Humanoid Robots: From Playing Soccer to Rescue Operations

Sven Behnke

Autonomous Intelligent Systems

universität bonn ais

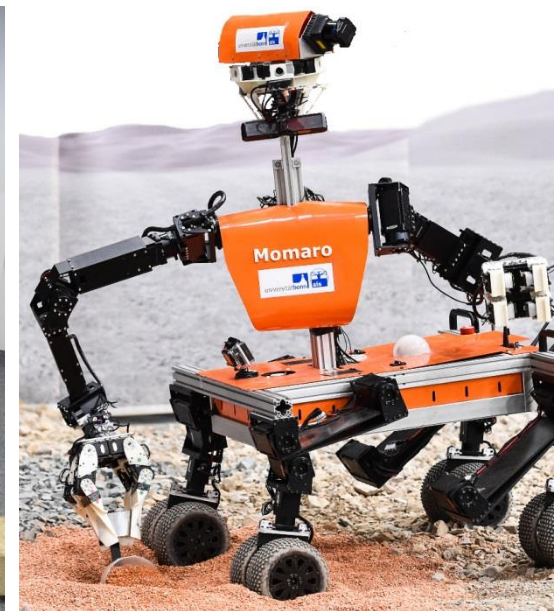
Robot Competitions

- Provide common test bed for benchmarking
- Promote exchange of ideas
- Foster robotics research

RoboCup Soccer

RoboCup @Home

DARPA Robotics Challenge

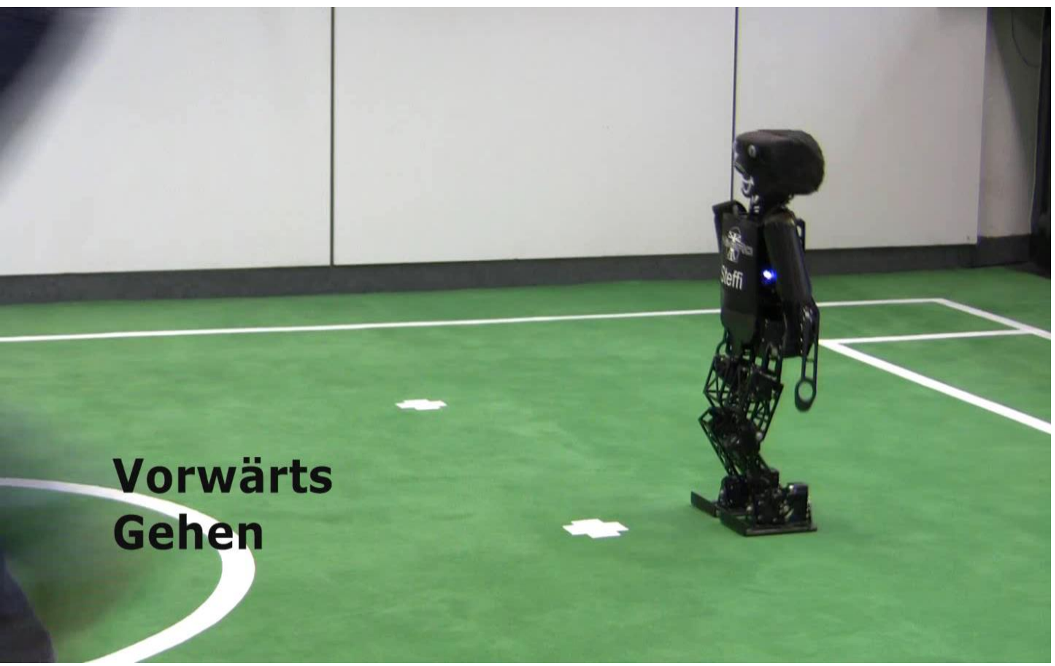


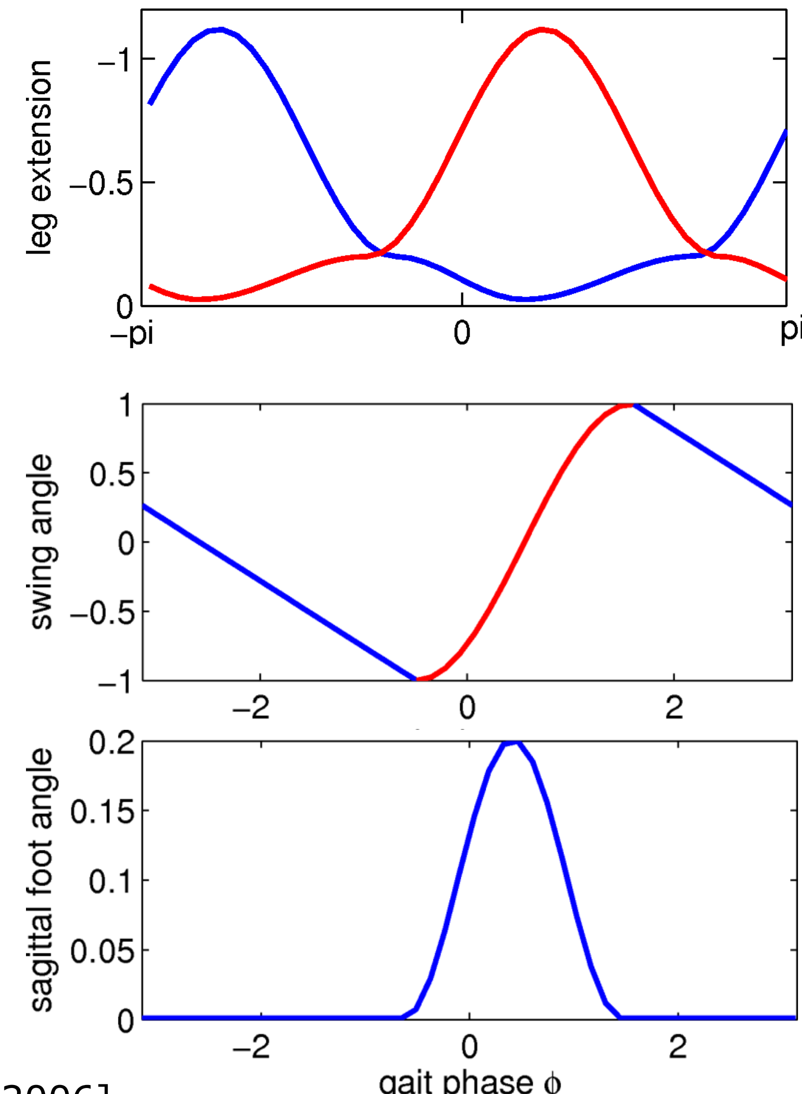
DLR SpaceBot Cup

RoboCup 2008 KidSize Final
NimbRo vs. Team Osaka

Omnidirectional Walking

- Continuously changing walking speeds: sagittal, lateral, yaw
- Key ingredients:
  - Rhythmic weight shifting
  - Leg shortening
  - Swing in walking direction

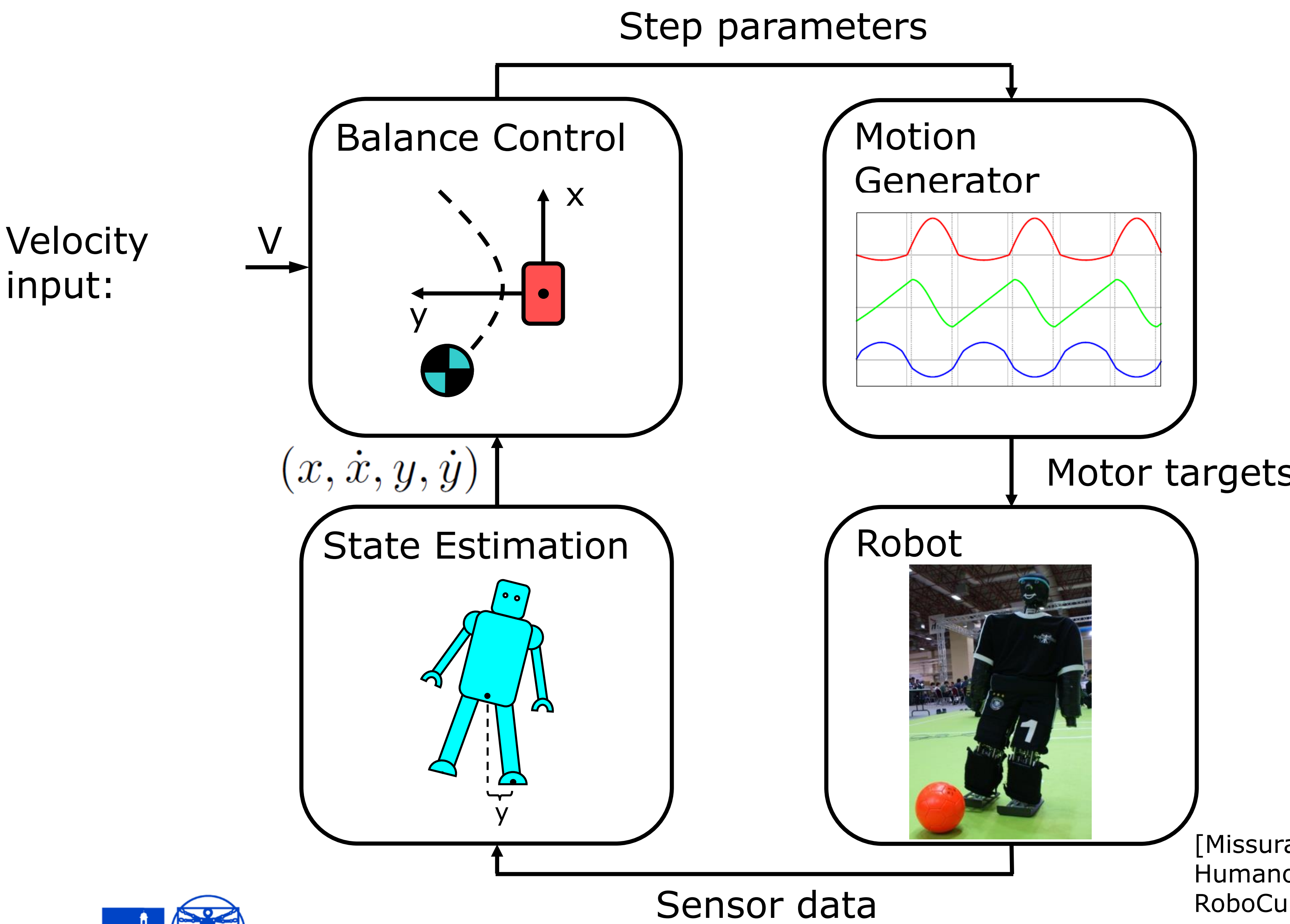




[Behnke: ICRA 2006]

RoboCup 2013 Final

Capture Step Framework



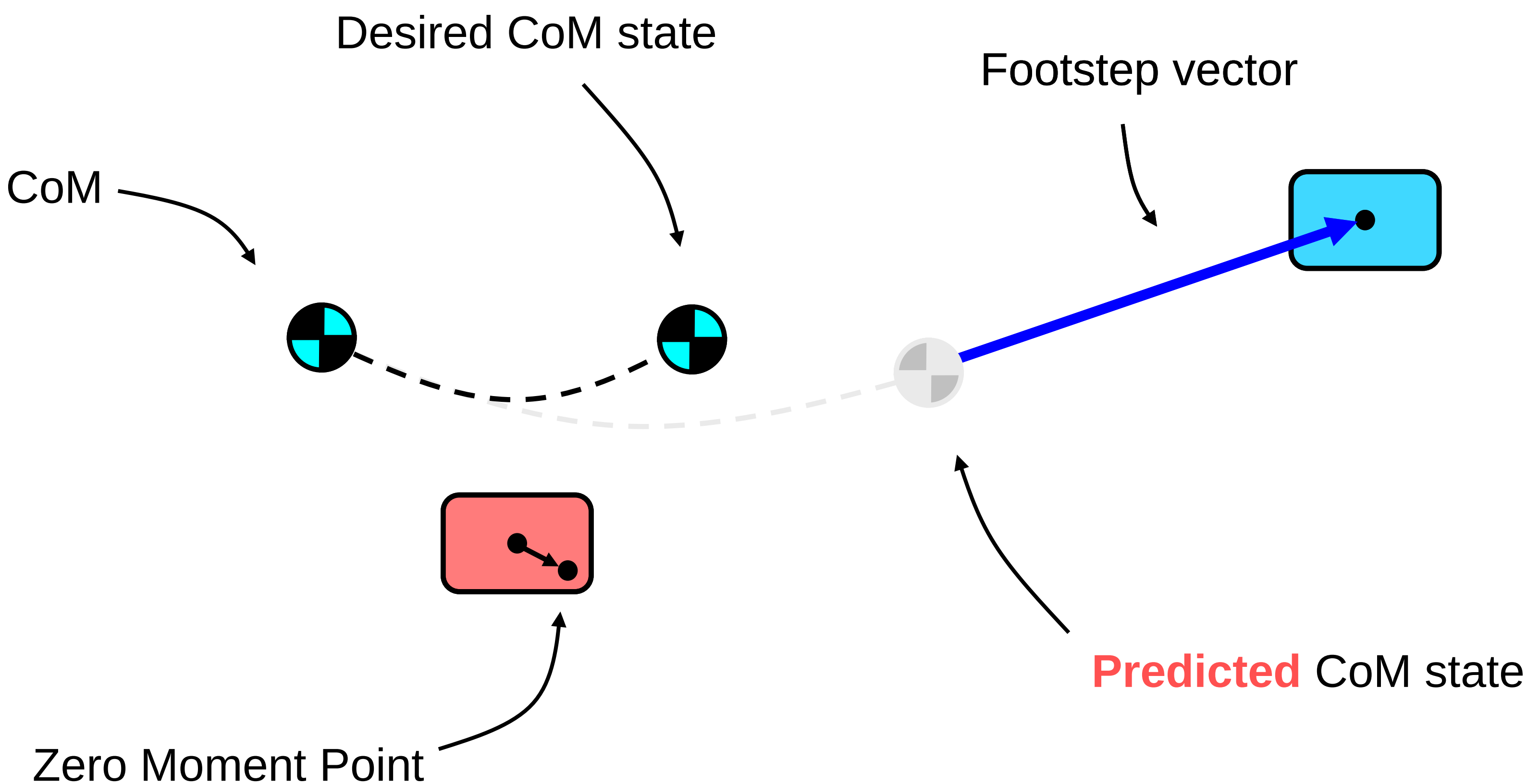
[Missura, Behnke: Humanoids 2013, RoboCup 2014]

Omnidirectional Capture Steps

[Missura and Behnke: Humanoids 2013, RoboCup 2014]

Balance Control

- Adapt ZMP, timing, and foot placement



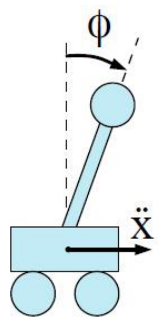
[Missura and Behnke: Humanoids 2013, RoboCup 2014]

Dynaped with Small Feet

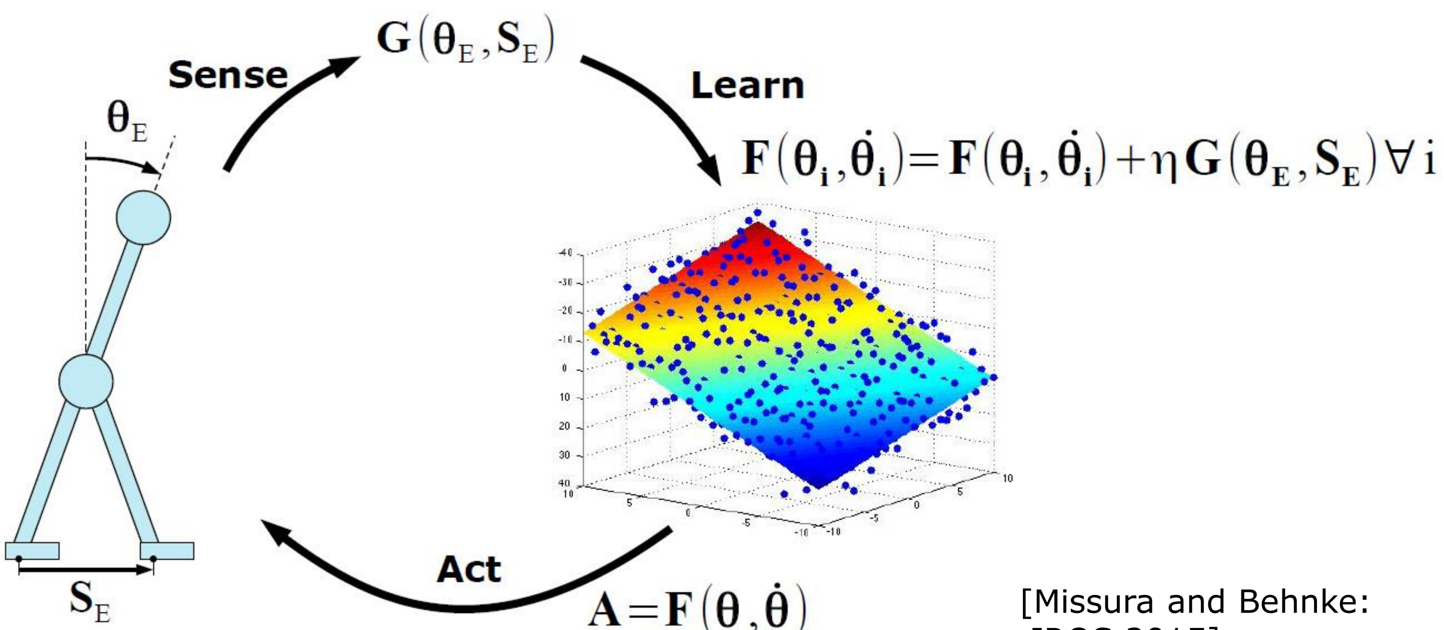
[Missura and Behnke: Humanoids 2013, RoboCup 2014]

Online Learning of Foot Placement

- Function approximator for step size
- Online update based on tilt and step size error



$$G(\theta_E, S_E) = \theta_E + p_1 \tanh(p_2 S_E)$$



[Missura and Behnke: IROS 2015]

