Universität Hamburg
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MIN Faculty
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Introduction to Robotics

Principles of Walking

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Technical Aspects of Multimodal Systems

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Outline

Outline (cont.)

- Enabling locomotion in difficult terrain
- Legs can be used for other things
- Necessary to integrate robots in a human environment


[26]


[27]

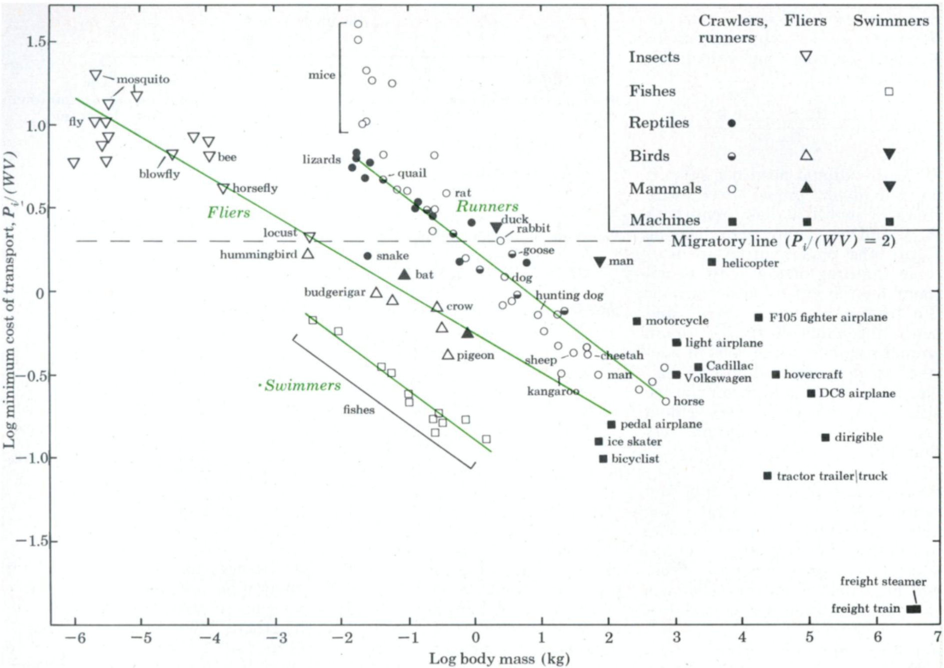
[26] http://1.bp.blogspot.com/-MhFnvPPR5V4/UmifTu4r_OI/AAAAAAAAFtI/FvJqeWu9Ahc/s1600/13-pictures-of-crazy-goats-on-cliff.jpg
[27] https://www.allposters.com

Problems

- Stability (and safety)
- Complex control
- Hardware costs
- Energy consumption

[28]

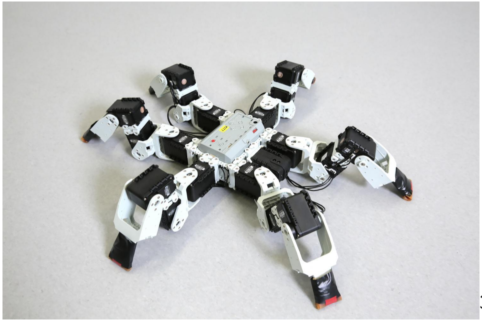
[28] https://www.wikihow.com/Recognize-the-Signs-of-Intoxication



[29] Tucker, Vance A. "The energetic cost of moving about: walking and running are extremely inefficient forms of locomotion. Much greater efficiency is achieved by birds, fish—and bicyclists." American Scientist 63.4 (1975): 413-419.

