# Anthropomorphic Robots for Disaster Response

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# Robot Competitions

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


RoboCup Soccer

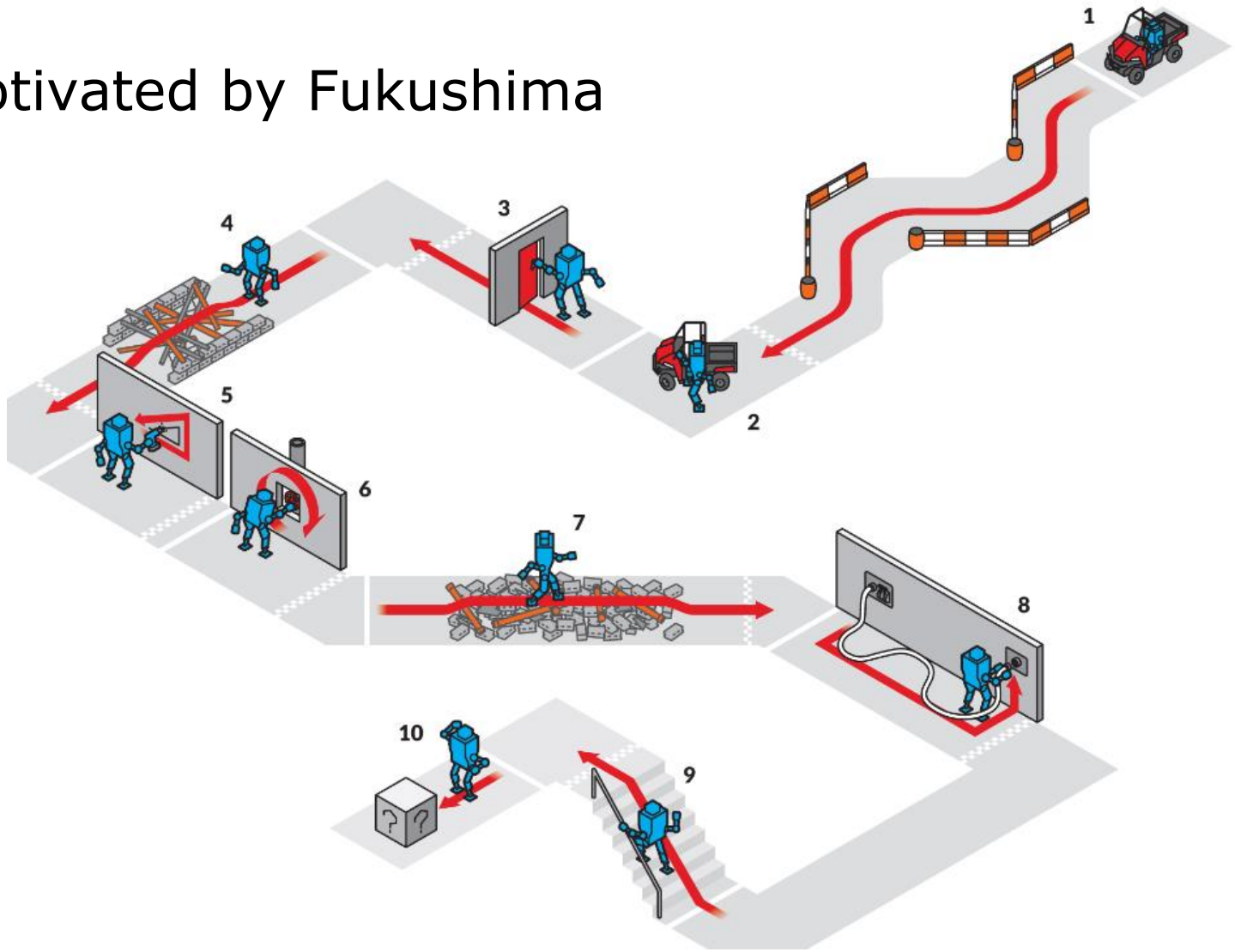

RoboCup @Home


DARPA Robotics Challenge


DLR SpaceBot Cup

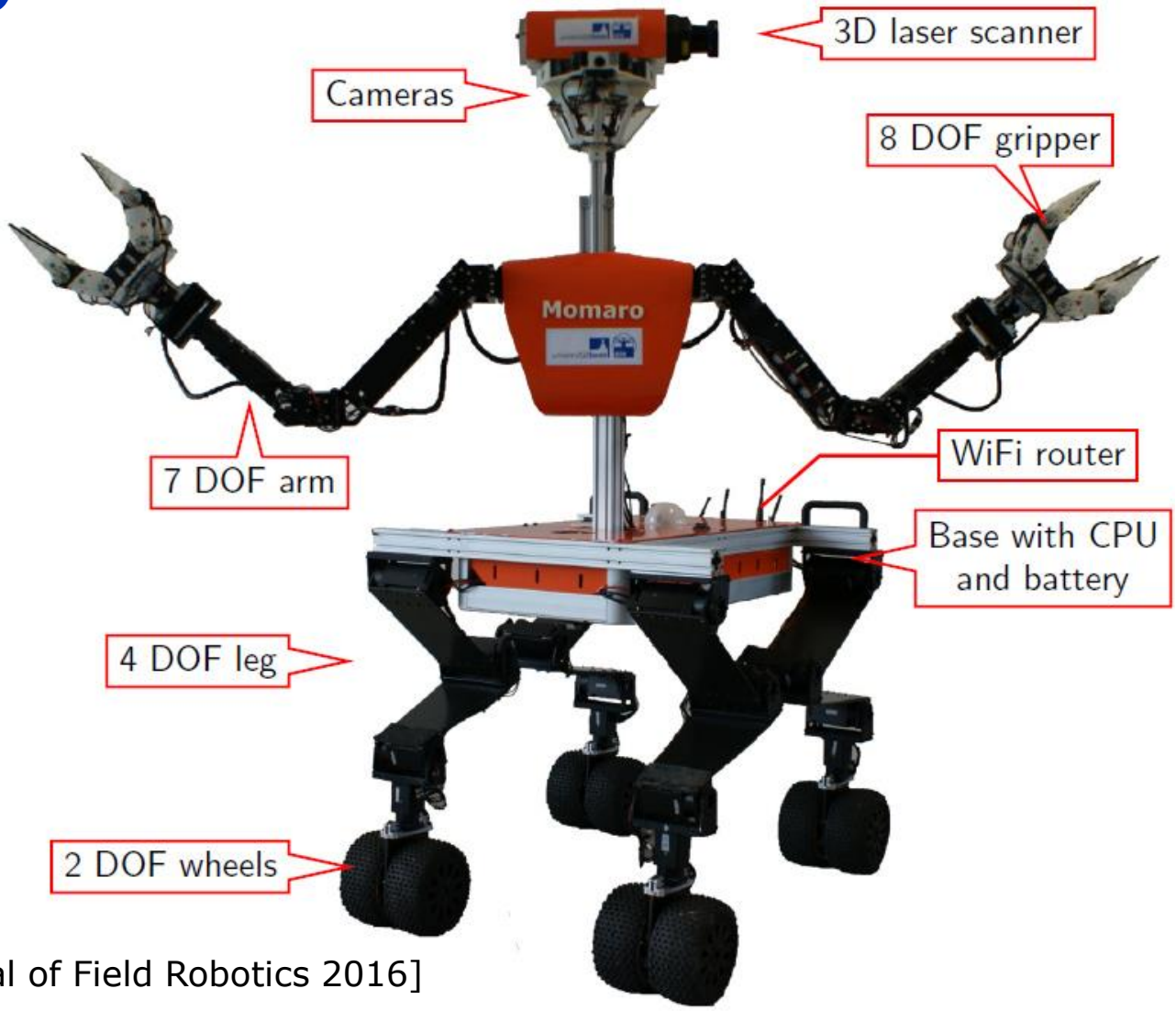
# DARPA Robotics Challenge

- 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]

# Momaro Leg Design

- Robotis Dynamixel Pro Actuators
  - Hip, knee: 44 Nm
  - Ankle pitch: 25 Nm
  - Ankle yaw: 6 Nm
  - Wheel drive: 2× 6 Nm
- Carbon composite springs in links
- Omnidirectional driving
- Base height and attitude changes
- Terrain adaptation
- Making steps

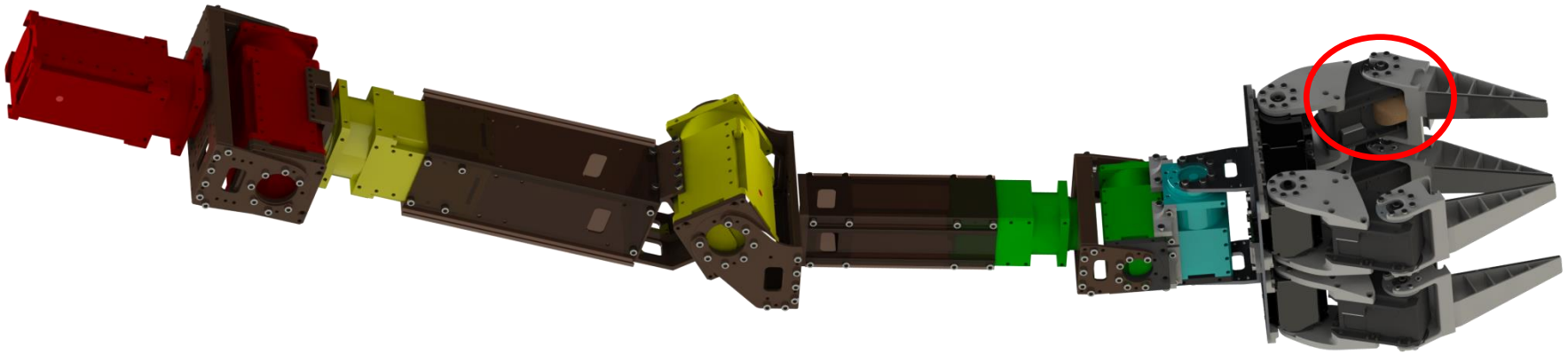
[Schwarz et al. Journal of Field Robotics 2016]

# Egress


[Schwarz et al. Journal of Field Robotics 2016]

# Momaro Arm Design

- Seven Robotis Dynamixel Pro actuators
  - Shoulder roll & pitch 2x 44.2 Nm, yaw 25 Nm
  - Elbow 24.8 Nm
  - Wrist roll & pitch 6.3 Nm, yaw 1.4 Nm



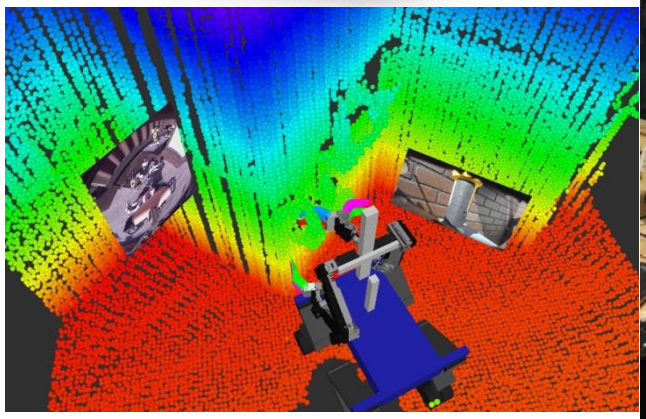
- Four fingers with two Dynamixel actuators
  - Proximal 8.4 Nm, distal 6.0 Nm
  - Bump for pushing tool trigger

[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

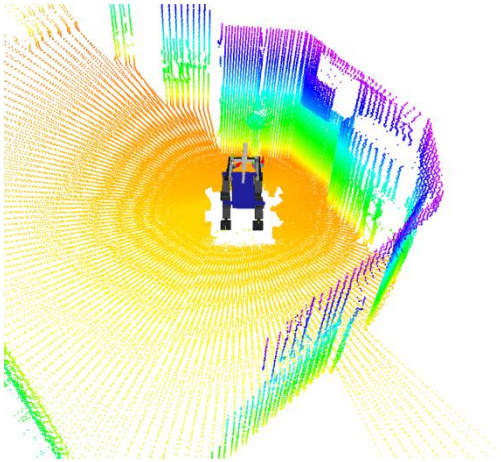

[Schwarz et al. Journal of Field Robotics 2016]

# Local Multiresolution Surfel Map

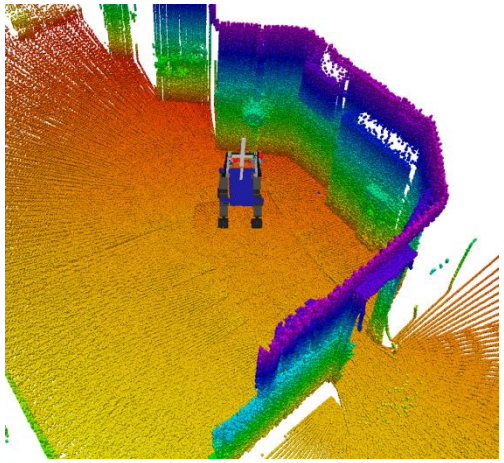
- Registration and aggregation of 3D laser scans
- Local multiresolution grid
- Surfel in grid cells

[Droeschel et al., Robotics and Autonomous Systems 2016]

