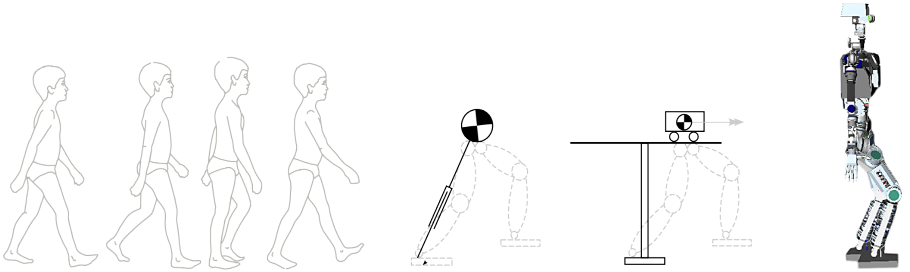
Dynamically Stable Walking For Humanoid Bipedal Robots Based On Walking Patterns

Bachelor Thesis

Patrick Niklaus | November 25, 2014

INSTITUTE FOR ANTHROPOMATICS AND ROBOTICS: HIGH PERFOMANCE HUMANOID TECHNOLOGIES LAB



Outline

1. Motivation
2. Walking Pattern Generation
3. Walking Stabilization
4. Push recovery

Why bipedal walking?

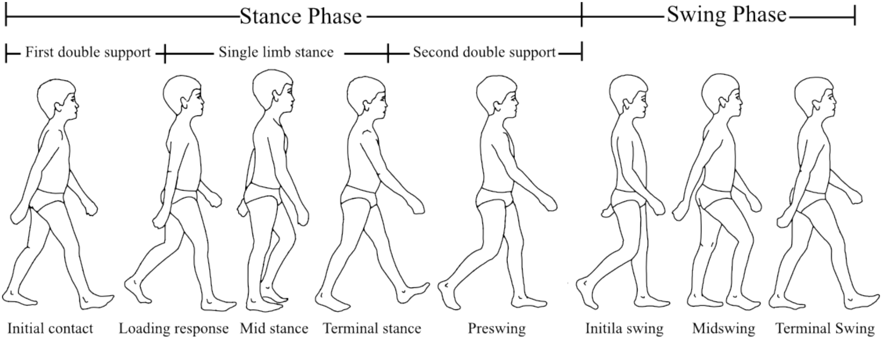
- Robots should be able to navigate in environments made for humans:
  - Little space
  - Obstacles

$\Rightarrow$ Wheeled base not flexible enough.

- **Problem:** How do you guarantee stability during walking?

The Human Gait

- Of primary interest for stability: Number of feet that are in contact with ground
- **Walking:** Dual support phase and single support phase.
- **Running:** Single support and no ground contact



Source: Dynamics of Human Gait

Application to robots?

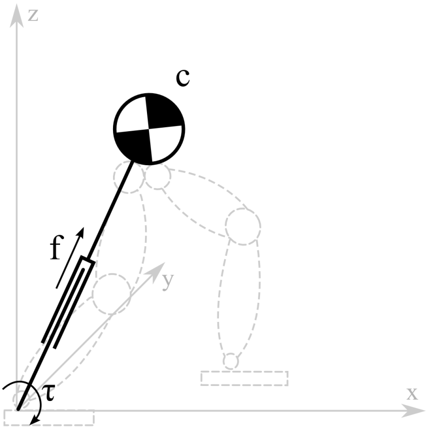
1. Adapt recorded human motions to robot:
   - Kinematic structure different: Not clear how to map to robot
   - Dynamic properties (weight, inertia) different

   $\rightarrow$ Might not yield dynamically stable walking at all
2. Derive stable trajectories from dynamic models of the robot:
   - Most popular: 3D-Linear Inverted Pendulum Model and ZMP
   - Simplification: Height of the CoM is constant with respect to ground (only approximately true for humans see Orendurff et al. [5])

This work is build on the second approach.