Types of Walking

- Static - Dynamic
- Passiv - Active
- 2,4,6,8,... legged
- Open loop - closed loop
- This lecture: active bipedal walking, no running


[30]

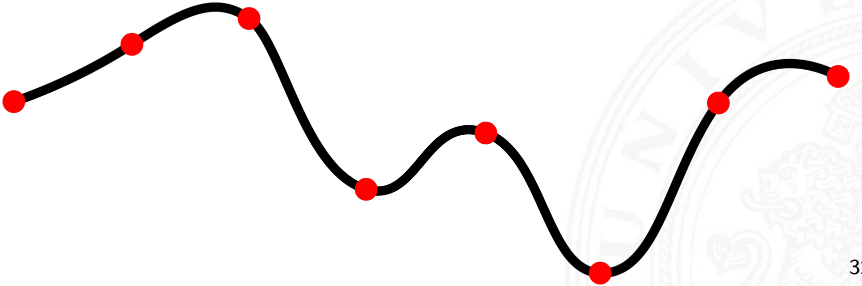

[31]

[30] https://3c1703fe8d.site.internapcdn.net/newman/gfx/news/hires/2017/1-sixleggedrob.jpg
[31] https://asl.ethz.ch/research/legged-robots.html

Video

Types of Implementing Walking

- Control Theory
- Neural Networks
- Central Pattern Generators
- Evolutional Computing
- Expert Solution


[32]

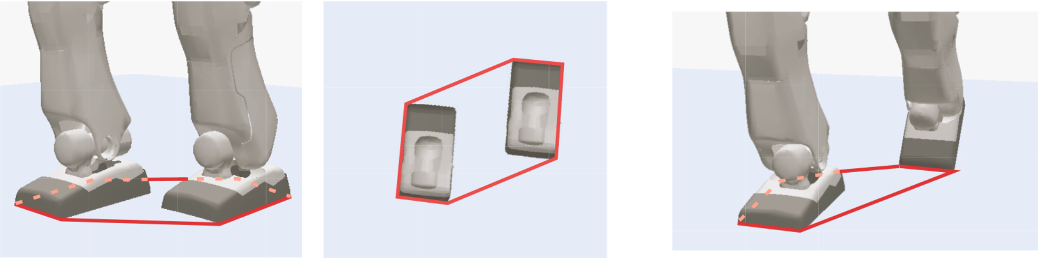
[32] https://de.wikipedia.org/wiki/Spline-Interpolation

Important Words

- Support leg/foot
- Flying leg/foot
- Torso / trunk
- Step / double step
- Sagittal / lateral

Support Polygon

- Convex hull of all ground contact points

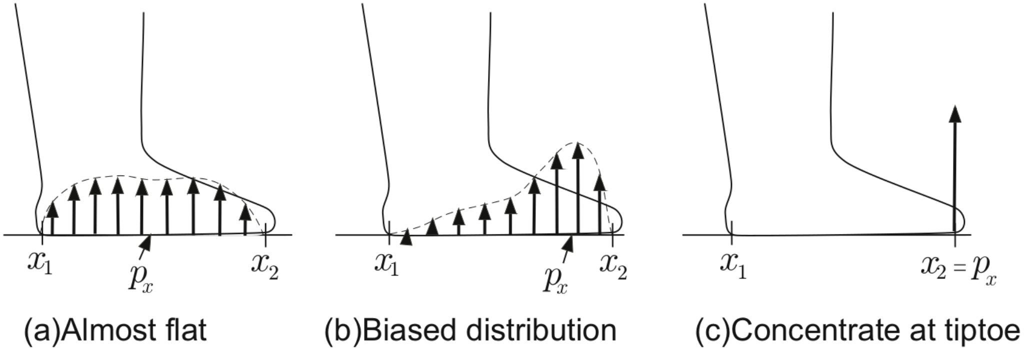


(a) Full contact of both feet (b) Partial contact [33]

[33] Introduction to Humanoid Robotics, Shuuji Kajita, 2015

Center of Pressure (CoP)

- Center of ground reaction forces
- Those can also be horizontal
- Moment becomes zero
- Equals the zero moment point (ZMP)



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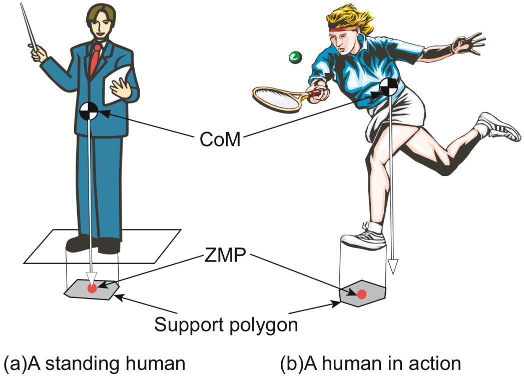
[34] Introduction to Humanoid Robotics, Shuuji Kajita, 2015