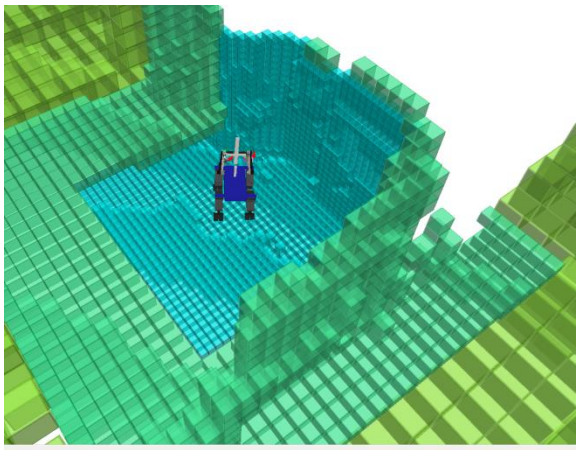
3D scan



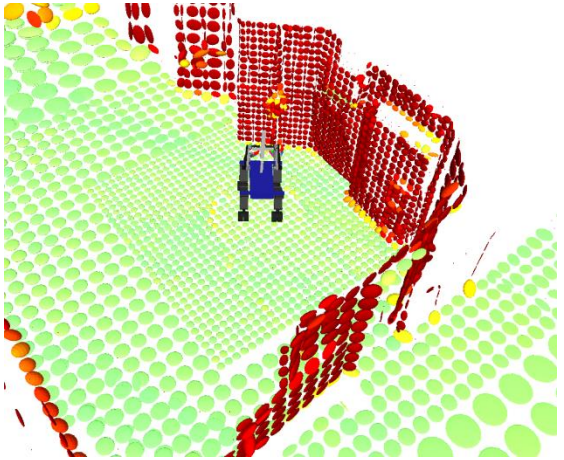
Aggregated scans



Multiresolution grid

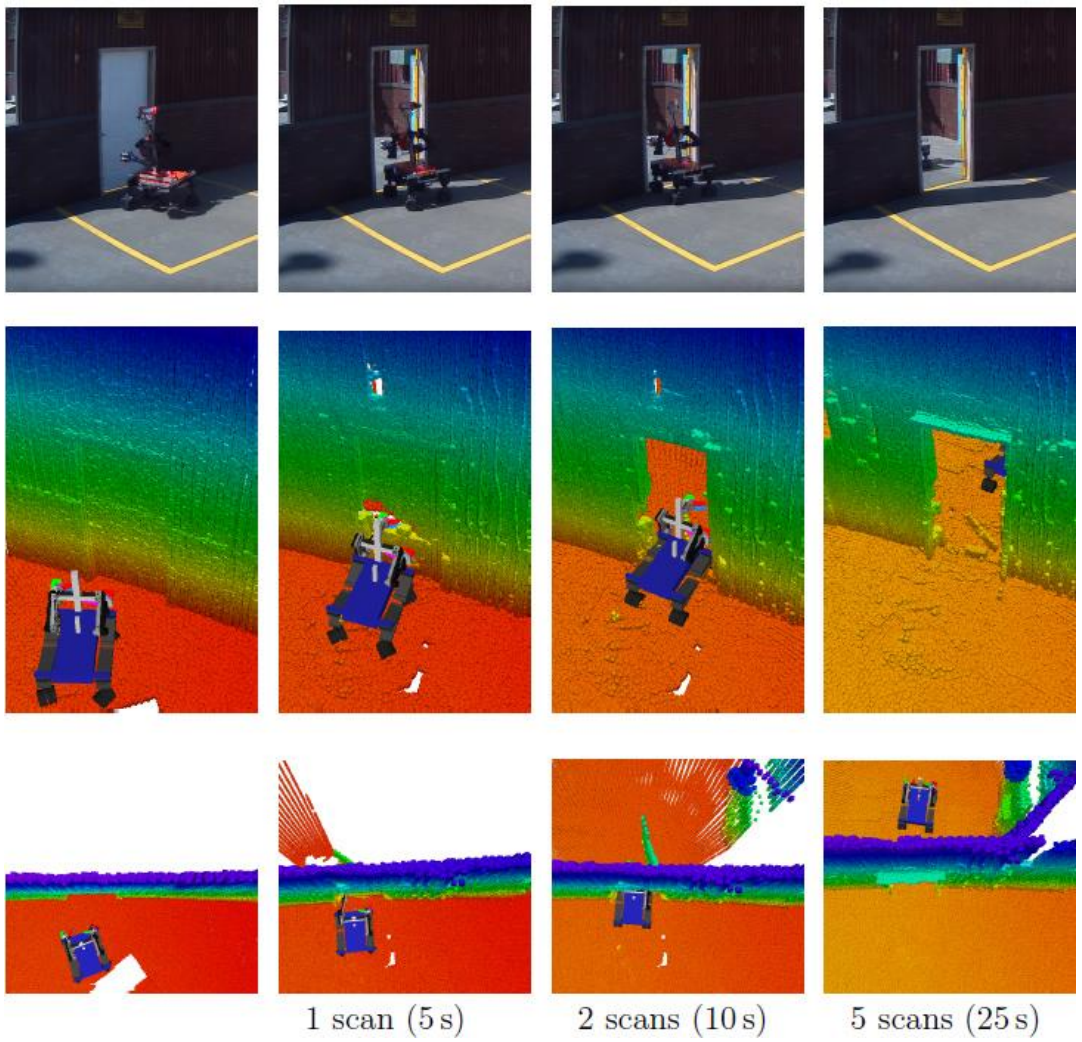


Surfels



# Filtering Dynamic Objects

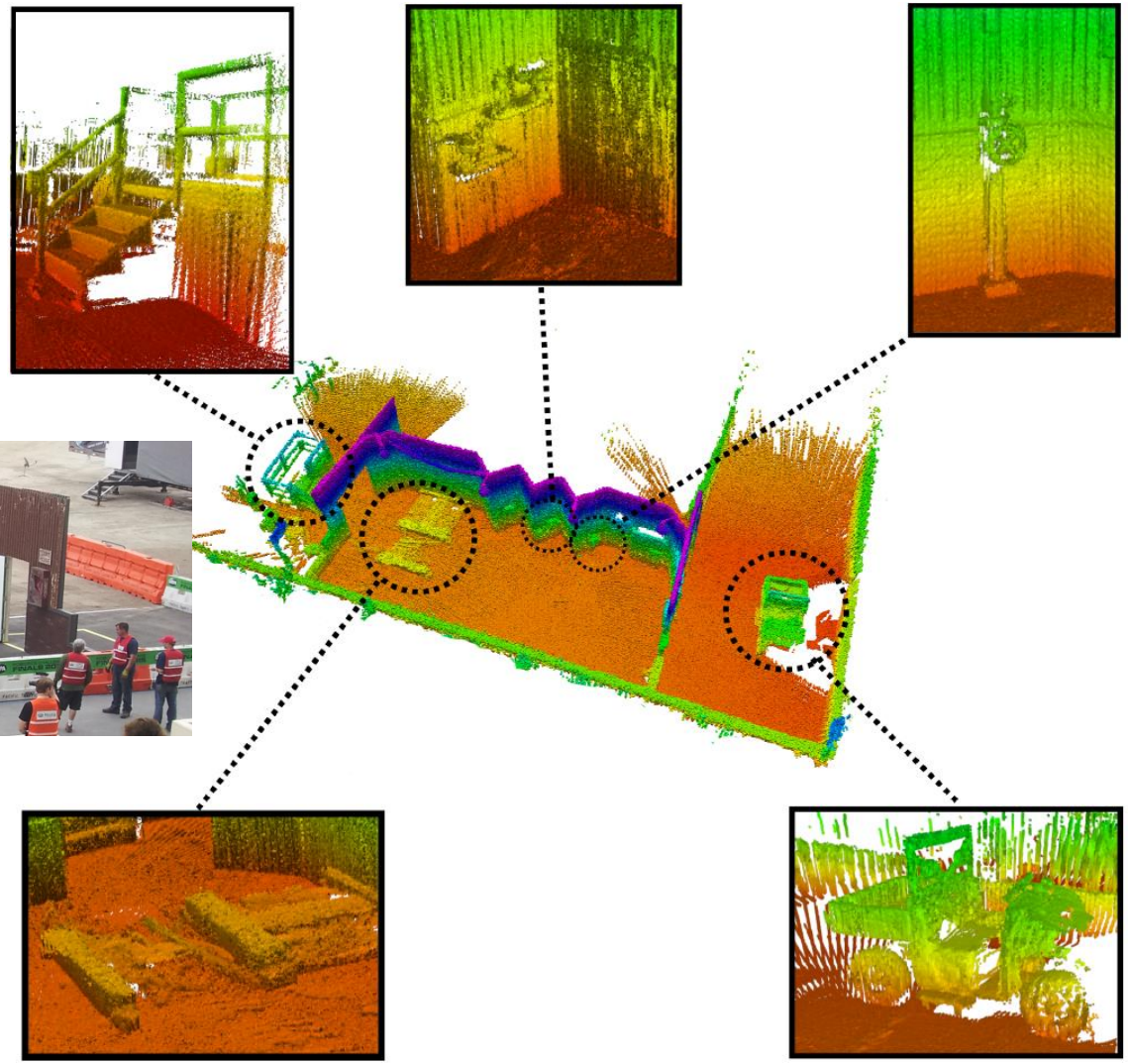
- Maintain occupancy in each cell




[Droeschel et al., Robotics and Autonomous Systems 2016]

# Allocentric 3D Mapping

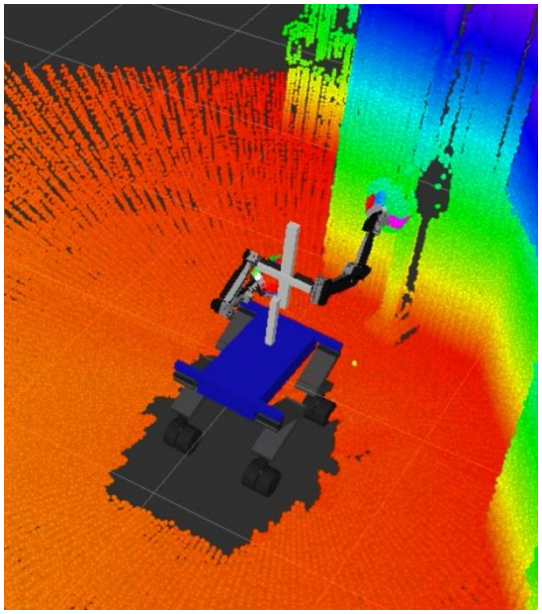
- Registration of egocentric maps by graph optimization



[Droeschel et al., Robotics and Autonomous Systems 2016]

# Valve Turning Interface

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



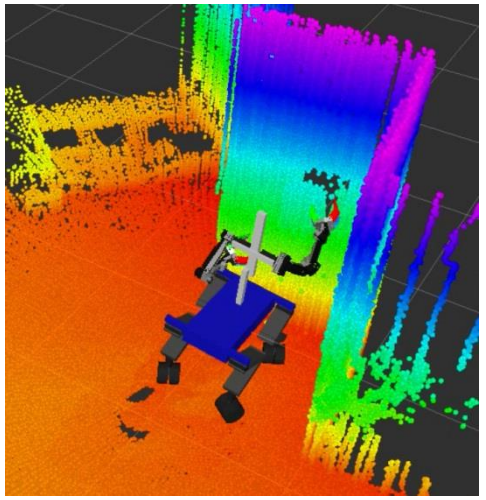
[Schwarz et al. Journal of Field Robotics 2016]

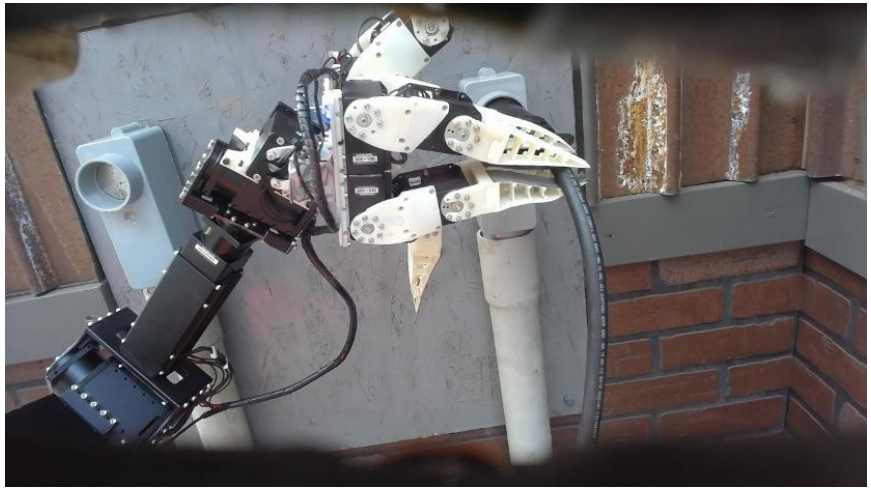
# Turning a Valve


[Schwarz et al. Journal of Field Robotics 2016]

# 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





[Schwarz et al. Journal of Field Robotics 2016]

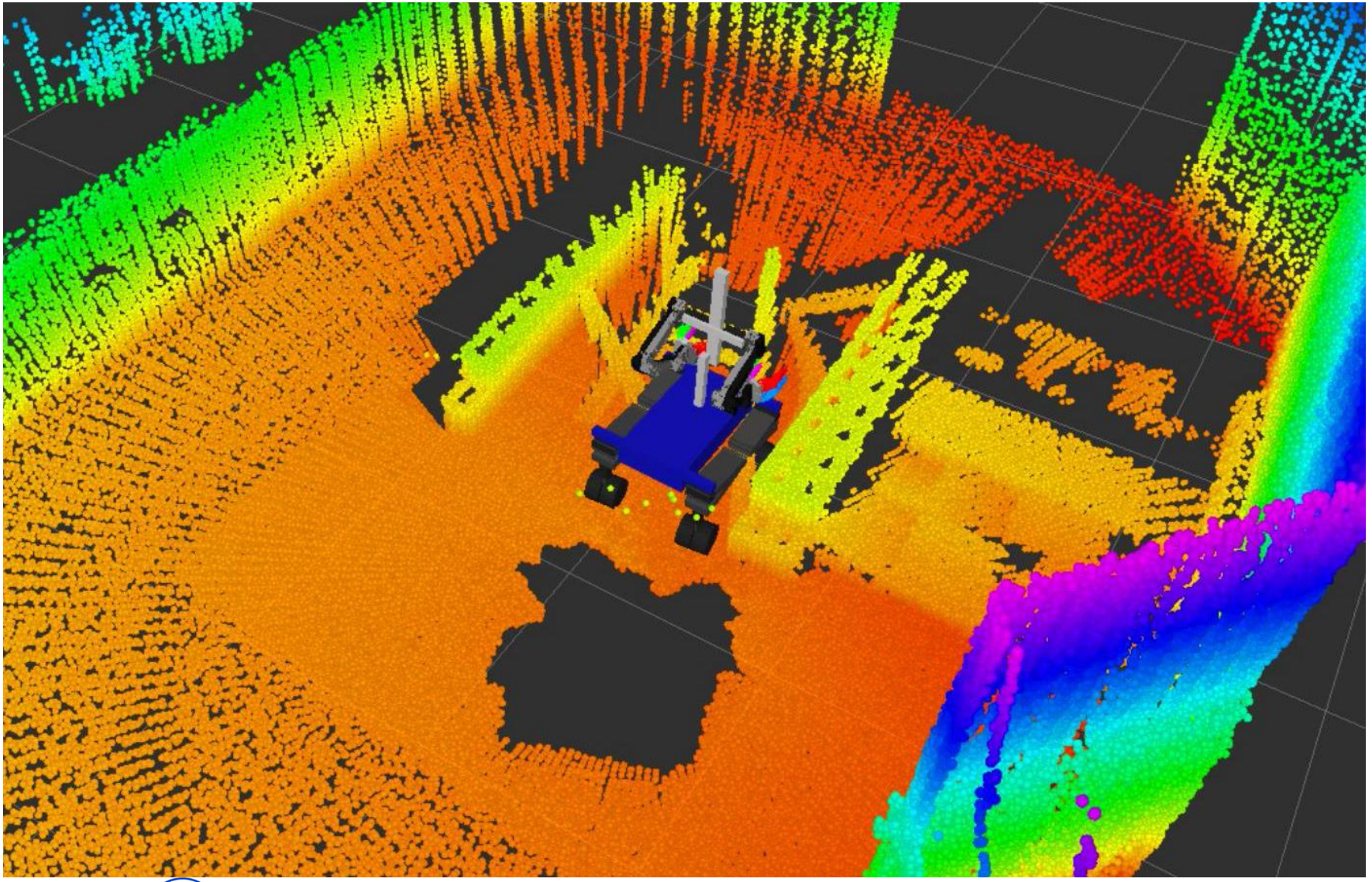
# Operating a Switch


[Schwarz et al. Journal of Field Robotics 2016]

