Chair of Applied Mechanics
Department of Mechanical Engineering
Technical University of Munich

Versatile and Robust Walking in Uneven Terrains

Workshop: Dynamic Legged Locomotion in Realistic Terrains

ICRA 2018

25 May 2018

Daniel Rixen

Chair of Applied Mechanics
Department of Mechanical Engineering
Technical University of Munich

Team

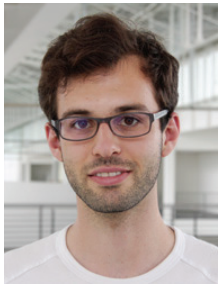
DFG Deutsche Forschungsgemeinschaft

Daniel Rixen

Nora-Sophie Staufenberg

Philipp Seiwald

Felix Sygulla



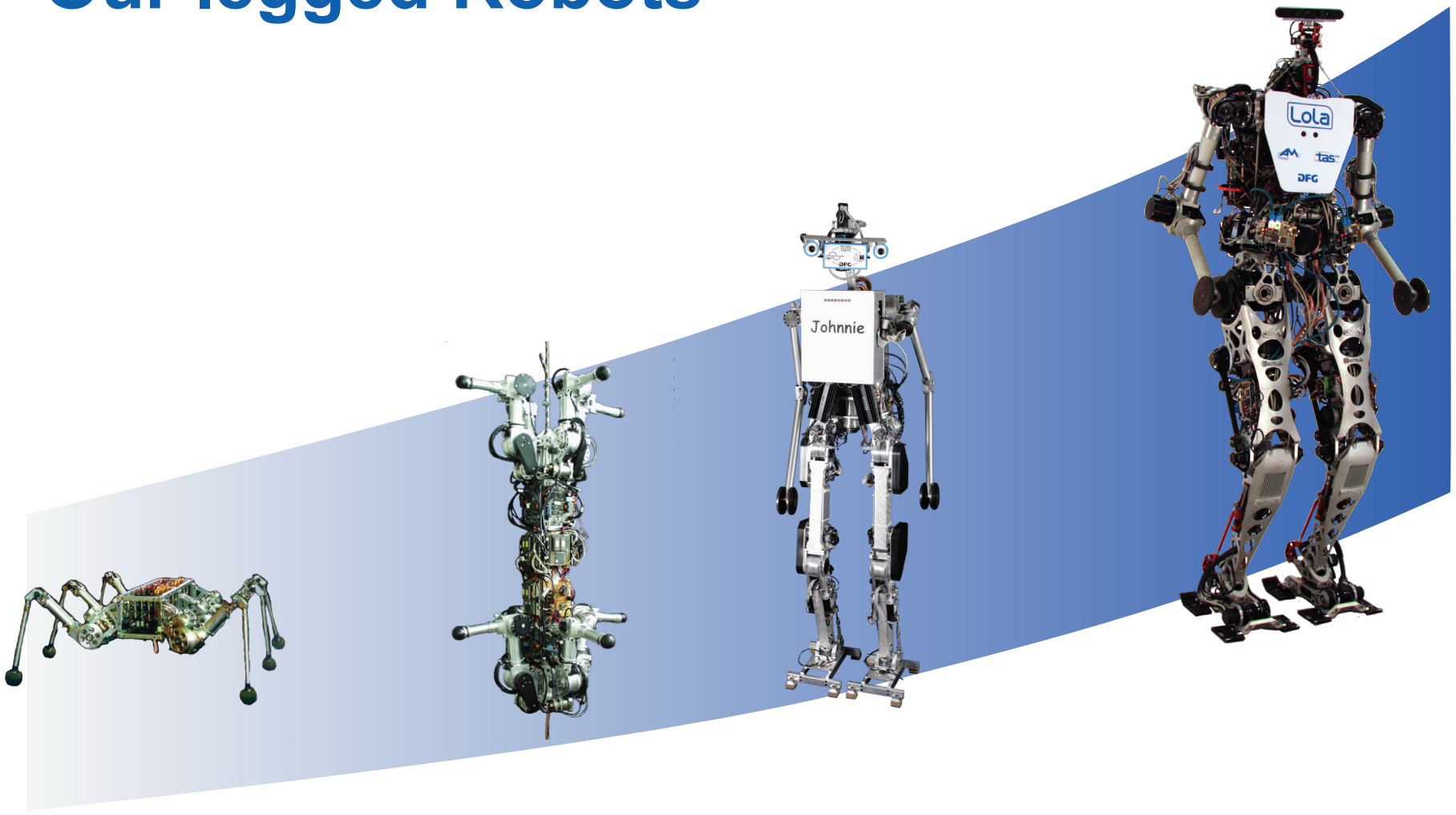
Robert Wittmann

Arne-Christoph Hildebrandt

Daniel Wahrmann

Chair of Applied Mechanics
Department of Mechanical Engineering
Technical University of Munich

Our legged Robots

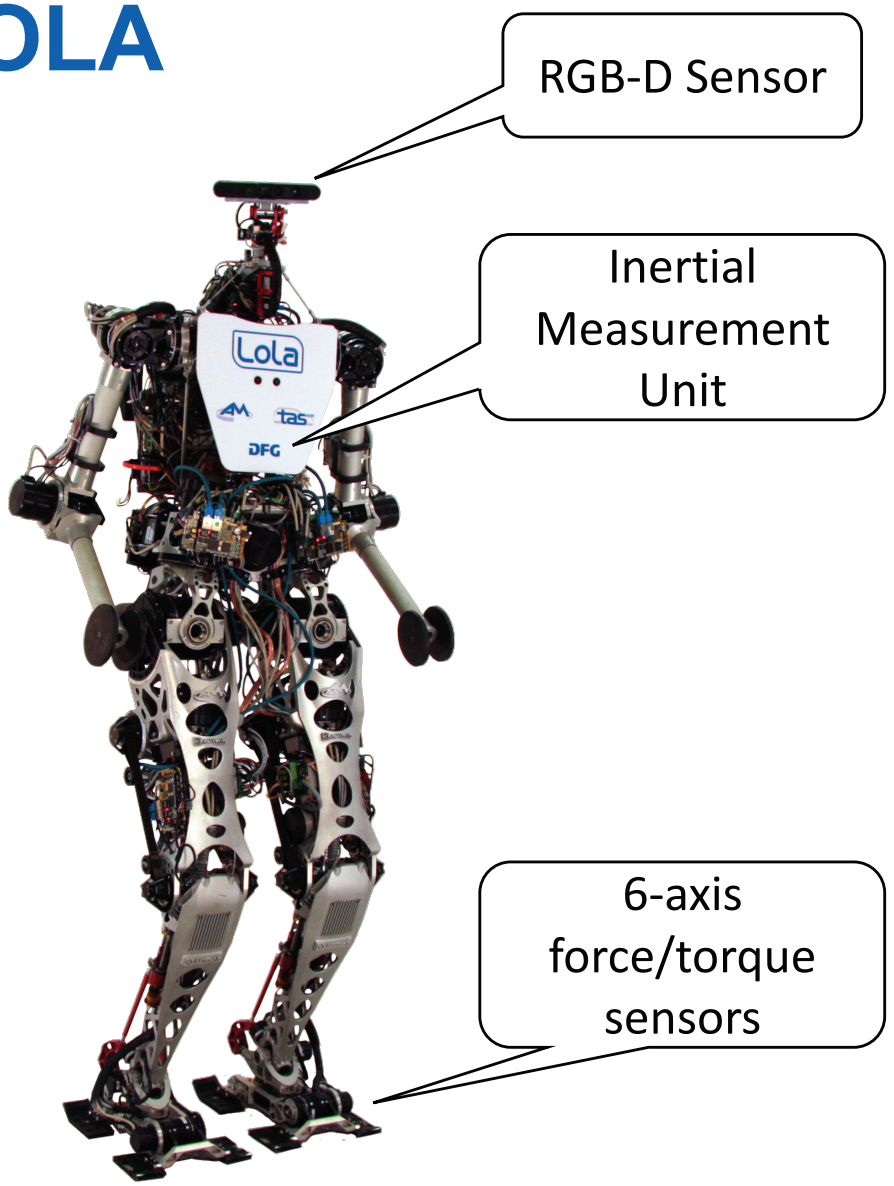


1993 1995 1997 - 2003 2001 - today

Our legged Robot LOLA

Specification:

- ~ 1.8 m
- ~ 60 kg
- max. 3.34 km/h
- 24 electric joint drives
- Position-controlled
- EtherCAT Bus