Zero Moment Point (ZMP)

- When standing, projection of CoM coincides with ZMP
- When dynamic, CoM outside of support polygon
- ZMP is always inside support polygon

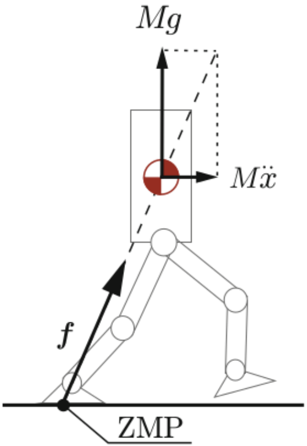


[35]

35 Introduction to Humanoid Robotics, Shuuji Kajita, 2015

ZMP

- Forces of the robot define position of ZMP
- Can it get outside of the support polygon?

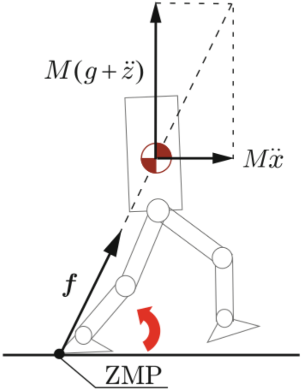


[36]

[36] Introduction to Humanoid Robotics, Shuuji Kajita, 2015

ZMP

- No! The ZMP is always in the support polygon
- If it is on an edge, the robot rotates



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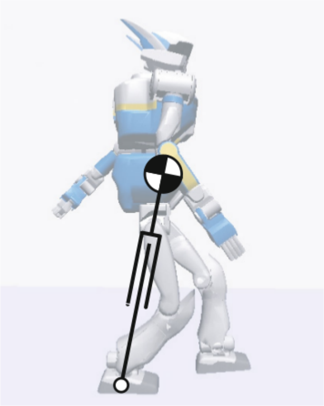
37 Introduction to Humanoid Robotics, Shuuji Kajita, 2015

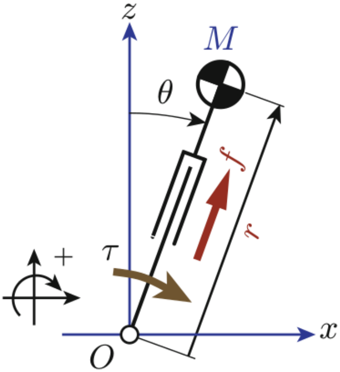
Limitations of ZMP

- Sole slips on ground
- Other parts of the robot are in contact with environment
- Ground is not perfectly level

Linear Inverted Pendulum

- Simplest model for walking robot or human
- Point mass at end of massless telescopic leg
- f: kick force, tau: torque





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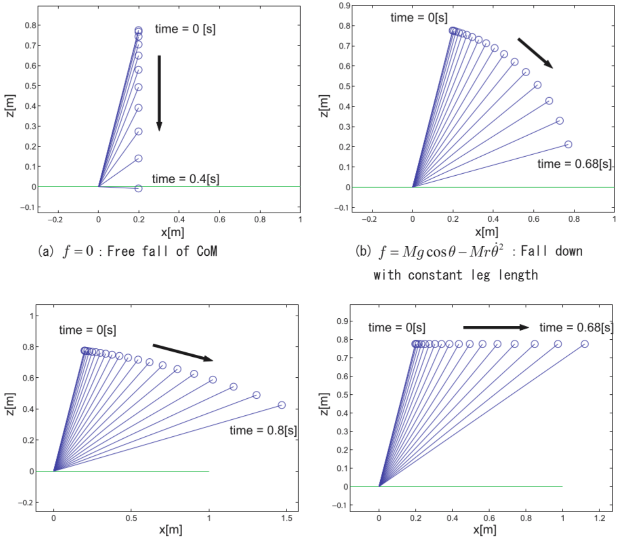
[38] Introduction to Humanoid Robotics, Shuuji Kajita, 2015