# Plug Task at DRC

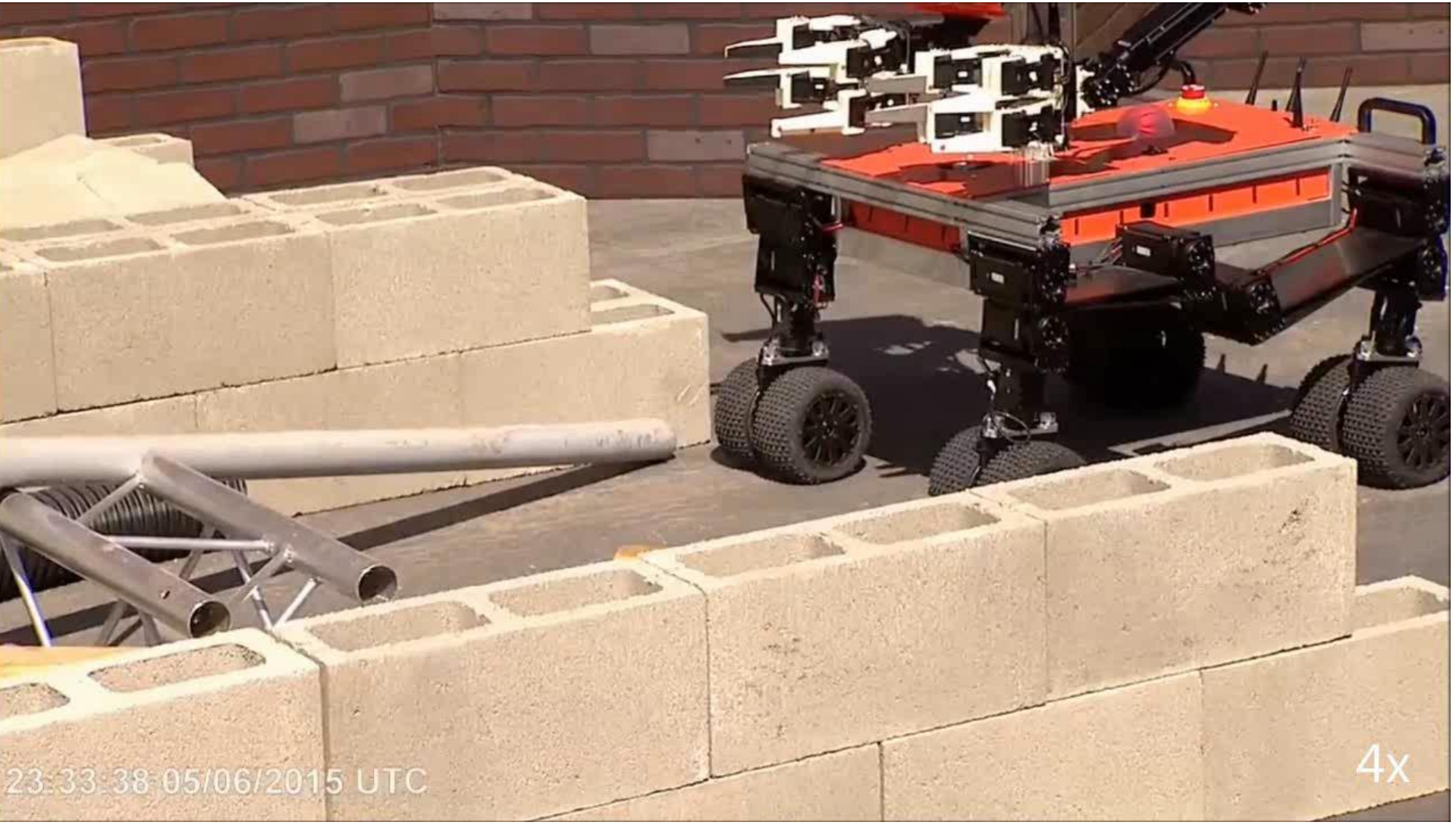

[Schwarz et al. Journal of Field Robotics 2016]

# Debris Task



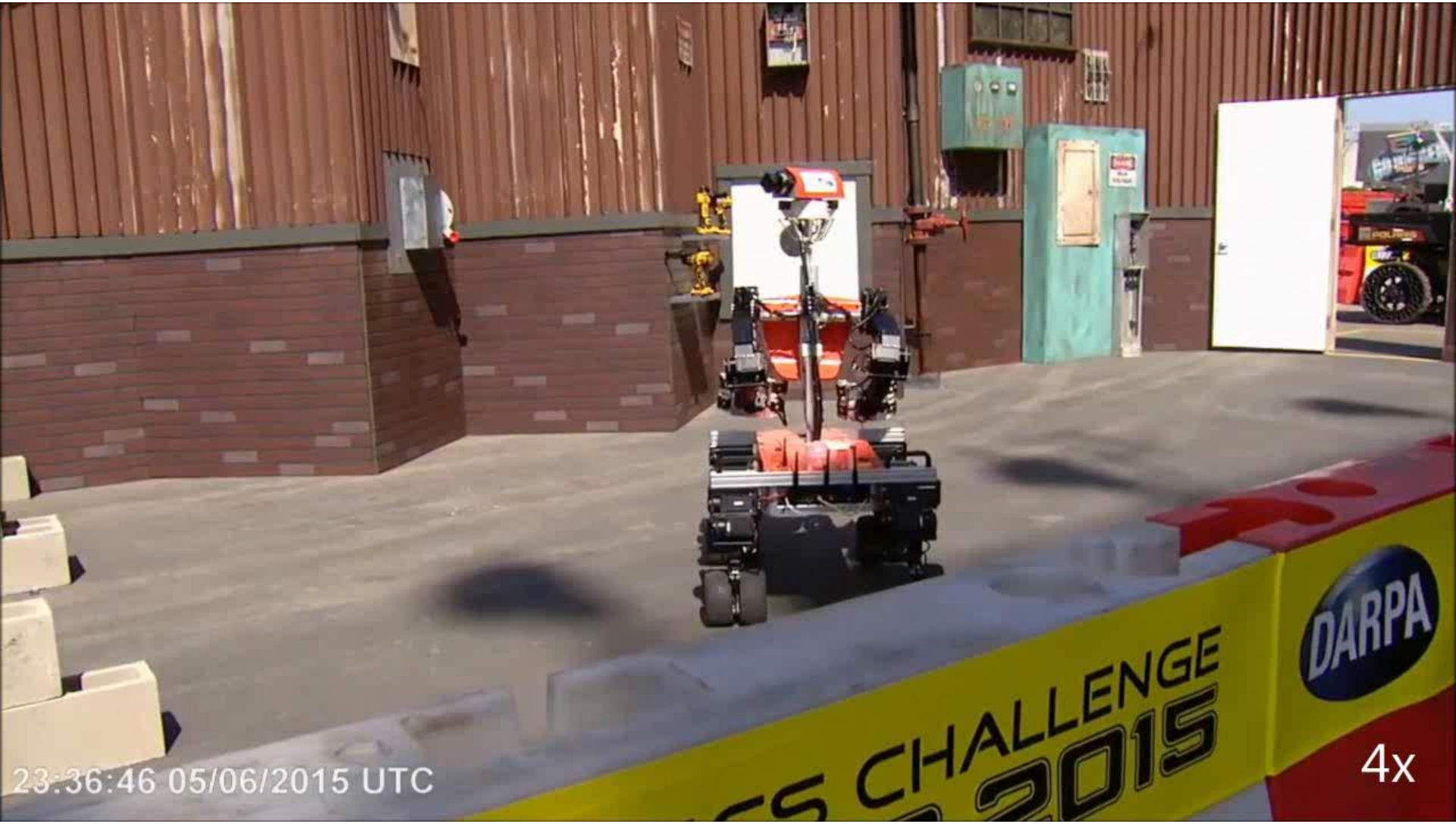
[Schwarz et al. Journal of Field Robotics 2016]

# Drive Through Debris




[Schwarz et al. Journal of Field Robotics 2016]

# Cutting Drywall




[Schwarz et al. Journal of Field Robotics 2016]

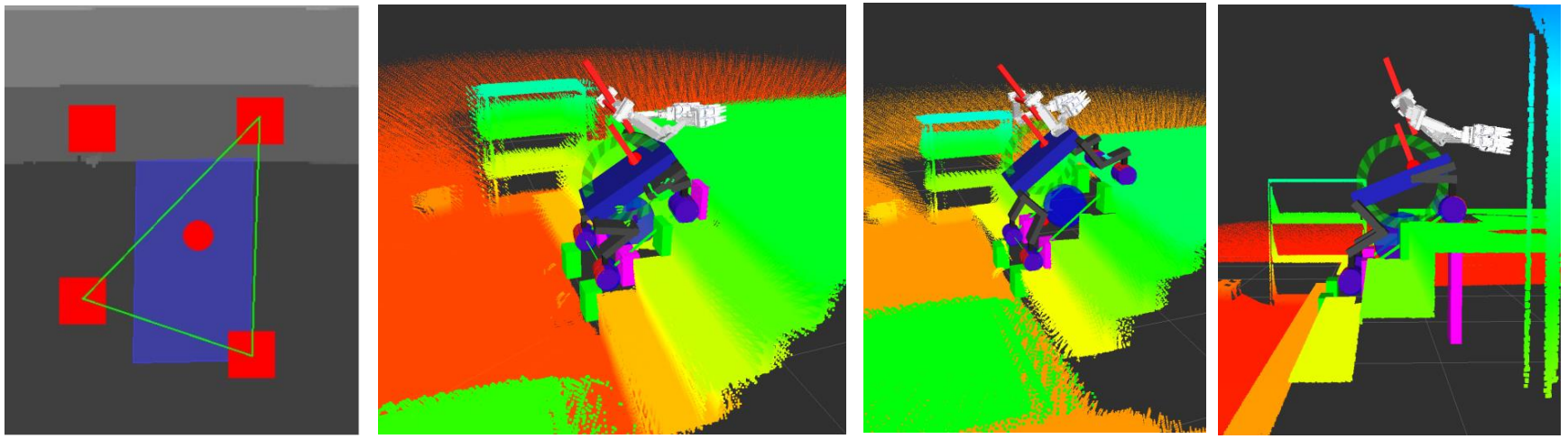
# Team NimbRo Rescue


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

[Schwarz et al. Journal of Field Robotics 2016]

# 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



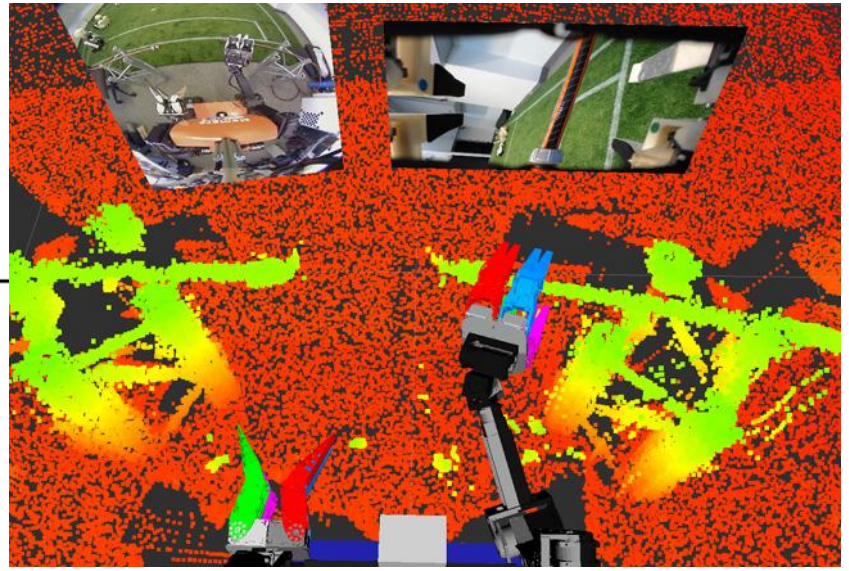
[Schwarz et al., ICRA 2016]

# 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



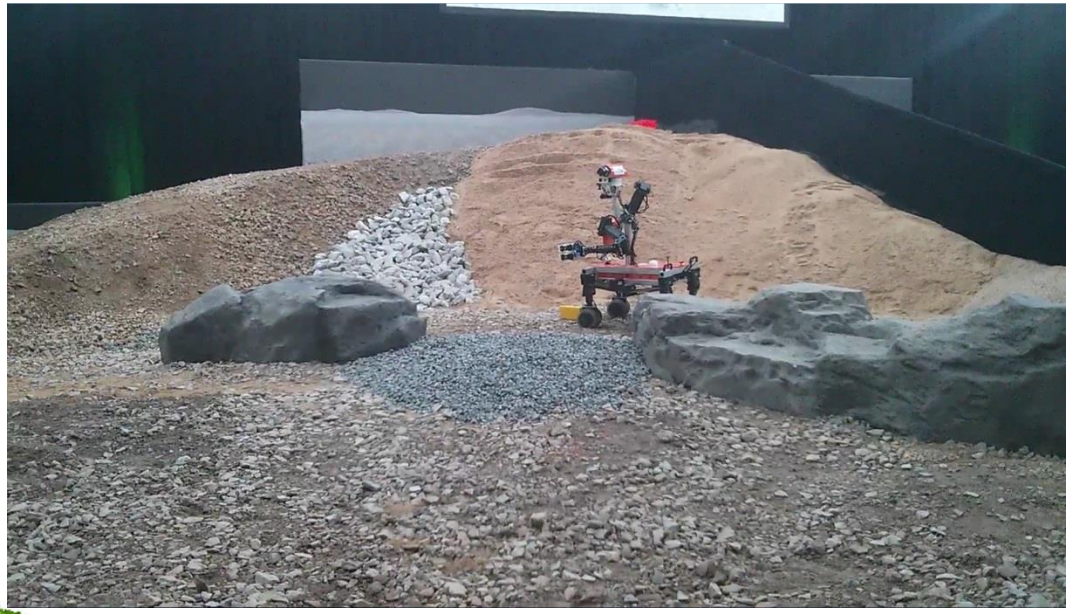
| Task | Time [min:s] | | | | |
|---|---|---|---|---|---|
| | Avg. | Median | Min. | Max. | Std. Dev. |
| Left grasp | 0:44 | 0:38 | 0:27 | 1:20 | 0:16 |
| Right grasp | 0:45 | 0:40 | 0:34 | 1:04 | 0:10 |
| Connect | 1:36 | 1:32 | 1:07 | 2:04 | 0:21 |
| Total | 3:04 | 2:57 | 2:21 | 3:51 | 0:28 |