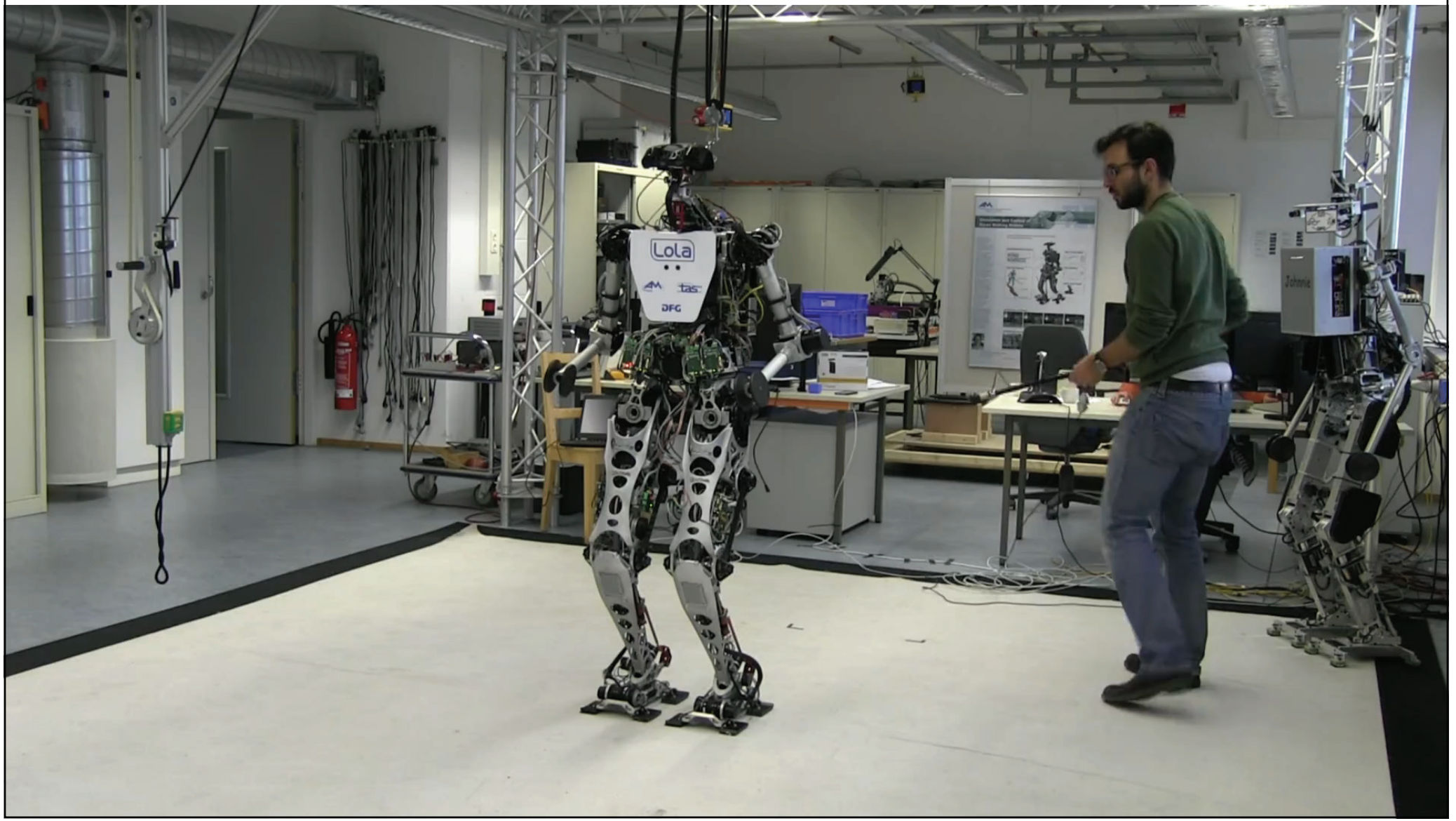


Chair of Applied Mechanics
Department of Mechanical Engineering
Technical University of Munich

See videos on

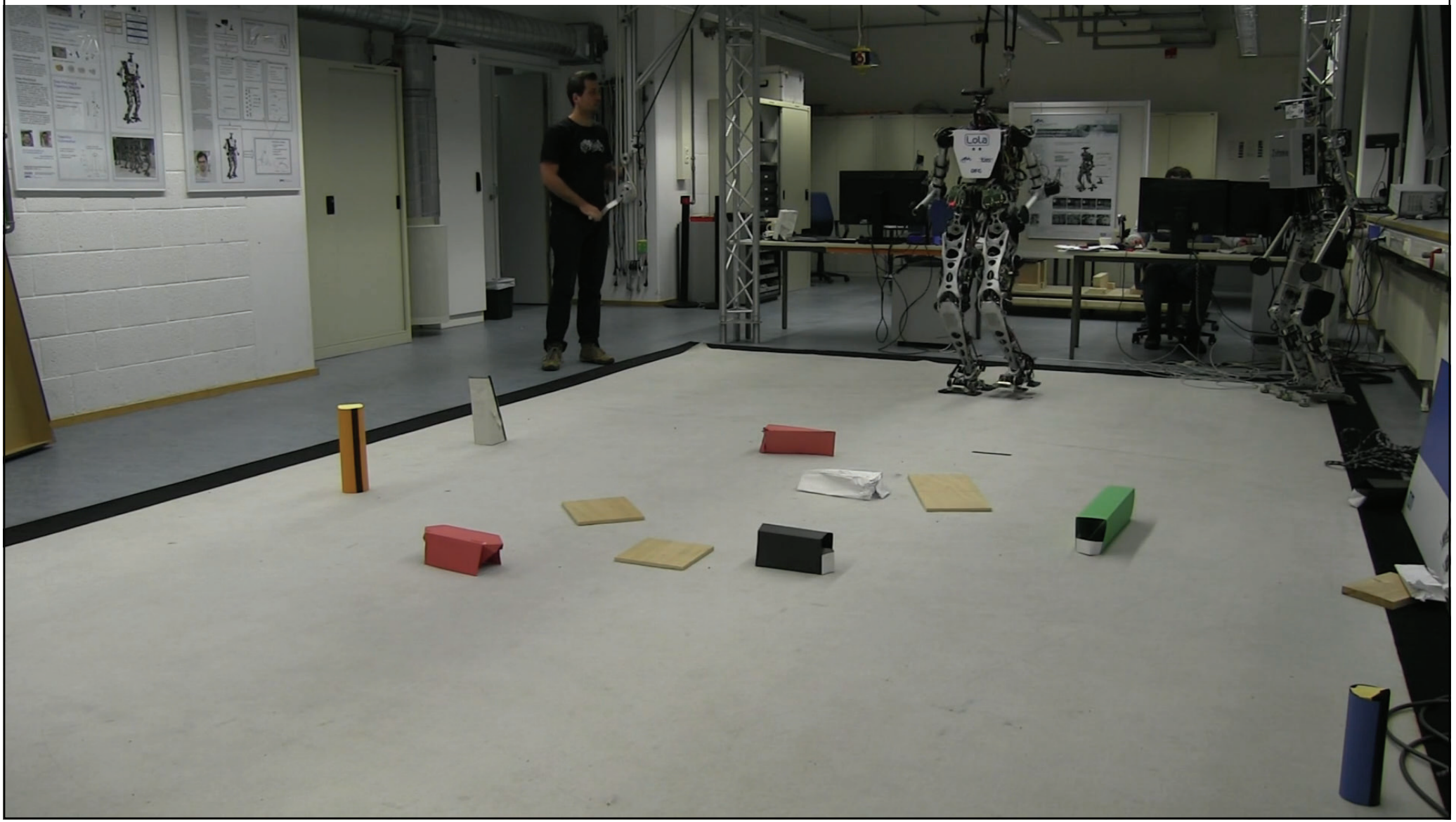
https://www.youtube.com/watch?v=EeDR1UNDpIY

Disturbance Rejection



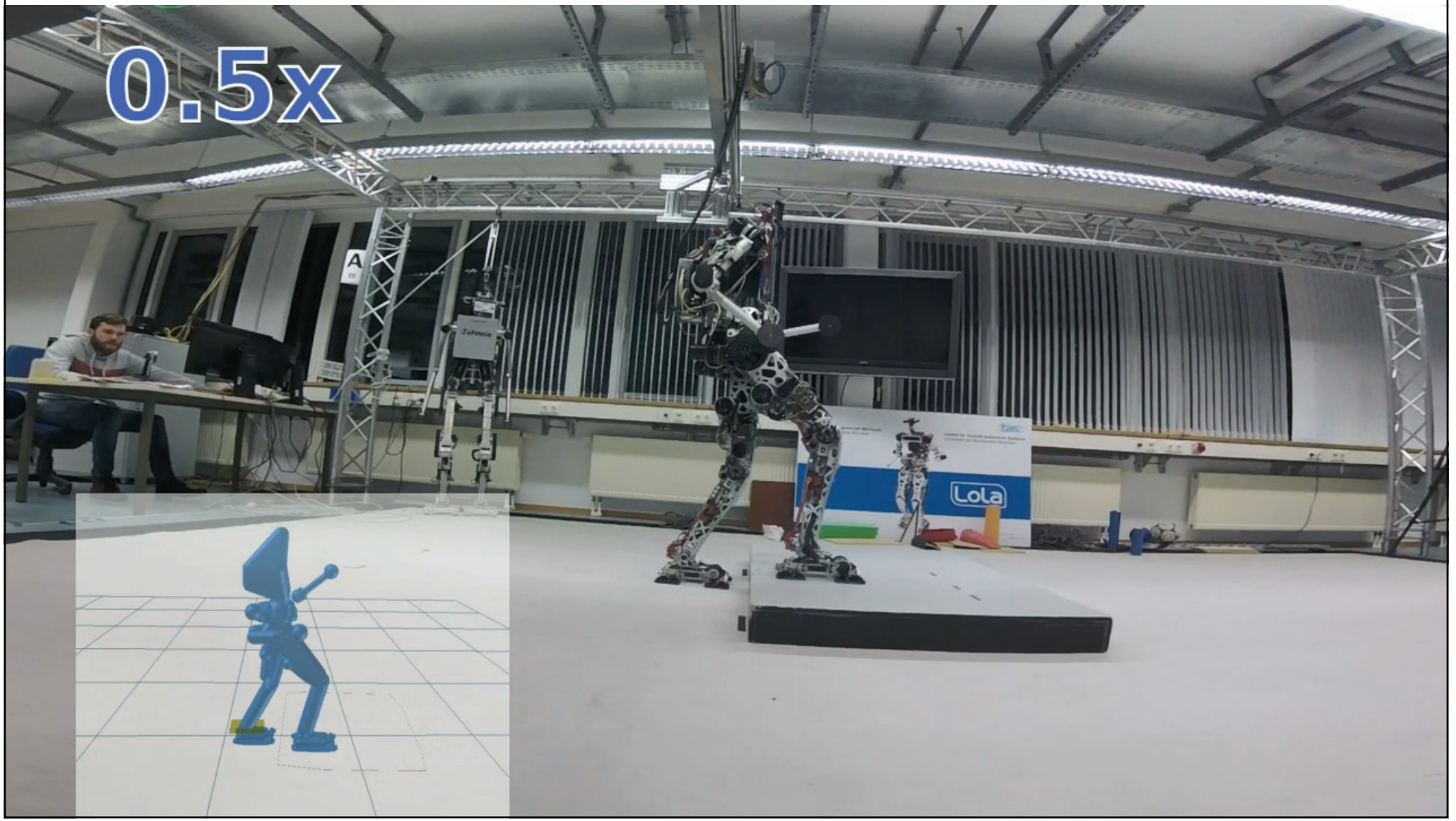
Chair of Applied Mechanics
Department of Mechanical Engineering
Technical University of Munich

