Karlsruher Institut für Technologie

Dynamically Stable Walking For Humanoid Bipedal Robots Based On Walking Patterns

Bachelor Thesis

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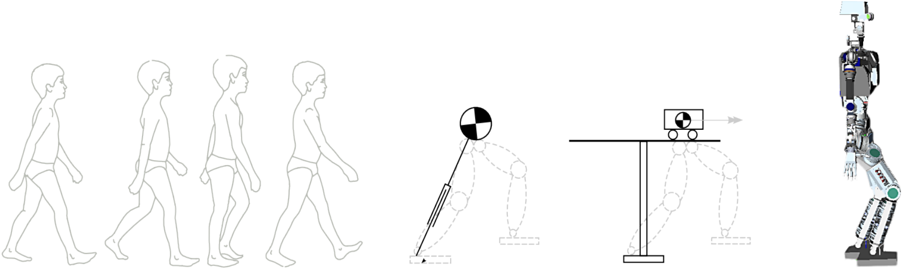
Institute for Anthropomatics and Robotics: High Perfomance Humanoid Technologies Lab



Outline

Why bipedal walking?

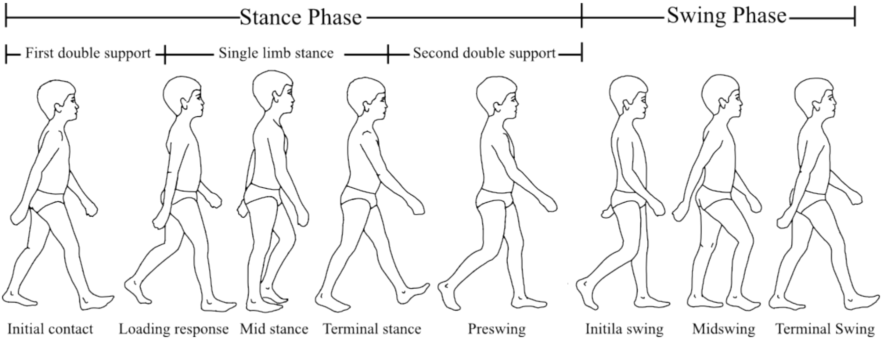
- Robots should be able to navigate in environments made for humans:
  - Little space
  - Obstacles (e.g. stairs)

$\Rightarrow$ 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
- Dual support phase: Shift weight from last support leg to next one
- Single support phase: Move swing leg to next foot position



Source: Dynamics of Human Gait

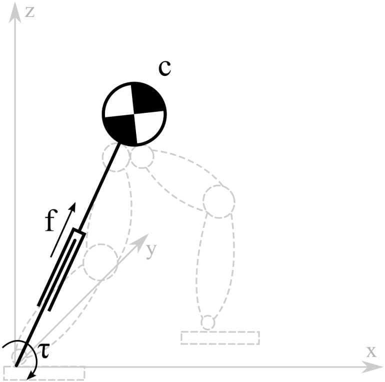
Application to robots?

1. Adapt recorded human motions to robot:
   - Kinematic structure and dynamic properties are different: Mapping needs to be found.
   - Mapping is computationally expensive (offline), but trajectory looks very natural
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])
   - Can be computed online, but looks less natural

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* $c = (c_x, c_y)^T$ (the head of the pendulum)
- To make the dynamics *linear* we constrain the head of the pendulum to a constant height



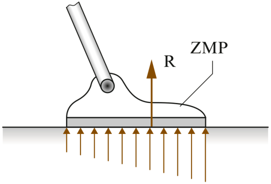
Resulting Equation:

$$\ddot{c}_x = \frac{g}{z_c} c_x$$

Contact forces

We can reduce all contact forces acting on the foot to a single force at the *Center of Pressure* which is computed as:

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

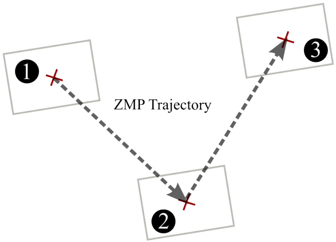


- If all contact forces are in the same plane: Torque around x and y axis at this point is zero
- Thus we can call this point the *Zero Moment Point* (ZMP).

