

Obtained trajectories

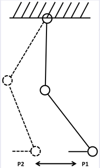


First movements of the robot (Experiments)

Scenario 1

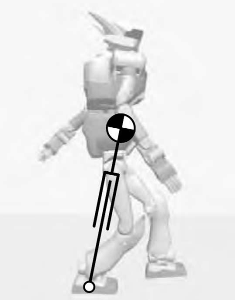


Scenario 2

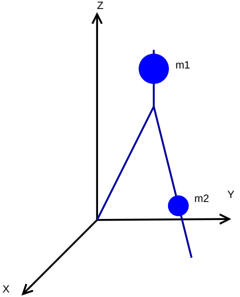


Outline

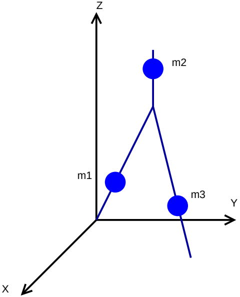
Simplified models



LIPM
[Kajita et al., 2009]



2MLIPM
[Albert and Gerth, 2003]

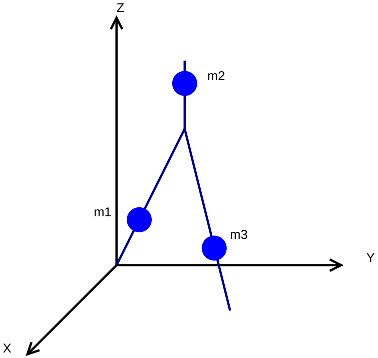


3MLIPM
[Feng and Sun, 2008]

Reduce the dynamic of the robot to the dynamic of a point mass.

The three masses linear inverted pendulum model

"3 Mass Linear Inverted Pendulum Model (3MLIPM)" [Feng and Sun, 2008]



Properties

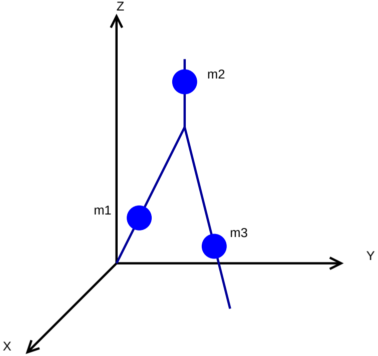
- Simplified model of the robot
- Three point masses
- Three massless links

Hypothesis

- Walk on flat ground
- No double support phases

The three masses linear inverted pendulum model

"3 Mass Linear Inverted Pendulum Model (3MLIPM)" [Feng and Sun, 2008]



Properties

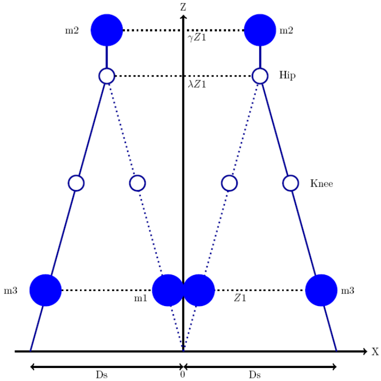
- Simplified model of the robot
- Three point masses
- Three massless links

Hypothesis

- Walk on flat ground
- No double support phases

Decoupled equations   Motion generated separately { Sagittal plane / Frontal plane

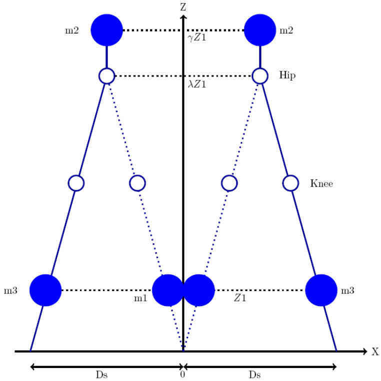
Motion in sagittal plane



Dynamic of 3MLIPM in the sagittal plane

x_i :Cartesian position of mass m_i in x axis
z_i :Cartesian position of mass m_i in z axis

Motion in sagittal plane

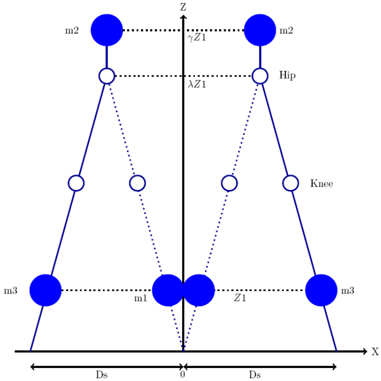


Dynamic of 3MLIPM in the sagittal plane

$$\sum_{i=1}^{3} m_i \ddot{x}_i z_i = \sum_{i=1}^{3} m_i g x_i$$

x_i :Cartesian position of mass m_i in x axis
z_i :Cartesian position of mass m_i in z axis