Obstacle Avoidance

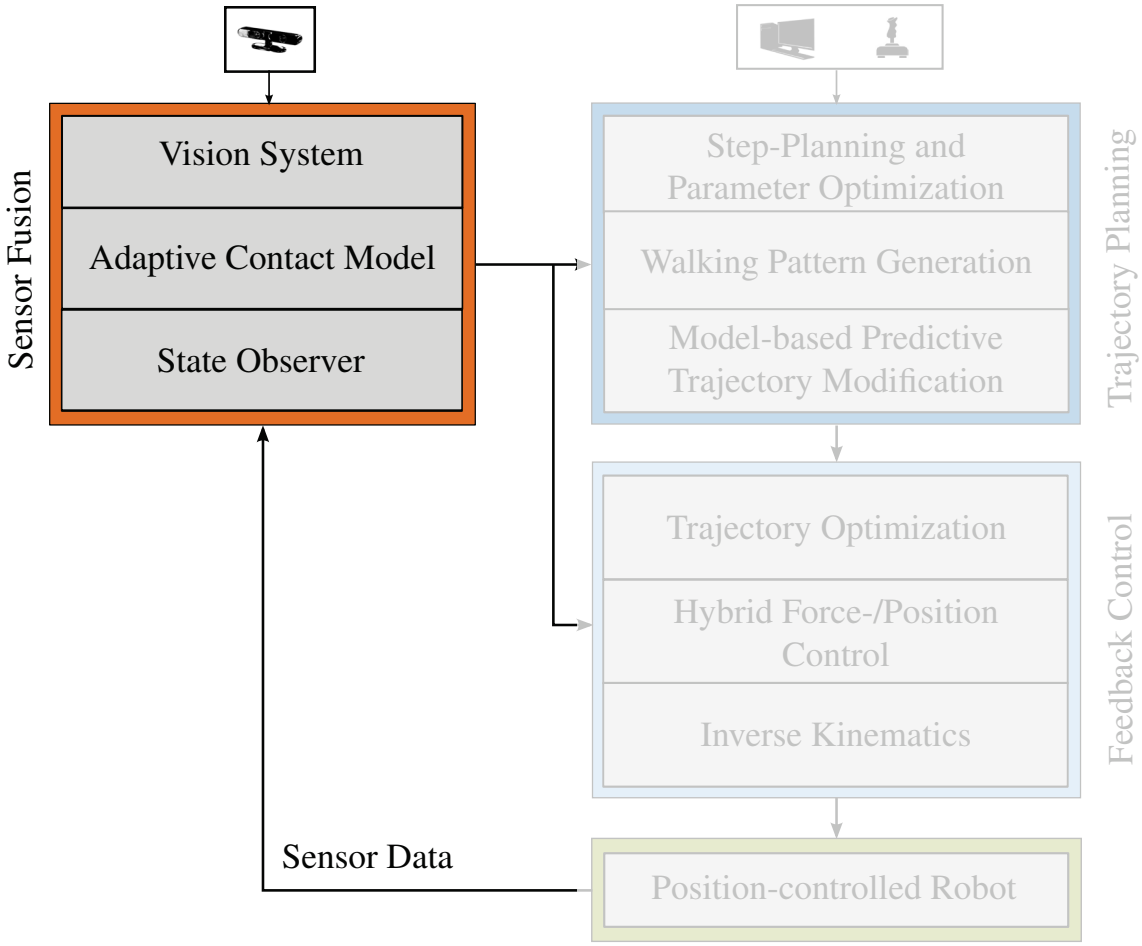


Chair of Applied Mechanics
Department of Mechanical Engineering
Technical University of Munich

Platforms



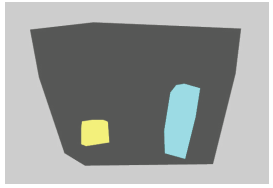
Control System



Vision System

Surface Approximation

- Segmentation
- Clustering
- Approximation
- Tracking



Plane Recognition

not-so-RANSAC

http://github.com/am-lola/lepp3

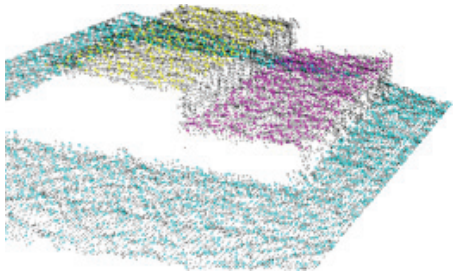
Obstacle Approximation

- Segmentation
- Clustering
- Approximation
- Tracking

Wahrmann et al.: *Vision-Based 3D Modeling of Unknown Dynamic Environments for Real-Time Humanoid Navigation*, in International Journal of Humanoid Robotics, submitted

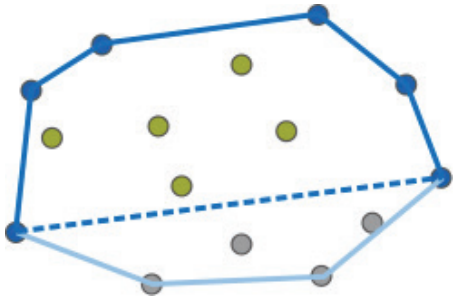
Chair of Applied Mechanics
Department of Mechanical Engineering
Technical University of Munich

Vision System - Surfaces



Euclidean Clustering

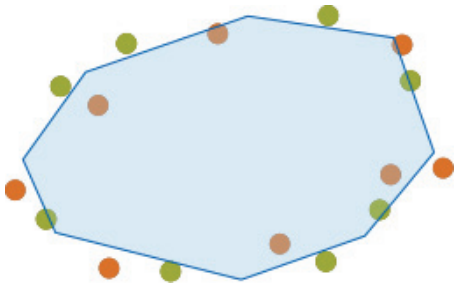
Classification based on plane inclination



Polygon Approximation

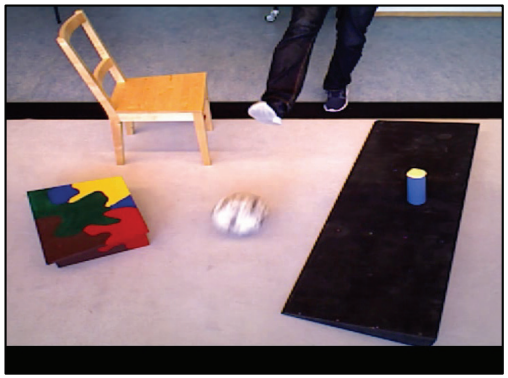
Quickhull Algorithm

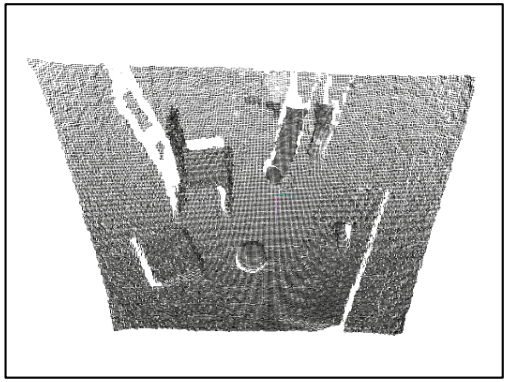
Iterative reduction to a n-sided polygon

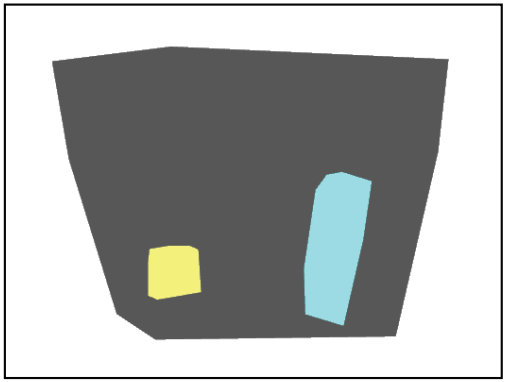


Polygon Tracking

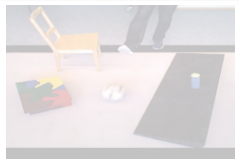
Geometric low-pass filter

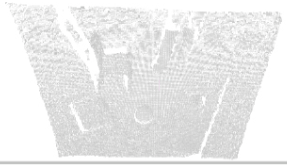






Vision System





Surface Approximation

- Segmentation
- Clustering
- Approximation
- Tracking

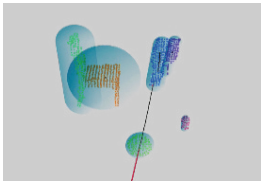
Plane Recognition

not-so-RANSAC

http://github.com/am-lola/lepp3

Obstacle Approximation

- Segmentation
- Clustering
- Approximation
- Tracking

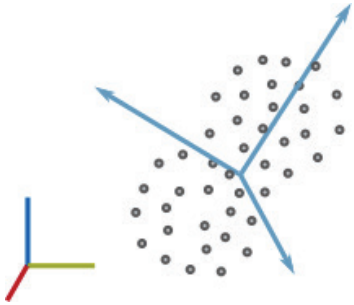


Wahrmann et al.: *Vision-Based 3D Modeling of Unknown Dynamic Environments for Real-Time Humanoid Navigation*, in International Journal of Humanoid Robotics, submitted

Vision System - Obstacles

Gaussian Clustering

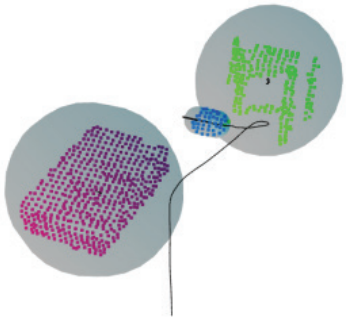
- „Gaussian Mixture Models“
- Probabilistic fit of a 3D normal distribution



„Swept-Sphere-Volumes“ (SSVs)

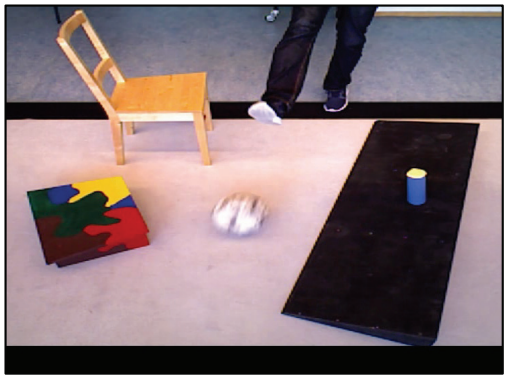
Approximation

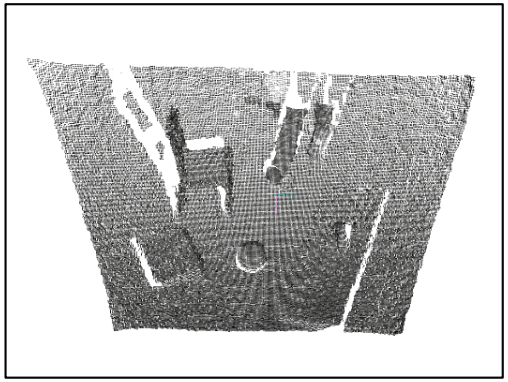
- Inertia tensor analysis (PAD)
- Main moments of inertia