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.

Use 2. to derive dynamically stable trajectory by constraining ZMP to support polygones:

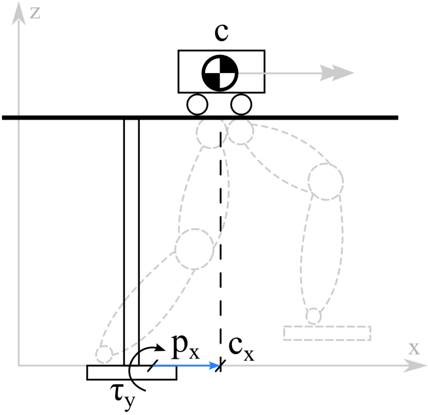


Cart-Table-Model

- 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

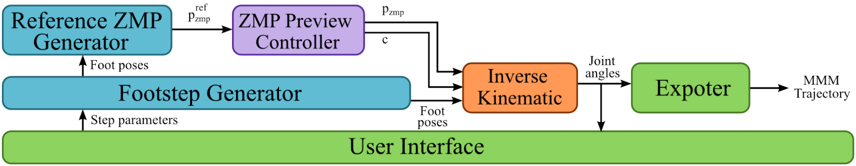
Resulting ZMP:

$$p_x = c_x - \frac{z_c}{g}\ddot{c}_x$$



Pattern generation as control problem

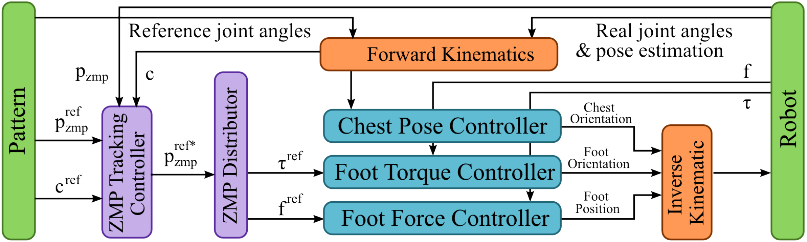
- **Idea:** Formulate dynamic walking as a control problem
- **Goal:** Realize given reference ZMP position
- **Result:** Array of system states (position, velocity, acceleration of the CoM and realized ZMP position)
- **Implementation**: Uses a Preview Controller (Kajita et al. 2003 [1]) that utilizes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