Motion in sagittal plane



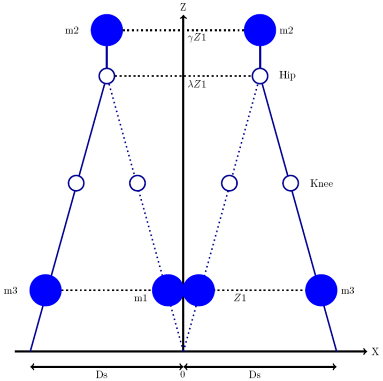
Dynamic of 3MLIPM in the sagittal plane

$$\sum_{i=1}^{3} m_i \ddot{x}_i z_i = \sum_{i=1}^{3} m_i g x_i$$

$$b\ddot{x}_1 + d\ddot{x}_3 = ax_1 + x_3$$

x_i :Cartesian position of mass m_i in x axis
z_i :Cartesian position of mass m_i in z axis

Motion in sagittal plane



Dynamic of 3MLIPM in the sagittal plane

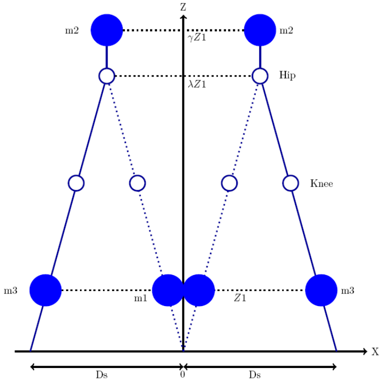
$$\sum_{i=1}^{3} m_i \ddot{x}_i z_i = \sum_{i=1}^{3} m_i g x_i$$

$$b\ddot{x}_1 + d\ddot{x}_3 = ax_1 + x_3$$

Choose a trajectory for the swinging foot

x_i :Cartesian position of mass m_i in x axis
z_i :Cartesian position of mass m_i in z axis

Motion in sagittal plane



x_i :Cartesian position of mass m_i in x axis
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Dynamic of 3MLIPM in the sagittal plane

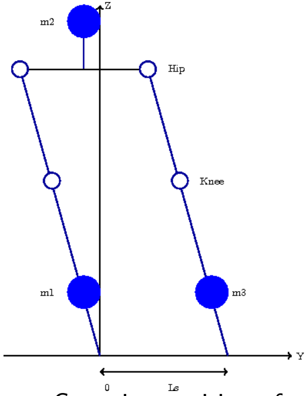
$$\sum_{i=1}^{3} m_i \ddot{x}_i z_i = \sum_{i=1}^{3} m_i g x_i$$

$$b\ddot{x}_1 + d\ddot{x}_3 = a x_1 + x_3$$

Choose a trajectory for the swinging foot

Motion of the three masses

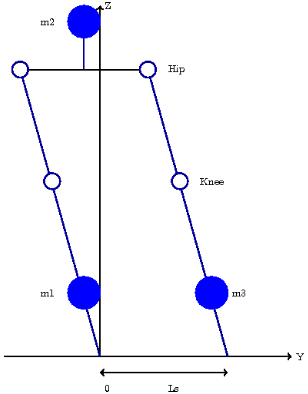
Motion in frontal plane



Dynamic of 3MLIPM in the frontal plane

x_i :Cartesian position of mass m_i in x axis
z_i :Cartesian position of mass m_i in z axis

Motion in frontal plane

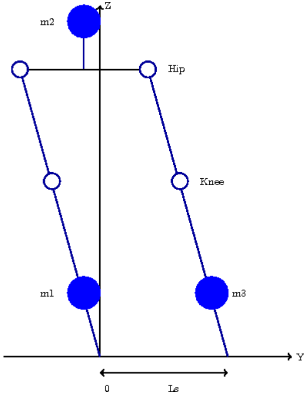


Dynamic of 3MLIPM in the frontal plane

$$\sum_{i=1}^{3} m_i \ddot{y}_i z_i = \sum_{i=1}^{3} m_i g y_i$$

x_i :Cartesian position of mass m_i in x axis
z_i :Cartesian position of mass m_i in z axis

Motion in frontal plane



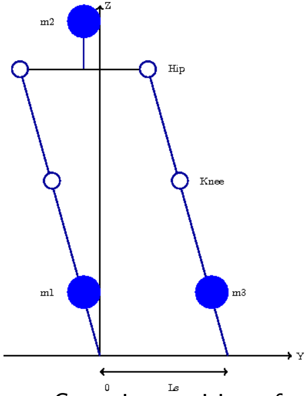
Dynamic of 3MLIPM in the frontal plane

$$\sum_{i=1}^{3} m_i \ddot{y}_i z_i = \sum_{i=1}^{3} m_i g y_i$$

$$u\ddot{y}_1 - v y_1 = w$$

x_i :Cartesian position of mass m_i in x axis
z_i :Cartesian position of mass m_i in z axis