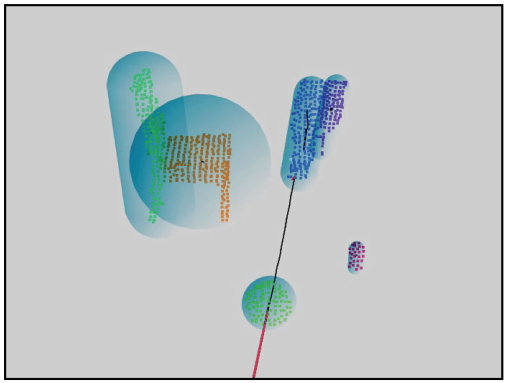


Obstacle-Tracking

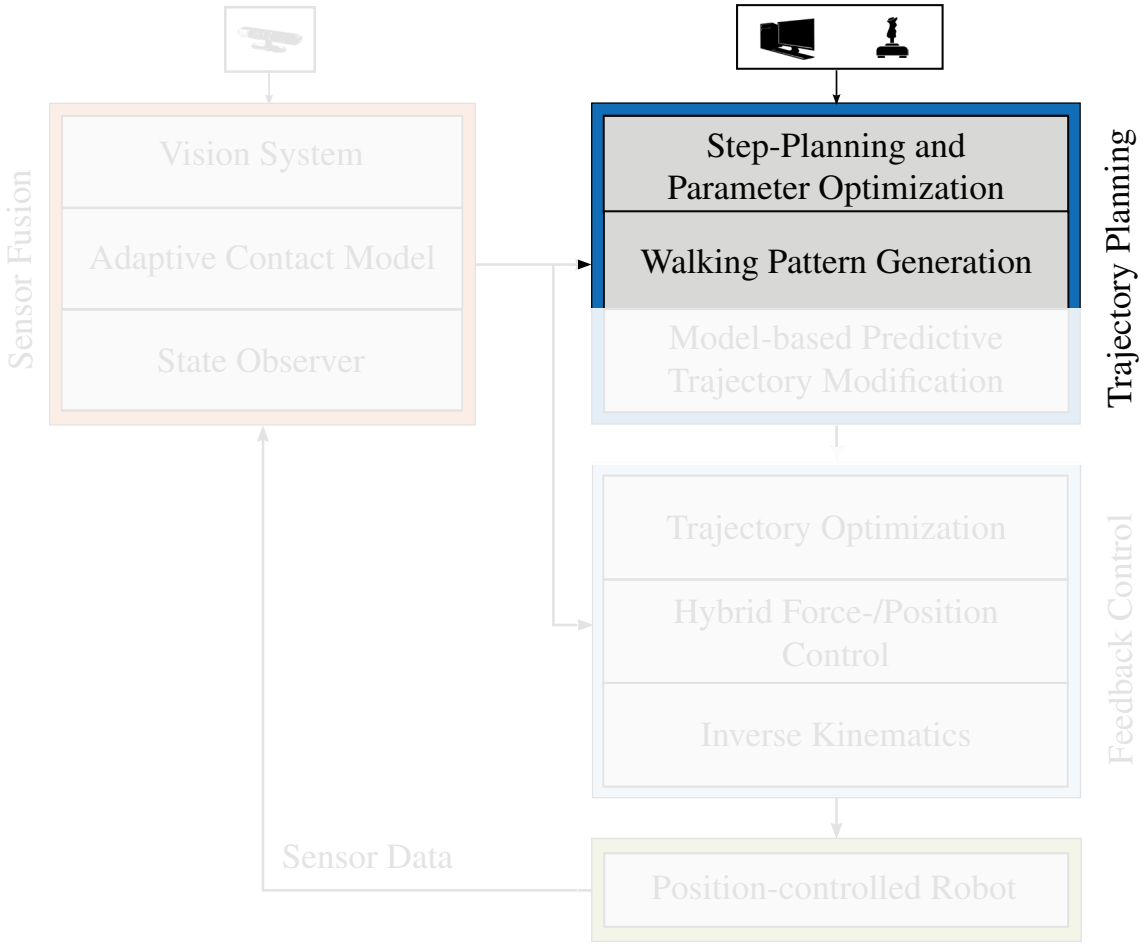
- Kalman-Filter on the obstacle’s centroid with constant $\dot{x}$ and Gaussian noise on x and $\dot{x}$







Control System



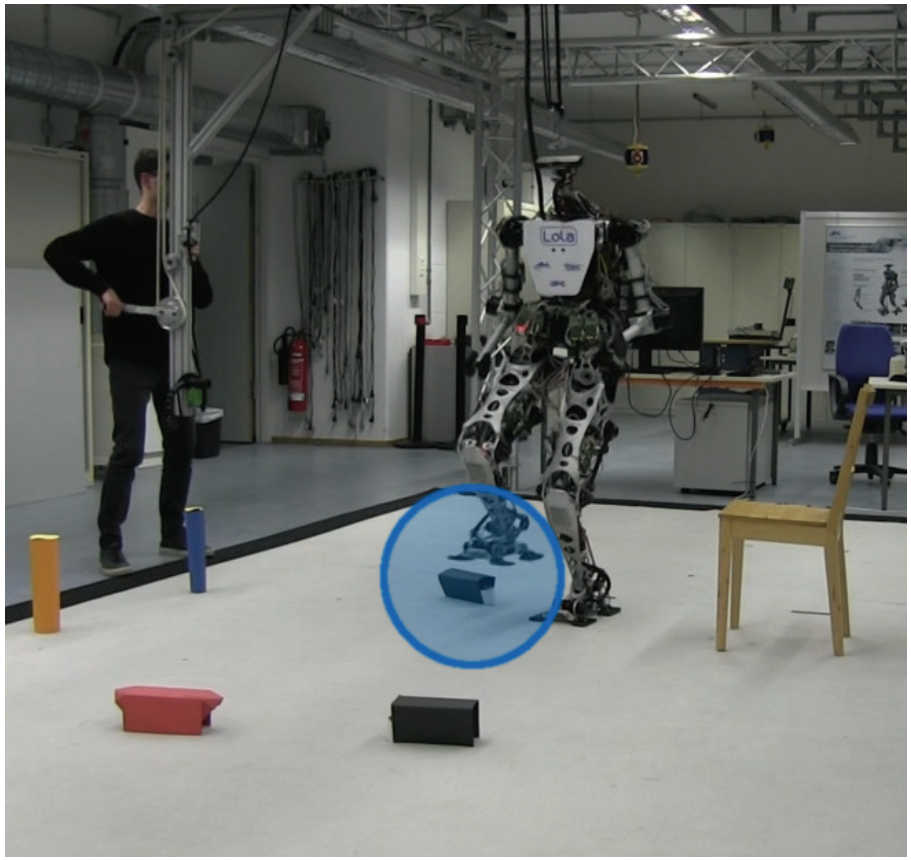
Step Planning - Motivation

Collision avoidance

- … by bypassing
- … by stepping over

Challenges

- Dynamic environments
- Real-time requirements



Details:

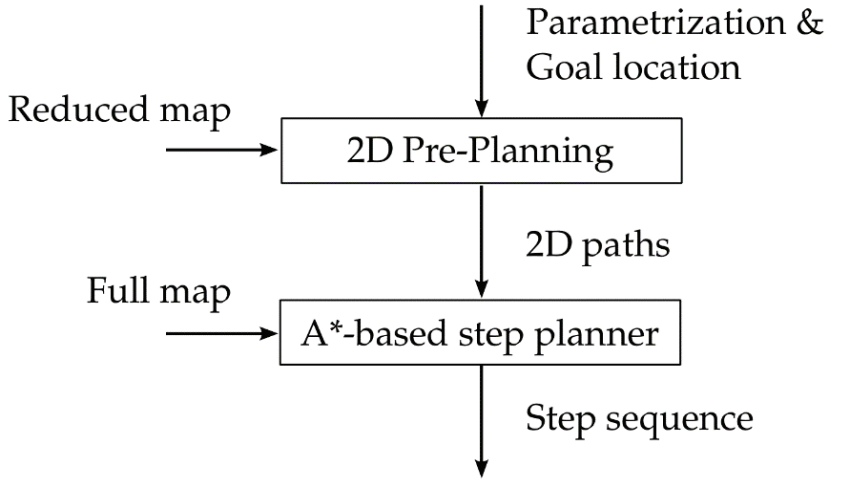
see **Hildebrandt et al.**: *Real-Time Path Planning in Unknown Environments for Bipedal Robots*, in IEEE Robotics and Automation Letters, Vol. 2, Nr. 4, Oct. **2017**

Chair of Applied Mechanics
Department of Mechanical Engineering
Technical University of Munich