(a) $f = 0$: Free fall of CoM

(b) $f = Mg\cos\theta - Mr\dot{\theta}^2$: Fall down with constant leg length

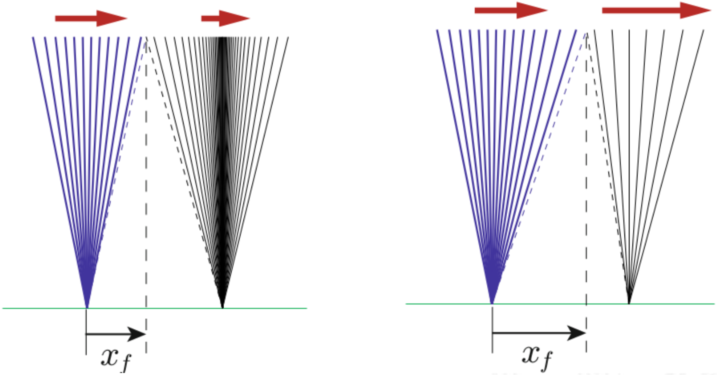
(c) $f = Mg$: Fall down and acceleration

(d) $f = Mg/\cos\theta$: CoM accelerates while keeping the initial height [39]

[39] Introduction to Humanoid Robotics, Shuuji Kajita, 2015

Support Leg Exchange

- Considering fixed step length
- Earlier touchdown of the next step results slow down
- Later touchdown of the next step results speed ups



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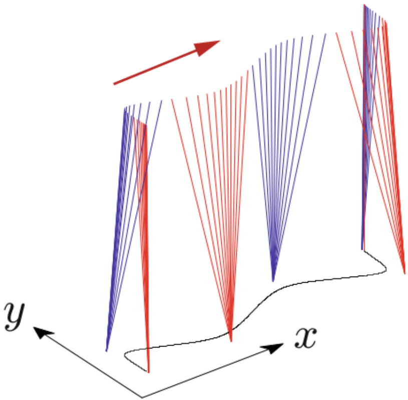
[40] Introduction to Humanoid Robotics, Shuuji Kajita, 2015

3D Support Leg Exchange

- Transfer to 3D
- Introduction of lateral movement



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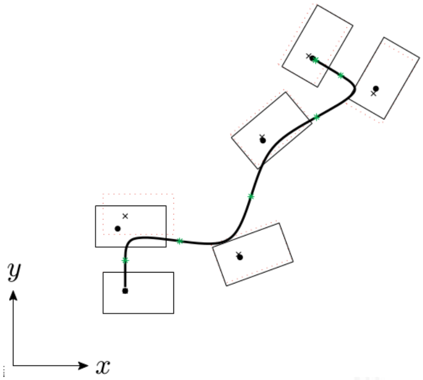
41 Introduction to Humanoid Robotics, Shuuji Kajita, 2015

Omni-directional (holonomic) Walking

- Forward (x)
- Sideward (y)
- Turn (yaw)

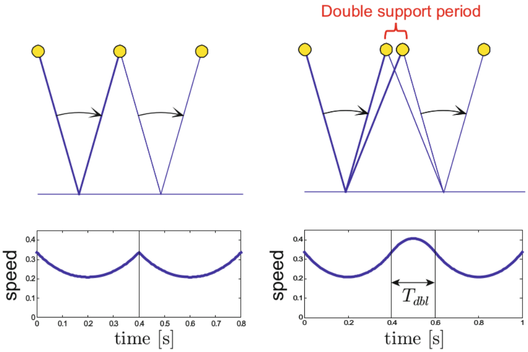


[42]

[42] Introduction to Humanoid Robotics, Shuuji Kajita, 2015

Double Support Phase

- Accelerations are extreme on support change
- Not feasible in reality
- Introduction of a double support phase



[43]