3D Linear Inverted Pendulum Model

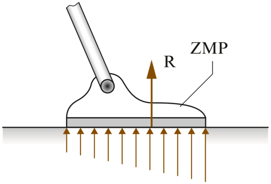
- Simplified dynamic description of robot
- Reduce robot to pendulum with massless rod and point contact
- *Linear actuator* in rod of pendulum
- Mass of robot gets reduced to the *CoM* (the head of the pendulum)
- To make the dynamics *linear* we constrain the head of the pendulum to a constant height



Zero Moment Point

If all contact forces are in the same plane, we can define the *Center of Pressure* as:

$$p := \begin{pmatrix} p_x \\ p_y \\ p_z \end{pmatrix} = \frac{\sum_{i=1}^{N} p_i f_{iz}}{\sum_{i=1}^{N} f_{iz}}$$



- Torque around x and y axis at this point is zero
- Thus we can call this point the *Zero Moment Point*.

Why is the ZMP interesting?

1. Describes the *foot-floor contact dynamics* in case of flat ground contact
2. Can be used to derive a *condition to ensure dynamically stable pose*: If the ZMP is **strictly inside the support polygon**, the foot-floor contact will be preserved.

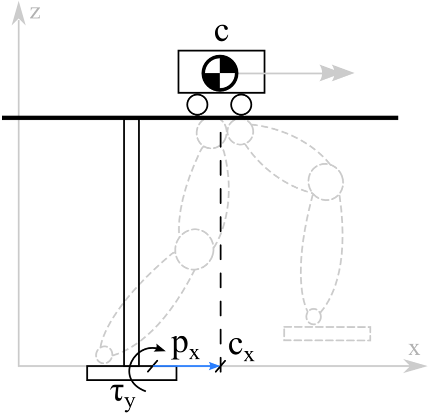
We will use 2. to derive dynamically stable trajectories by constraining the ZMP to the support polygon.

Cart-Table-Model

- Simple model to compute the ZMP
- Does not require knowledge about contact forces
- For each dimension: Cart on massless table
- Cart represents the CoM of the robot
- Foot of the table corresponds to the support polygon

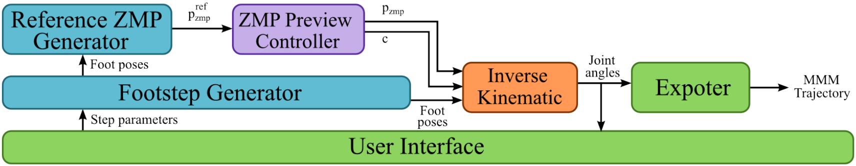
Resulting ZMP:

$$p_x = c_x - \frac{z_c}{g} \ddot{c}_x \qquad (1)$$



Pattern generation as control problem

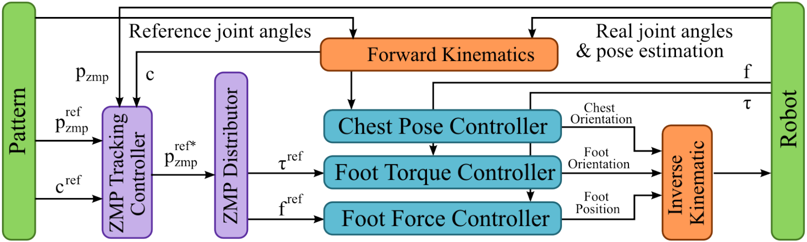
- **Idea:** Formulate dynamic walking as a control problem
- **Goal:** Realize given reference ZMP position
- **Result:** Array of system states (position, velocity, acceleration of the CoM and realized ZMP position)
- **Implementation**: Uses a Preview Controller (Kajita et al. 2003 [1]) that utilizes knowledge about the future trajectory