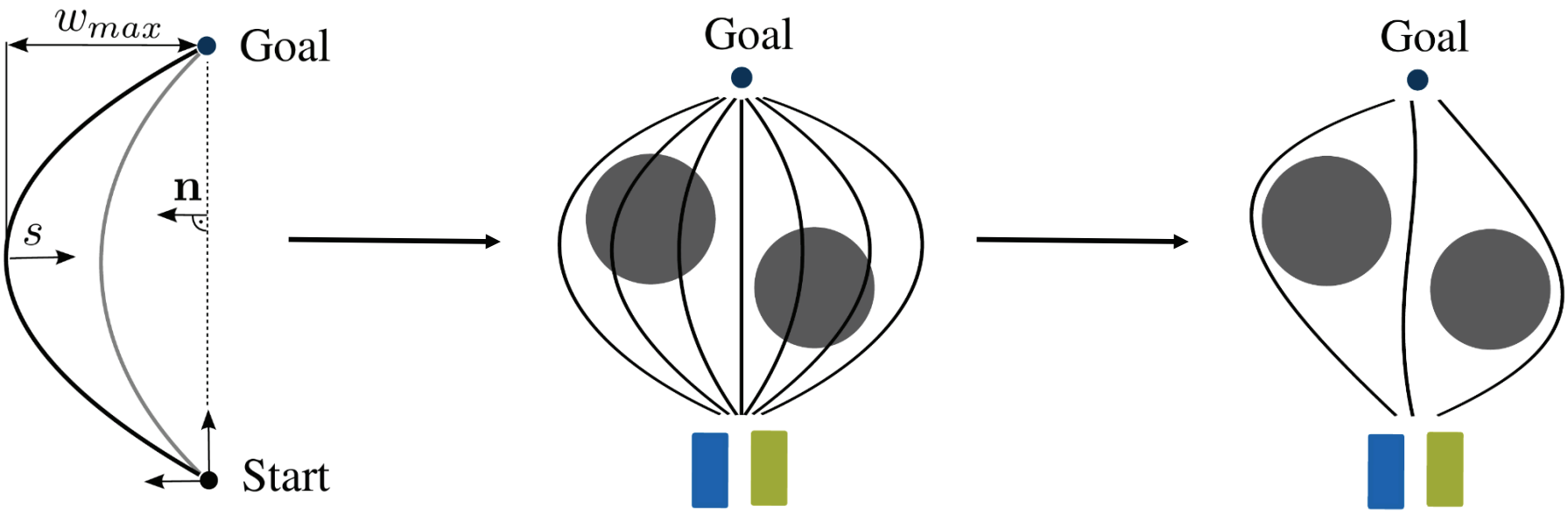
Step Planning - Approach

Two-level approach

1. Pre-planning continuous paths
2. A*-based discrete step-planner



1. Level: Pre-planning



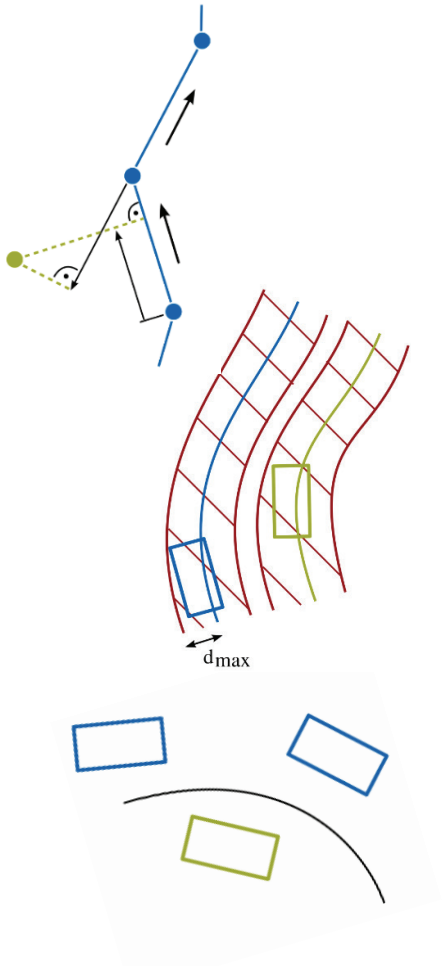
Chair of Applied Mechanics
Department of Mechanical Engineering
Technical University of Munich

Step Planning - Graph-Based Search

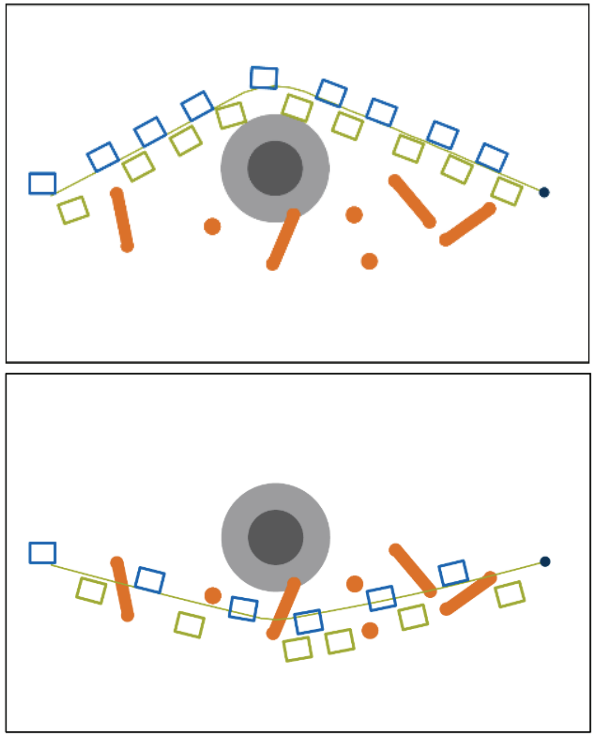
2. Level: Discrete step-planner – A*

Methods:

- Heuristic
  - …stay near to path
- Restriction
  - …of search space
- Reduction
  - …of search space (fixed angle)



Parallel evaluation of solutions possible!



Trajectory Planning

Parameter Optimization

… global optimization for next step, considering kinematic limitations

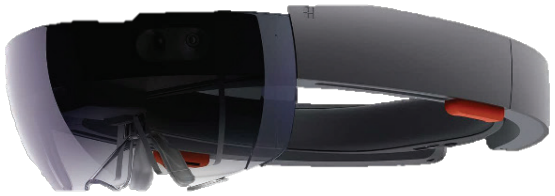
see **Hildebrandt et al**.: *Real-Time Predictive Kinematic Evaluation and Optimization for Biped Robots*, in IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), **2016**

Reactive Collision Avoidance

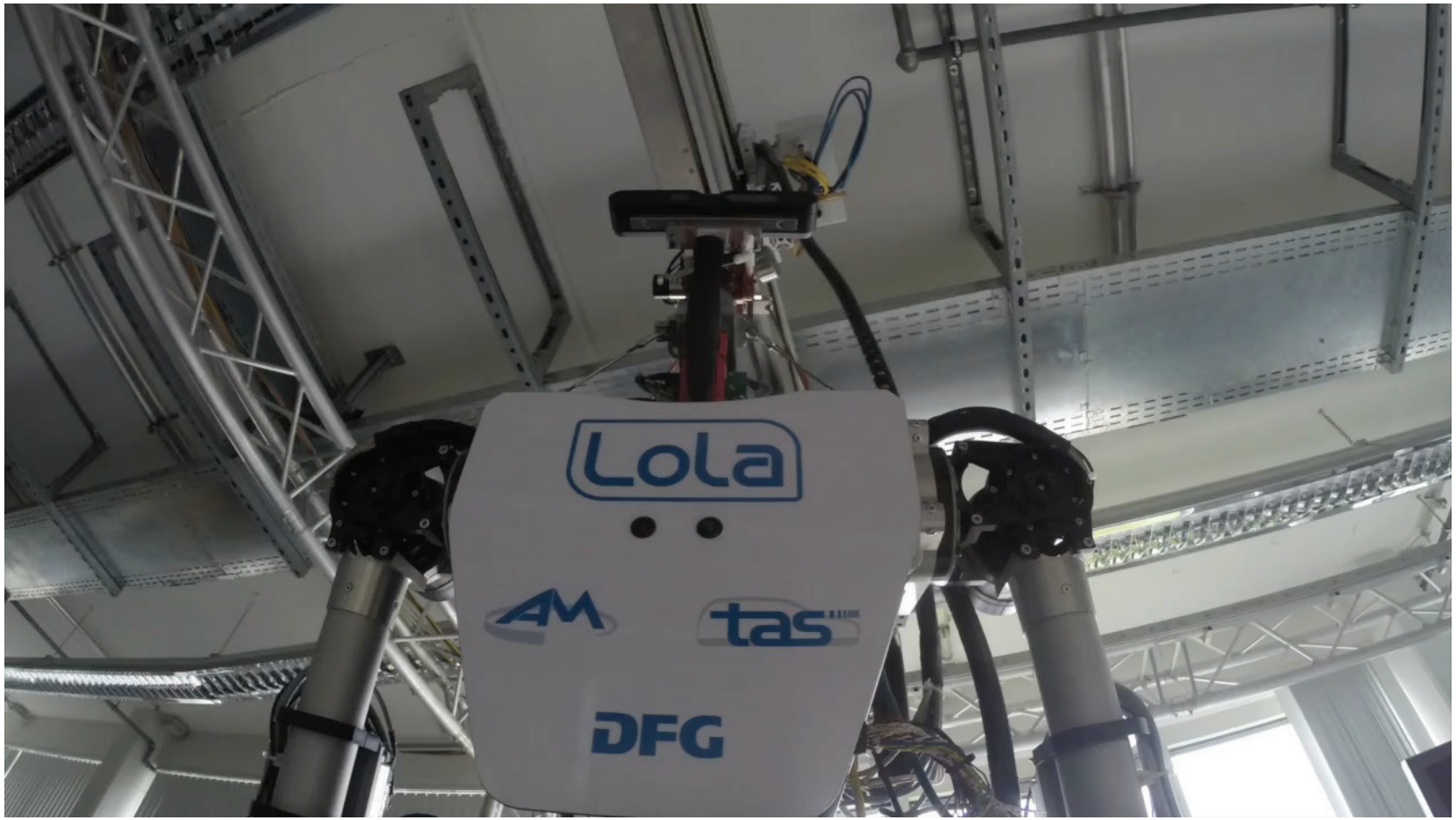
…modify foot motion for current step

see **Hildebrandt et al**.: *Real-Time 3D Collision Avoidance for Biped Robots*, in IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), **2014**

A nice debugging tool - HoloLens for Lola (HoLola)