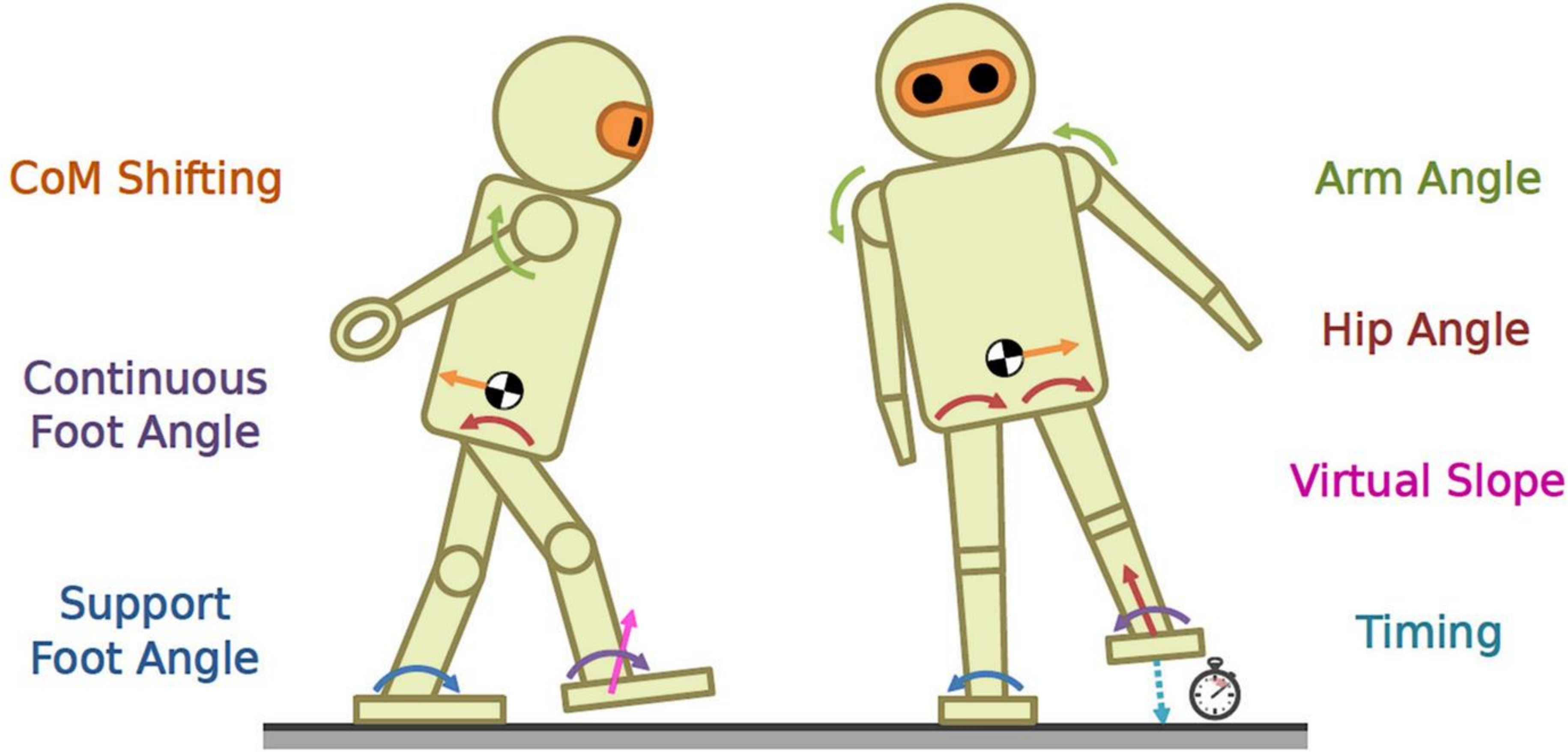
Online Learning of Foot Placement

[Missura and Behnke: IROS 2015]

igus Humanoid Open Platform

- 90 cm, 6.6 kg
- 3D printed structure
- 20 DoF
- Dual-core PC
- Wide-angle camera(s)
- IMU
- ROS-based software
- Hard- and software released: nimbro.net/OP

Feedback Mechanisms



[Allgeuer and Behnke: Humanoids 2016]

PD Feedback

[Allgeuer and Behnke: Humanoids 2016]

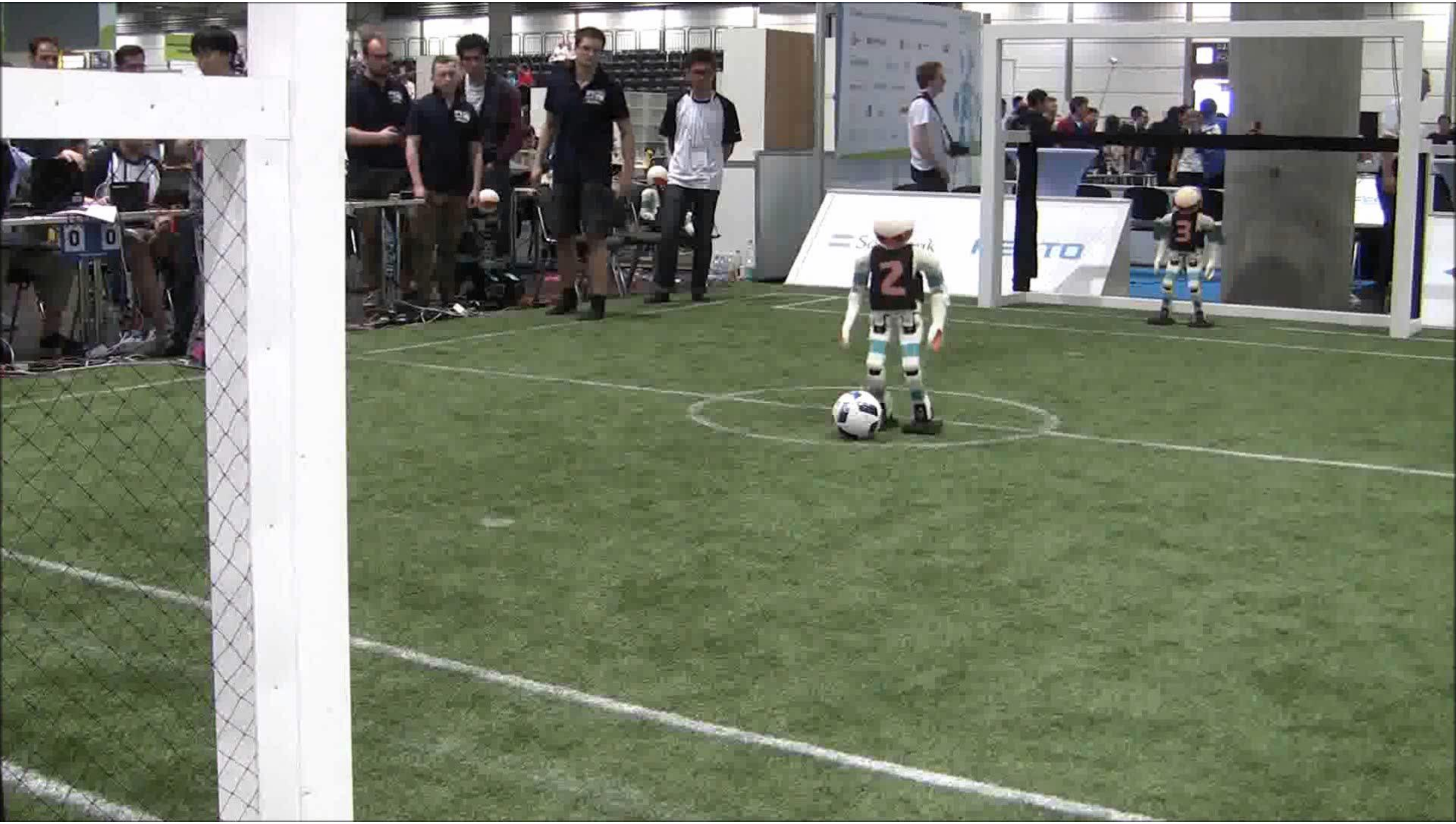
Getting Up

[Allgeuer et al. Humanoids 2015]

Visual Perception

[Farazi & Behnke: Humanoid Soccer Workshop 2015]

RoboCup 2016 Final



Team NimbRo TeenSize 2016

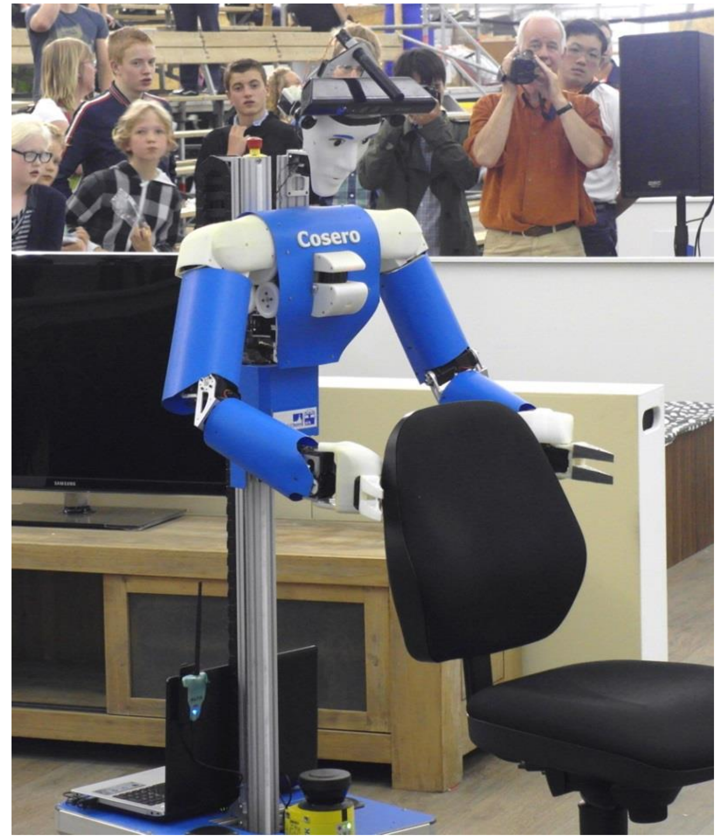
RoboCup@Home

- Since 2006
- Focus on applications in domestic environments and on human-robot interaction
- **Goal:** Develop robots that support humans in everyday tasks
- **Competition:**
  - Predefined tests
    - Follow a person
    - Find and put away objects
    - Fetch drinks
    - Understand complex speech commands
  - Open demonstrations
- Bar raised every year

[Stückler et al.: Robotics and Automation Magazine 2012]

Our Domestic Service Robots

Dynamaid



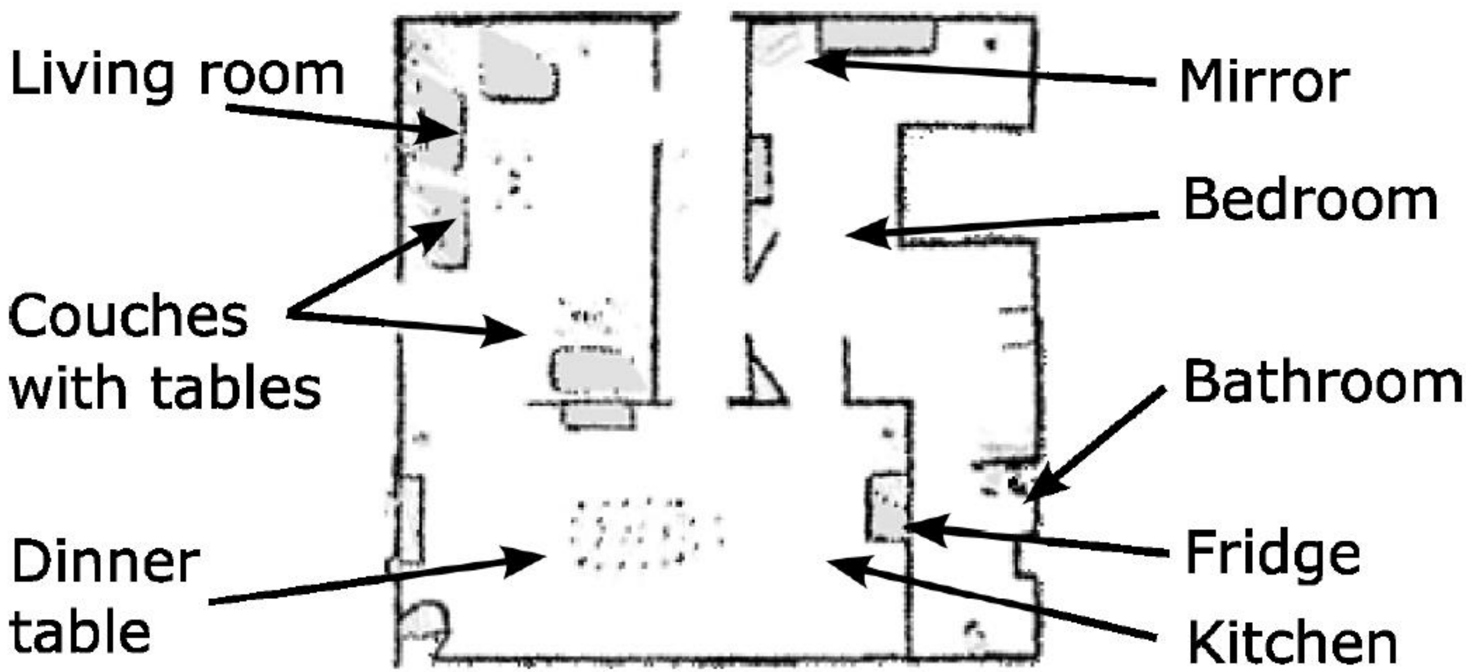
Cosero

- Size: 100-180 cm, weight: 30-35 kg
- 36 articulated joints
- PC, laser scanners, Kinect, microphone, …

[Stückler et al.: Frontiers in Robotics and AI 2016]

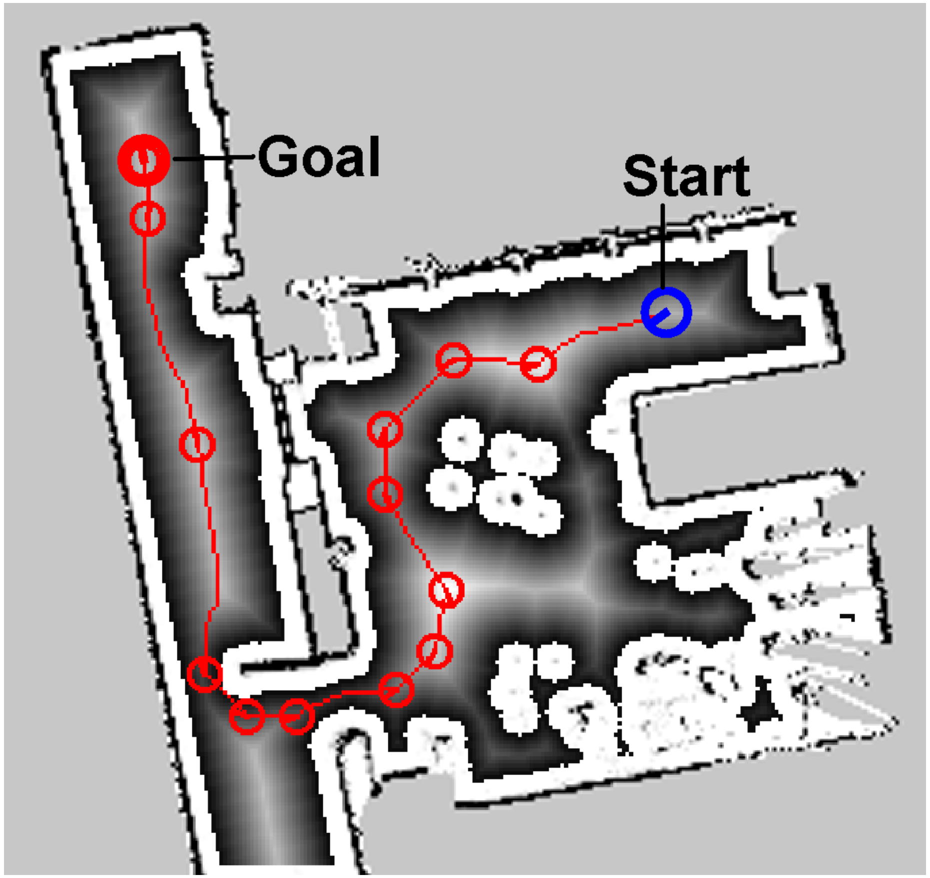
RoboCup 2013 Eindhoven

Mapping the Environment



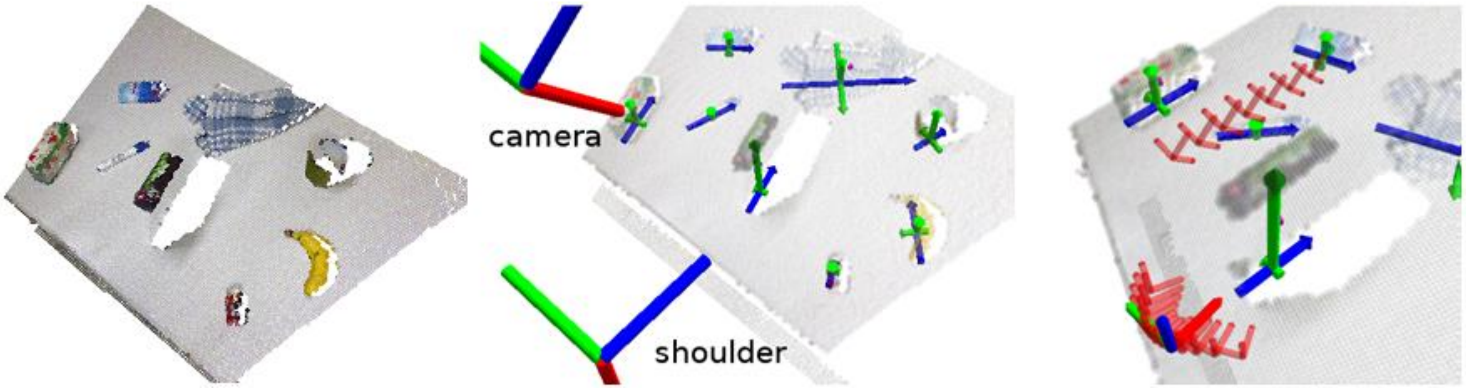
Path Planning

- Global planning tries to keep away from obstacles
- Obstacle avoidance using two lasers
- Robot alignment in narrow passages
- Plan revision when path blocked

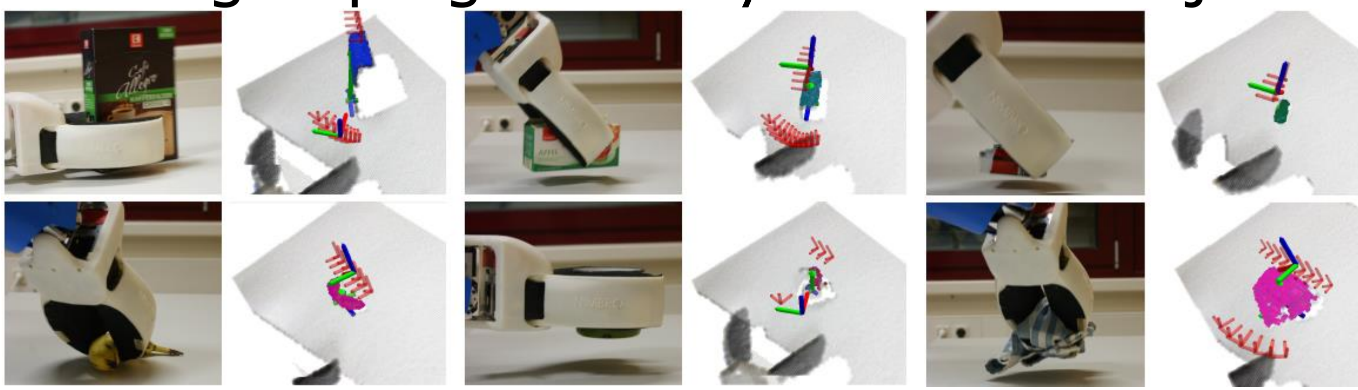


Object Perception and Grasp Planning

- Detection of clusters above horizontal plane
- Two grasps (top, side)