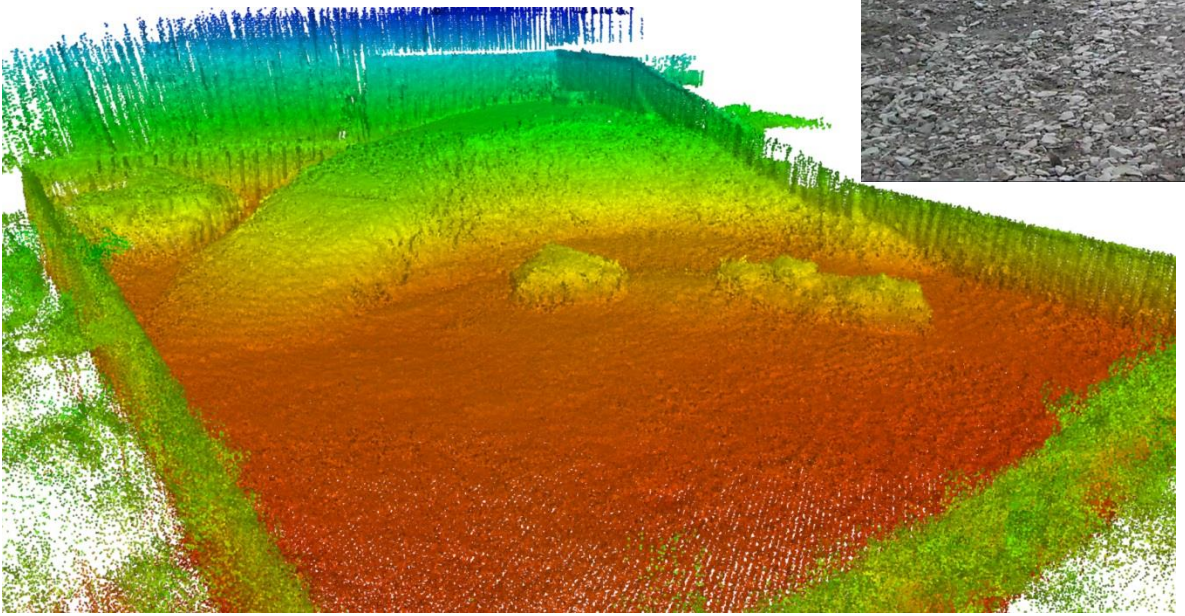
[Rodehutskors et al., Humanoids 2015]

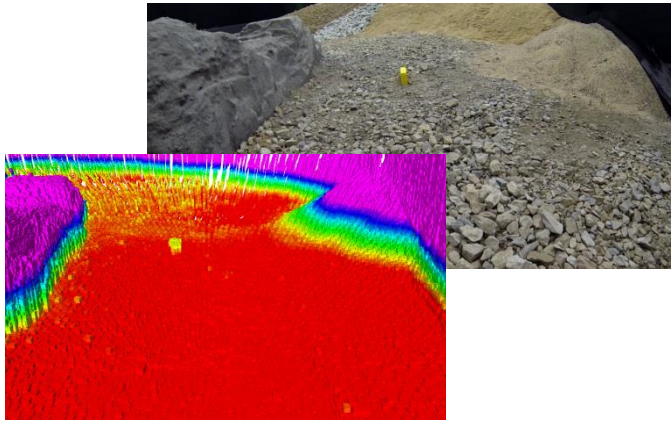
# DLR SpaceBot Cup 2015

- Mobile manipulation in rough terrain

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





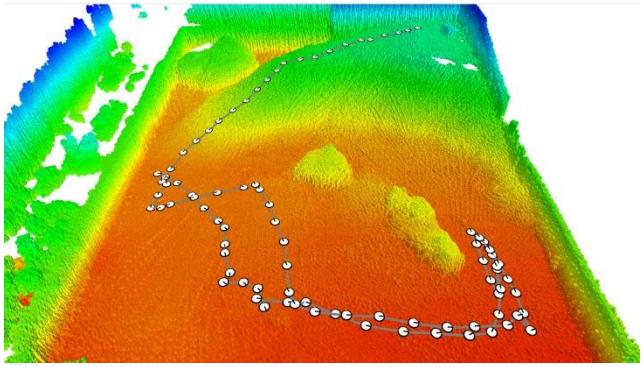


# DLR SpaceBot Camp 2015

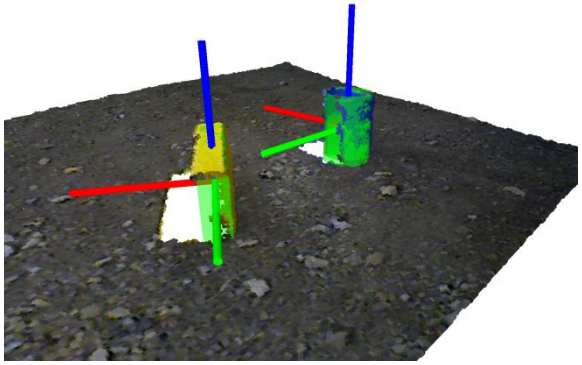

[Schwarz et al., Frontiers in Robotics and AI 2016]

