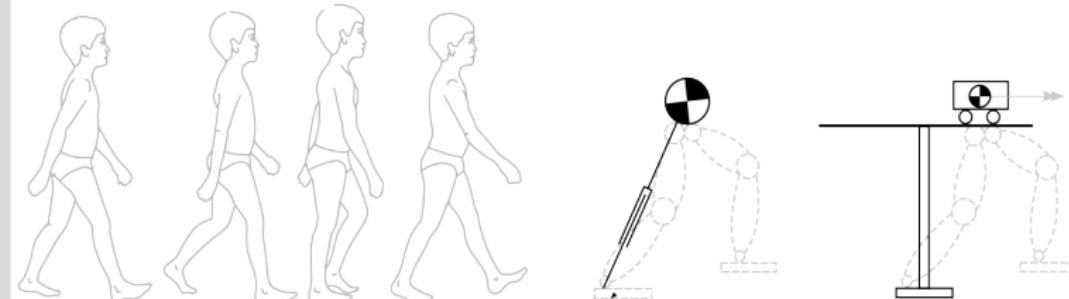


# Dynamically Stable Walking For Humanoid Bipedal Robots Based On Walking Patterns

Bachelor Thesis

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INSTITUTE FOR ANTHROPOMATICS AND ROBOTICS: HIGH PERFORMANCE HUMANOID TECHNOLOGIES LAB



# Outline

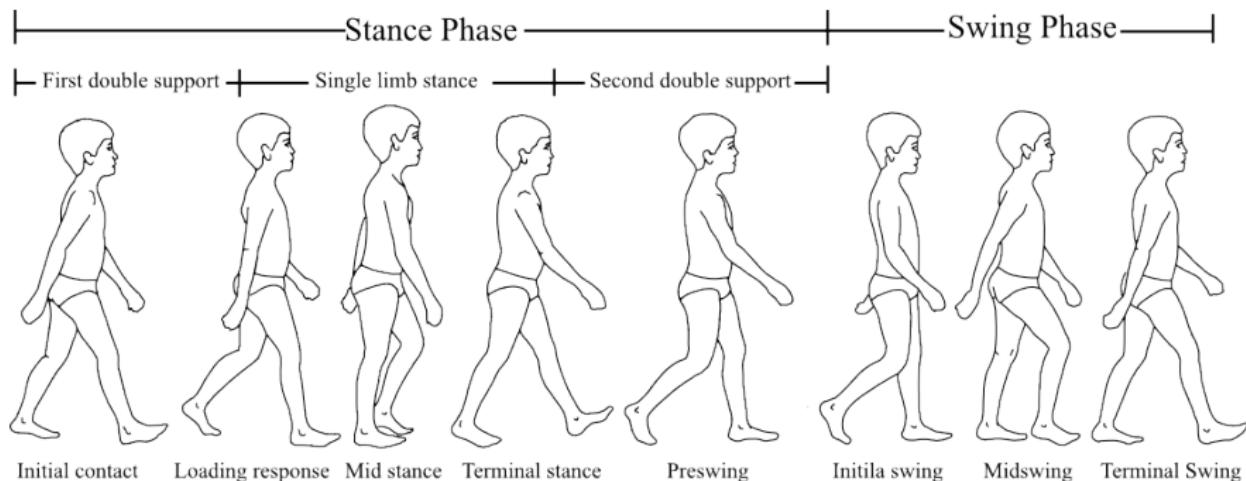
- 1 Motivation
- 2 Walking Pattern Generation
- 3 Walking Stabilization
- 4 Push recovery
- 5 Conclusion & Future Work

# Why bipedal walking?

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

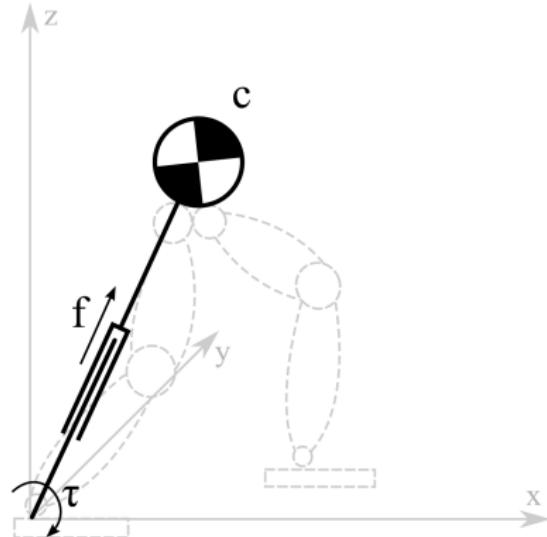
# Application to robots?