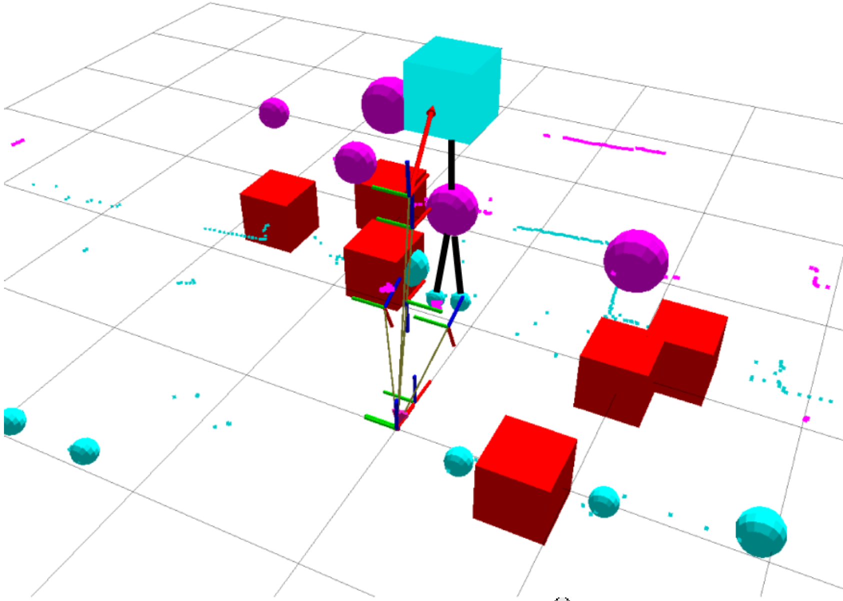
- Flexible grasping of many unknown objects

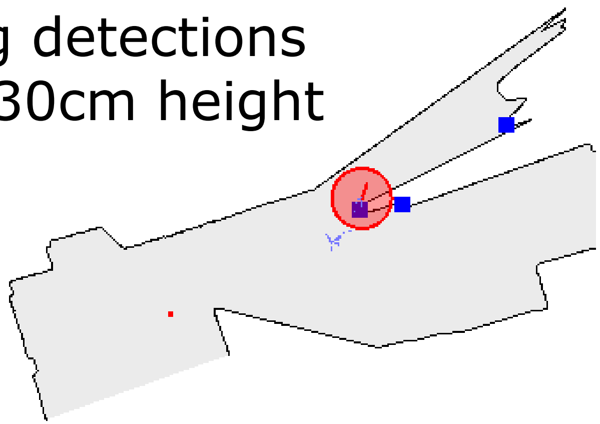


[Stückler, Steffens, Holz, Behnke, Robotics and Autonomous Systems 2012]

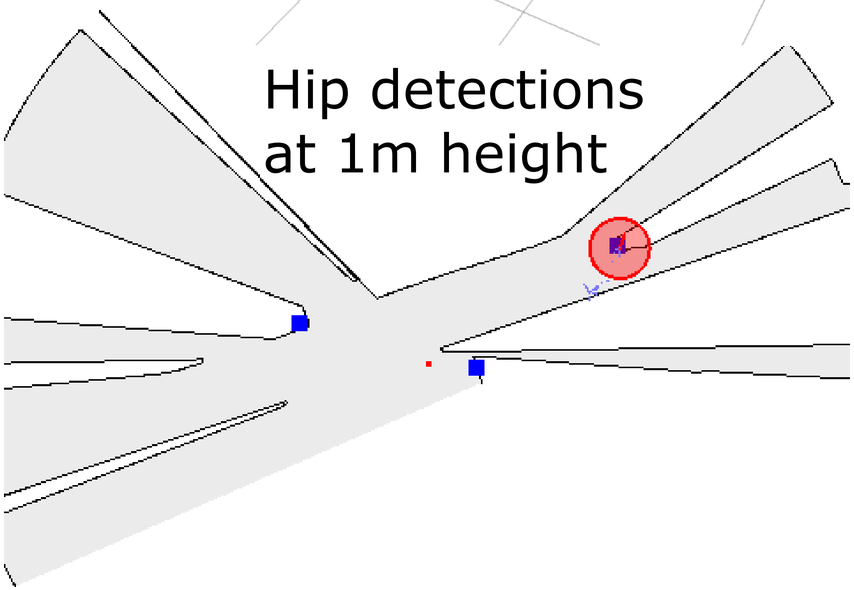
Continuous Person Awareness

- Detect persons using LRFs at two heights
- Visual person verification and identification
- Natural gaze strategies





Leg detections at 30cm height



Hip detections at 1m height

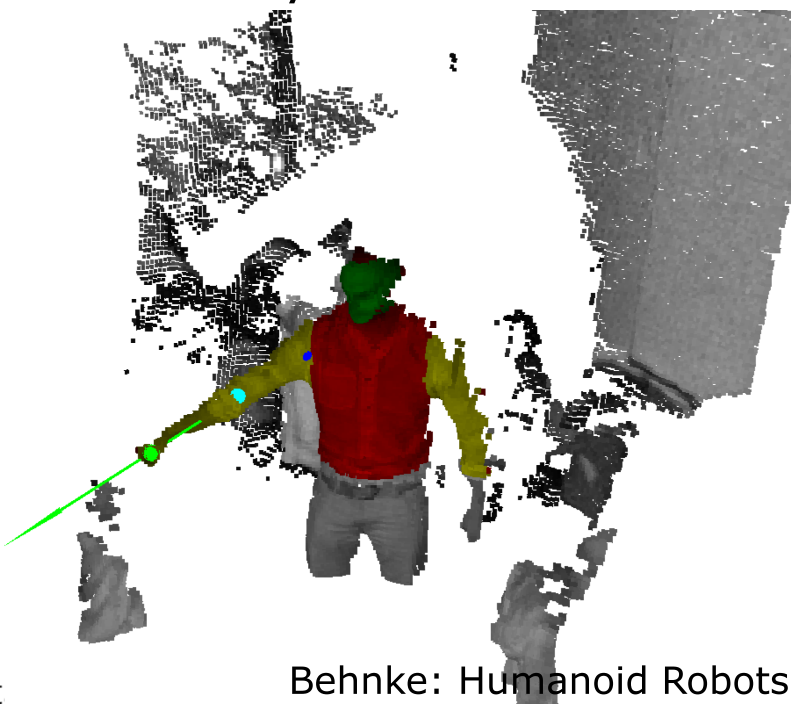
Face Recognition

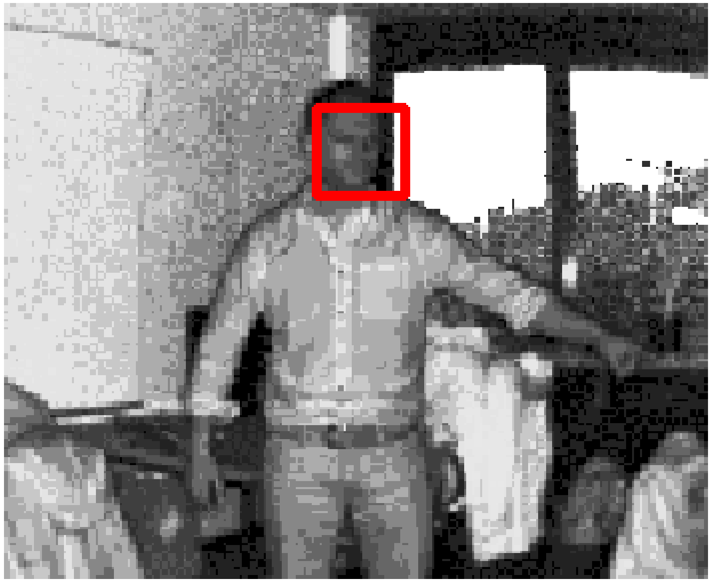
- Viola & Jones face detection & tracking
- VeriLook SDK for face recognition
- Robot detects persons, approaches them, asks for their name, remembers face, and recognizes persons again

Follow Me Test

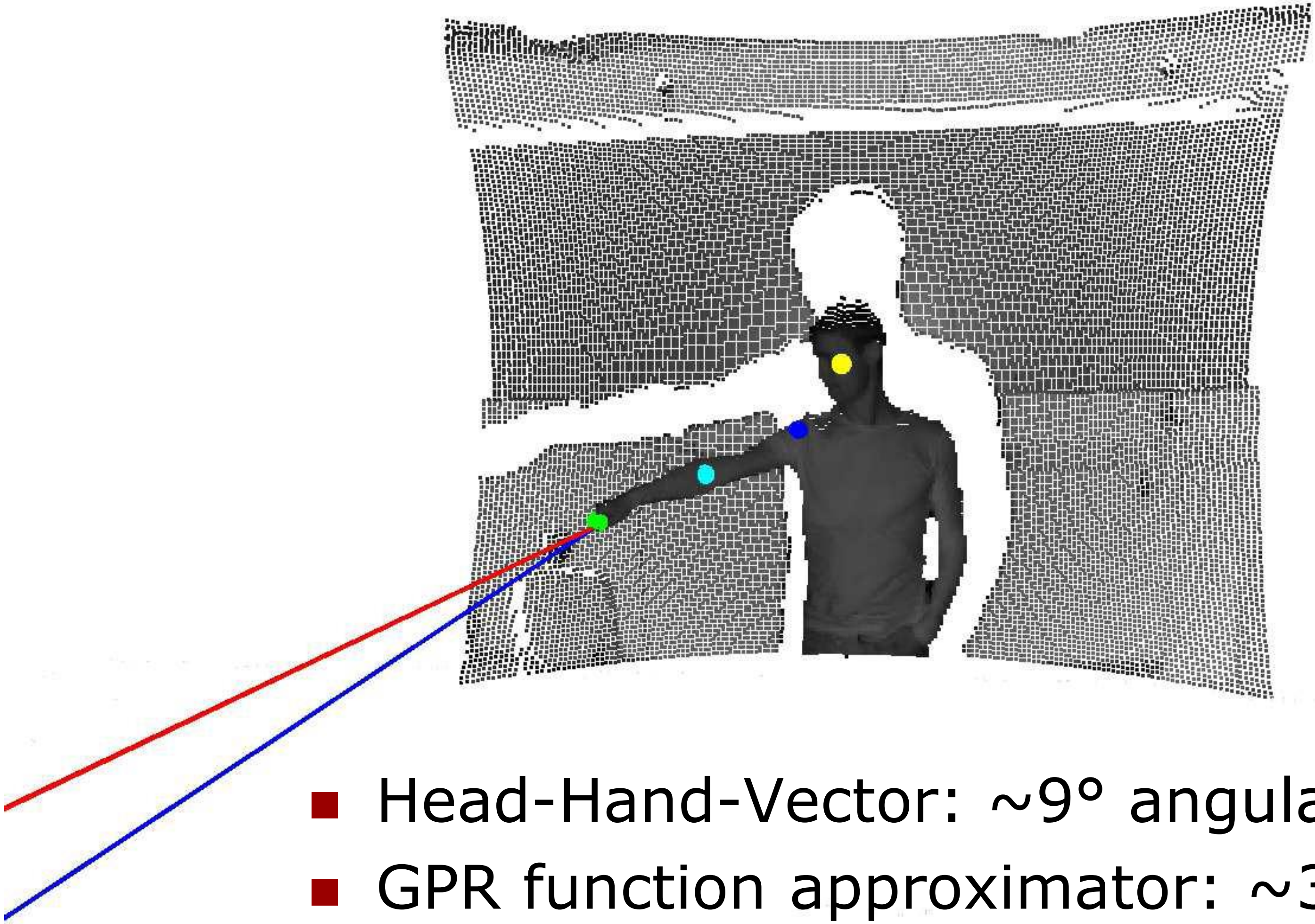
Gesture Recognition using a ToF Camera

- Find and track face in amplitude image
- Find body by region growing
- Segment torso and arms
- Identify elbow and hand





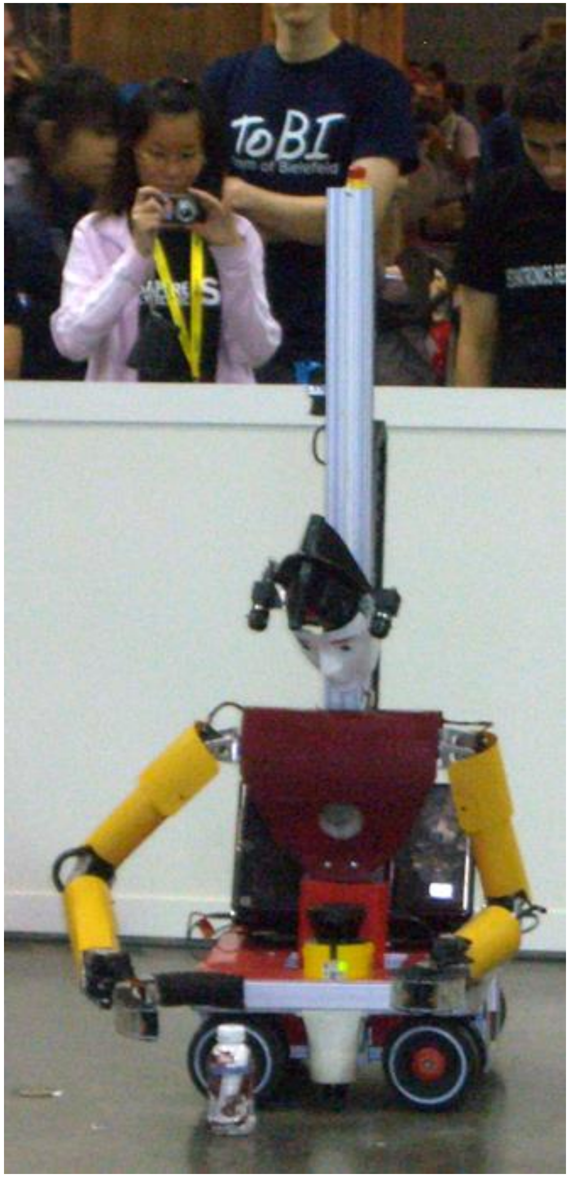
Estimating Pointing Direction

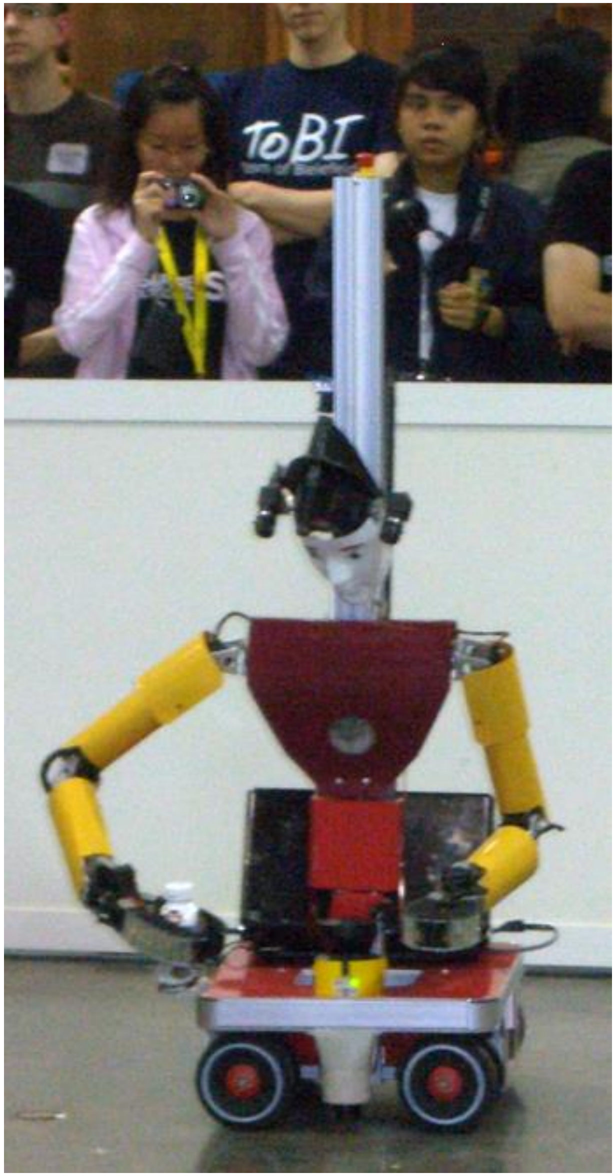


- Head-Hand-Vector: ~9° angular error
- GPR function approximator: ~3° error

[Dröschel, Stückler, Behnke: HRI 2011]

Picking-up Objects from the Floor

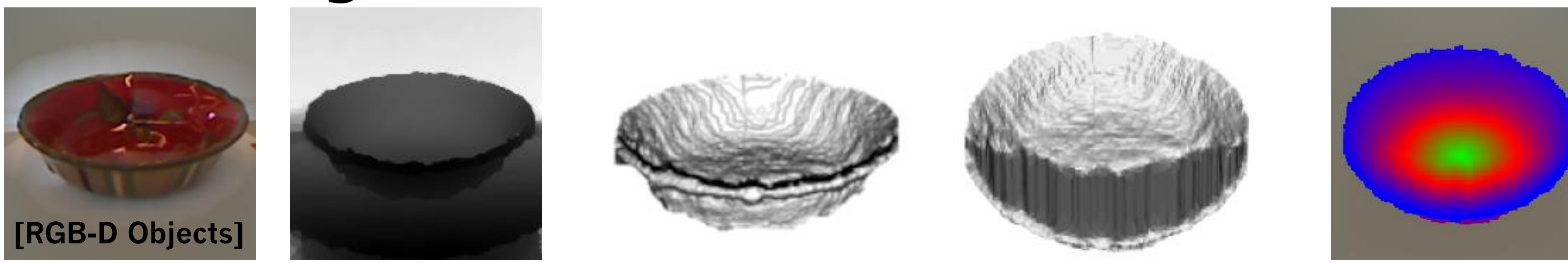




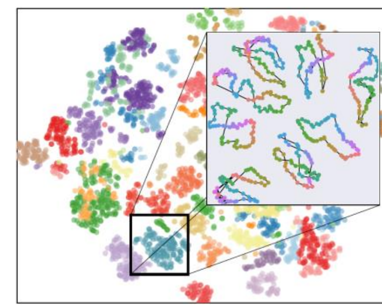
Showing Gesture

Object Recognition and Pose Estimation

- Rendering canonical views

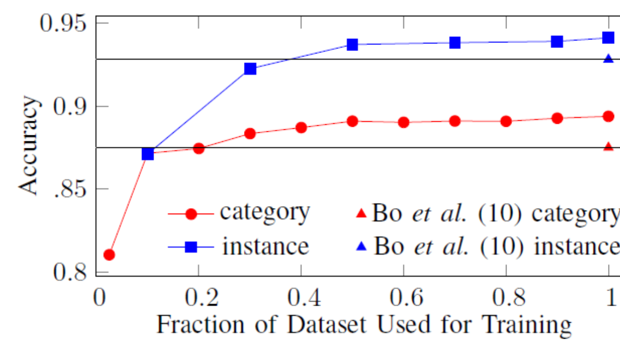


- Pretrained convolutional neural network



- Linear SVM / SV regression

Method	Category Accuracy (%) RGB	Category Accuracy (%) RGB-D	Instance Accuracy (%) RGB	Instance Accuracy (%) RGB-D
Lai *et al.* (8)	74.3 ± 3.3	81.9 ± 2.8	59.3	73.9
Bo *et al.* (10)	82.4 ± 3.1	87.5 ± 2.9	**92.1**	92.8
Ours	$\mathbf{83.1 \pm 2.0}$	$\mathbf{89.4 \pm 1.3}$	92.0	**94.1**