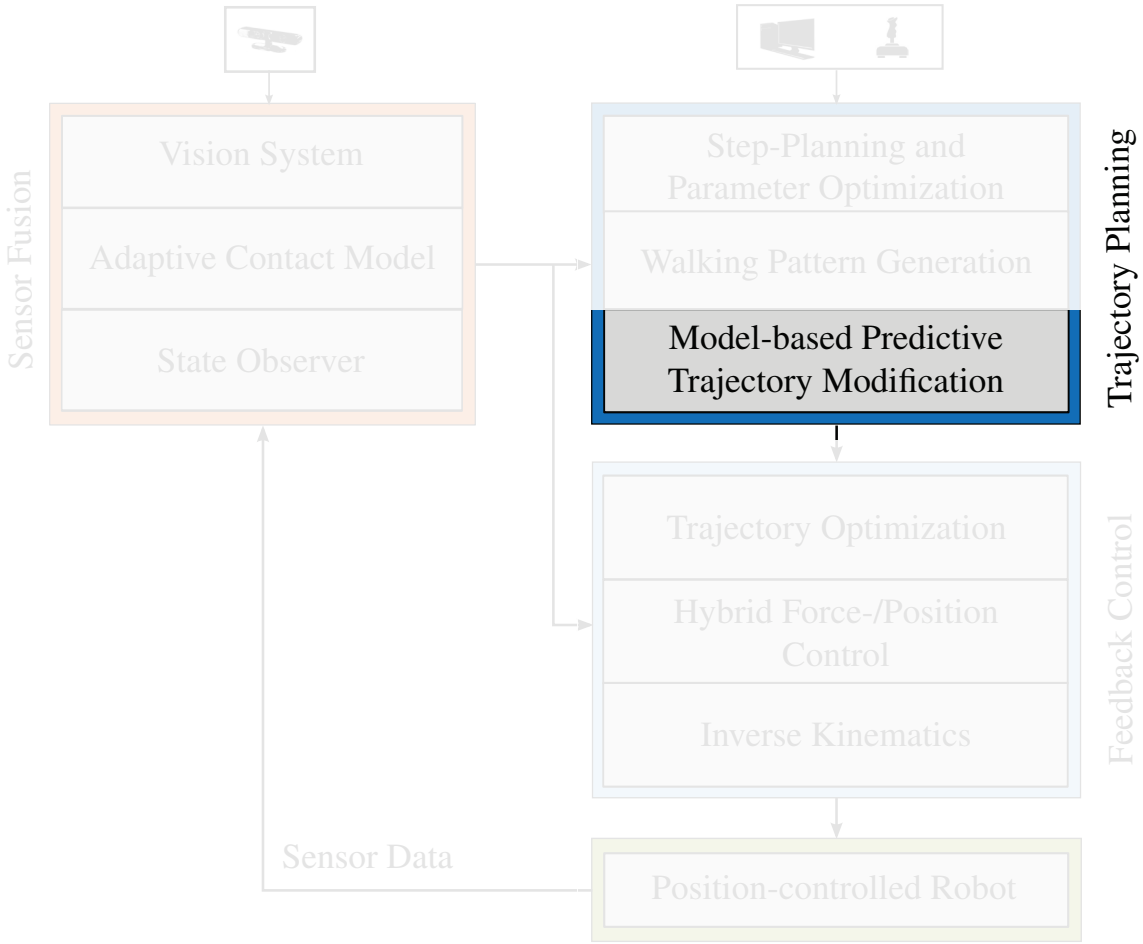


http://github.com/am-lola/HoLola



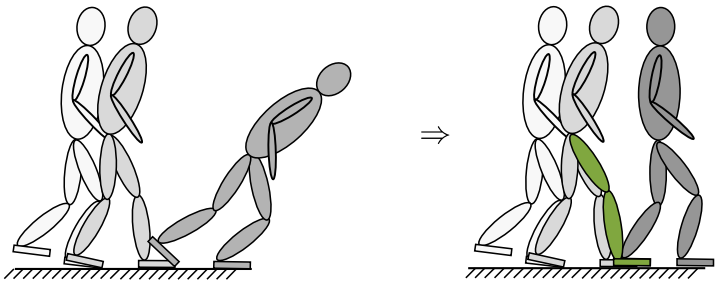
Chair of Applied Mechanics
Department of Mechanical Engineering
Technical University of Munich

Control System

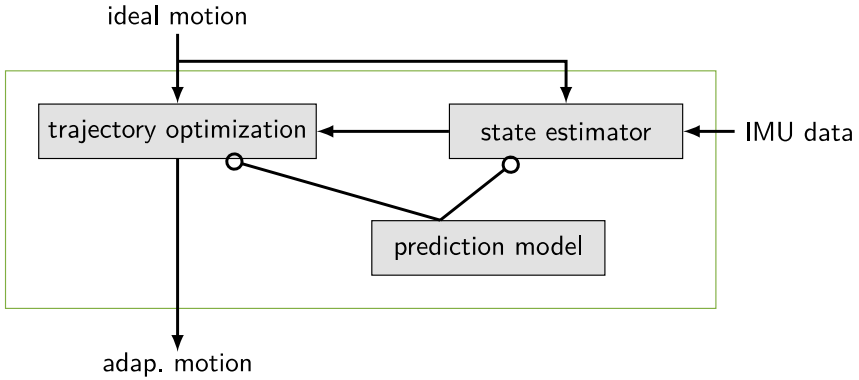


Chair of Applied Mechanics
Department of Mechanical Engineering
Technical University of Munich

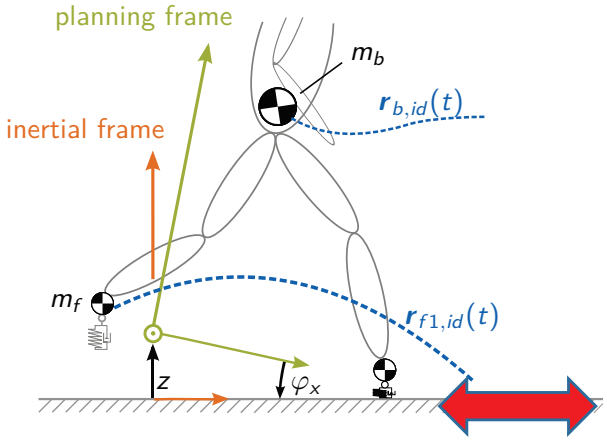
Disturbance Rejection



Trajectory Adaptation



Dynamic Prediction Model

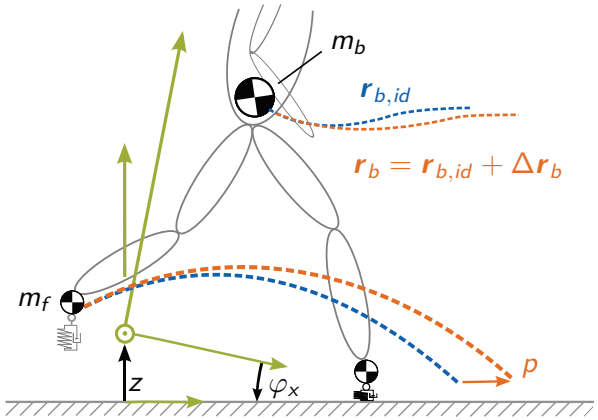


Model Properties:

- nonlinear & planar
- 3 point masses
- 2 unilateral contacts
- 2 passive dofs
- with local contact force control

Disturbance Rejection

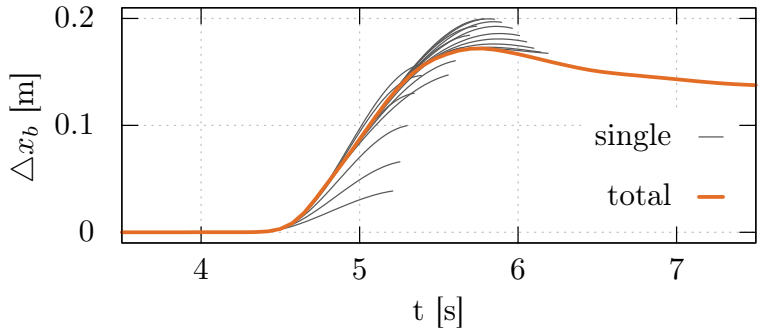
- Real-Time solution with conjugate gradient method
- Receeding horizon with 50 Hz
- 3 iterations take max. 3.5 ms



modifications:

- final swing foot position p
- CoG trajectory $\Delta r_b(t)$

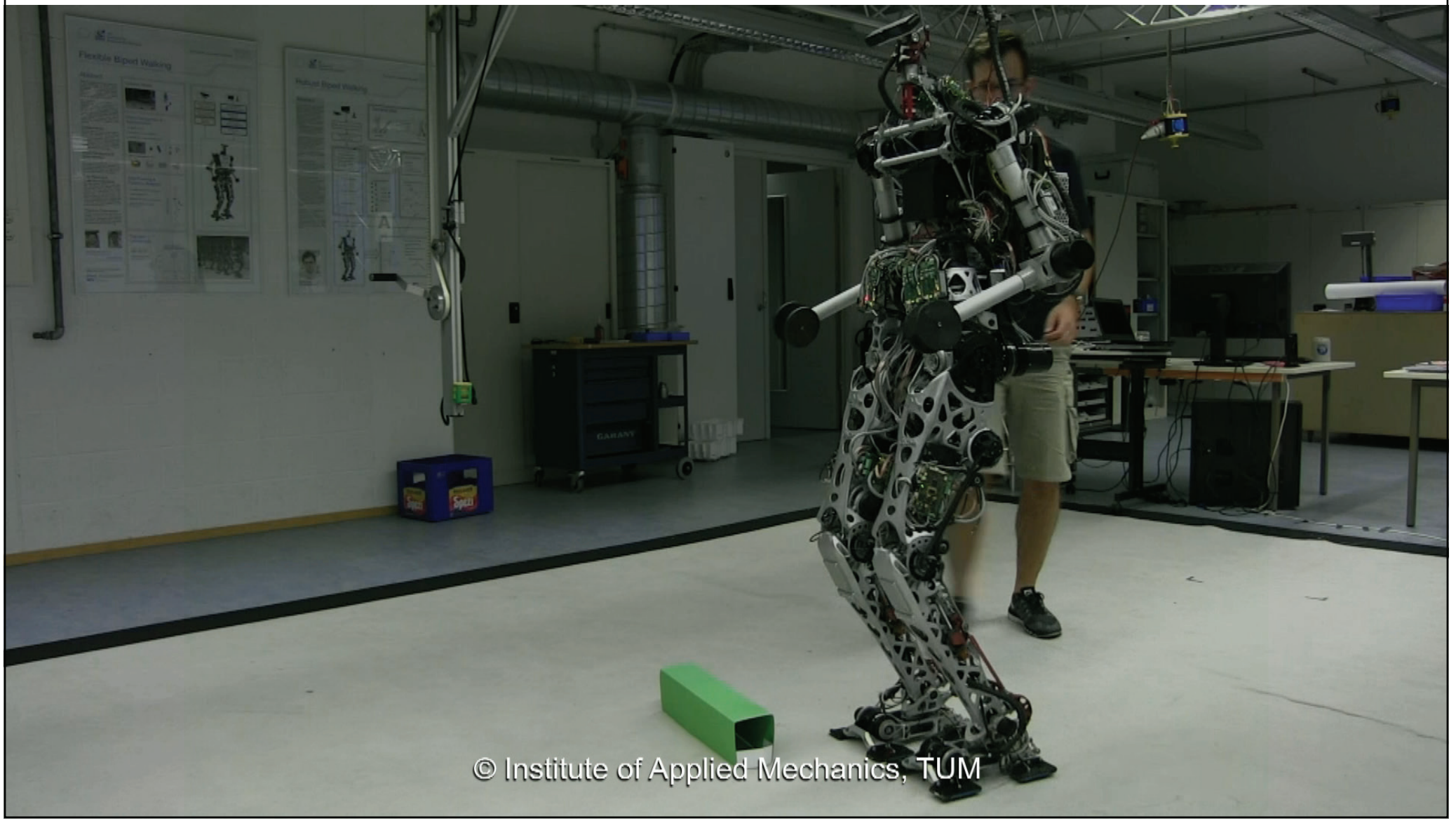
receeding horizon for CoG modification:



see **Wittmann et al.**: Model-Based Predictive Bipedal Walking Stabilization, in IEEE-RAS International Conference on Humanoid Robots (Humanoids), **2016**