Video of pattern based walking

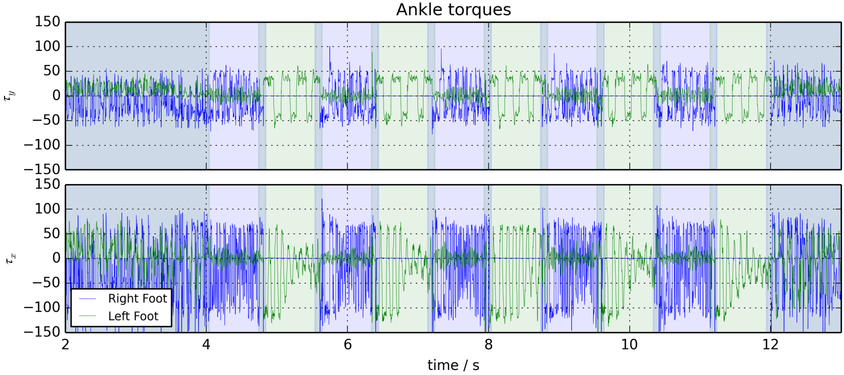
Stabilizer

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



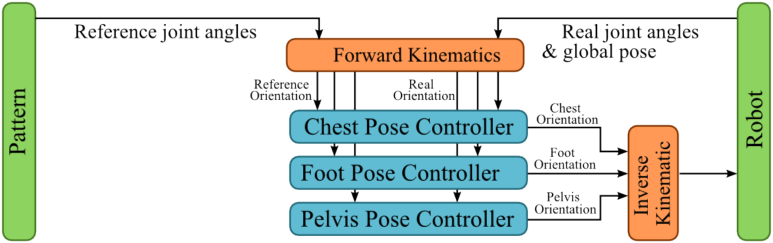
Ankle torques

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

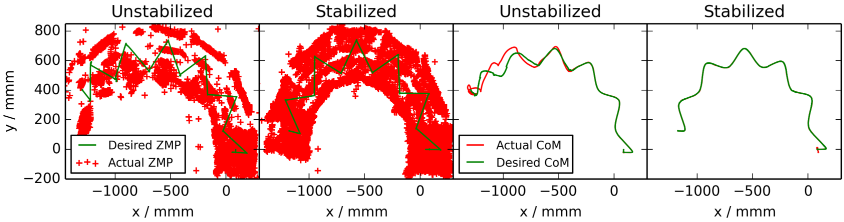


Figure: Walking in a half-circle.

Walking with disturbances

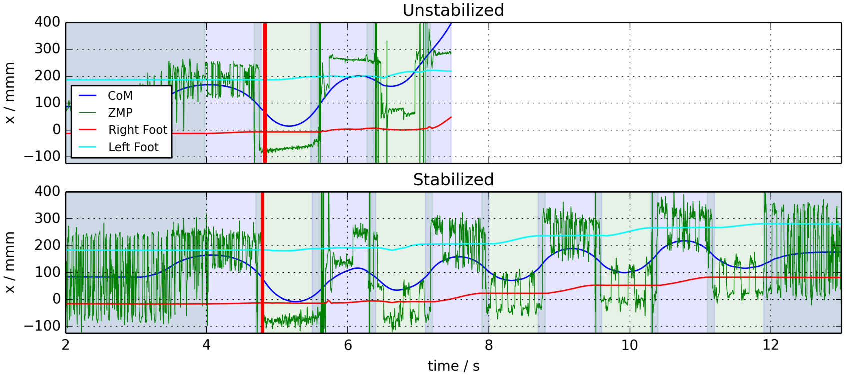
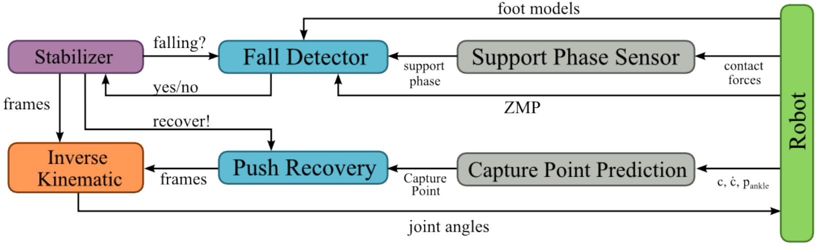


Figure: Push without stabilization

Figure: Push with stabilization.

Push recovery based on 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}

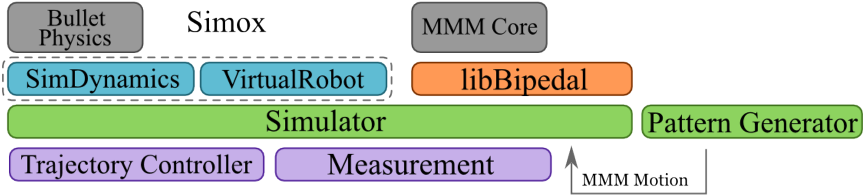


Capture Point Video

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



Conclusion

- Implemented a **dynamic simulator** that can test MMM trajectories
- **Verified** walking patterns in dynamic simulation
- Implemented multiple **stabilizers** and tested in simulation
- Implemented simple **push recovery** mechanism based on the Capture Point

Future Work

- Implement different pattern generation schemes (simple 3D-LIPM based, CP based)
- Make walking more natural: Use toe joint. $\rightarrow$ Kajita et al. [2] proposed extension of the methodes implemented here to include a toe support phase
- Better push recovery: General case, use extended LIP models proposed by Pratt

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