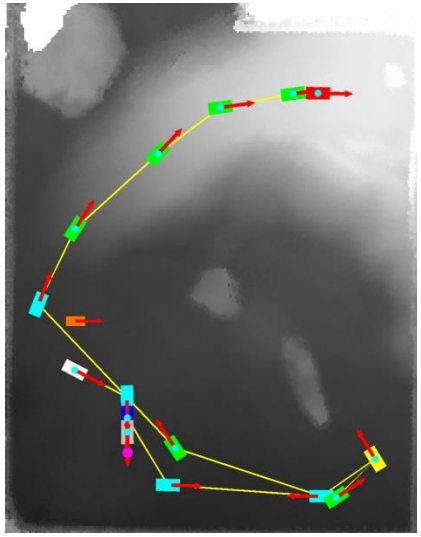
# Autonomous Mission Execution

3D Mapping & Localization

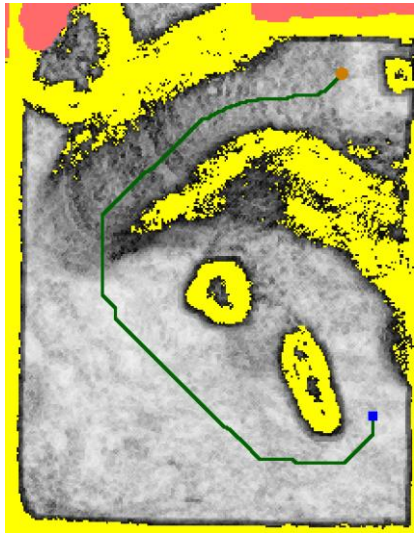


Object perception

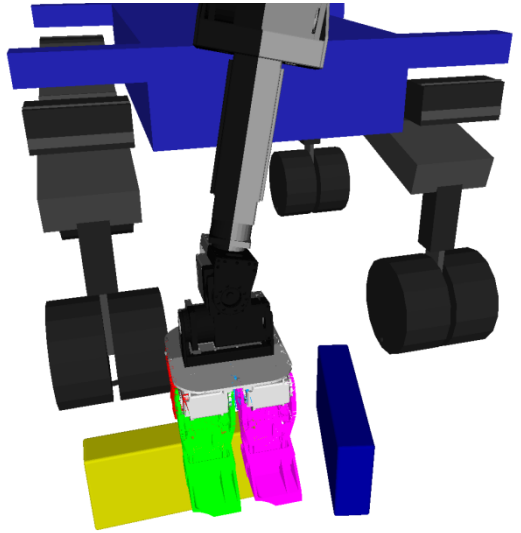




Mission plan



Navigation plan

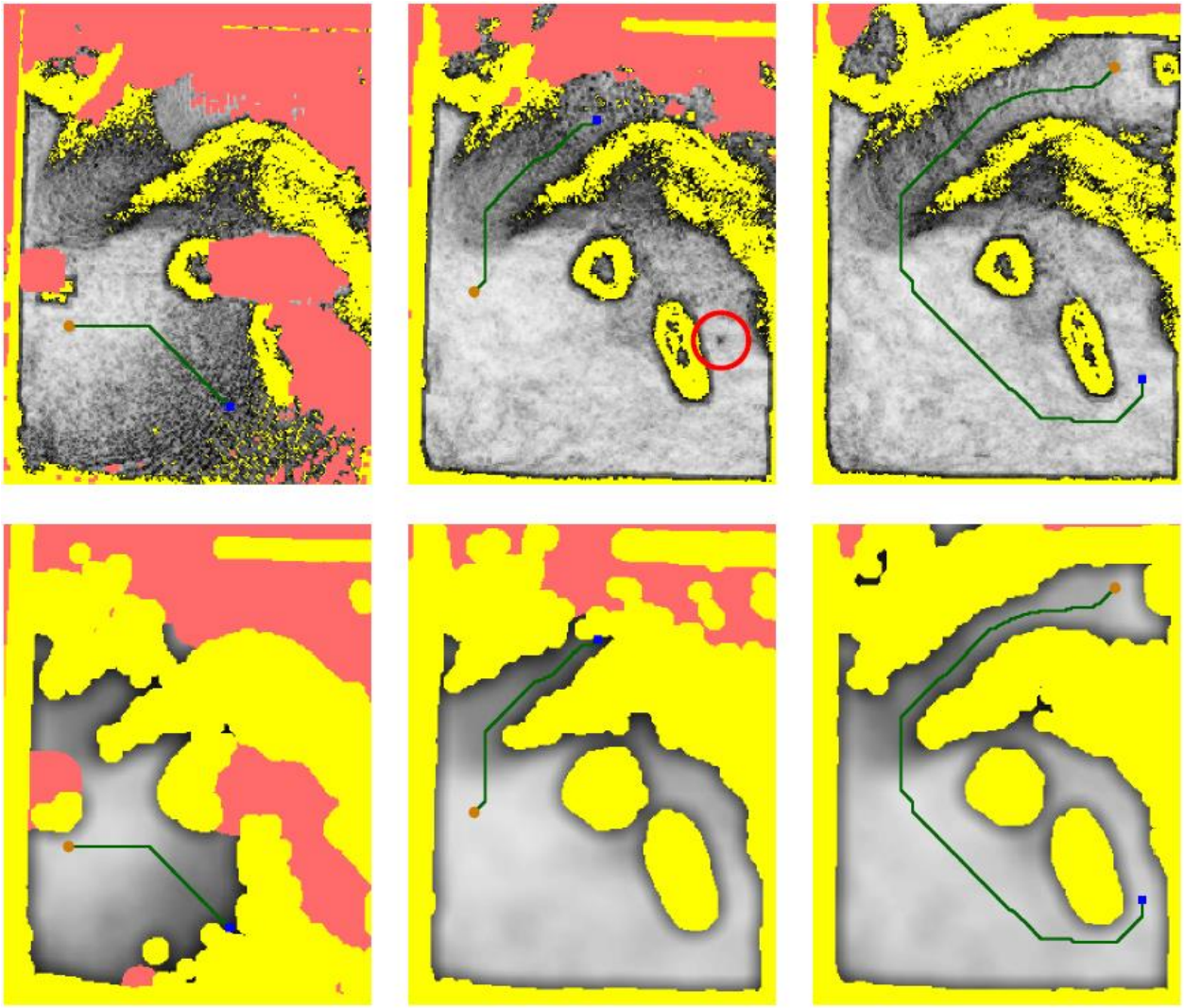


Grasping

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

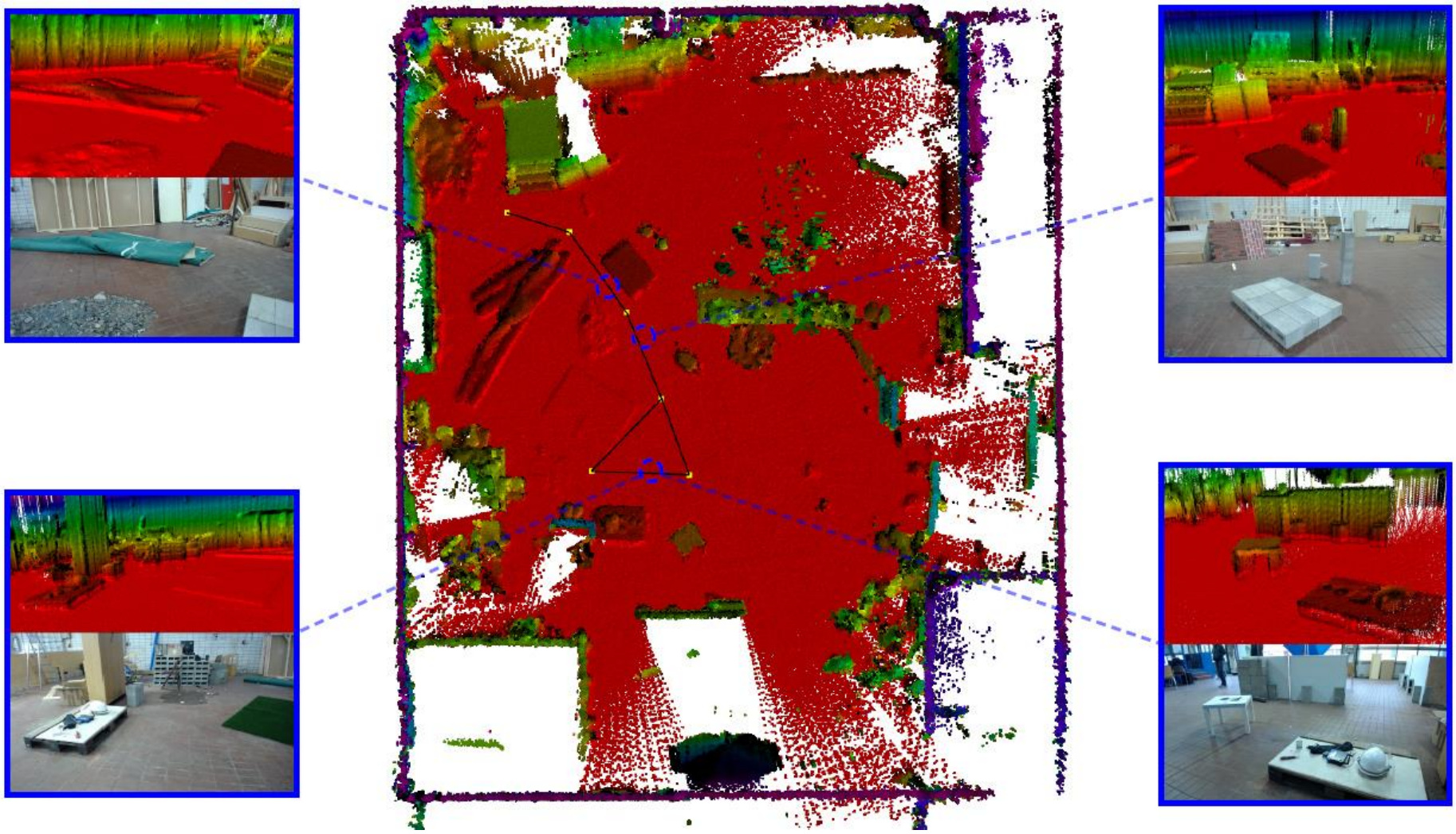
# Navigation Planning

- Costs from local height differences
- A* path planning



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

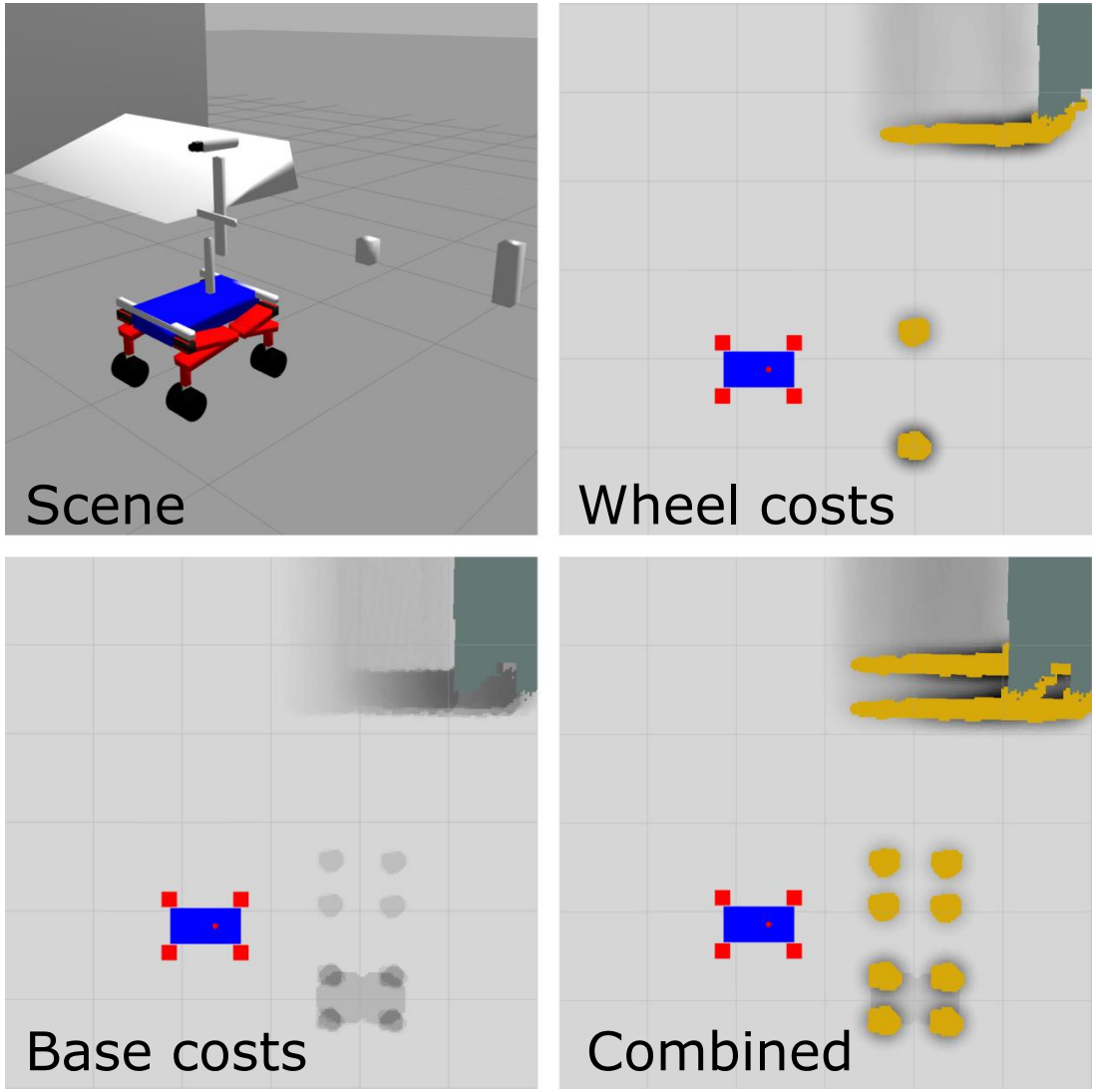
# 3D Map of Disaster-like Scene



[Droeschel et al., Robotics and Autonomous Systems 2016]

# Considering Robot Footprint

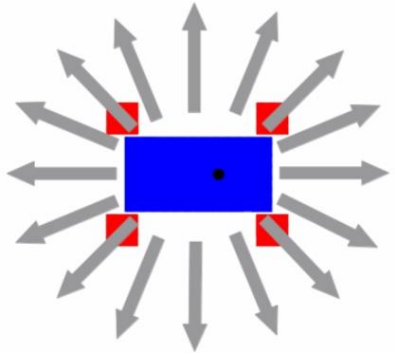
- Costs for individual wheel pairs from height differences
- Base costs
- Non-linear combination yields 3D (x, y, θ) cost map



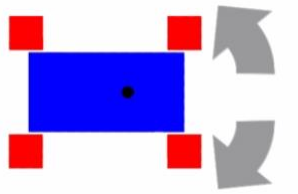

[Klamt and Behnke, under review]

# 3D Driving Planning (x, y, θ): A*

- 16 driving directions

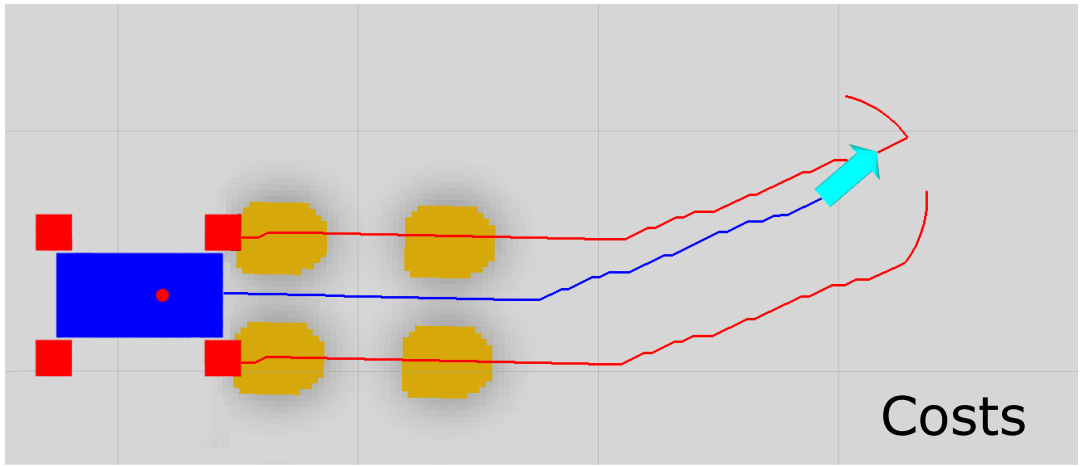


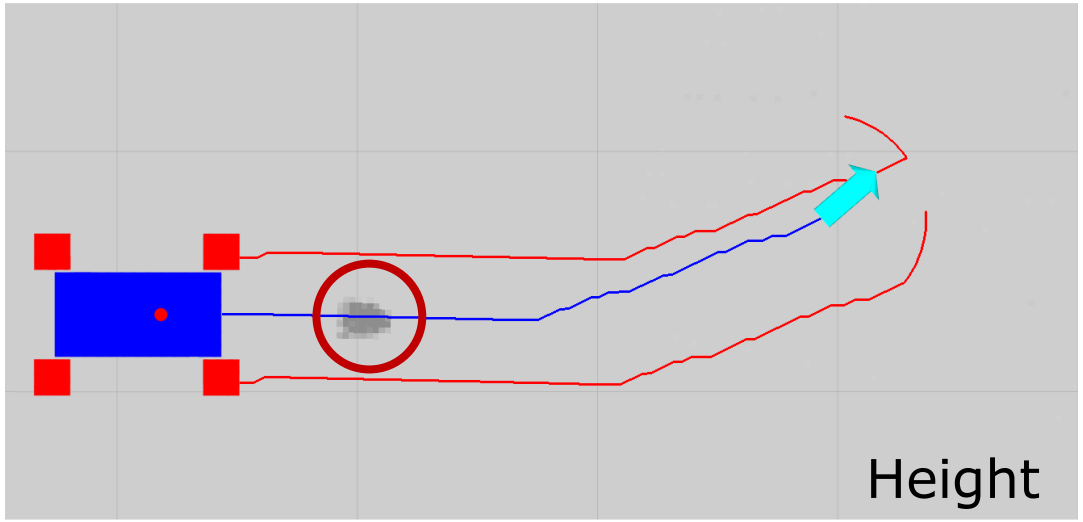
- Orientation changes



**=> Obstacle between wheels**

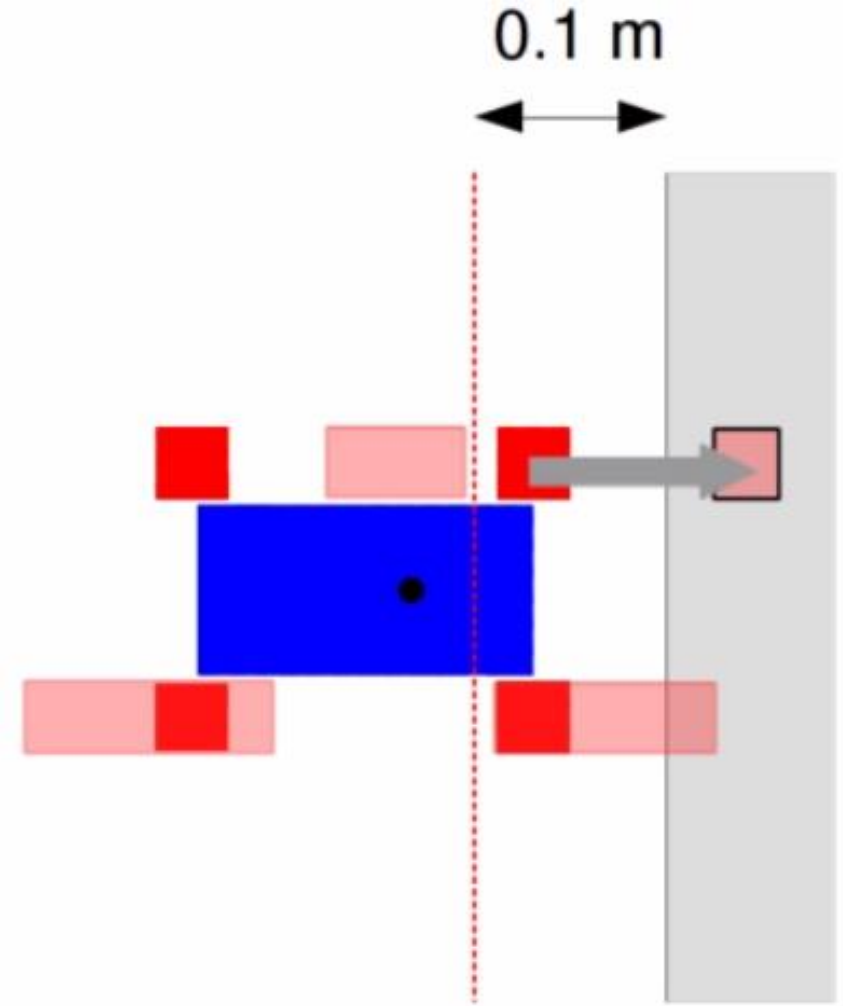
[Klamt and Behnke, under review]



# Making Steps

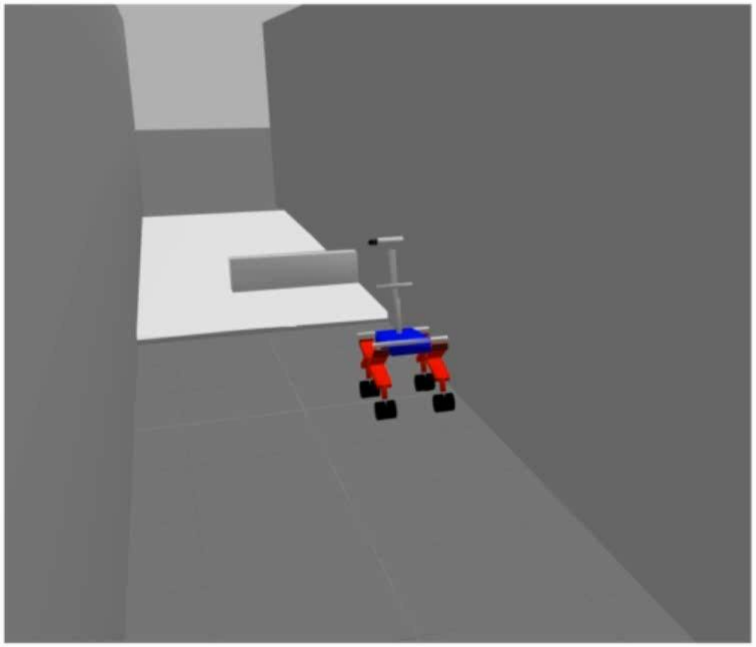
- If not drivable obstacle in front of a wheel
- Step landing must be drivable
- Support leg positions must be drivable




[Klamt and Behnke, under review]