Video of pattern based walking

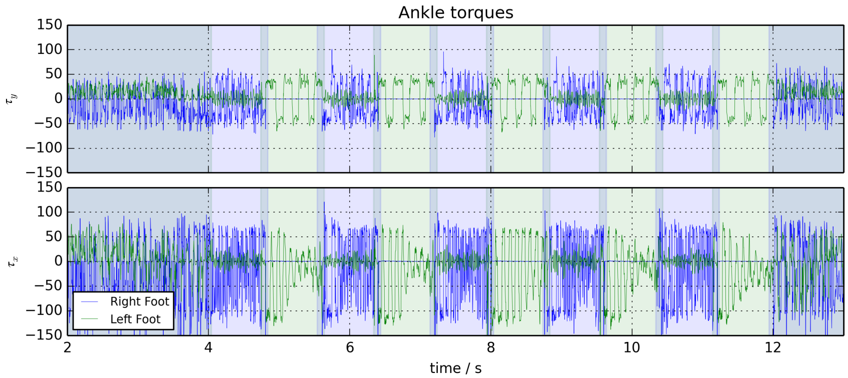
Stabilizer

- **Problem:** Disturbances cause instabilities (even though the pattern is dynamically stable!)
- **Solution:** Adapt pattern to disturbances $\rightarrow$ stabilizer
- **Implemented:** Stabilizer based on Kajita et al. 2010 [3]. Adapts frames in Cartesian space (no torque control needed).



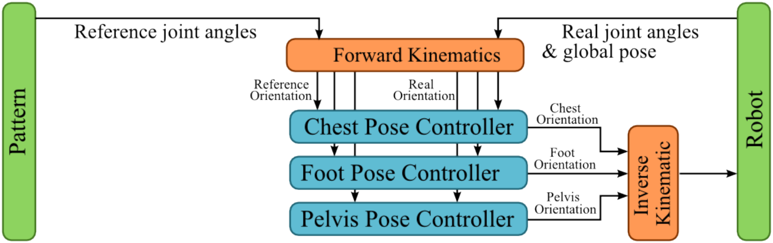
Ankle torques

Problem: Needs accurately measured torques. Bullet does not provide realistic torques.



Heuristic Stabilizer

- Works very similar to stabilizer proposed by Kajita
- Instead of torque feedback, we use the pose of error of the frames
- **Problem**: Accurately measuring pose error for each frame not possible in reality



Stabilized walking in a circle

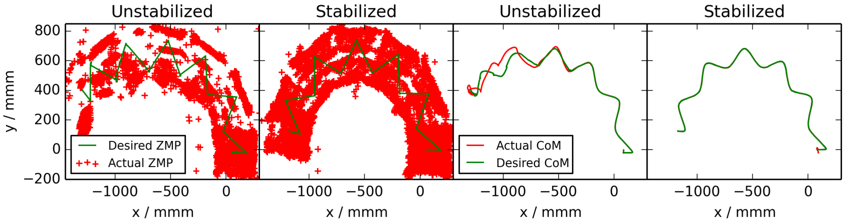


Figure: Walking in a half-circle.

Walking with disturbances

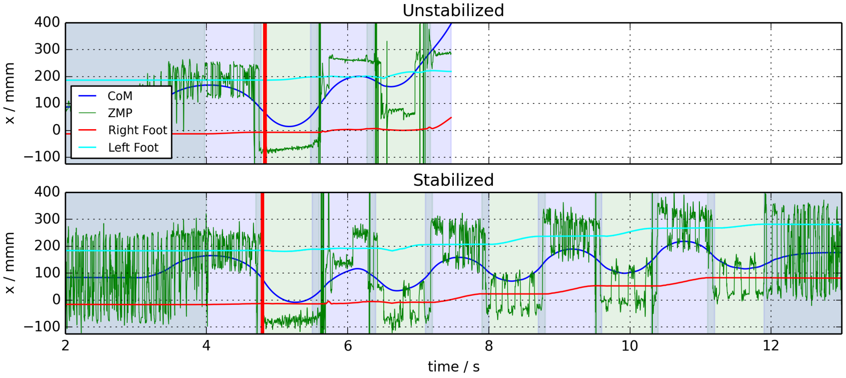
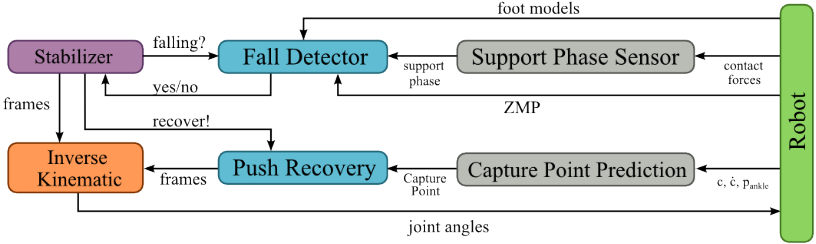


Figure: Push without stabilization

Figure: Push with stabilization.