Motion in frontal plane



Dynamic of 3MLIPM in the frontal plane

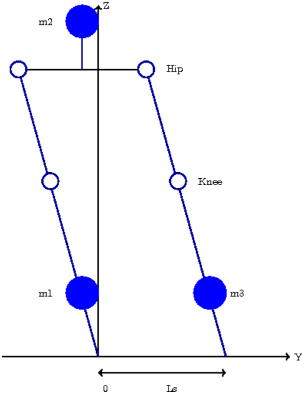
$$\sum_{i=1}^{3} m_i \ddot{y}_i z_i = \sum_{i=1}^{3} m_i g y_i$$

$$u\ddot{y}_1 - v y_1 = w$$

3D trajectories of hip and ankles

x_i :Cartesian position of mass m_i in x axis
z_i :Cartesian position of mass m_i in z axis

Motion in frontal plane



Dynamic of 3MLIPM in the frontal plane

$$\sum_{i=1}^{3} m_i \ddot{y}_i z_i = \sum_{i=1}^{3} m_i g y_i$$

$$u\ddot{y}_1 - v y_1 = w$$

3D trajectories of hip and ankles

Inverse kinematics → Joints space trajectories

x_i :Cartesian position of mass m_i in x axis
z_i :Cartesian position of mass m_i in z axis

Outline

1. Context and motivation
2. SHERPA walking robot
3. Basic 3MLIPM pattern generator
4. Limitations and improvements
5. Simulation results
6. Conclusion and Future work

First contribution

First limitation of the 3MLIPM model :

The dynamic stability is not guaranteed

Proposed improvement : Optimization with respect to ZMP

Principle : optimal value of mass m_1 and its position z_1 :

$$\begin{bmatrix} \hat{z}_1 \\ \hat{m}_1 \end{bmatrix} = Arg \underset{\begin{bmatrix} z_1 \\ m_1 \end{bmatrix}}{Min} \; Max \left(\sqrt{\alpha(x_{zmp} - x_{dzmp})^2 + \beta(y_{zmp} - y_{dzmp})^2} \right)$$

This optimization aims to find the best fit between the desired and the computed ZMP.

Second contribution

Second limitation of the 3MLIPM model :

Change of walking direction is not allowed

Proposed improvement : Modification of the hip trajectory

Principle : the hip trajectory is modified as follow :

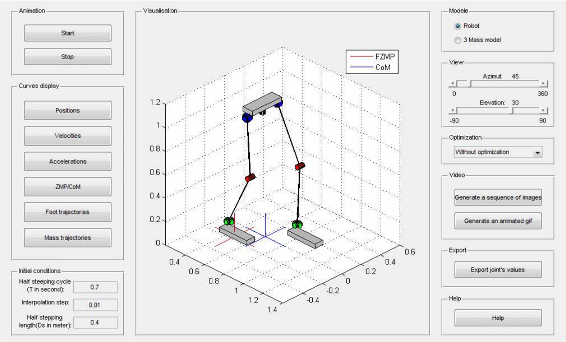
$$\Omega(t) = -\frac{R}{2}\cos(\frac{\pi t}{T}) \quad t \in [0, T]$$

with T : half step period and R : amplitude of rotation.

The modification of the hip trajectory allows a change of walking direction.

Outline

Developed simulator



Proposed scenarios :

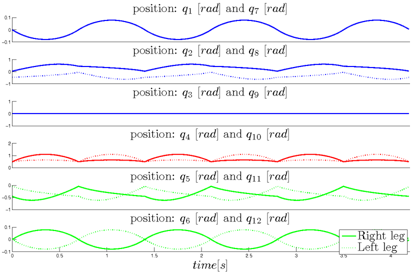
Scenario 1 :
Straight walking

Scenario 2 :
Change of walking direction

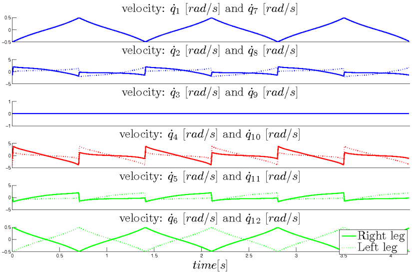
Comparison of the original pattern generator with the improved one