# Hybrid Driving-Stepping Plan

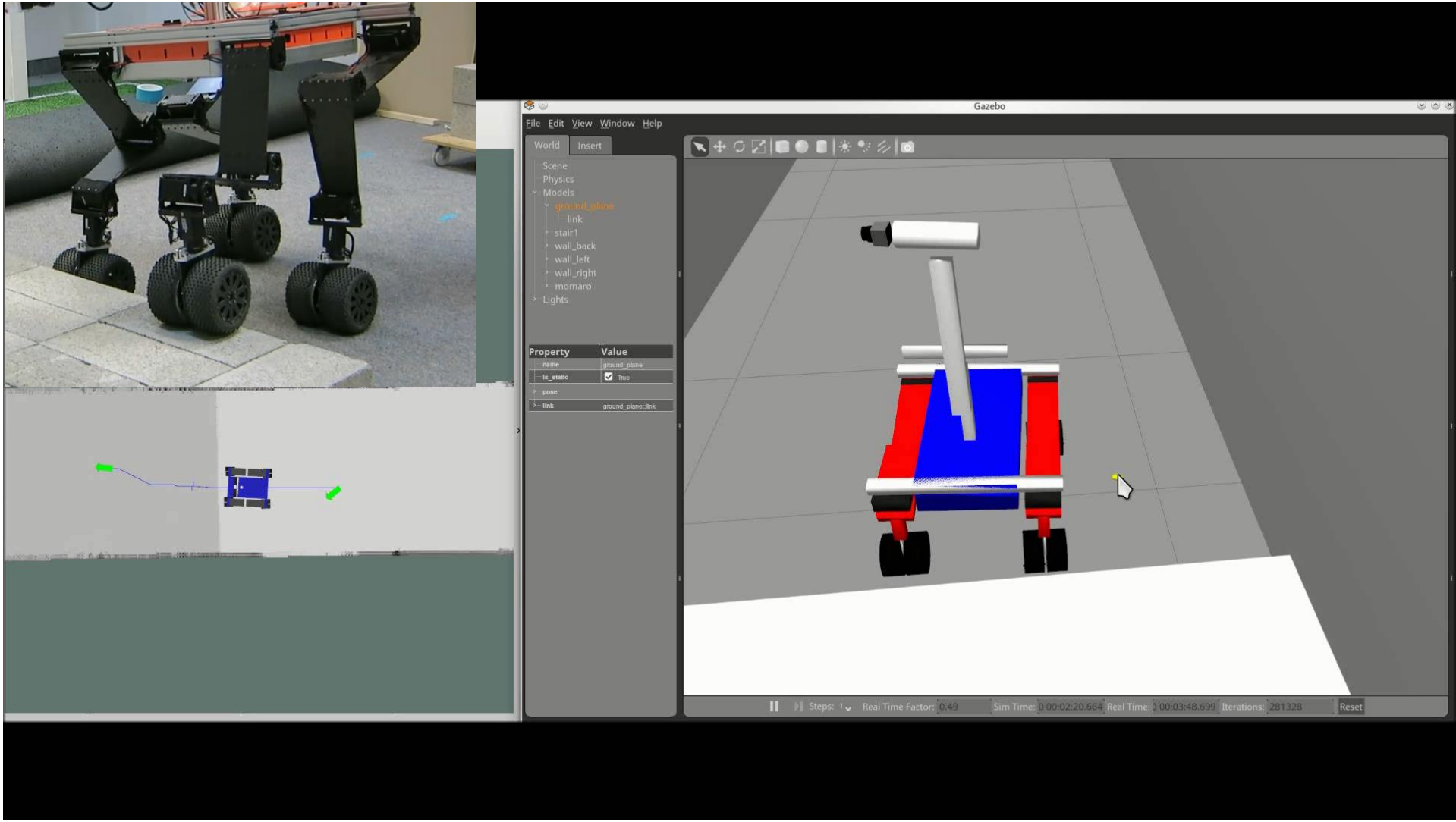
**Path Planning Example**



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

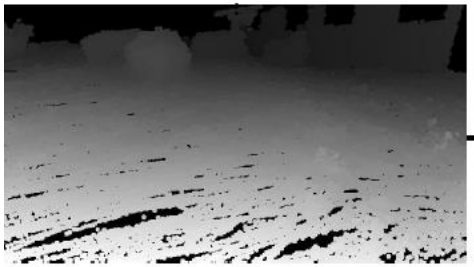
[Klamt and Behnke, under review]

# Detailed Realization of Steps




[Klamt and Behnke, under review]

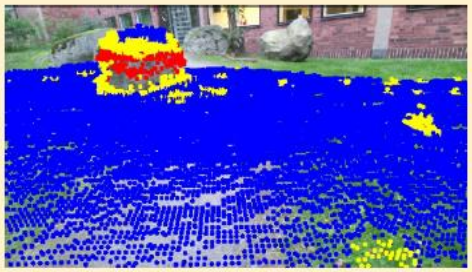
# Semantic Terrain Classification



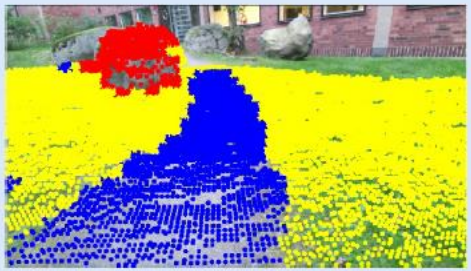
Disparity map
(from registered
Velodyne scans)

RGB image

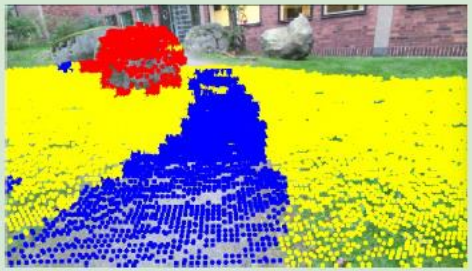
Geometric classifier



Visual classifier



Fused classifier



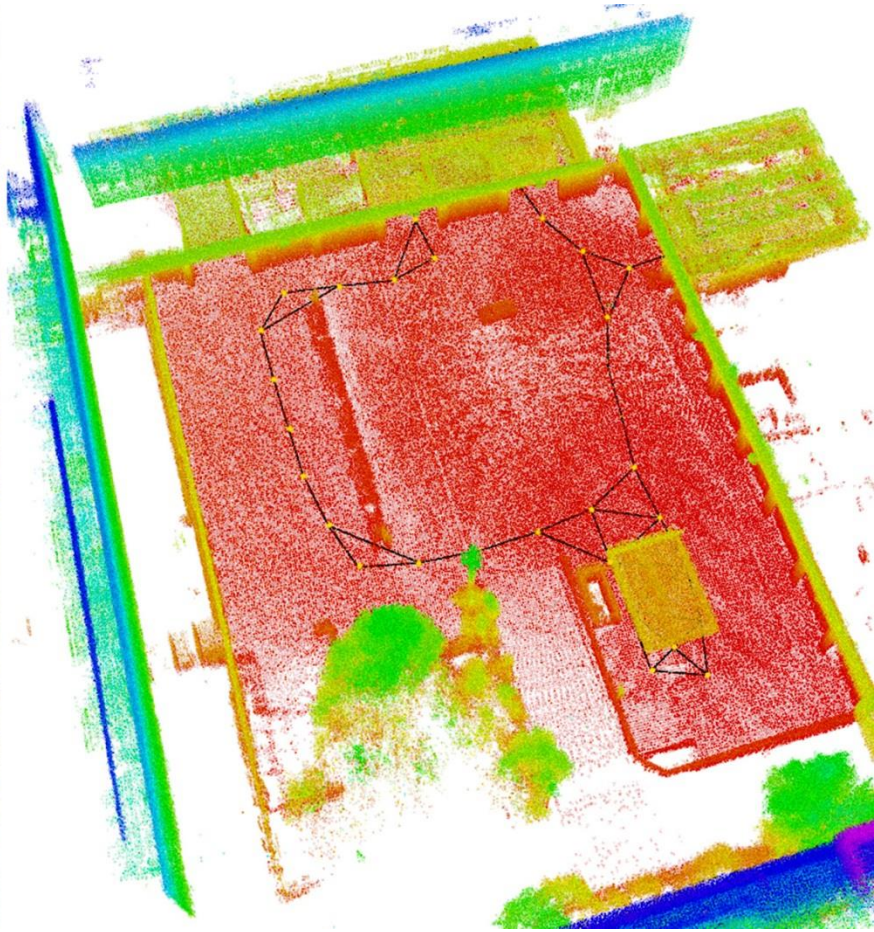
**Classes**
- Drivable (blue)
- Rough (yellow)
- Obstacle (red)

[Chen, Schilling et al.]

# Upgraded Sensor Head

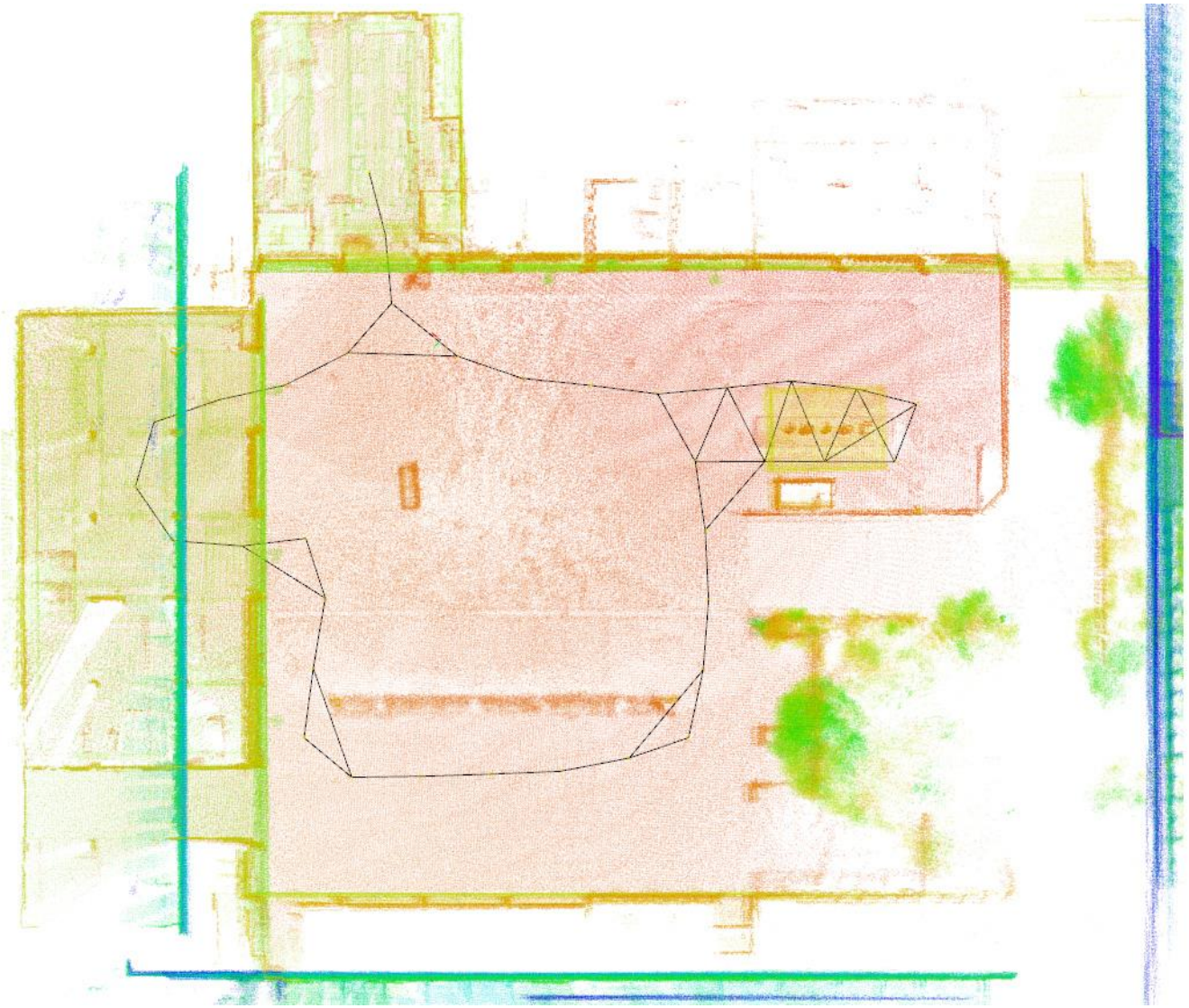
- Continuously rotating Velodyne Puck VLP-16
  - 300,000 3D points/s
  - 100 m range
  - Spherical field of view
- Three wide-angle color cameras (total FoV 210×103°)
- Kinect V2 RGB-D camera on pan-tilt unit

# 3D Map of Indoor+Outdoor Scene

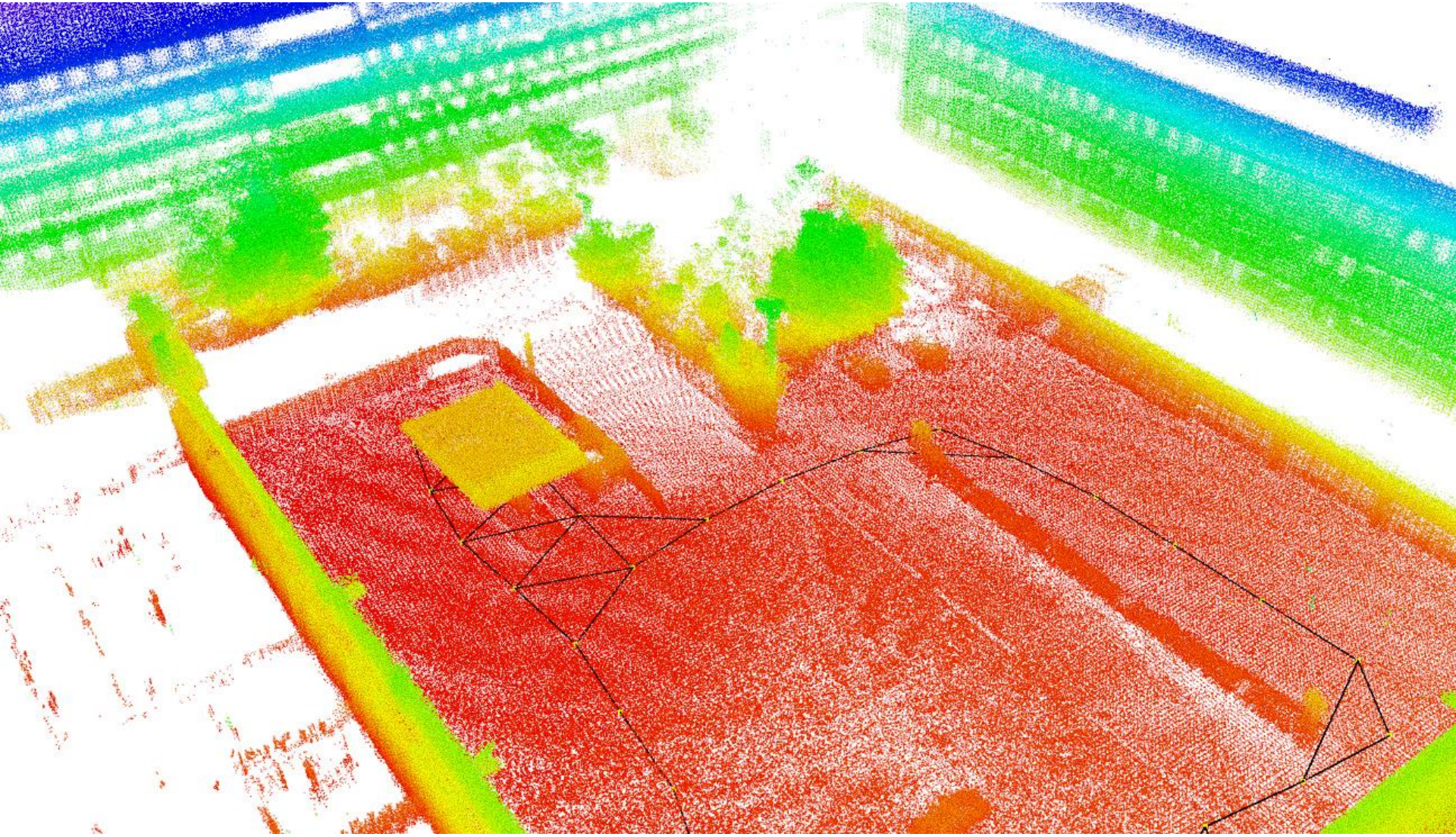
[Droeschel et al., Robotics and Autonomous Systems 2016]