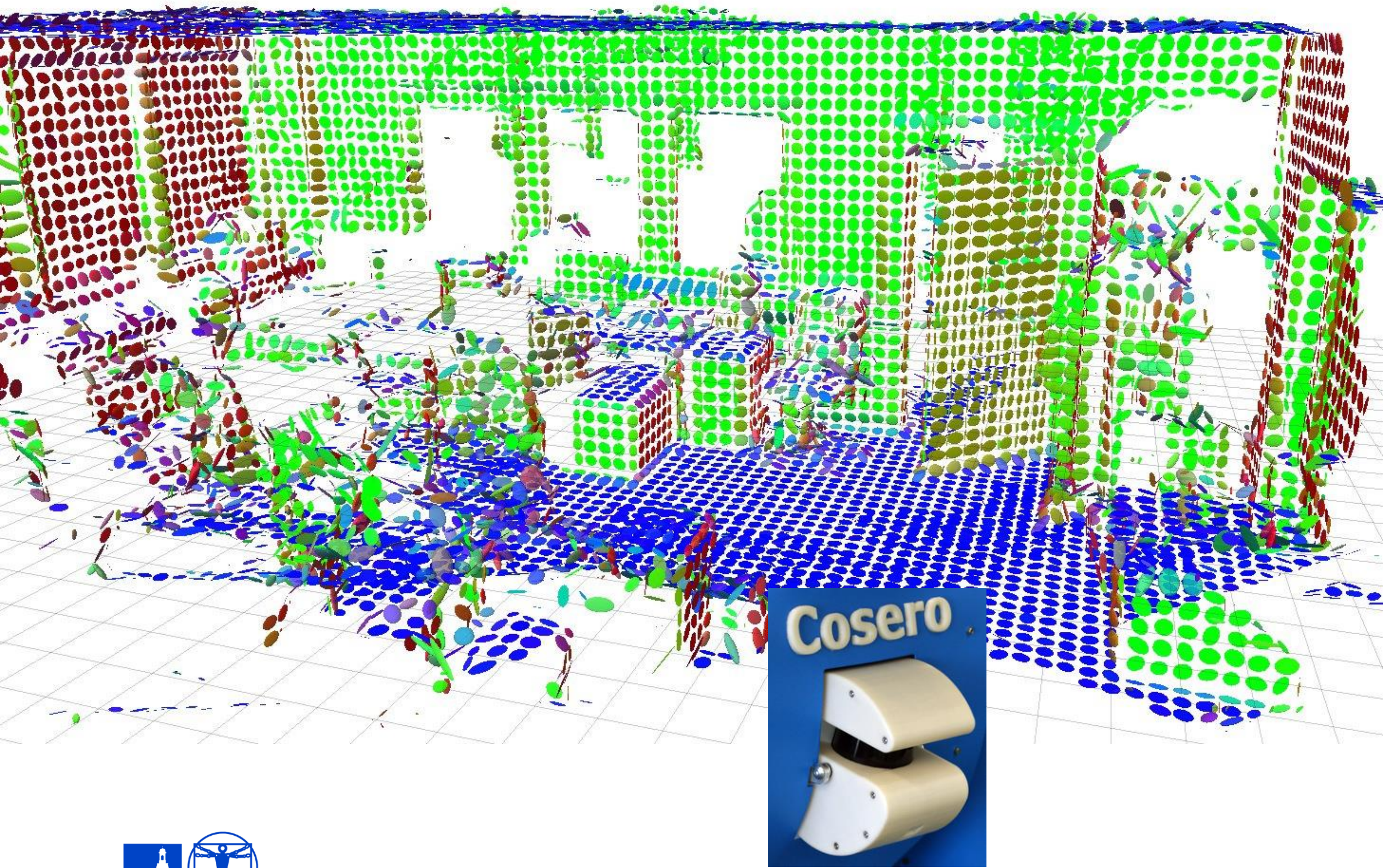
Work	MedPose	MedPose(C)	MedPose(I)	AvePose	AvePose(C)	AvePose(I)
Lai *et al.* (9)	62.6	51.5	30.2	83.7	77.7	57.1
Bo *et al.* (10)	20.0	**18.7**	**18.0**	53.6	47.5	44.8
Ours – instance level pose regression	20.4	20.4	18.7	51.0	50.4	**42.8**
Ours – category level pose regression	**19.2**	19.1	18.9	**45.0**	**44.5**	43.7

Angular error in °

[Schwarz, Schulz, Behnke, ICRA 2015]

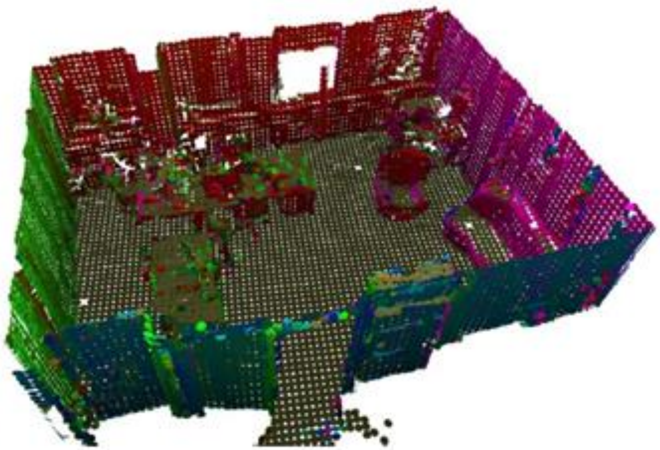
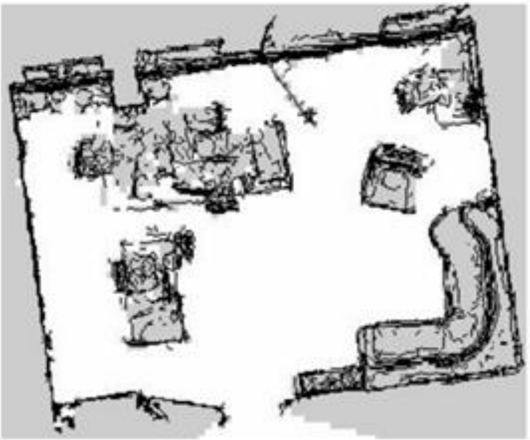
3D-Mapping with Surfels

3D-Mapping with Surfels



3D-Mapping and Localization

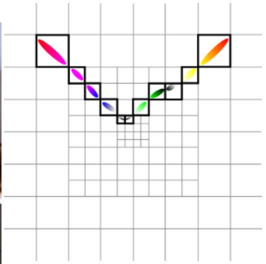
- Registration of 3D laser scans
- Representation of point distributions in voxels
- Drivability assessment through region growing
- Robust localization using 2D laser scans

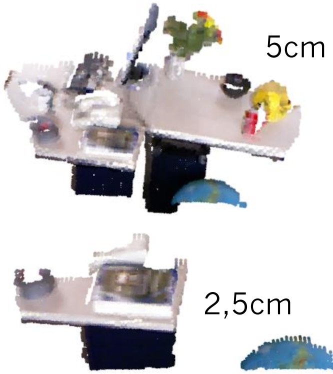




[Kläß, Stückler, Behnke: Robotik 2012]

3D Mapping by RGB-D SLAM

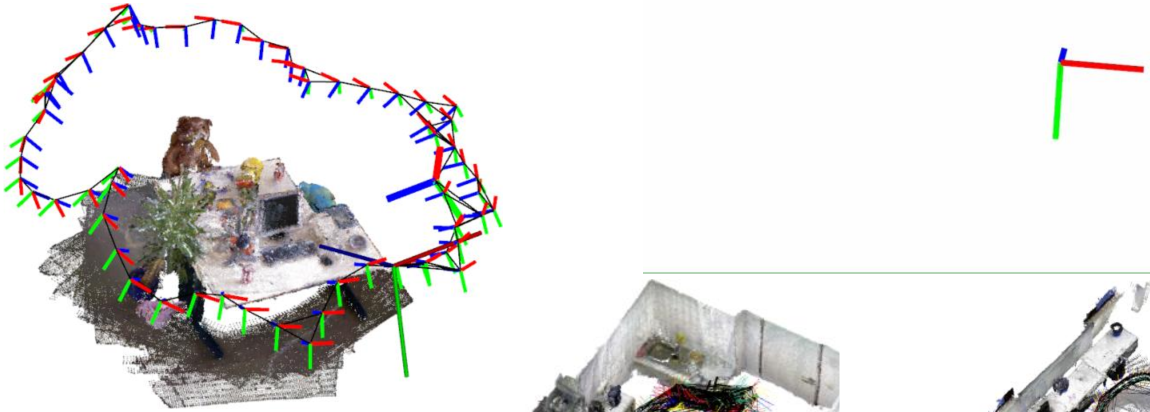
- Modelling of shape and color distributions in voxels
- Local multiresolution
- Efficient registration of views on CPU



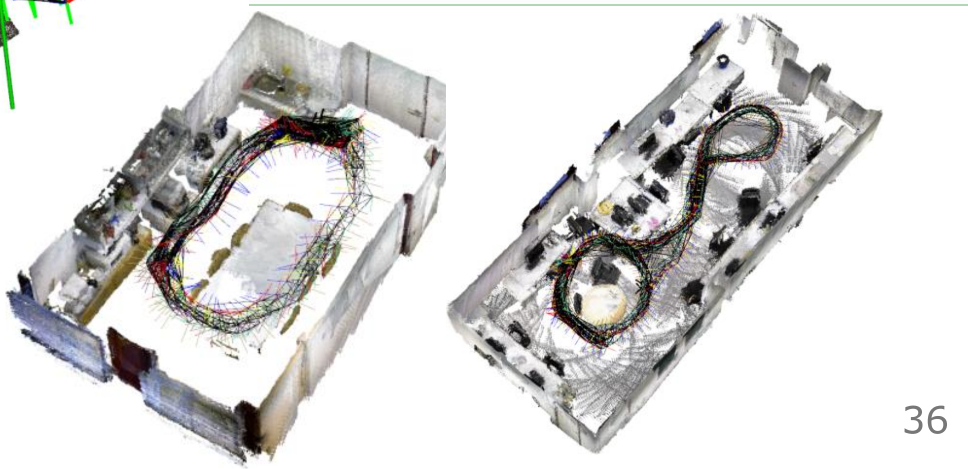


[Stückler, Behnke: Journal of Visual Communication and Image Representation 2013]

- Global optimization



- Multi-camera SLAM

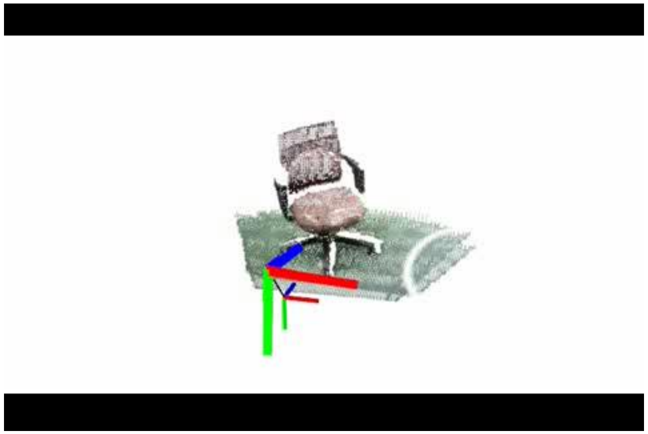


[Stoucken, Diplomarbeit 2013]

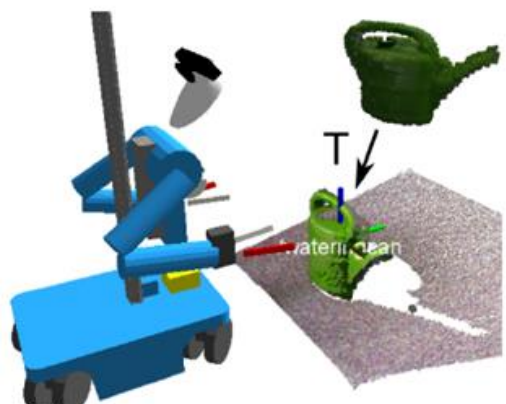
Learning and Tracking Object Models

[Stückler, Behnke: Journal of Visual Communication and Image Representation 2013]

- Modeling of objects by RGB-D SLAM

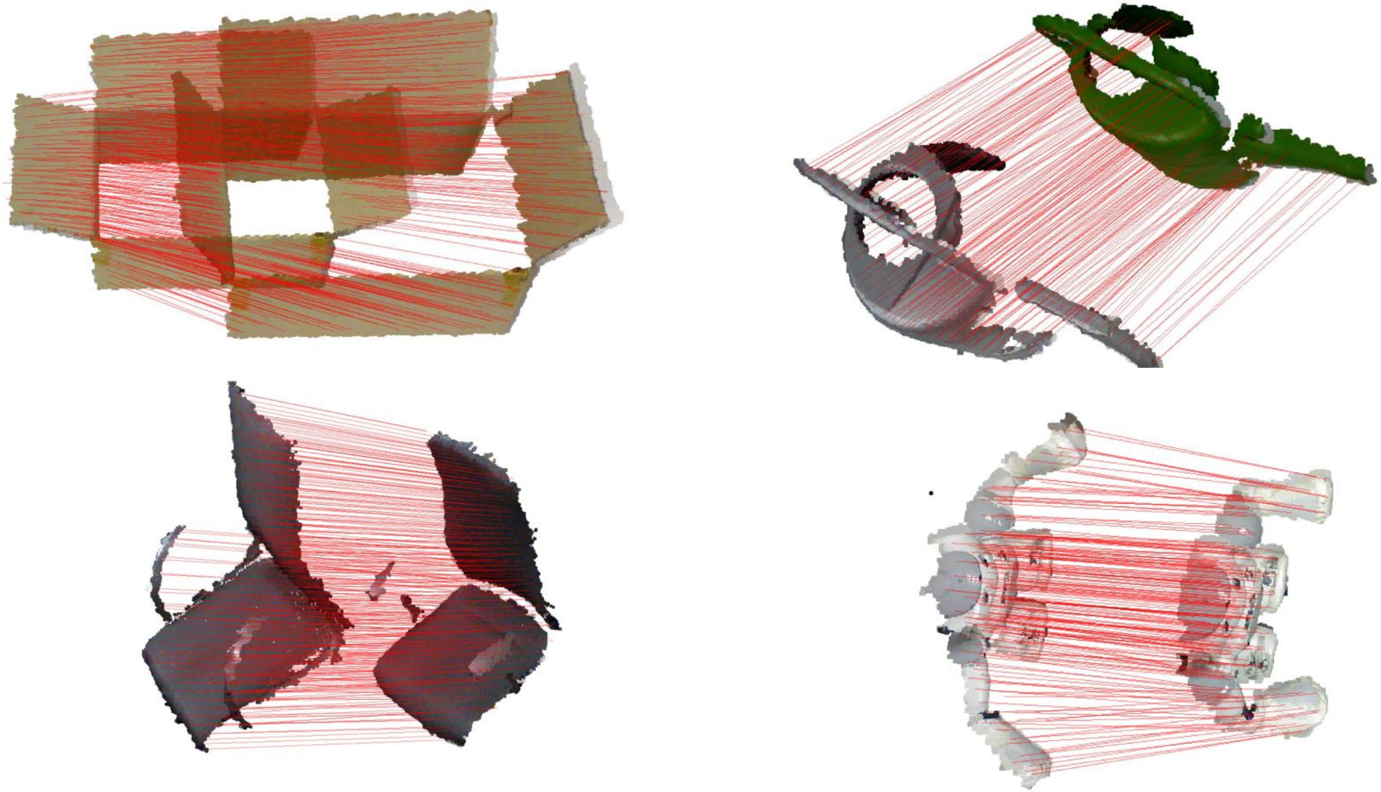



- Real-time registration with current RGB-D image

Deformable RGB-D Registration

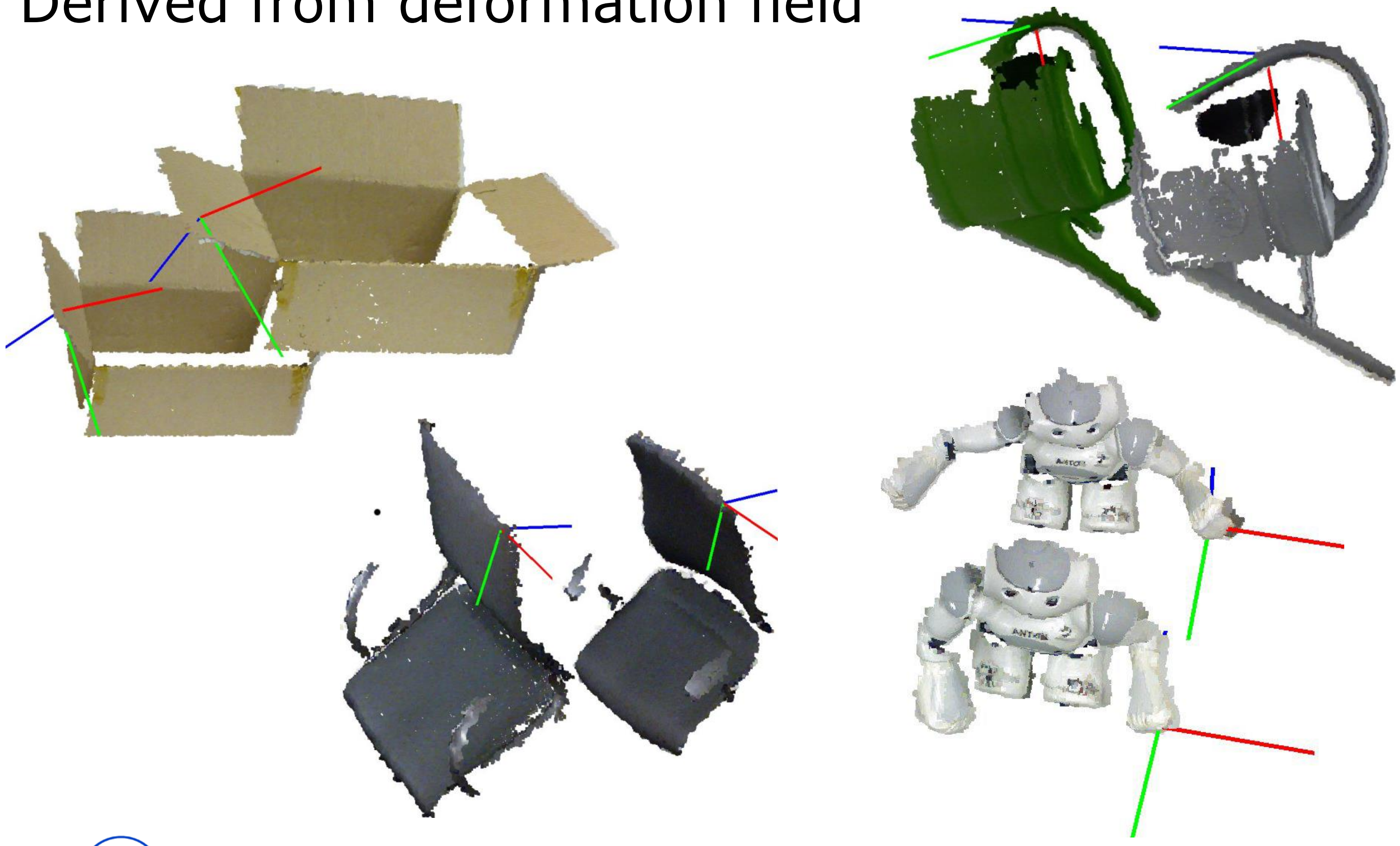
- Based on Coherent Point Drift method [Myronenko & Song, PAMI 2010]
- Multiresolution Surfel Map allows real-time registration