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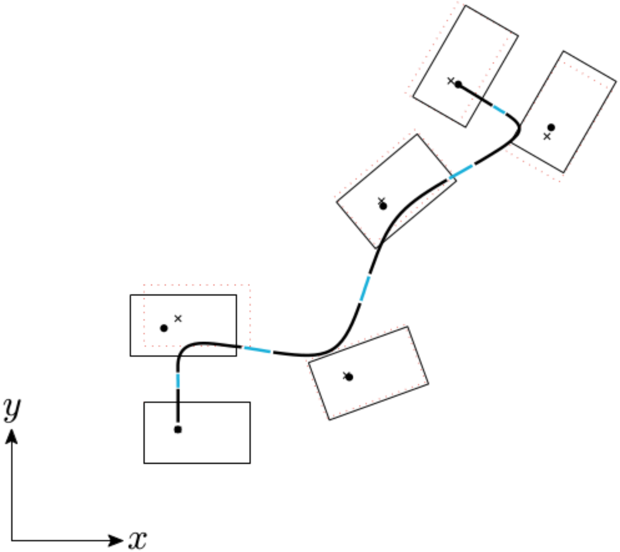
[43] Introduction to Humanoid Robotics, Shuuji Kajita, 2015

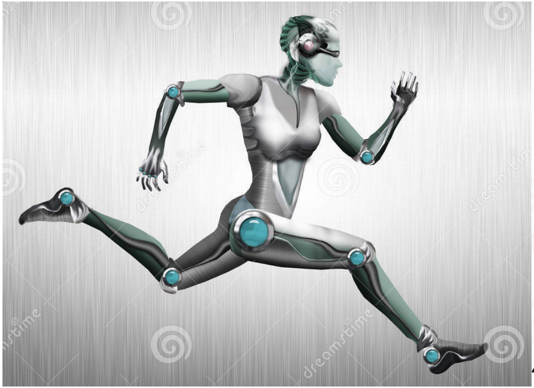
Double Support



44[44]

[44] Introduction to Humanoid Robotics, Shuuji Kajita, 2015

Zero Support

 [45]

[45] https://thumbs.dreamstime.com/z/running-robot-27653003.jpg

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- Why are we not finished yet?

Video

Detecting Instability

Which senses do you think humans use for walking?

Detecting Instability

- Sensors
  - IMU(s)
  - Force sensors on foot sole
  - 6 axis force/torque sensor in ankle
  - Joint Torques
  - Camera
- Model
  - Joint positions
  - Link masses and inertia
  - Rigidity of links (especially foot soles)

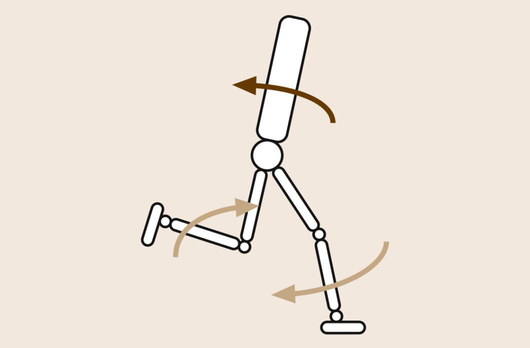
Stabilizing Approaches

- Simple stopping
- Counter movements with the arms/torso
- Change of step position (capture steps)

Video

Counter Movements with Upper Body

- Rotation around edge of support polygon
- Introduce counter force with arms/torso or flying leg
- Flying leg is mostly not usable

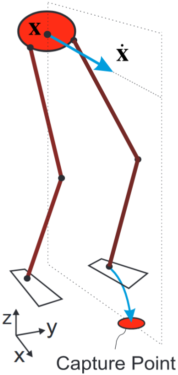

[46]

[46] Springer Handbook of Robotics, Bruno Siciliano, 2016

Video

Capture Step

- Capture point is where the robot comes to a complete stop
- Multiple capture steps may be necessary



[47]