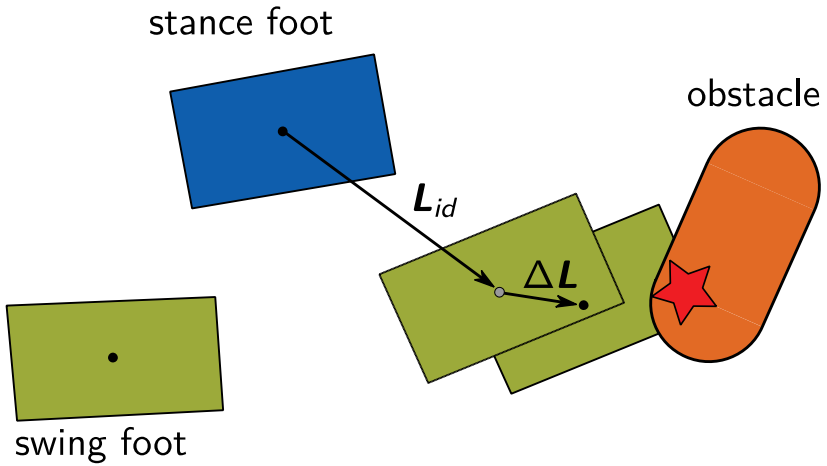
Chair of Applied Mechanics
Department of Mechanical Engineering
Technical University of Munich

Combining Obstacles + Disturbances



Chair of Applied Mechanics
Department of Mechanical Engineering
Technical University of Munich

Combining Obstacles + Disturbances



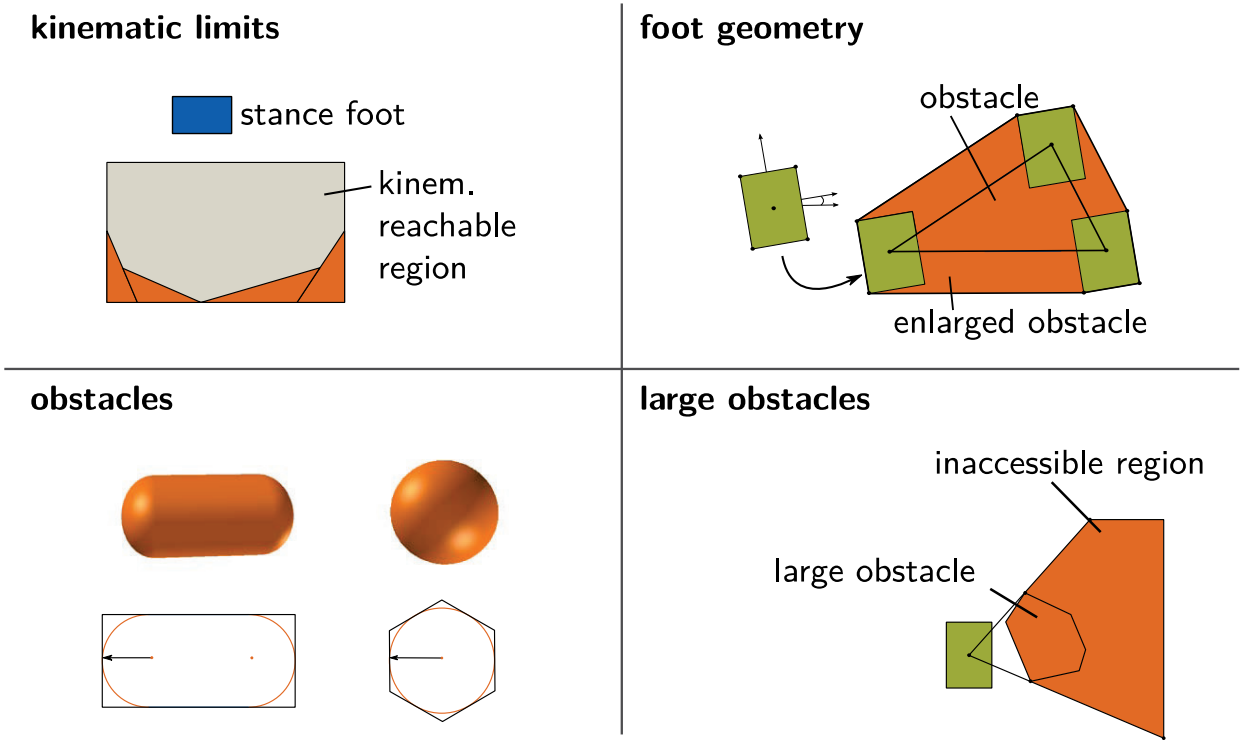
- L_{id}: ideal step
- ΔL: adaptation (disturbance)
- $L_{id} + \Delta L$: collision!

Strategy:

- Collision Avoidance > Stabilization
- Consider Geometric Constraints via inequality constraints
- Use closest viable solution to original adaptation

Chair of Applied Mechanics
Department of Mechanical Engineering
Technical University of Munich

Combining Obstacles + Disturbances

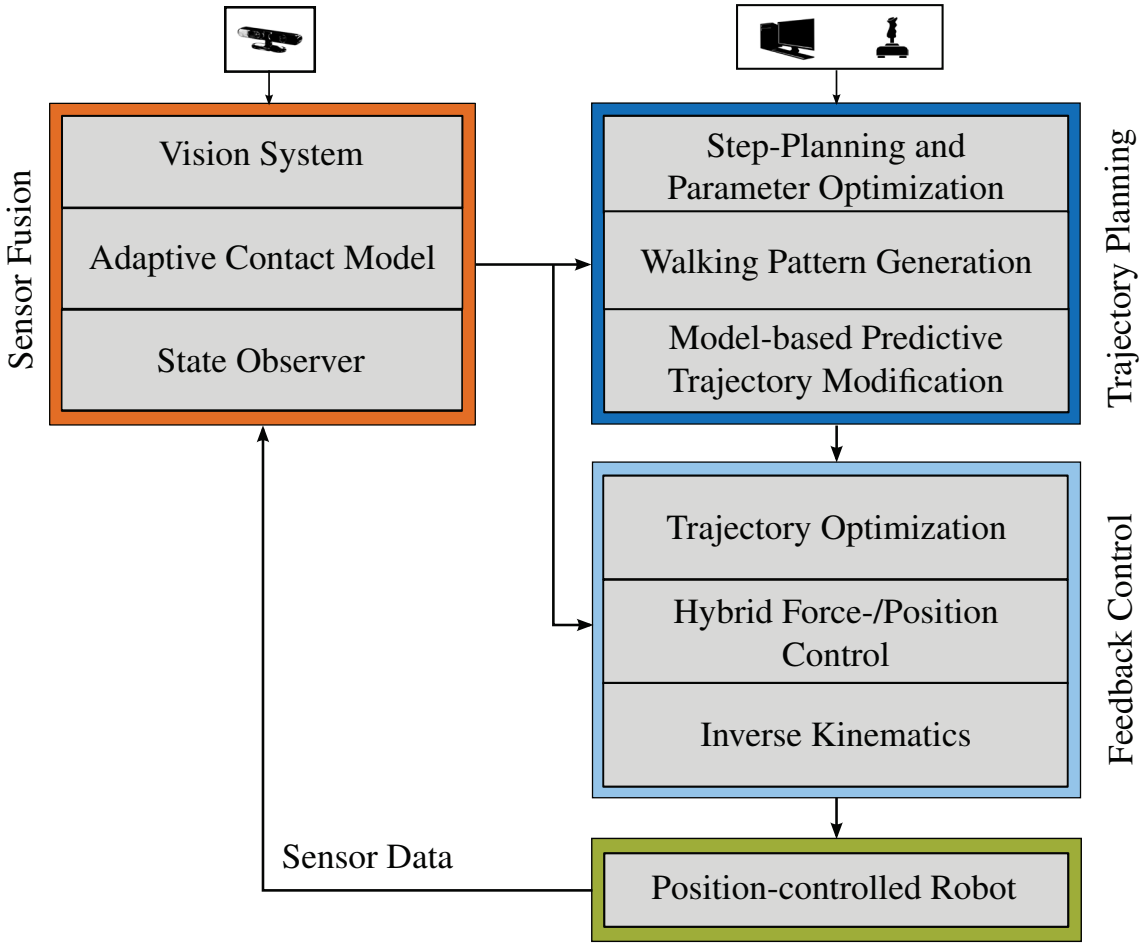


Geometric constraints:

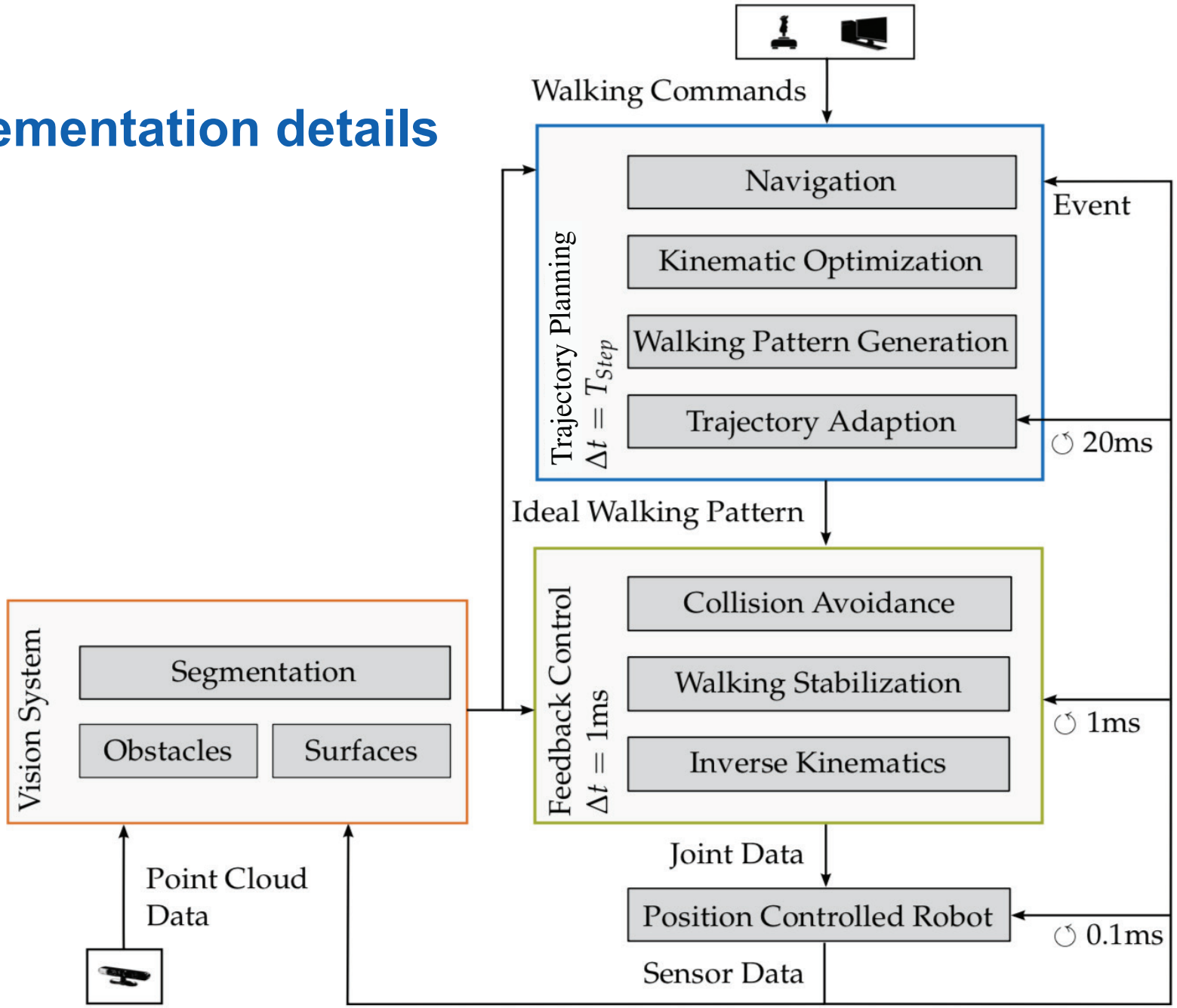
- Define invalid points via inequality constraints
- Search safe regions
- Compute closest viable point

see **Hildebrandt et al.**: Versatile and Robust Bipedal Walking in Unknown Environments, Pre-Print available online **robotics.amm.mw.tum.de**