# 3D Map of Indoor+Outdoor Scene



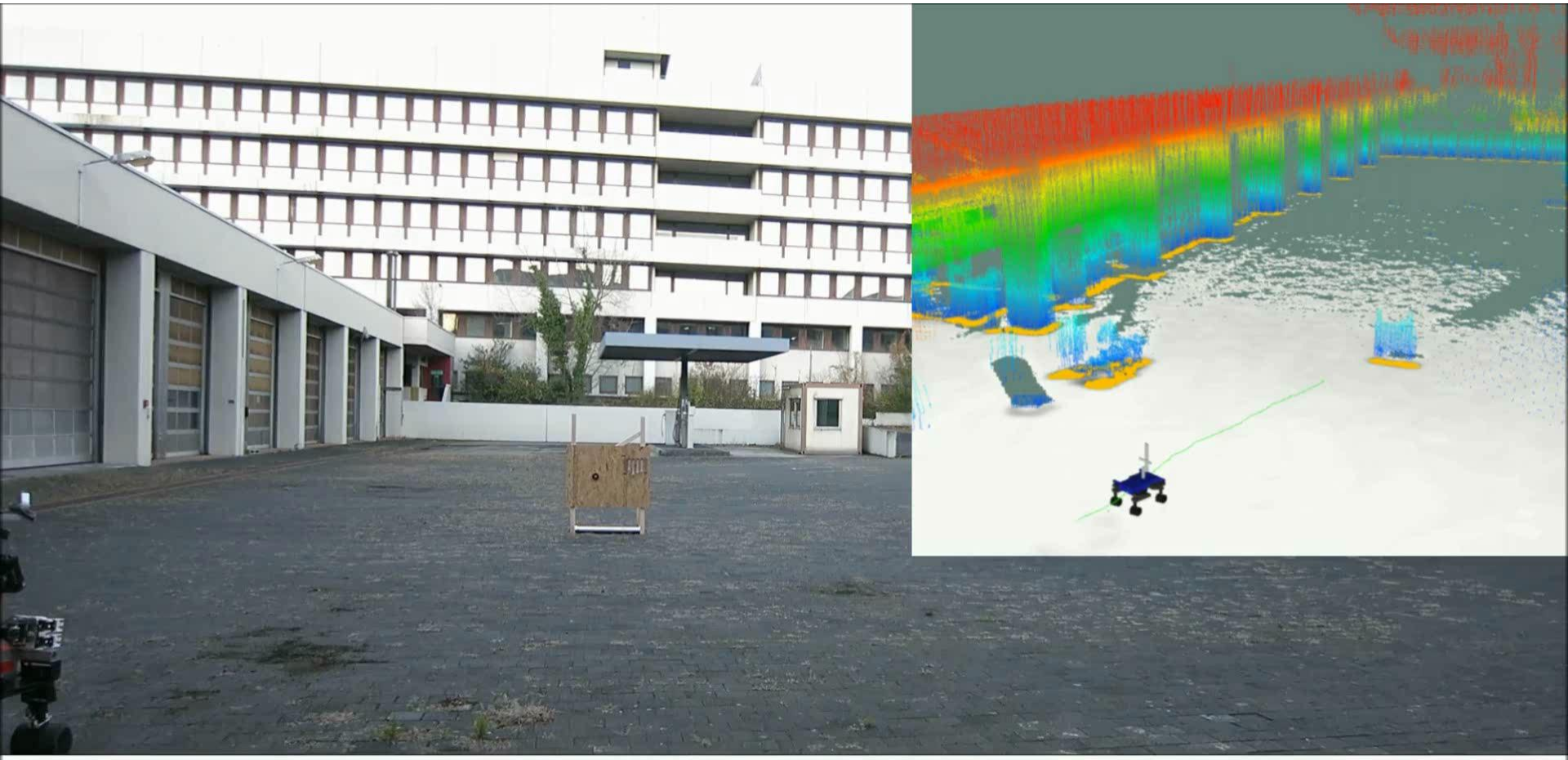
[Droeschel et al., Robotics and Autonomous Systems 2016]

# 3D Map of Indoor+Outdoor Scene



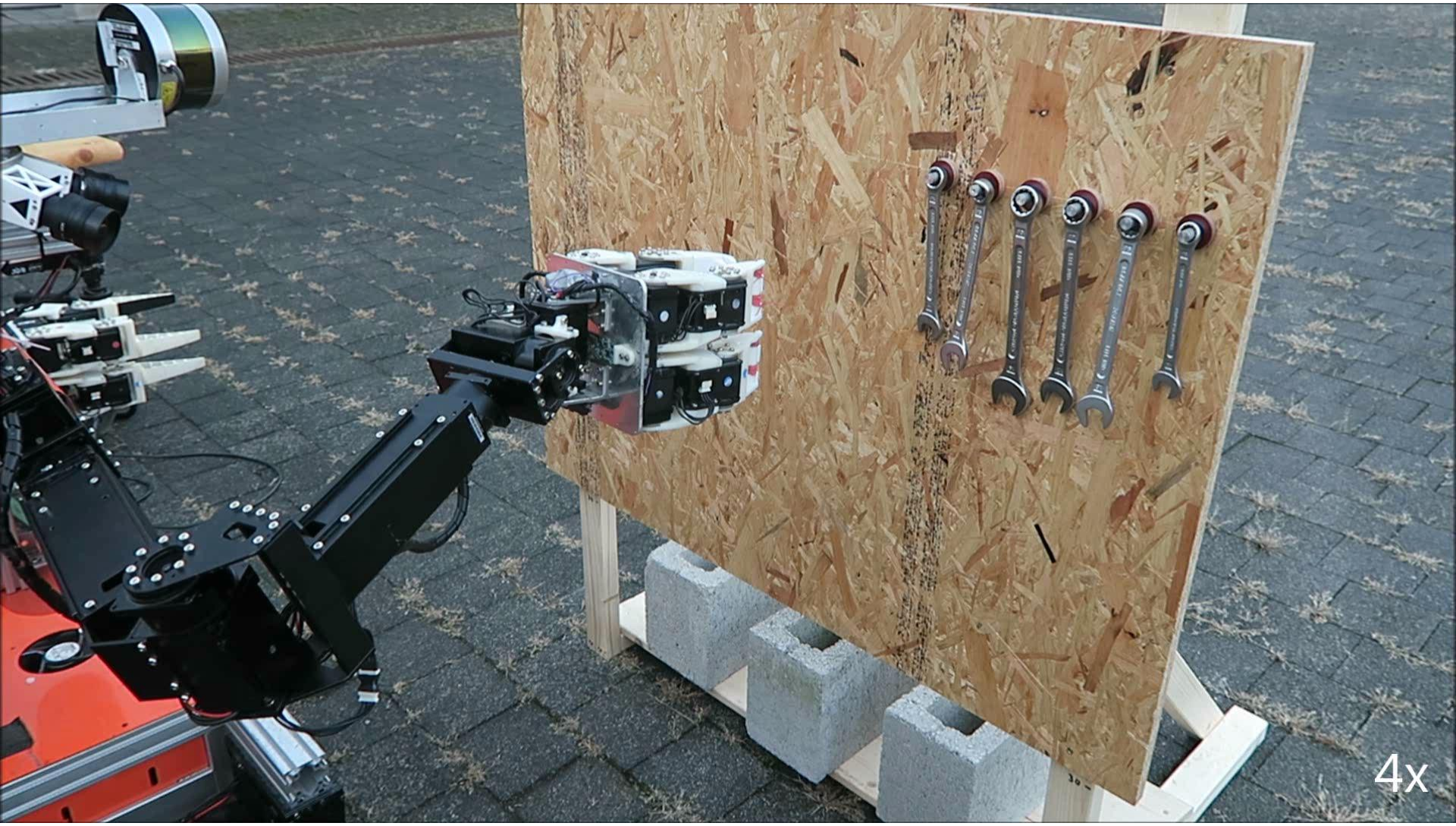
[Droeschel et al., Robotics and Autonomous Systems 2016]

# Global and Local Navigation



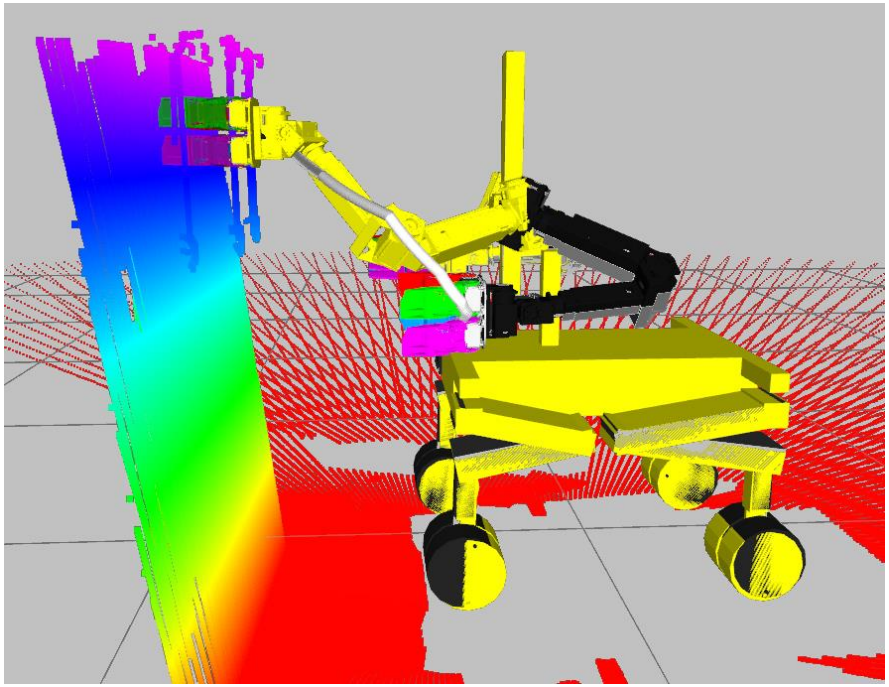
Navigation in allocentric laser map (colored points)

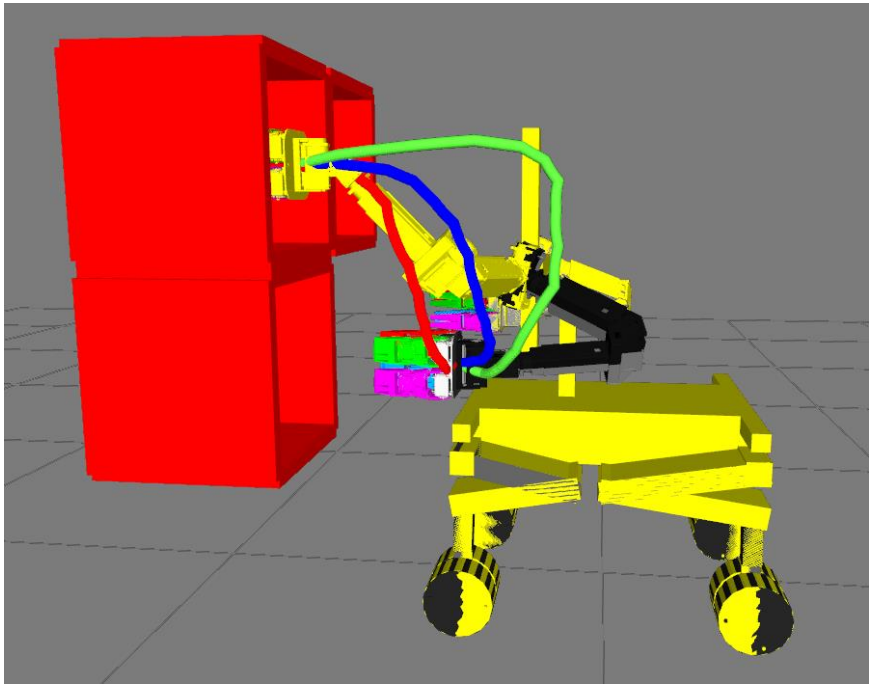
# Using a Wrench to Turn a Valve



# Manipulation Trajectory Optimization

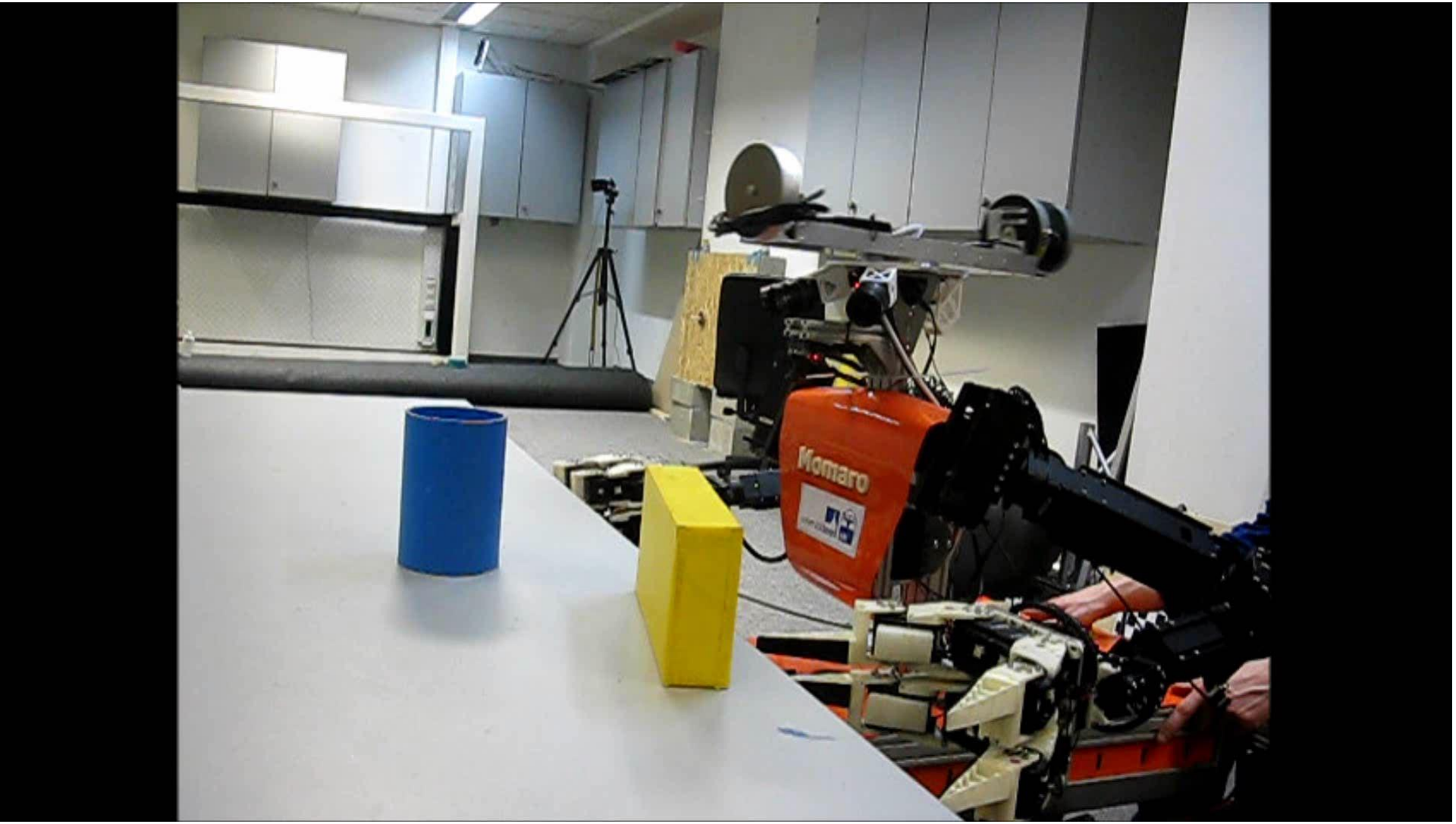
- Extended stochastic trajectory optimization (STOMP)
- 8 DoF (including torso yaw)
- Weighting multiple objectives
- Speed limits depend on distance to obstacles