Capture Point

- The (immediate) Capture Point is defined as the point on the floor, where by placing the base of the pendulum there, the CoM would come to a rest. [4]
- **Problem:** The base needs to be moved instantaneously to the Capture Point, but foot would at least need t_{min} seconds.
- **Solution:** Predict the future position of the immediate Capture Point in t_{min}

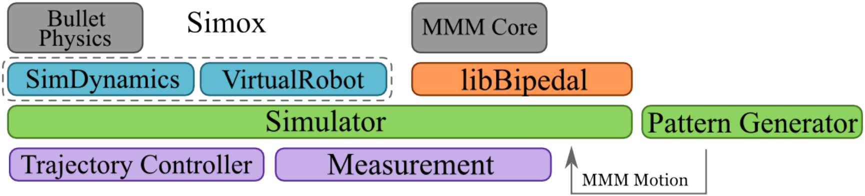


Capture Point Video

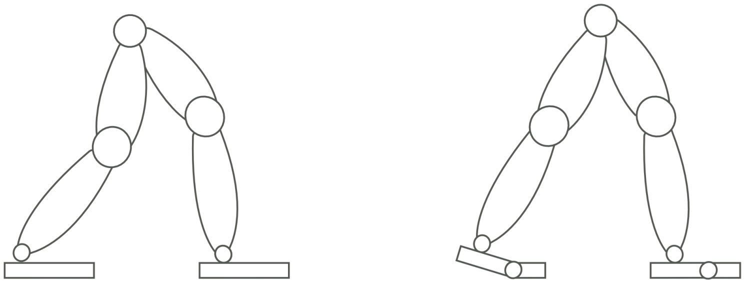
Figure: Push recovery, standing on left leg.

Implementation

- All algorithms implemented independent of the physical simulation (`libBipedal`): `https://github.com/TheMarex/libbipedal`
- Simulator using Simox with SimDynamics: `https://i61wiki.itec.uka.de/git/simdynamicsviewer.git`
- All C++11, needs Simox, MMMCore and Bullet 2.82 with double support



Future Work



- **Problem:** Constant CoM heigt requires knees to be bend: looks somewhat unnatural.
- **Solution:** Add additional DoF in the toe: foot can rotate forward without loosing ground contact
- Used successfuly in WABIAN or HRP-4C.
- Needs adapted stabilizer and pattern generator [2]

References

Shuuji Kajita, Fumio Kanehiro, Kenji Kaneko, Kiyoshi Fujiwara, Kensuke Harada, Kazuhito Yokoi, and Hirohisa Hirukawa.
Biped walking pattern generation by using preview control of zero-moment point.
In *Robotics and Automation, 2003. Proceedings. ICRA'03. IEEE International Conference on*, volume 2, pages 1620–1626. IEEE, 2003.

Shuuji Kajita, Kanako Miura, Mitsuharu Morisawa, Kenji Kaneko, Fumio Kanehiro, and Kazuhito Yokoi.
Evaluation of a stabilizer for biped walk with toe support phase.
In *Humanoid Robots (Humanoids), 2012 12th IEEE-RAS International Conference on*, pages 586–592. IEEE, 2012.

Shuuji Kajita, Mitsuharu Morisawa, Kanako Miura, Shinichiro Nakaoka, Kensuke Harada, Kenji Kaneko, Fumio Kanehiro, and Kazuhito Yokoi.
Biped walking stabilization based on linear inverted pendulum tracking.
In *Intelligent Robots and Systems (IROS), 2010 IEEE/RSJ International Conference on*, pages 4489–4496. IEEE, 2010.

Twan Koolen, Tomas De Boer, John Rebula, Ambarish Goswami, and Jerry Pratt.
Capturability-based analysis and control of legged locomotion, part 1: Theory and application to three simple gait models.
The International Journal of Robotics Research, 31(9):1094–1113, 2012.

Michael S Orendurff, Ava D Segal, Glenn K Klute, Jocelyn S Berge, Eric S Rohr, and Nancy J Kadel.
The effect of walking speed on center of mass displacement.
J Rehabil Res Dev, 41(6A):829–34, 2004.