First scenario : Straight walking

Joints' positions



Joints' velocities



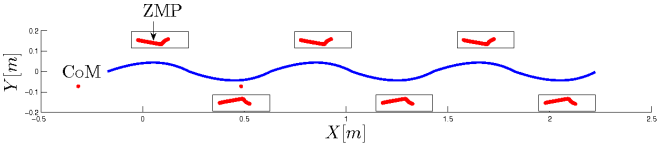
Characteristics :

- Joints' trajectories are periodic
- Discontinuities in joints' velocities

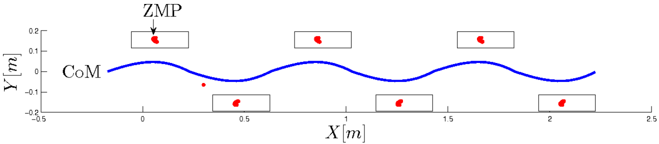
First scenario : Straight walking

Stability analysis through ZMP

Without optimization



With optimization



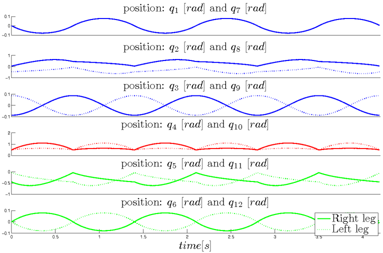
Optimization $\Rightarrow$ Improvement of the stability margins

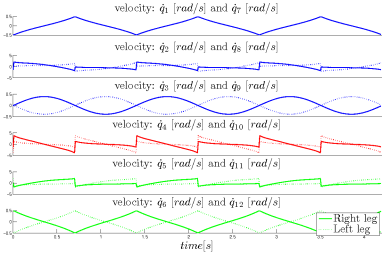
Second scenario : Change of walking direction

Joints' positions

Joints' velocities

Change of walking direction





Characteristics :

- Joints' trajectories are periodic
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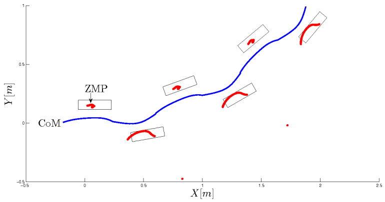
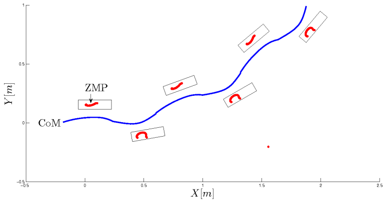
Second scenario : Change of walking direction

Stability analysis through ZMP

Without optimization



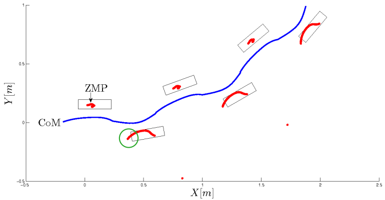
With optimization



Second scenario : Change of walking direction

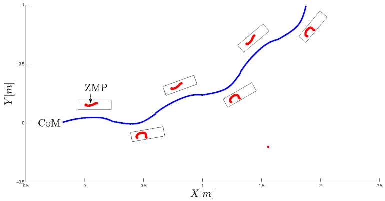
Stability analysis through ZMP

Without optimization



Instable dynamic walking

With optimization

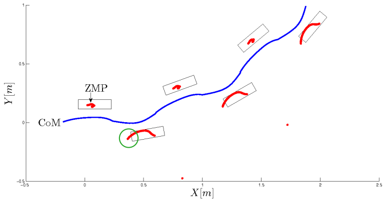


Stable dynamic walking

Second scenario : Change of walking direction

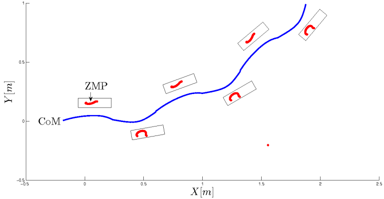
Stability analysis through ZMP

Without optimization



Instable dynamic walking

With optimization



Stable dynamic walking

Optimization $\Rightarrow$ Dynamic walking stability is guaranteed

Video

Outline

Conclusion

Motivation :

Design and implementation of a pattern generator for dynamically stable walking

Deals with :

- Stability of dynamic walking
- 3D Movements
- Complex nonlinear dynamics
- Low CoM position (no torso)

Proposed solution :

- A pattern generator based on a 3 masses simplified model
- Stability margin improvement using optimization
- Change of walking direction is allowed

Future work

Future work can include...

- Real-time implementation of the proposed pattern generator on the biped robot SHERPA
- Development of a hybrid Position/Force controller to stabilize dynamic walking (in progress)
- Combine the hybrid Position/Force controller with the developed pattern generator
- Test the effectiveness of controller for walking on uneven ground
- Compare this approach to other pattern generators

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