Control System



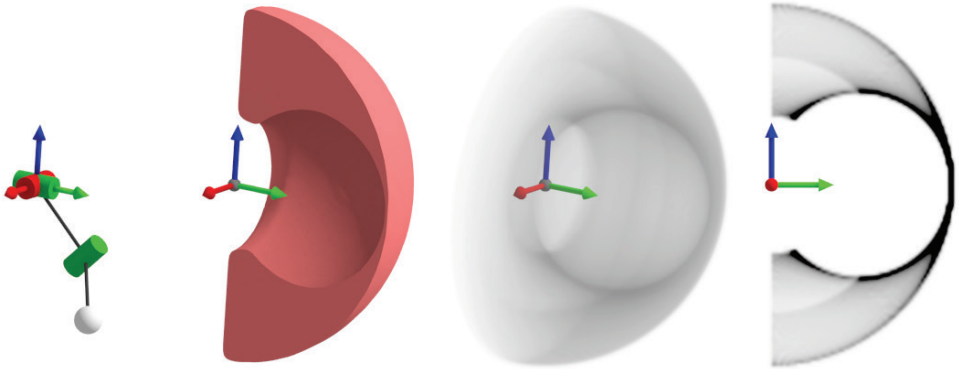
Some implementation details



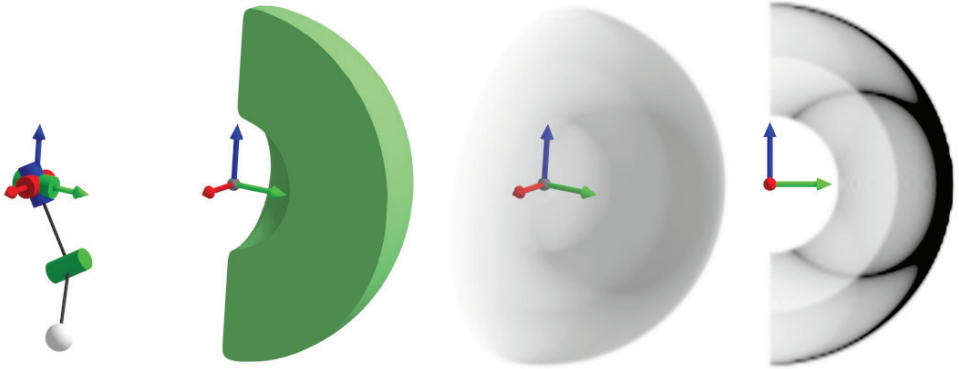
Outlook – currently under research

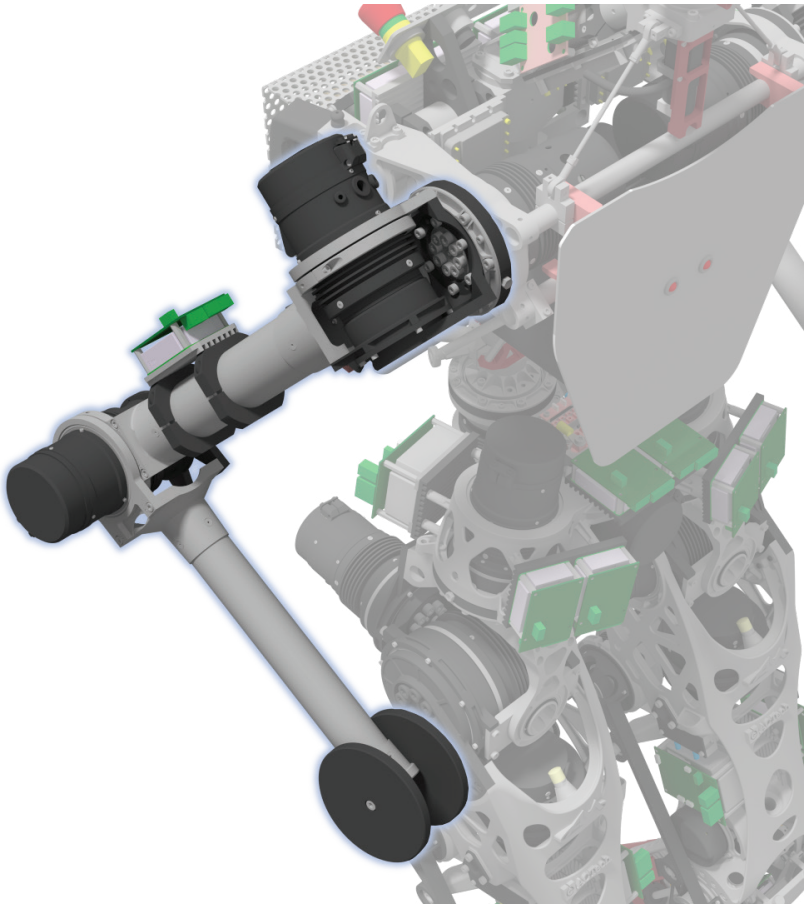
Outlook – Enhanced Arm Kinematics

Current configuration:



Target configuration:





Outlook – More Uneven Terrain II

see **Sygulla et al.**: *Hybrid Position/Force Control for Biped Robot Stabilization with Integrated Center of Mass Dynamics*, in IEEE-RAS International Conference on Humanoid Robots (Humanoids), **2017**

Chair of Applied Mechanics
Department of Mechanical Engineering
Technical University of Munich

Experimental Results

Walking from an unexpected (non-detected) platform of 5.5cm height.

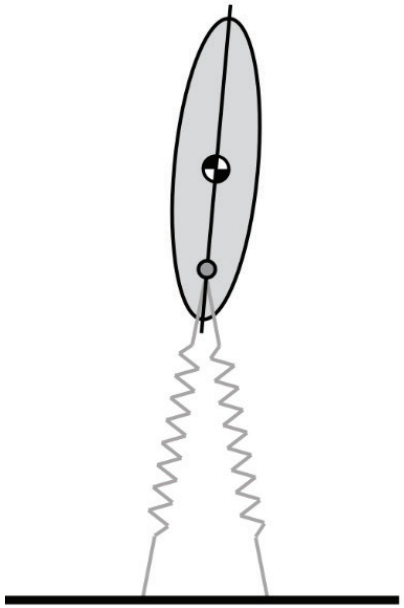
reference

with proposed contact model

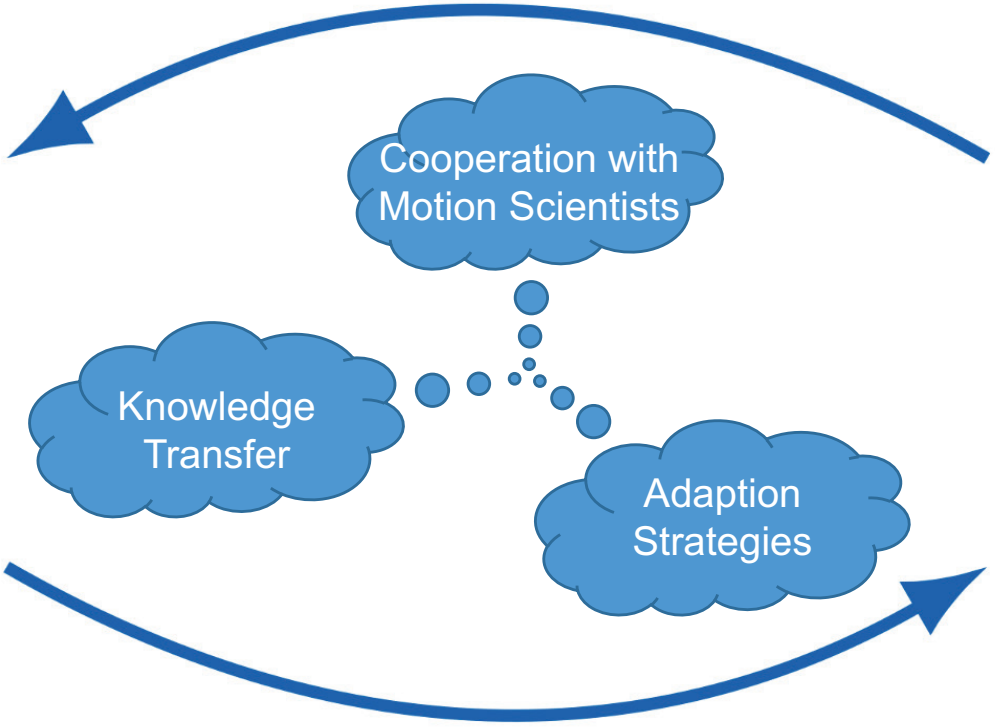
with integrated dynamics

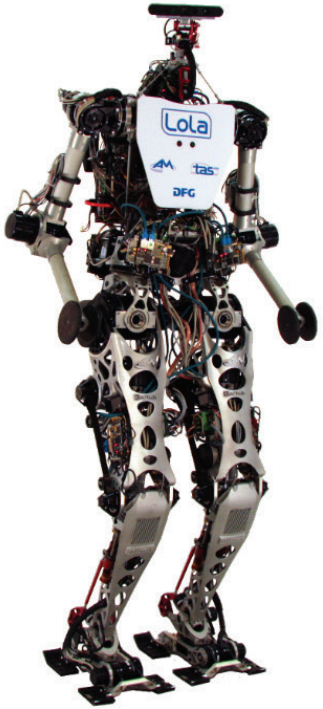
with proposed contact model and CoM dynamics in force controller

Outlook – More Uneven Terrain I



Human





Robot