- 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



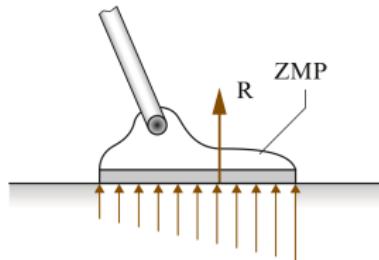
Resulting Equation:

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

# 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:

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

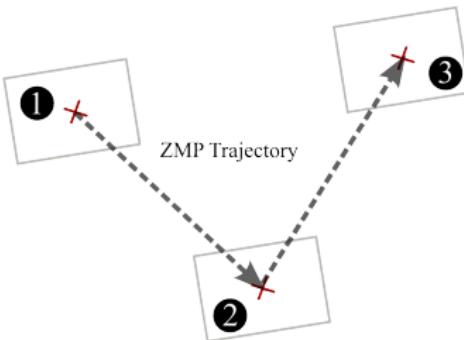


- If all contact forces are in the same plane: Torque around x and y axis at this point is zero
- Thus we can call this point the *Zero Moment Point (ZMP)*.

# 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 polygons:

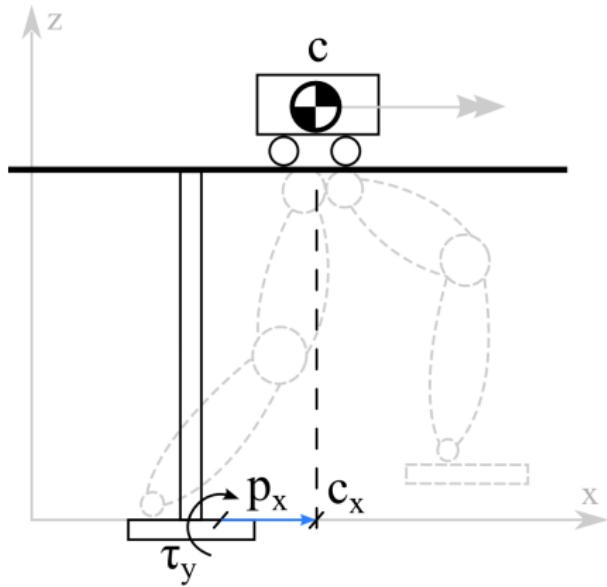


# Cart-Table-Model

- 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

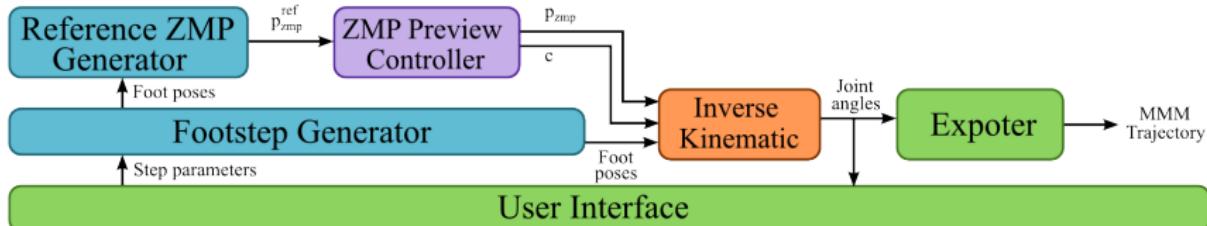
Resulting ZMP:

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



# 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



Motivation

Walking Pattern Generation

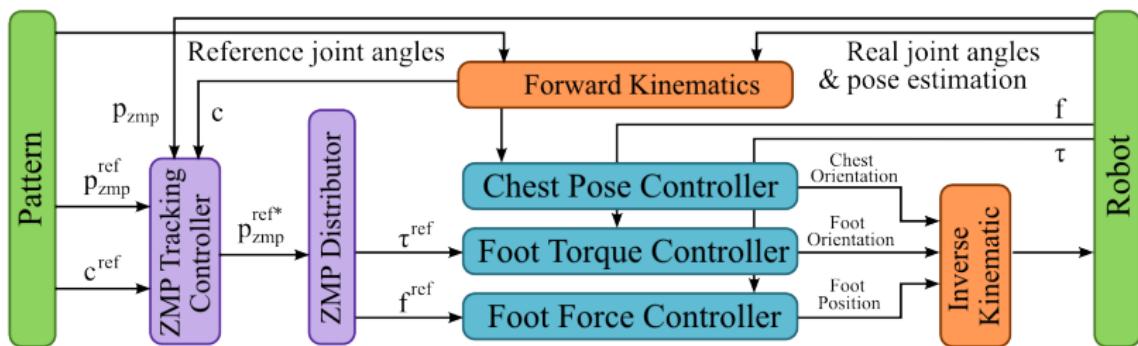
Walking Stabilization

Push recovery

Conclusion & Future Work

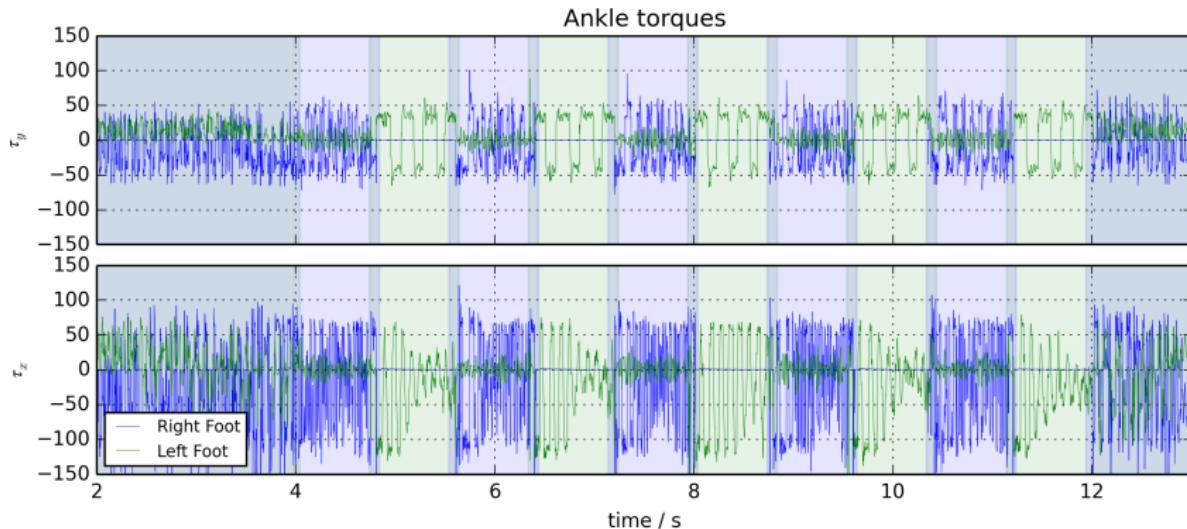
# Stabilizer

- **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).



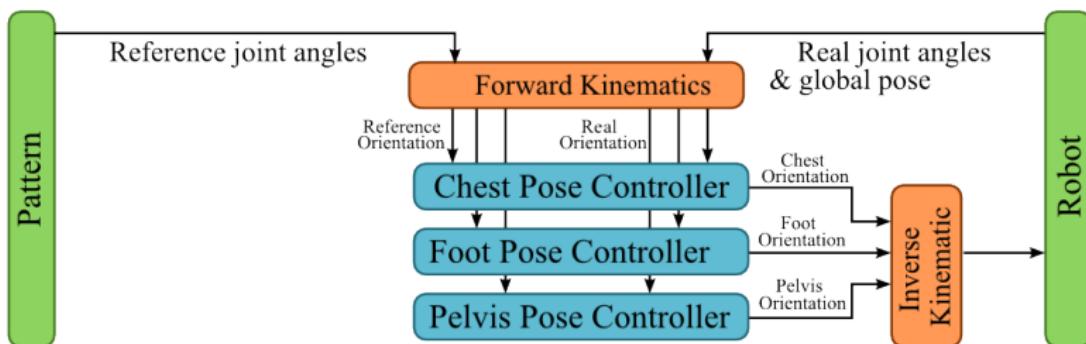
# Ankle torques

**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

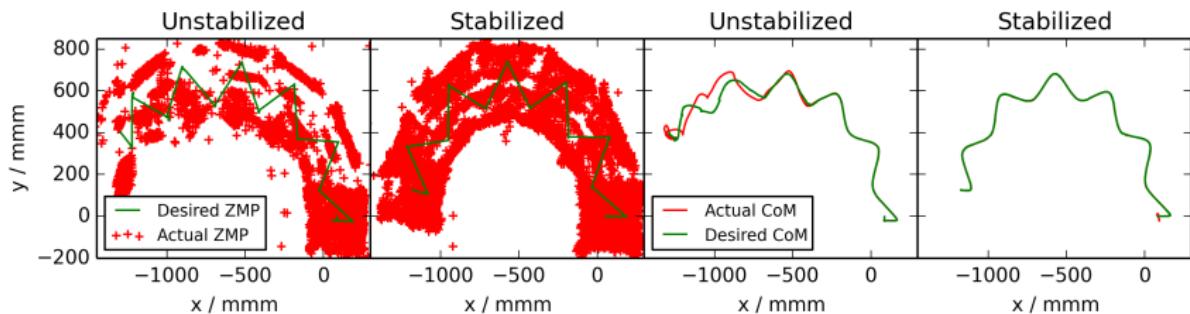


Figure: Walking in a half-circle.