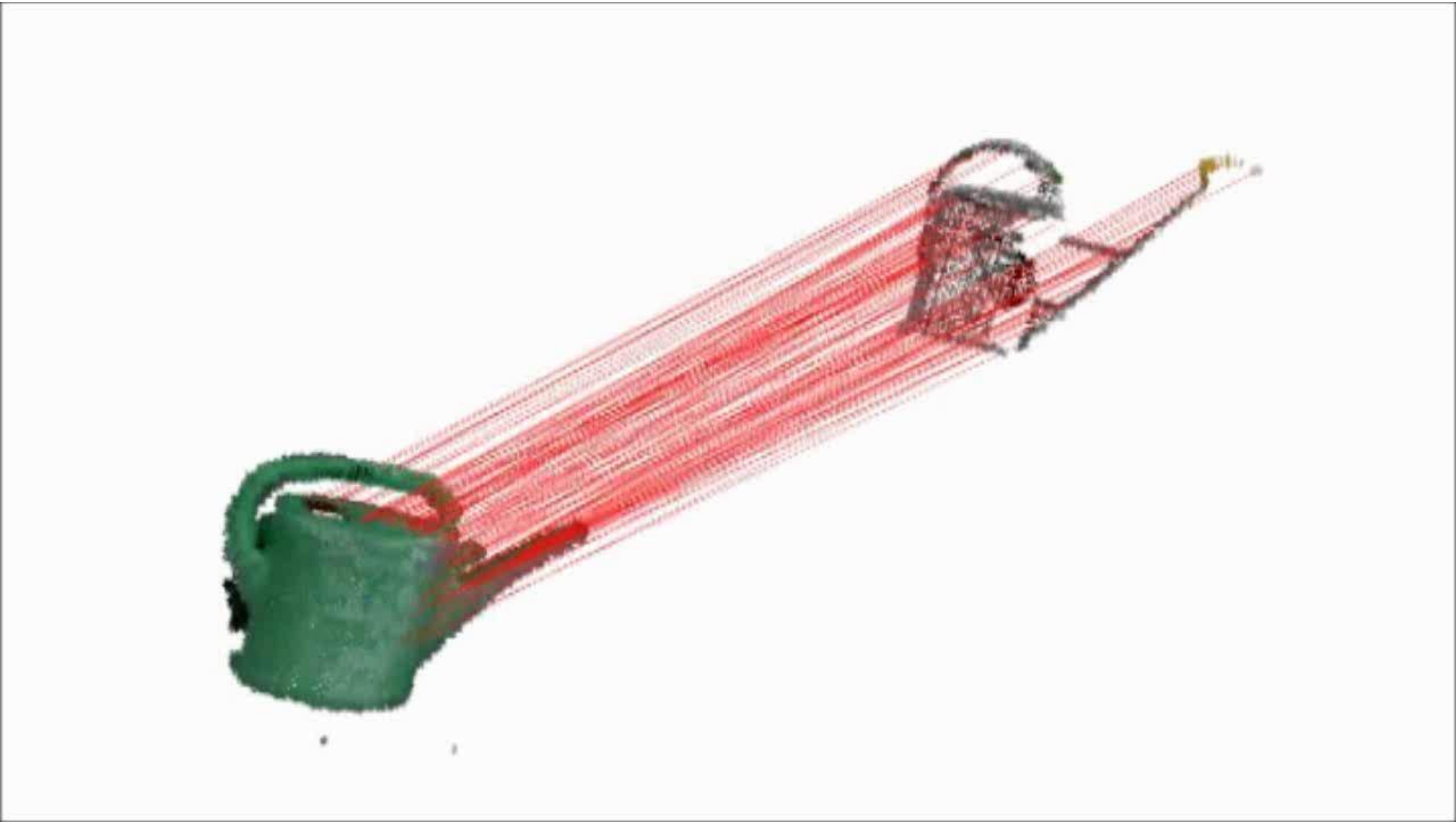
[Stückler, Behnke, ICRA2014]

Transformation of Poses on Object

- Derived from deformation field

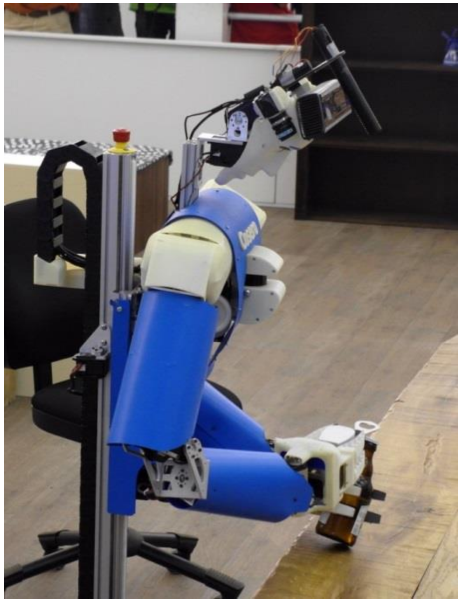


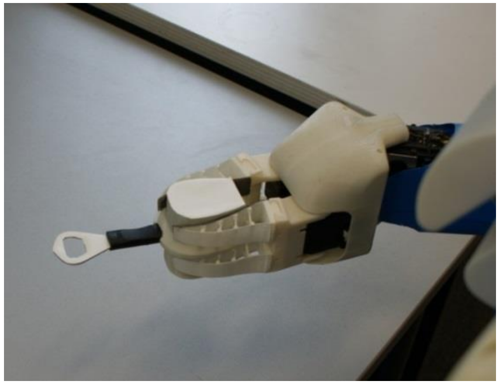
Grasp & Motion Skill Transfer

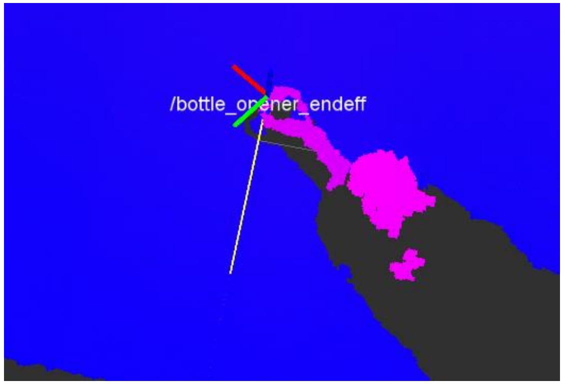


Tool use: Bottle Opener

- Tool tip perception
- Extension of arm kinematics
- Perception of crown cap
- Motion adaptation







Picking Sausage, Bimanual Transport

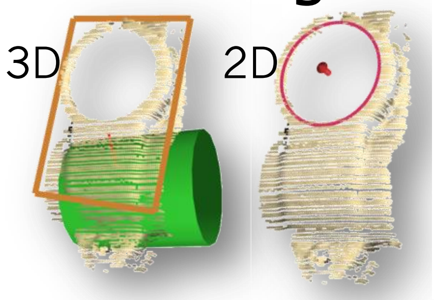
- Perception of tool tip and sausage
- Alignment with main axis of sausage

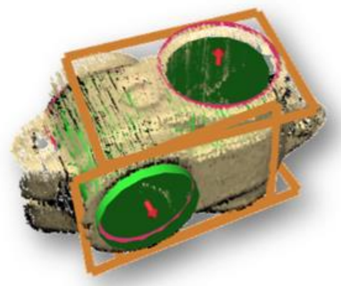
- Our team NimbRo won the RoboCup@Home League in three consecutive years

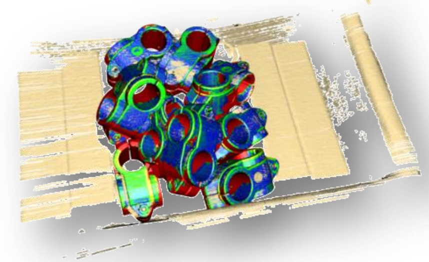
Bin Picking

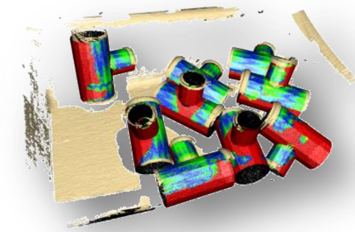
- Known objects in transport box

- Matching of graphs of 2D and 3D shape primitives

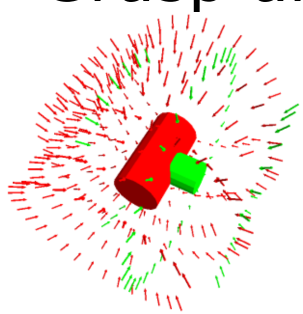




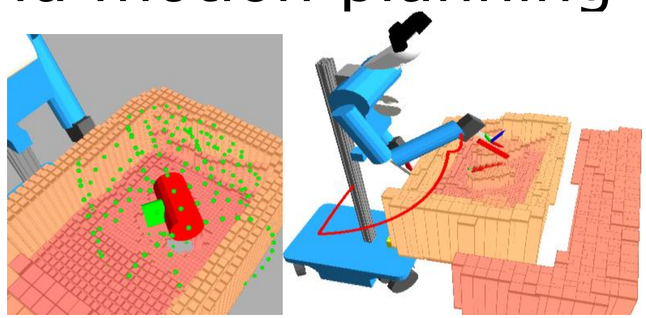




- Grasp and motion planning



Offline



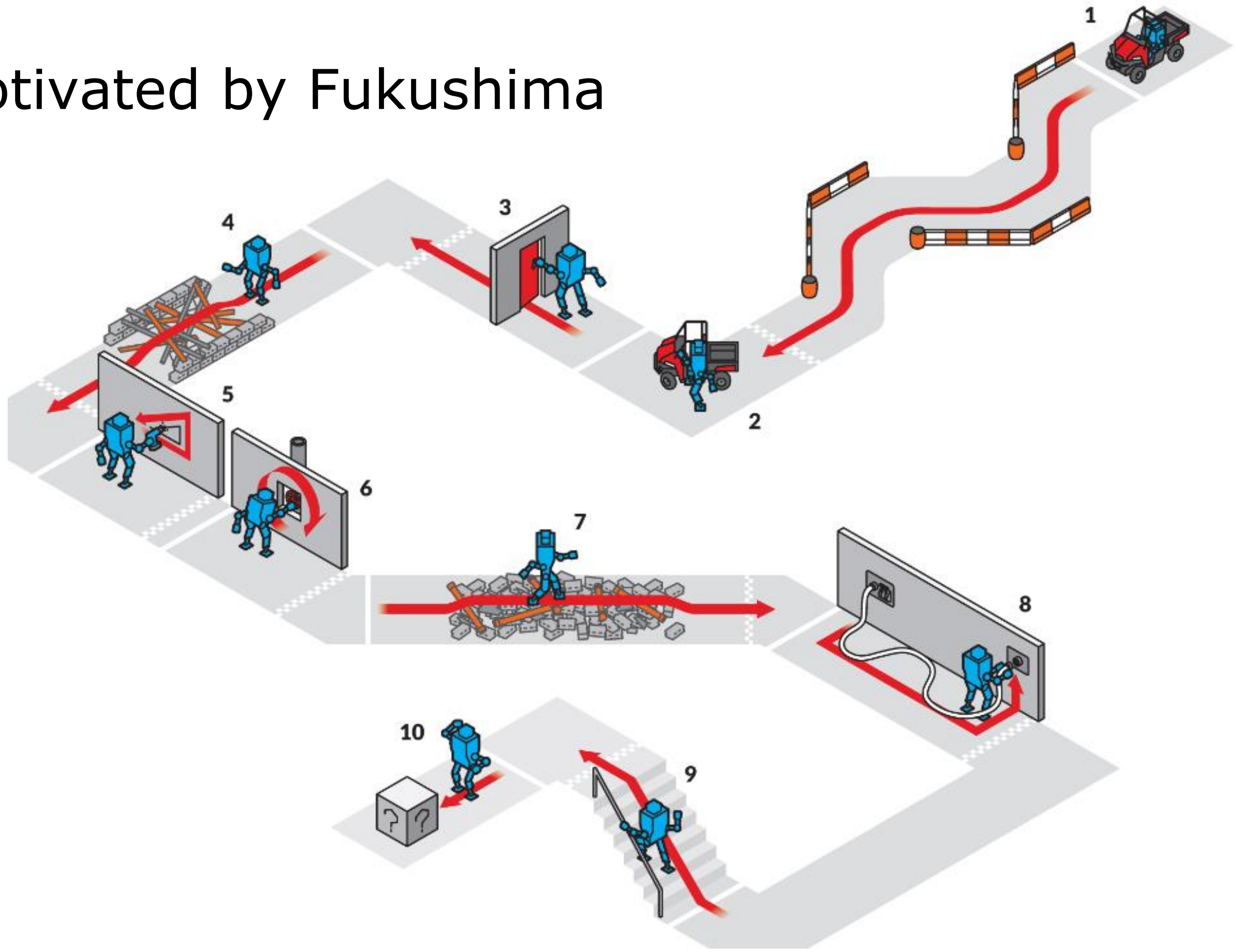
Online

[Nieuwenhuisen et al.: ICRA 2013]

Team NimbRo@Home

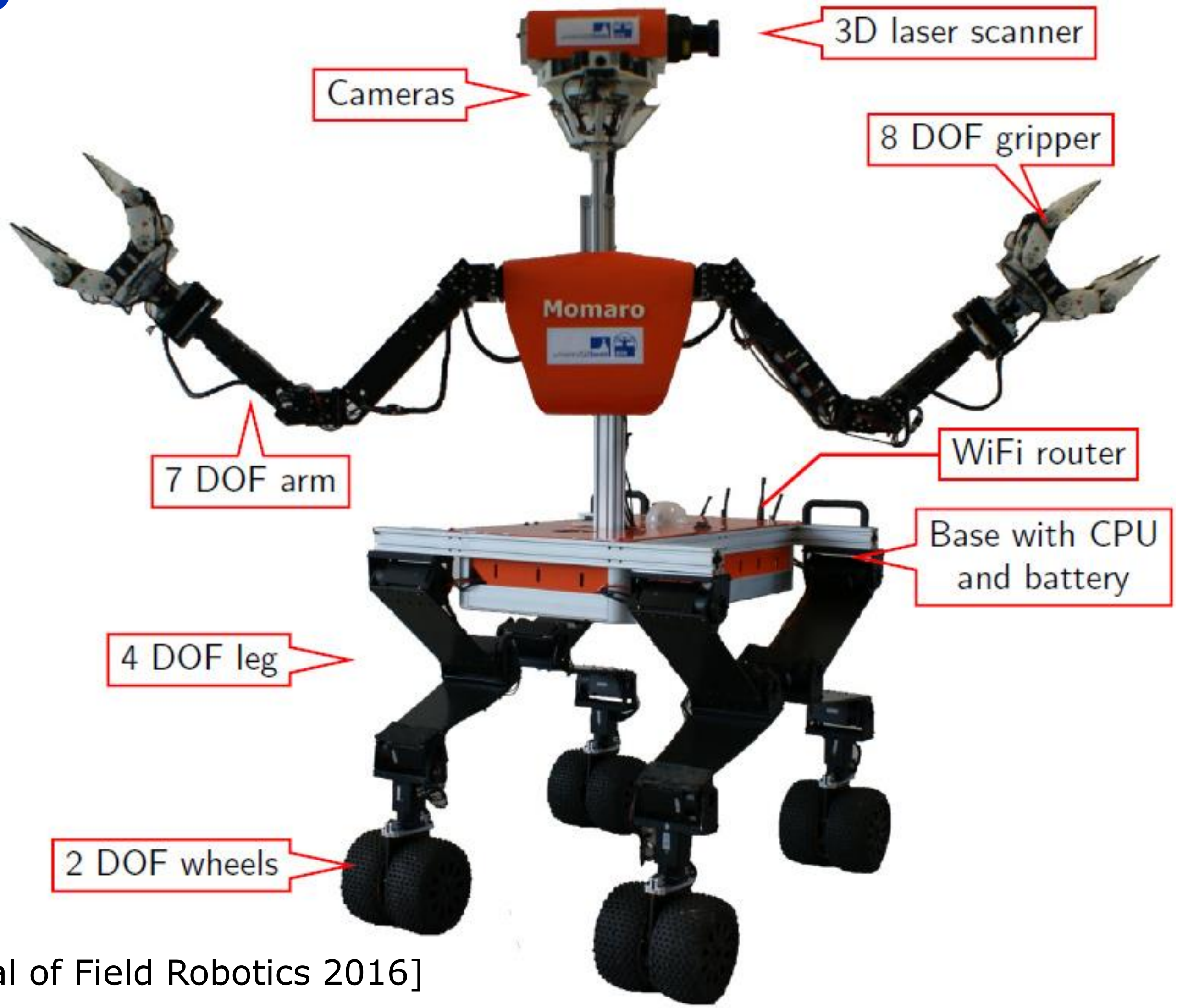
DARPA Robotics Challenge

- Motivated by Fukushima



Mobile Manipulation Robot Momaro

- Four compliant legs ending in pairs of steerable wheels
- Anthropo-morphic upper body
- Sensor head



[Schwarz et al. Journal of Field Robotics 2016]

Driving a Vehicle

[Schwarz et al. Journal of Field Robotics 2016]

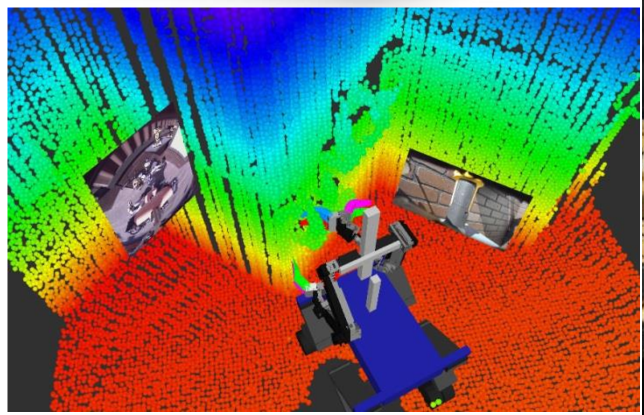
Egress

[Schwarz et al. Journal of Field Robotics 2016]

Manipulation Operator Interface

- 3D head-mounted display

- 3D environment model + images



- 6D magnetic tracker

[Rodehutskors et al., Humanoids 2015]

Opening a Door

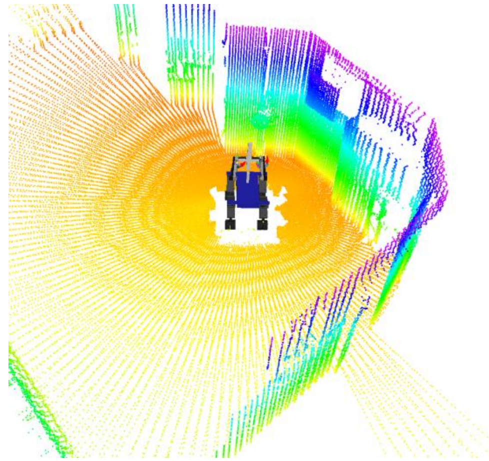
[Schwarz et al. Journal of Field Robotics 2016]

Local Multiresolution Surfel Map

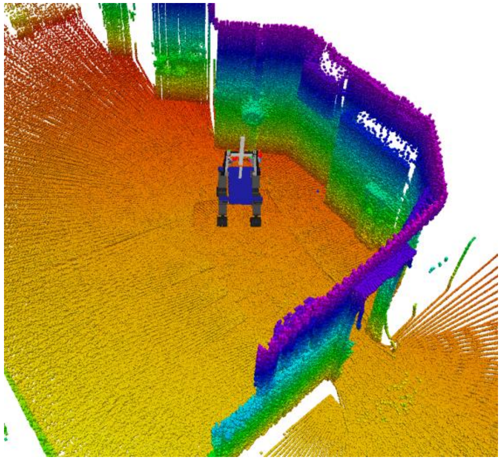
- Registration and aggregation of 3D laser scans
- Local multiresolution grid
- Surfel in grid cells