[47] https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6094435

Video

Machine Learning

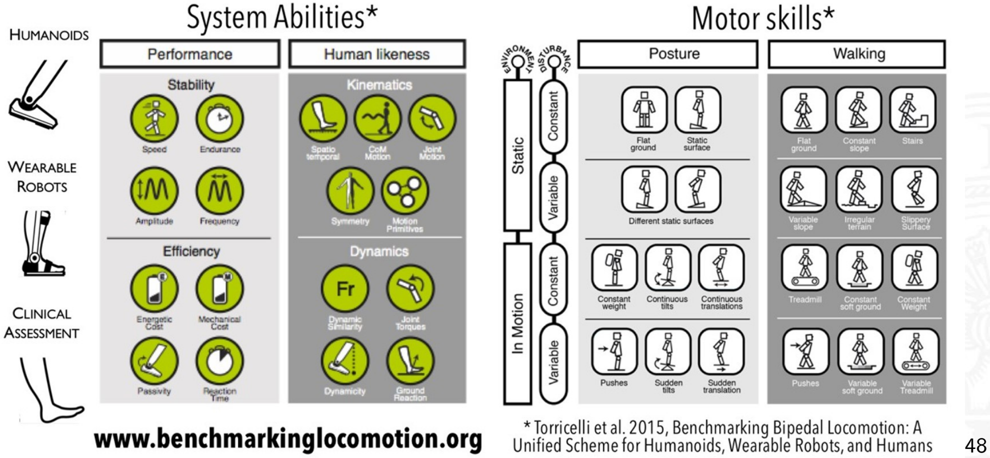
- We will not cover machine learning
- If you are interested join my lecture in "Intelligent Robotics" in the winter term
- General approaches are:
  - Learning parameter of a walking pattern generator (e.g. double support length)
  - Learning neural networks from scratch
  - Learning from demonstration
  - Artificial central pattern generators

Videos

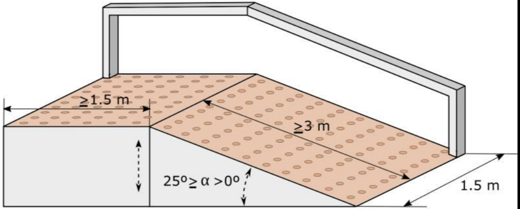
Current State of the Art

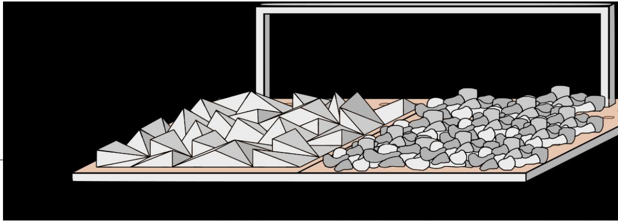
- Some very expensive robot manage to solve the problem (at least most of the time) using control theory
- Cheaper robots still struggle to achieve really stable walking
- Machine learning approaches still mostly only work in simulation (reality gap)
- Working on better comparison between approaches, e.g. EuroBench

BALANCE KOROIBOT BioMot WALK-MAN



[48] http://eurobench2020.eu/abstract/motivation-background/





[49] Eurobench Guide for Applications

Full Body Motion

- Small overview of full body motions
- Examples are: walking with hand on handrail or standing up
- Higher complexity since all limbs are involved
- Breaks assumptions that are often made for normal walking
- Motions can be periodic or non periodic

Walking with Hand Contacts

- Using handrail, pushing cart, opening door, holding hands, using walking stick, collaborative carrying
- Introduces additional forces on the robot
- Support polygon maybe totally different
- More complex models have to be used
- Currently mostly used approach: quadratic programming
  - Solve problem of optimizing a quadratic function with multiple linear constrains
  - Use rigid body dynamics together with a model
  - Problems
    - Model is not perfect
    - If caring an object, you need a model of it
    - Robot is maybe not perfectly rigid

Non Periodic Motions

- Simpler due to known start and end
- Examples
  - Standing up
  - Kicking
  - Grasping
  - Waving

Implementing Non Periodic Motions

- Keypoint teach in
  - Put robot into key positions manually
  - Save joint positions at these points
  - Interpolate
  - Useful for simple motions (e.g. waving) or static robots
- Learning from demonstration
  - Either demonstrate on the robot itself or by using motion capture
  - Normally more than one demonstration
  - Not just simply replaying
- Cartesian splines
  - Define trajectories of the limbs with Cartesian splines manually
  - Comparably easy to do for humans (much better than joint space)
  - Use inverse kinematics to compute joint goals
  - Splines configurable with few parameters
  - Optimize parameters, e.g. using tree-structured parzen estimator

Implementing Non Periodic Motions

- DeepLearning
  - Just let it learn in simulation till it works
  - Put it on the robot and hope for the best
  - Reality gap
- Control Theory
  - Have an open loop trajectory, e.g. from teach in or LIPM
  - Use a stability criterion, e.g. ZMP
  - Adjust joint goals with controller, e.g. PID
- More on the learning aspect in the intelligent robotics lecture

Questions

Questions?

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