# Walking with disturbances

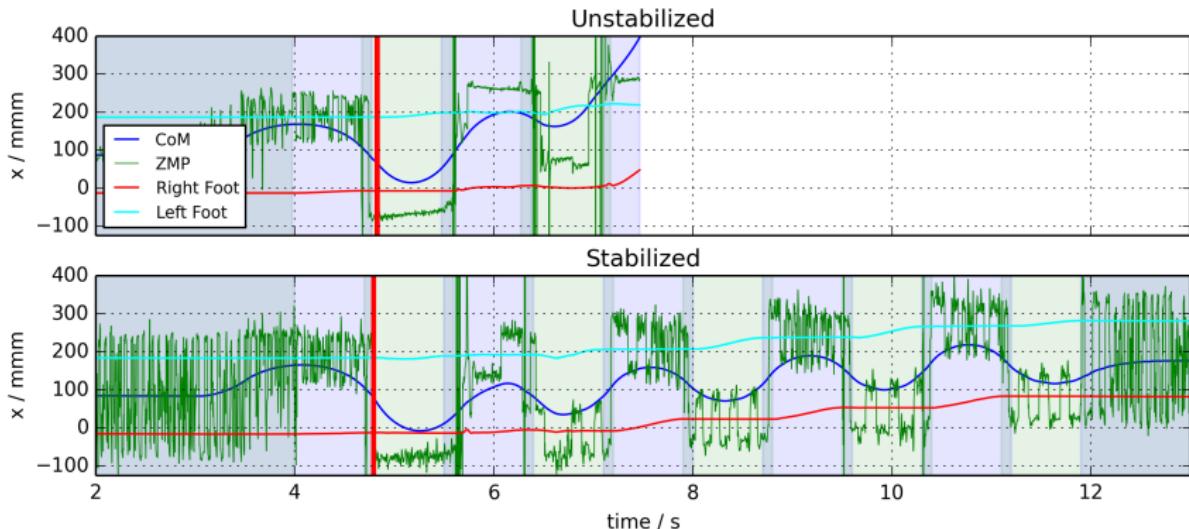
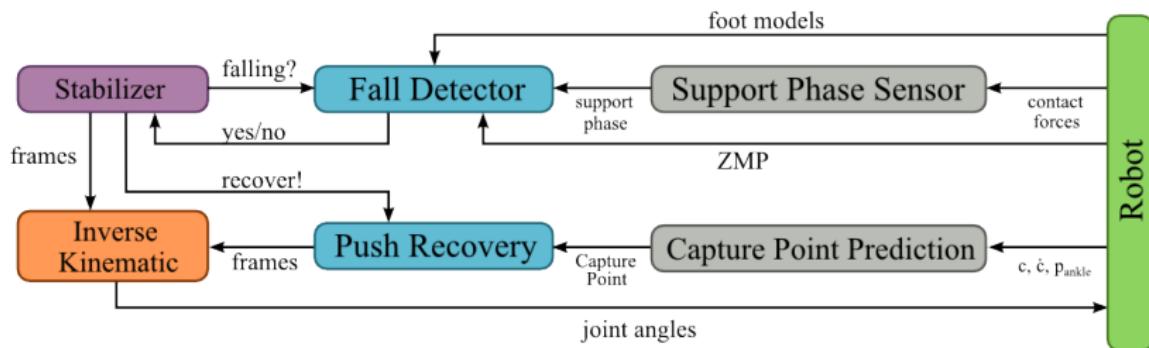


Figure: Push without stabilization

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  $t_{min}$

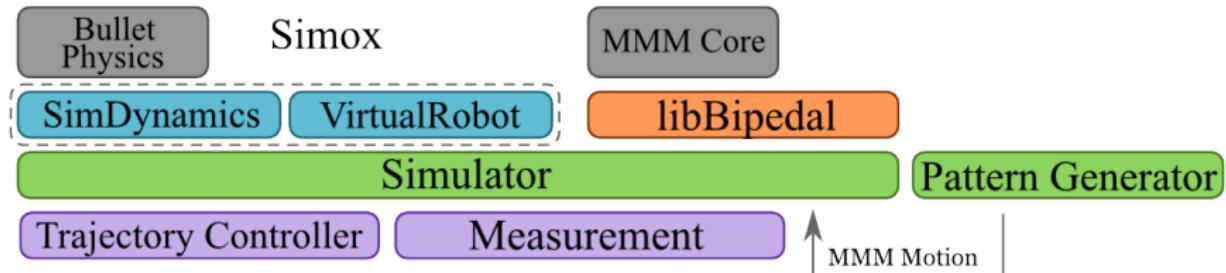


# Capture Point Video

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. → Kajita et al. [2] proposed extension of the methods implemented here to include a toe support phase
- Better push recovery: General case, use extended LIP models proposed by Pratt

# 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.