[Droeschel et al. ICRA 2014, IAS 2014]

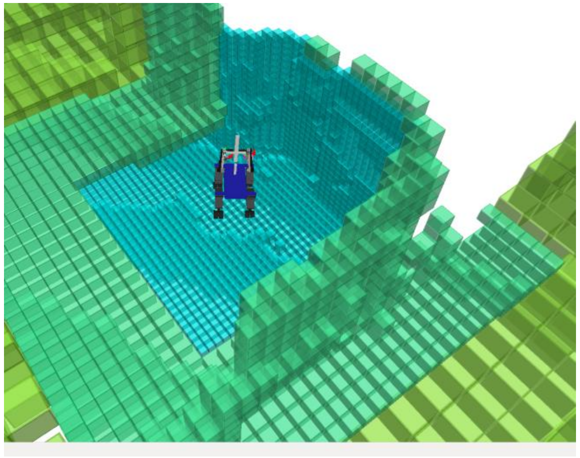
3D scan



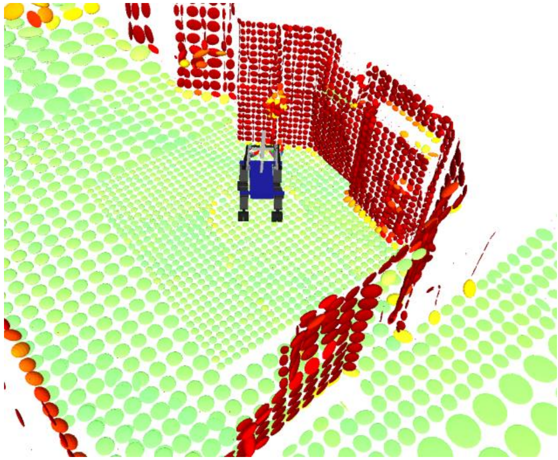
Aggregated scans



Multiresolution grid

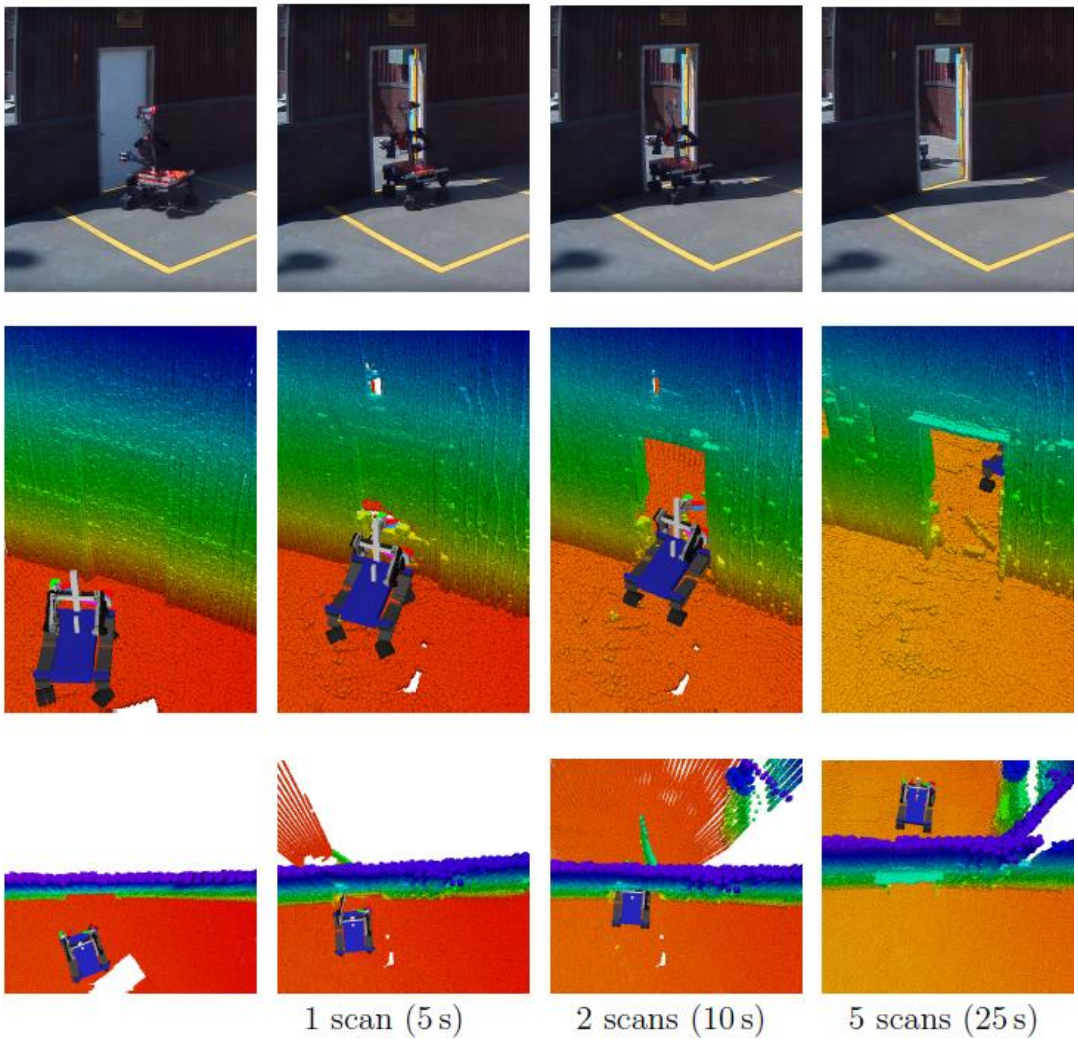


Surfels



Filtering Dynamic Objects

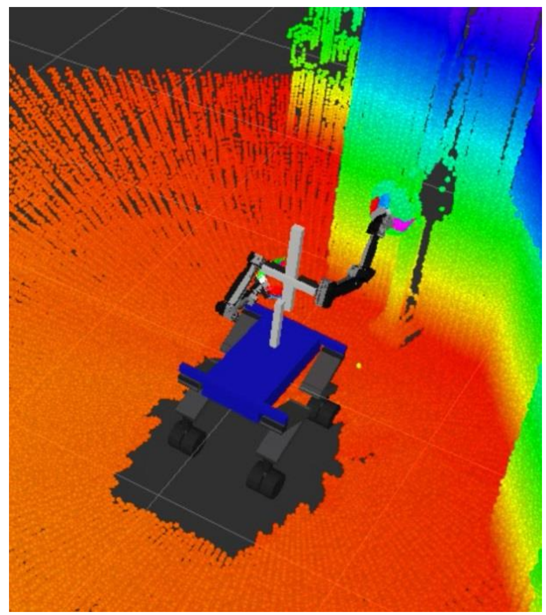
- Maintain occupancy in each cell

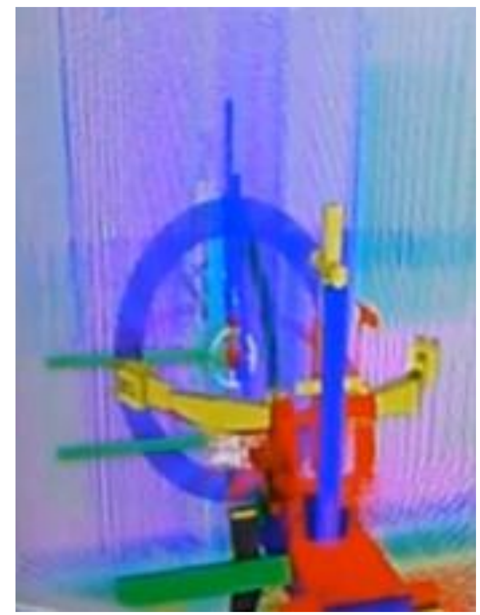


[Droeschel et al. under review]

Valve Turning Interface

- Align wheel model with 3D points using interactive marker
- Turning motion primitive

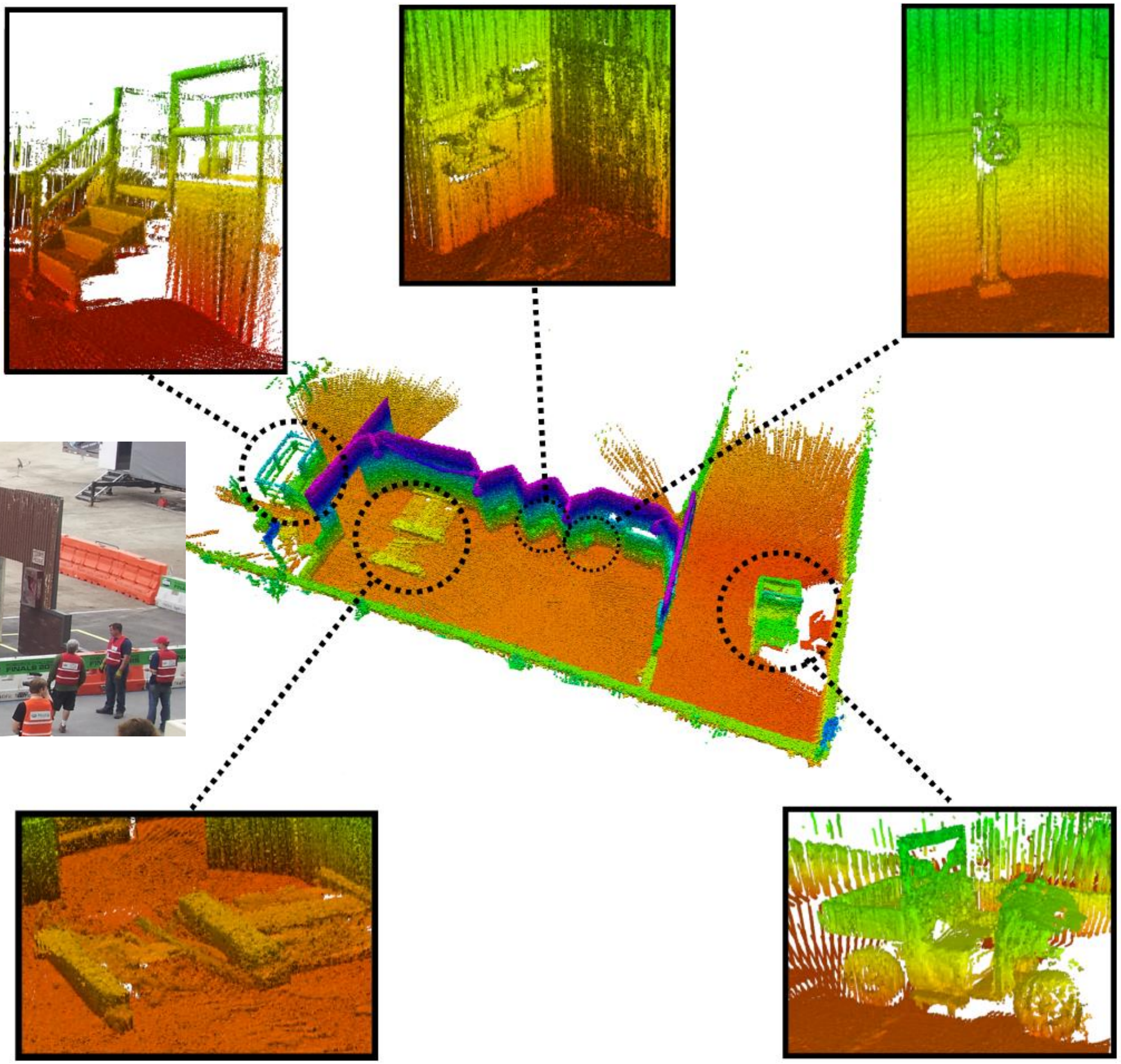




Turning a Valve

Allocentric 3D Mapping

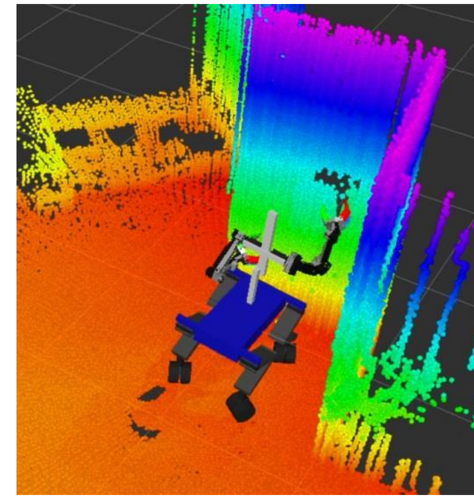
- Registration of egocentric maps by graph optimization

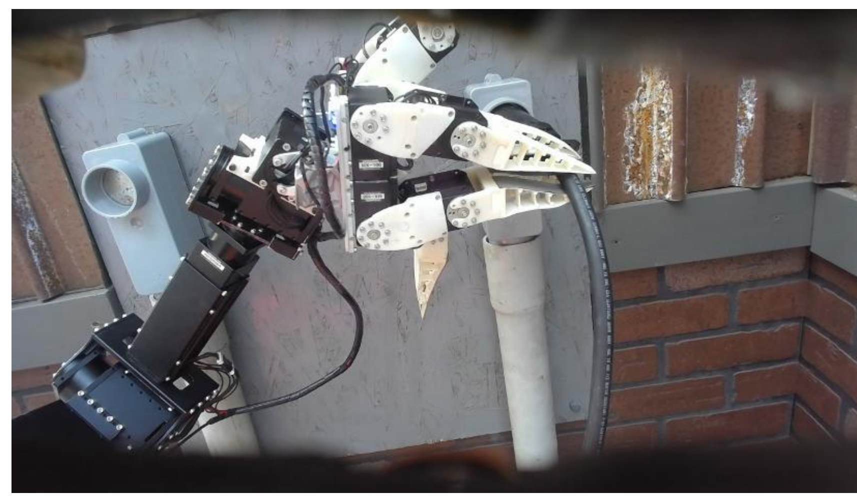


[Droeschel et al., ICRA 2014, IAS 2014]

Surprise Tasks

- Direct control of manipulation
- Open a cabinet and push a button
- Operate an electric switch
- Pull a plug and insert it into another socket

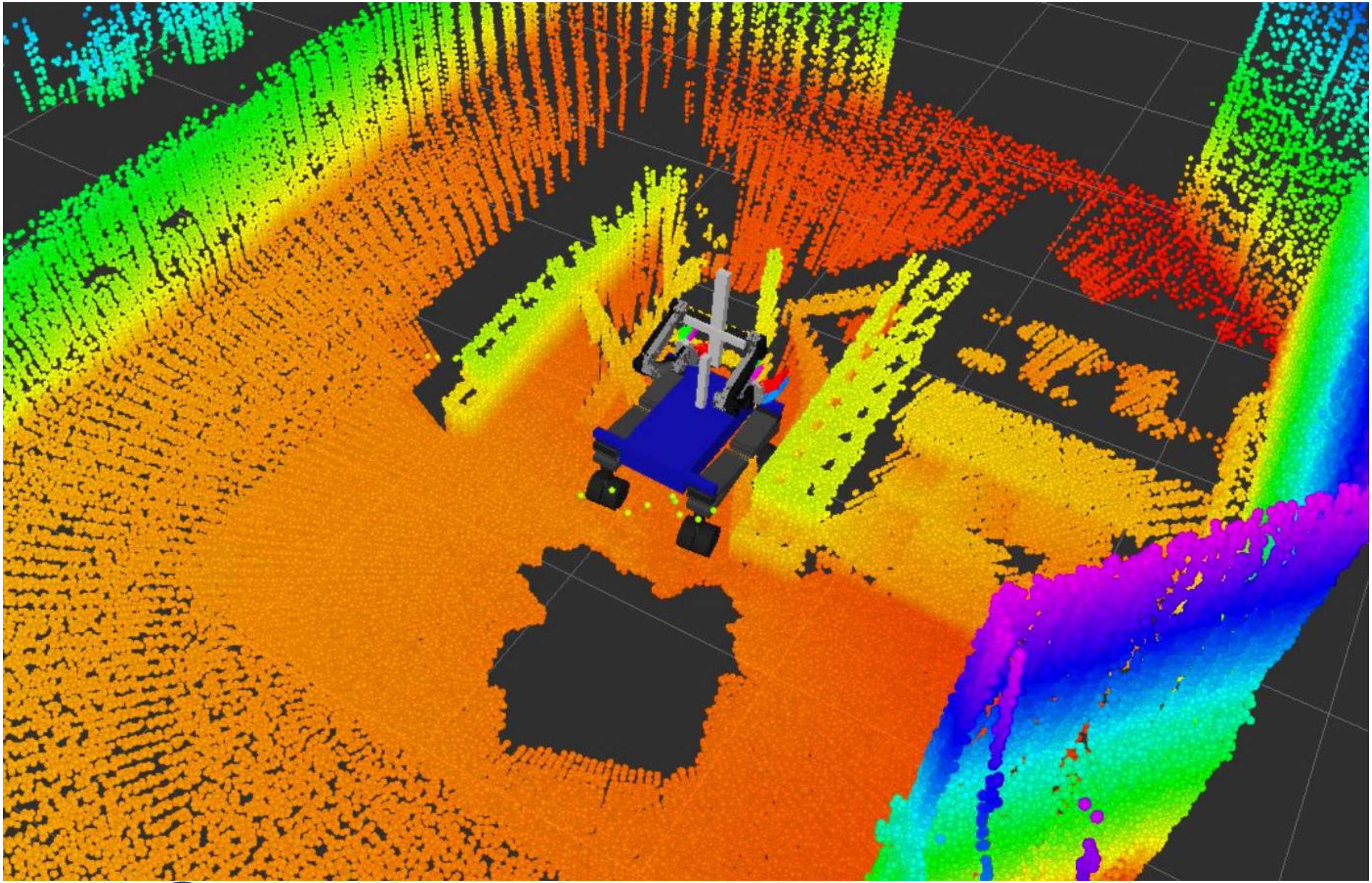




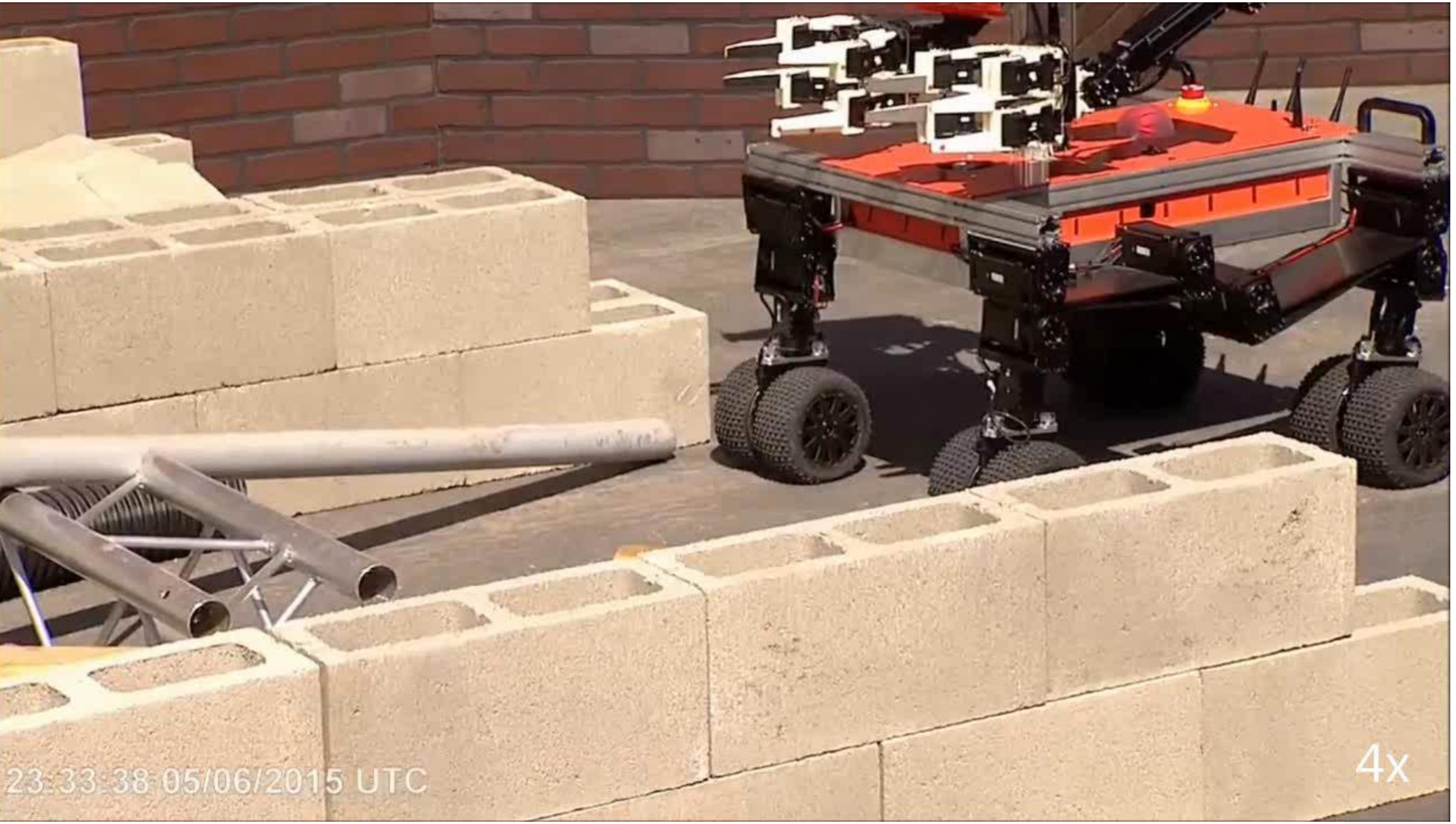
Operating a Switch

Plug Task at DRC

Debris Task

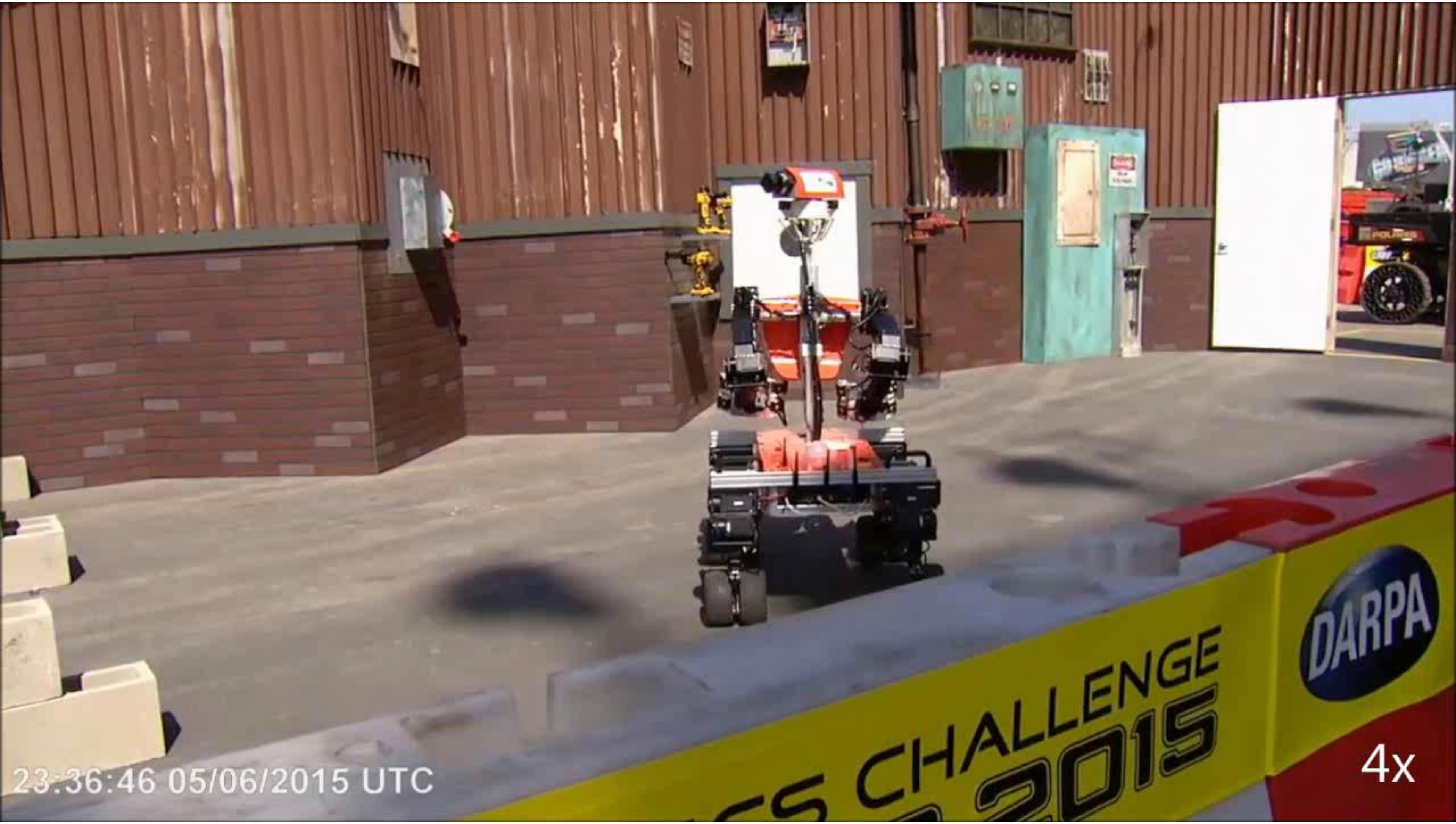


Drive Through Debris



[Schwarz et al. Journal of Field Robotics 2016]

Cutting Drywall

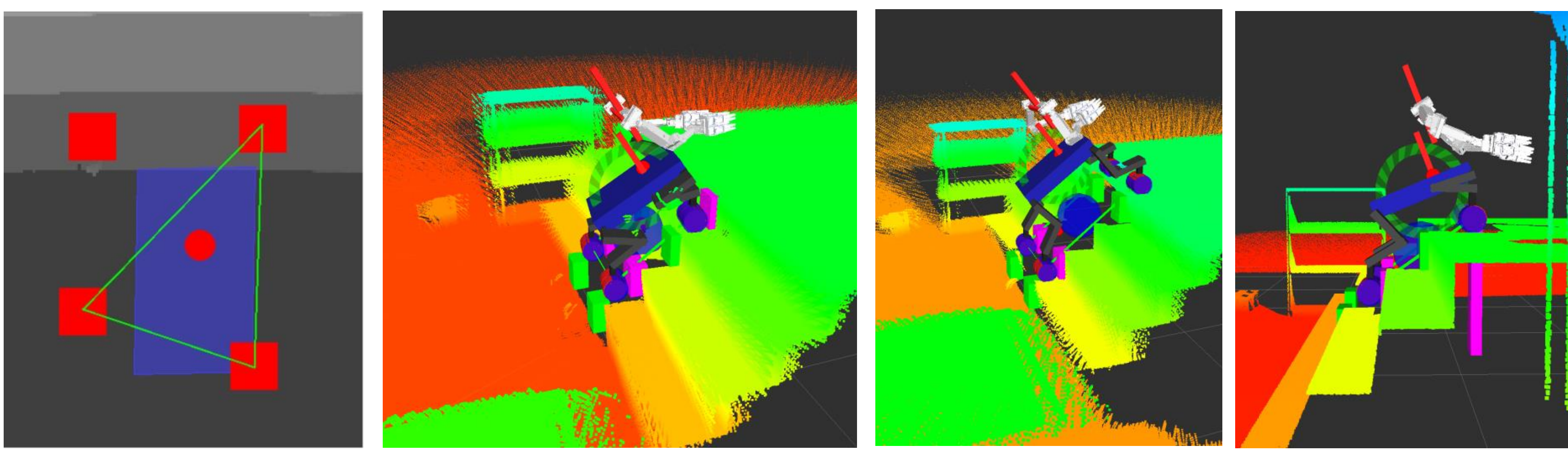


Team NimbRo Rescue

Best European Team (4th place overall), solved seven of eight tasks in 34 minutes

Stair Climbing

- Determine leg that most urgently needs to step
- Weight shift
  - Move the base relative to the wheels in sagittal direction
  - Drive the wheels on the ground relative to the base
  - Modify the leg lengths (and thus the base orientation)
- Step to first possible foot hold after height change



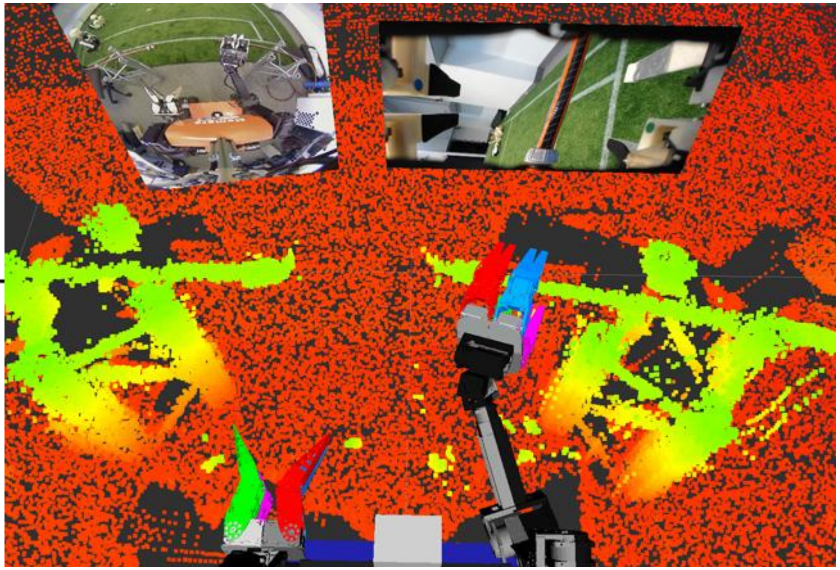
[Schwarz et al., ICRA 2016]

Stair Crawling

[Schwarz et al., ICRA 2016]

Hose Connecting Task

- Bimanual task
  - Grab the left hose with the left gripper,
  - Grab the right hose with the right gripper, and
  - Connect both hoses
- 10/11 trials successful
- Execution time



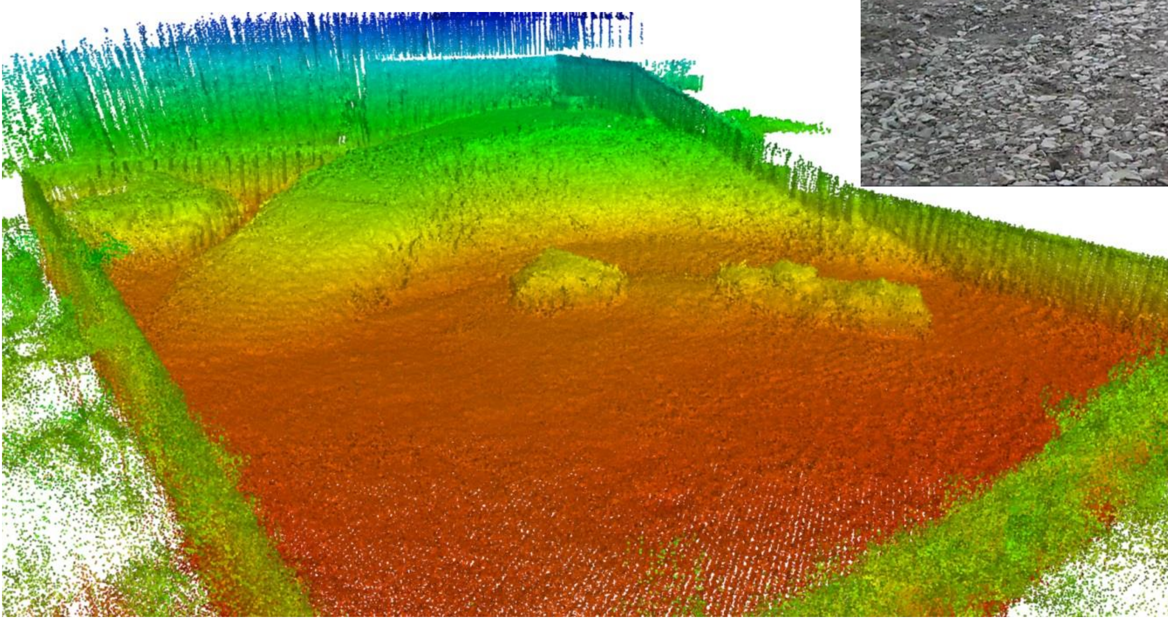
Task	Time [min:s]				
	Avg.	Median	Min.	Max.	Std. Dev.
Left grasp	0:44	0:38	0:27	1:20	0:16
Right grasp	0:45	0:40	0:34	1:04	0:10
Connect	1:36	1:32	1:07	2:04	0:21
Total	3:04	2:57	2:21	3:51	0:28

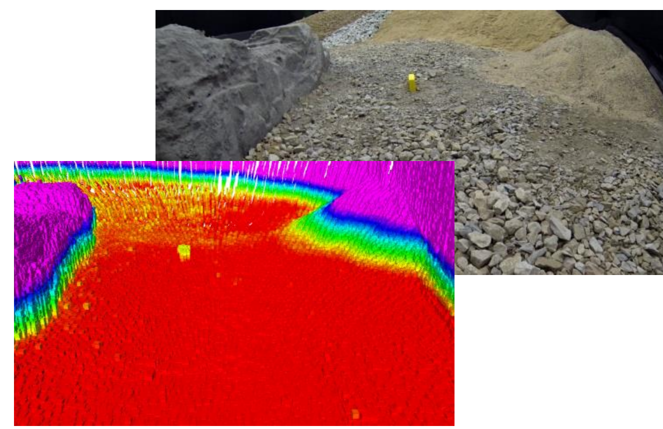
[Rodehutskors et al., Humanoids 2015]

DLR SpaceBot Cup 2015

- Mobile manipulation in rough terrain

[Schwarz et al., Frontiers on Robotics and AI 2016]

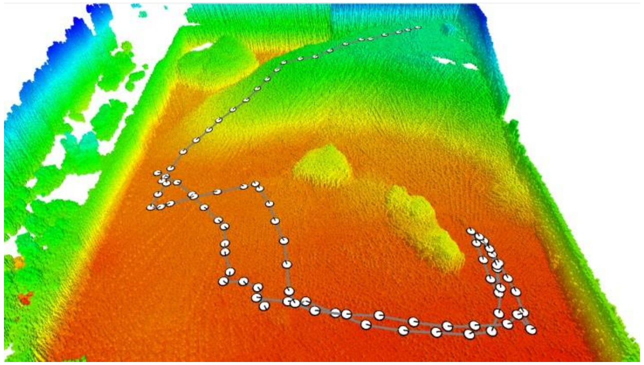




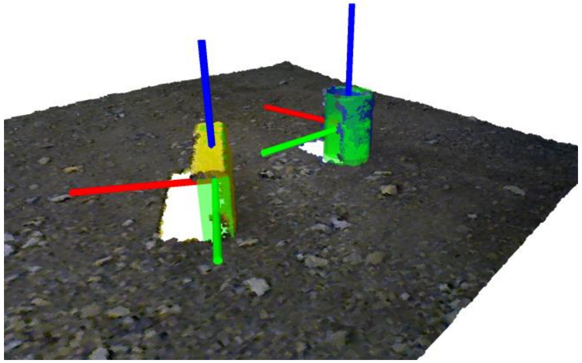
DLR SpaceBot Camp 2015

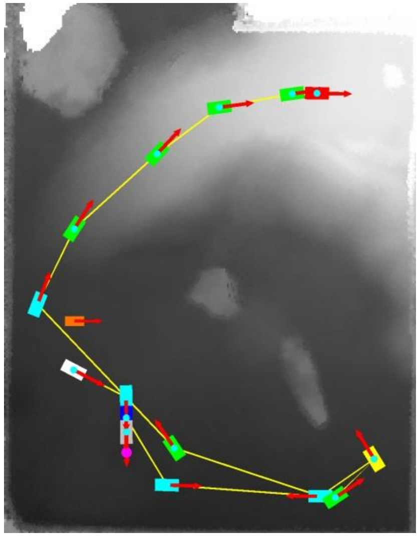
Autonomous Mission Execution

3D Mapping & Localization

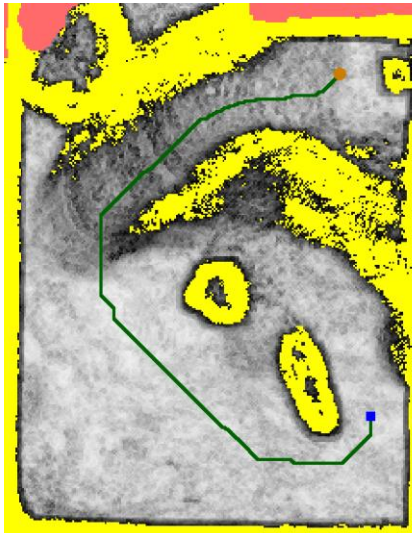


Object perception

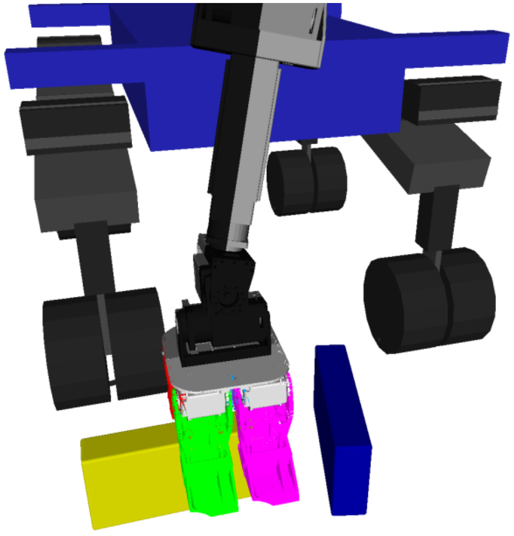




Mission plan



Navigation plan

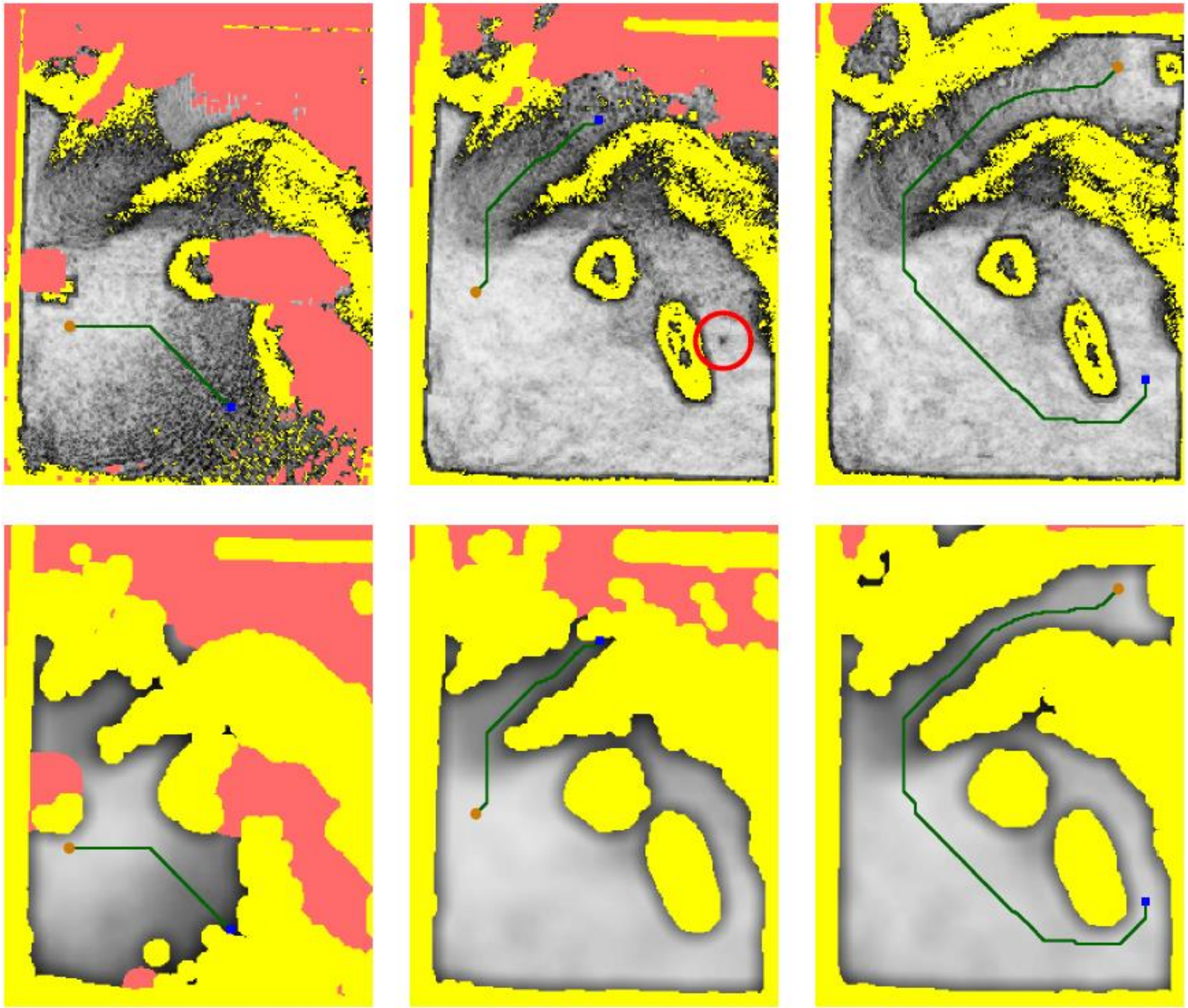


Grasping

[Schwarz et al., Frontiers in Robotics and AI 2016]

Navigation Planning

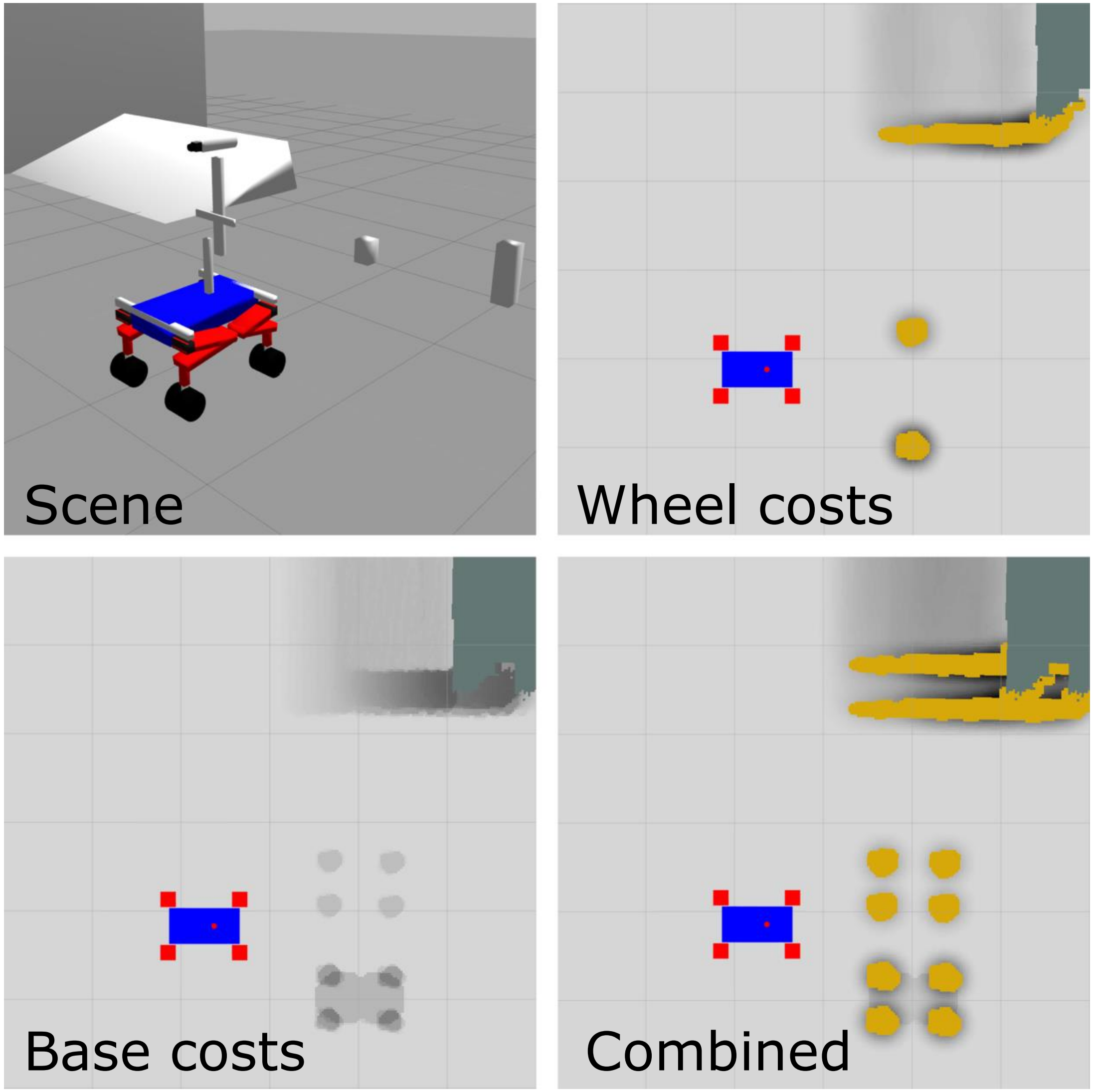
- Costs from local height differences
- A* path planning



[Schwarz et al., Frontiers in Robotics and AI 2016]

Considering Robot Footprint

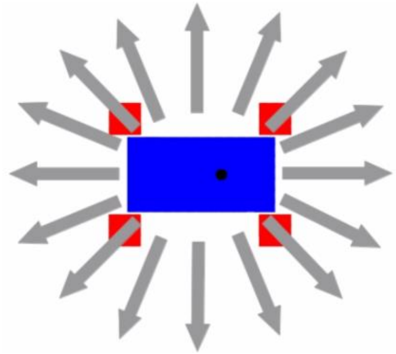
- Costs for individual wheel pairs from height differences
- Base costs
- Non-linear combination yields 3D (x, y, θ) cost map



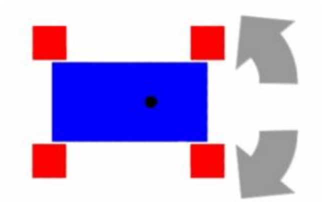
[Klamt and Behnke, under review]

3D Driving Planning (x, y, θ): A*

- 16 driving directions

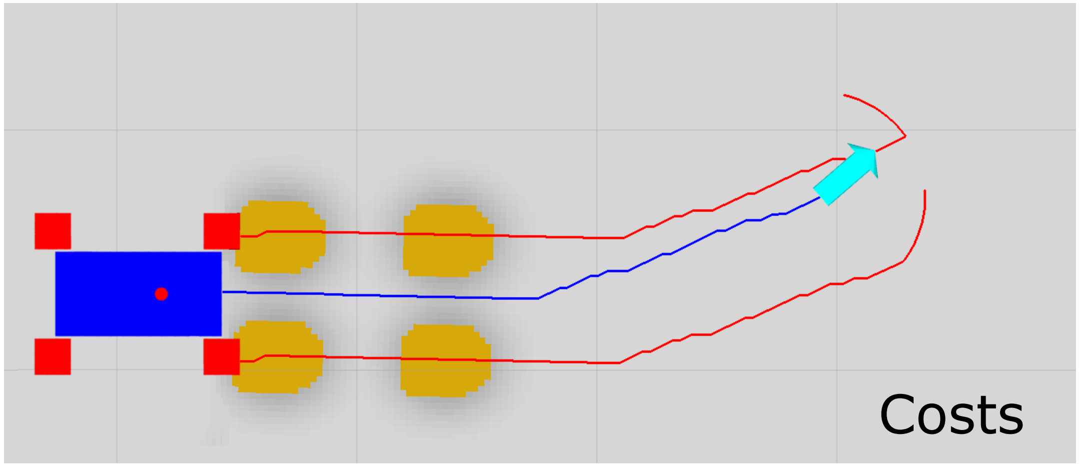


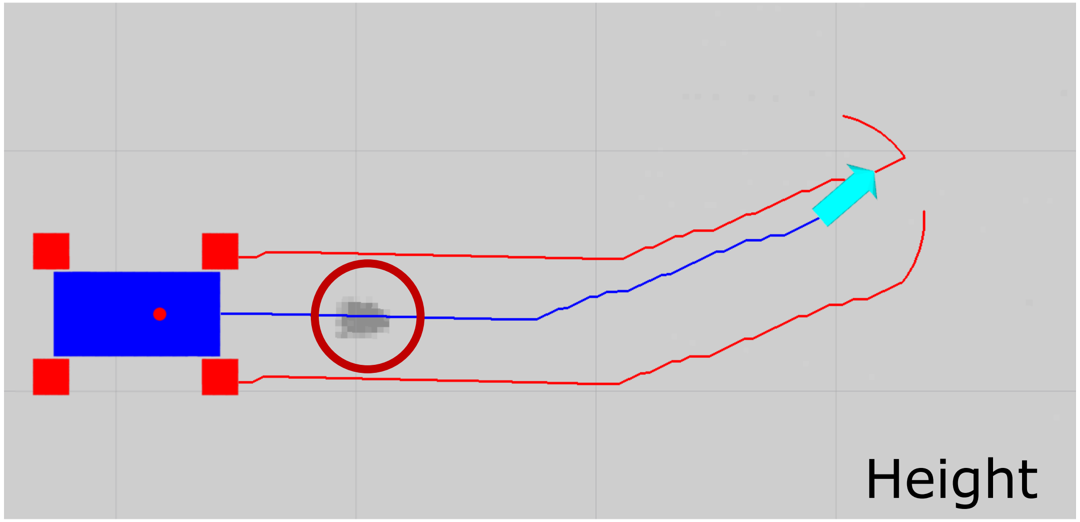
- Orientation changes



=> Obstacle between wheels

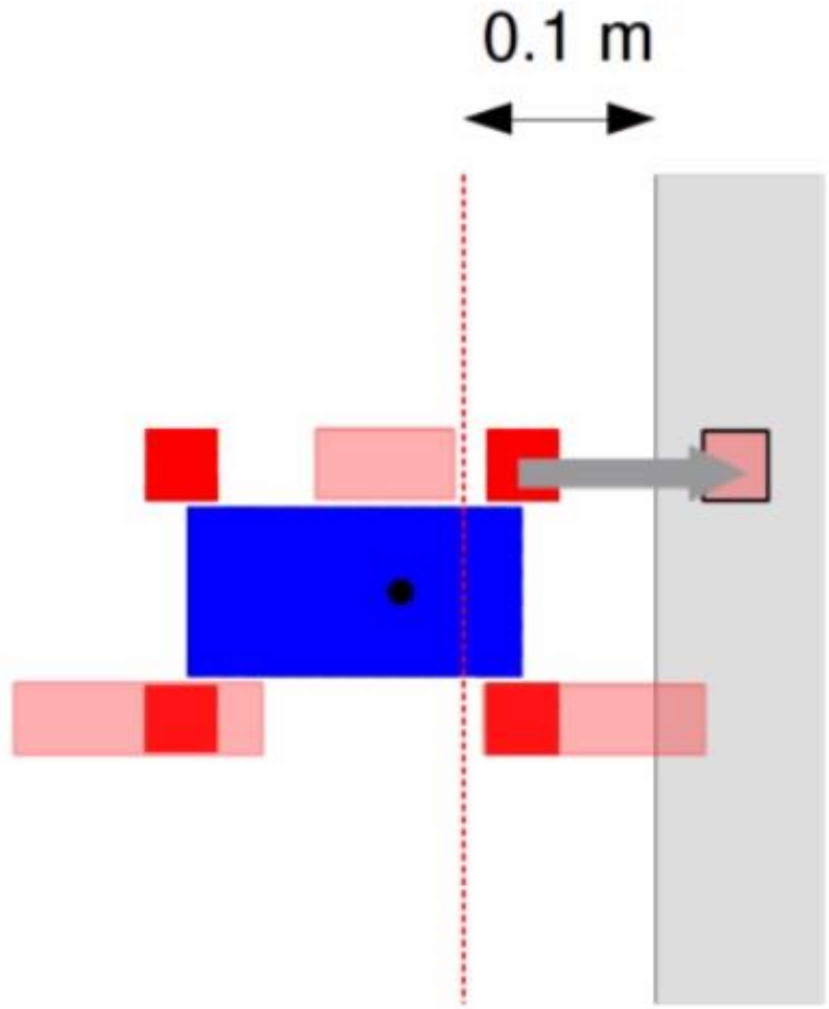
[Klamt and Behnke, under review]





Making Steps

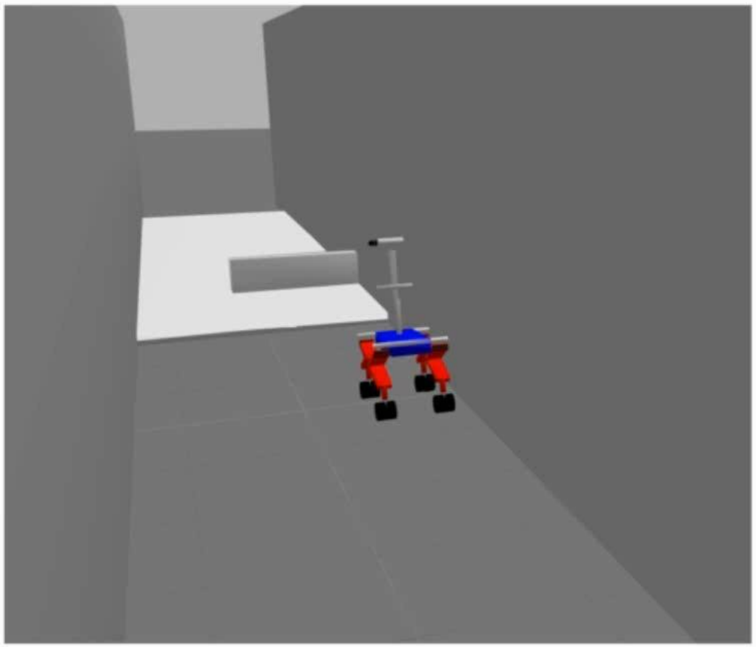
- If not drivable obstacle in front of a wheel
- Step landing must be drivable
- Support leg positions must be drivable



[Klamt and Behnke, under review]

Hybrid Driving-Stepping Plan

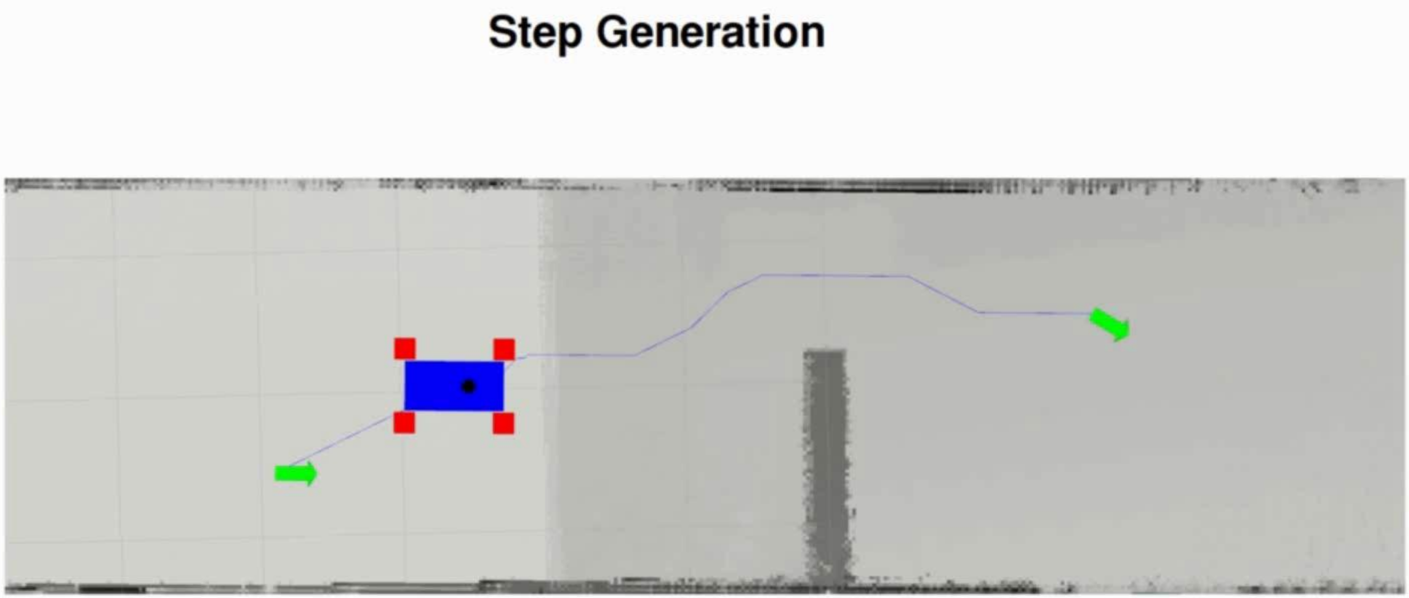
Path Planning Example



Scenario: Momaro has to step up a height difference and manoeuvre around a small wall.

[Klamt and Behnke, under review]

Detailed Realization of Steps



[Klamt and Behnke, under review]

Conclusion

- Developed methods for humanoid mobility, object manipulation, tool use, human-robot interaction in
  - Soccer,
  - Domestic service,
  - Search and rescue, and
  - Space exploration
- Challenges
  - Balance in bipedal walking
  - Variability of environments
  - Task complexity
- Need for further research
  - Mechatronic design
  - Environment perception
  - Motion planning and control
  - Learning

Questions?