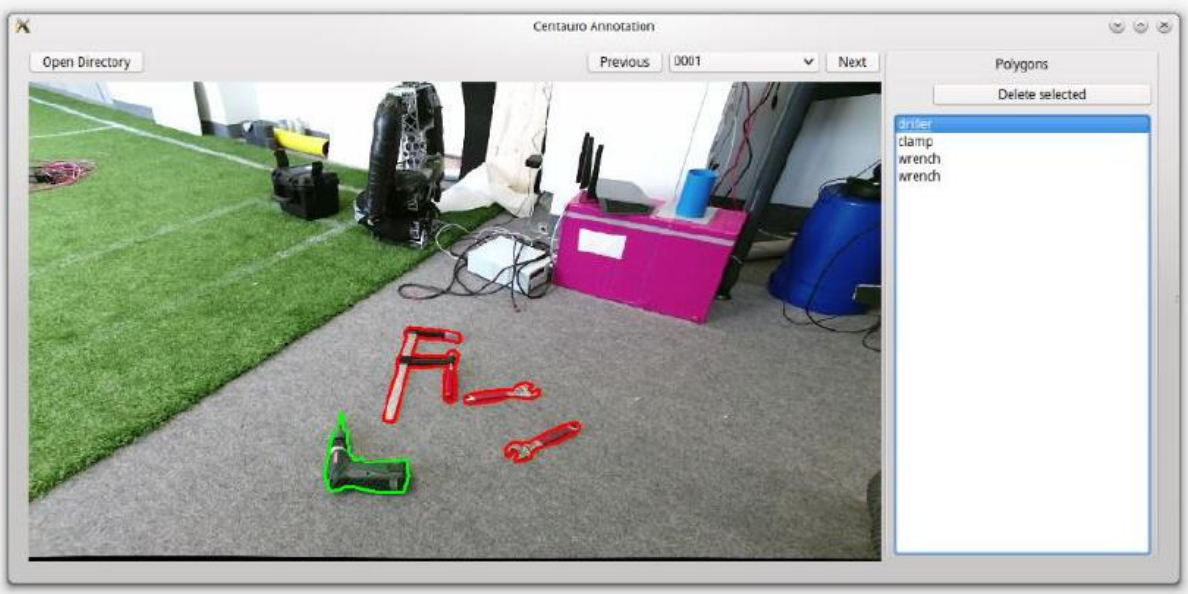
[Pavlichenko et al.]

# Momaro Reaching for an Object




[Pavlichenko et al.]

# Workspace Perception Data Set

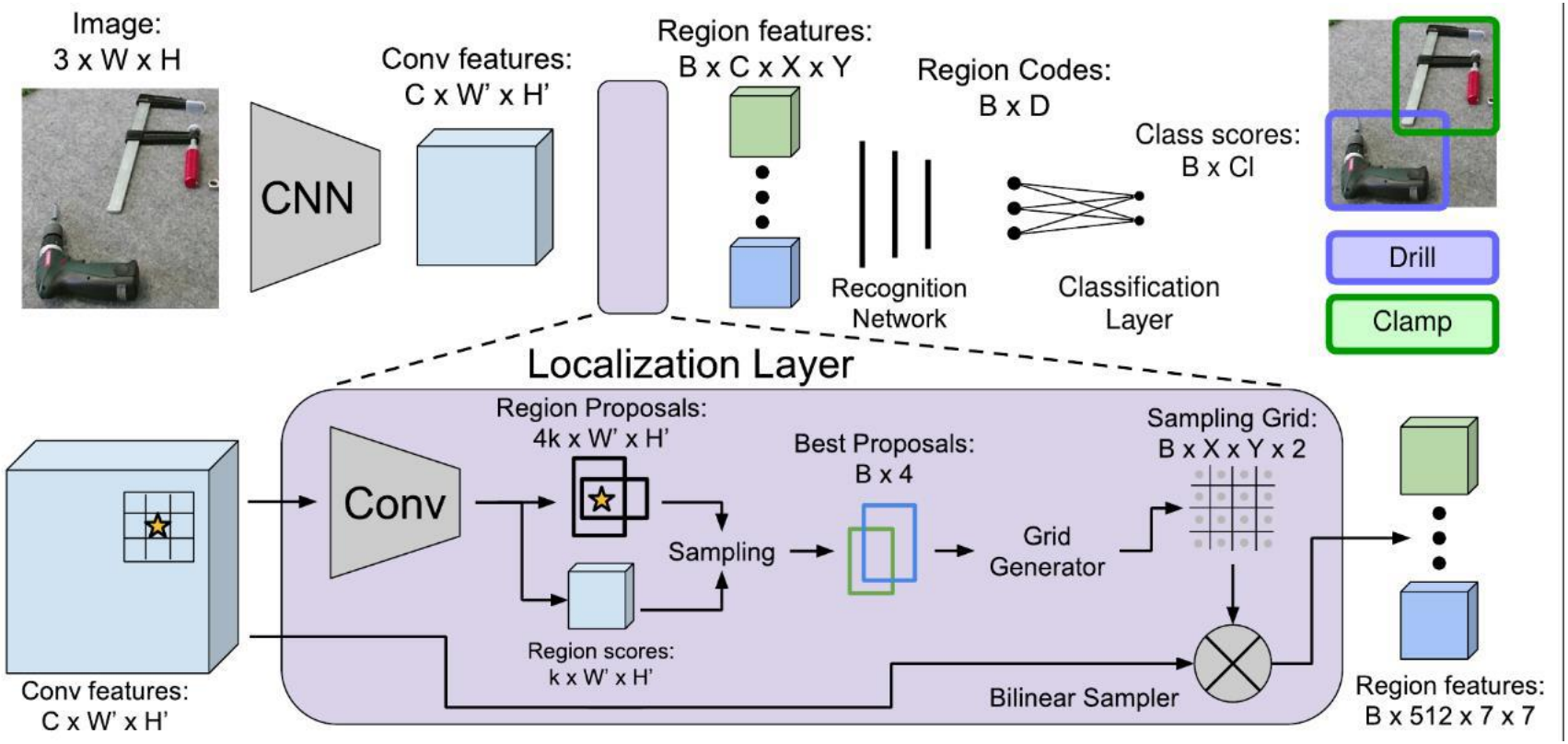



129 frames, 6 object classes

https://www.centauro-project.eu/data_multimedia/tools_data

# Deep Learning Object Detection

- Adapted DenseCap [Johnson et al. 2015] pipeline




- Transfer learning needs only few annotated images

[Schwarz et al.]

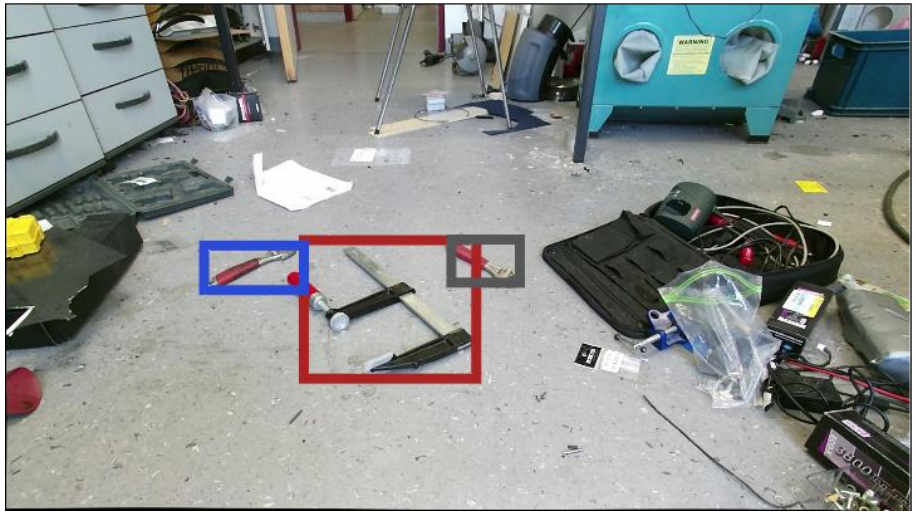
# Tool Detection Results


Average precision:

| Min overlap | Clamp | Door handle | Driller | Extension box | Stapler | Wrench |
|---|---|---|---|---|---|---|
| 0.5 | 81.2 | 21.7 | 80.7 | 100.0 | 85.2 | 57.6 |
| 0.2 | 93.3 | 67.6 | 97.0 | 100.0 | 95.2 | 85.7 |

[Schwarz et al.]

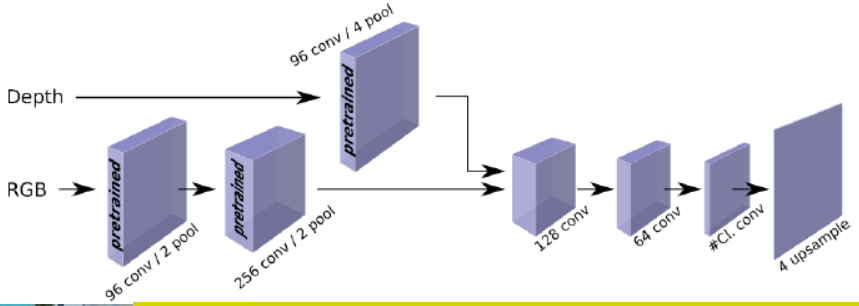
# Tool Detection Examples

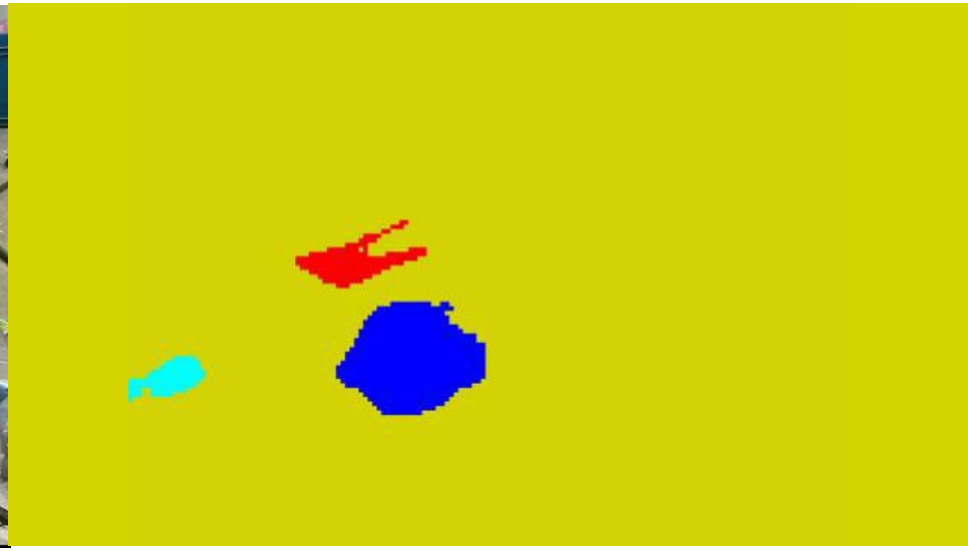


# Semantic Segmentation

- Deep CNN

[Husain et al. RA-L 2016]



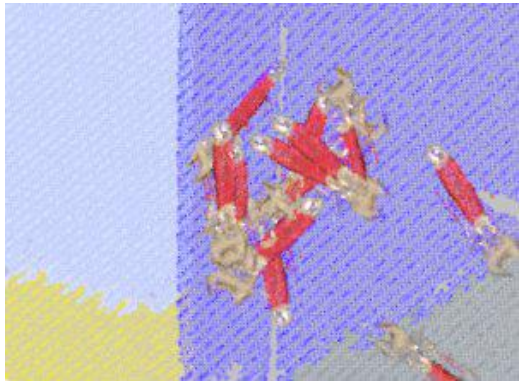



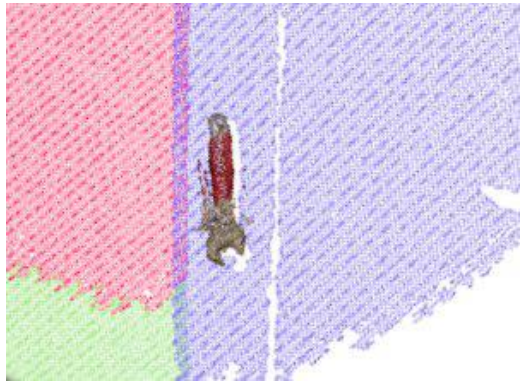
Pixel-wise accuracy:

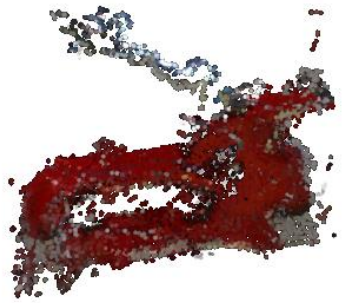
| Clamp | Door handle | Driller | Extension box | Stapler | Wrench |
|---|---|---|---|---|---|
| 92.0 | 83.3 | 93.1 | 98.8 | 98.5 | 88.9 |

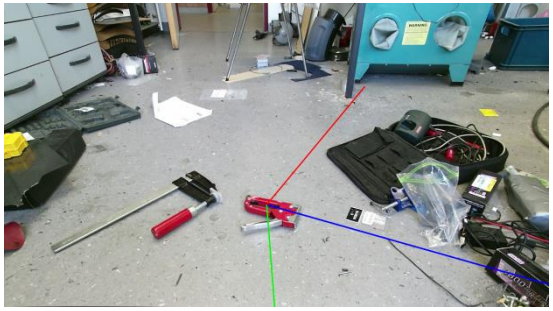
# 3D Object Modeling and 6D Pose Estimation

- Build 3D model on turn table
- Generate proposals
- Register to test image





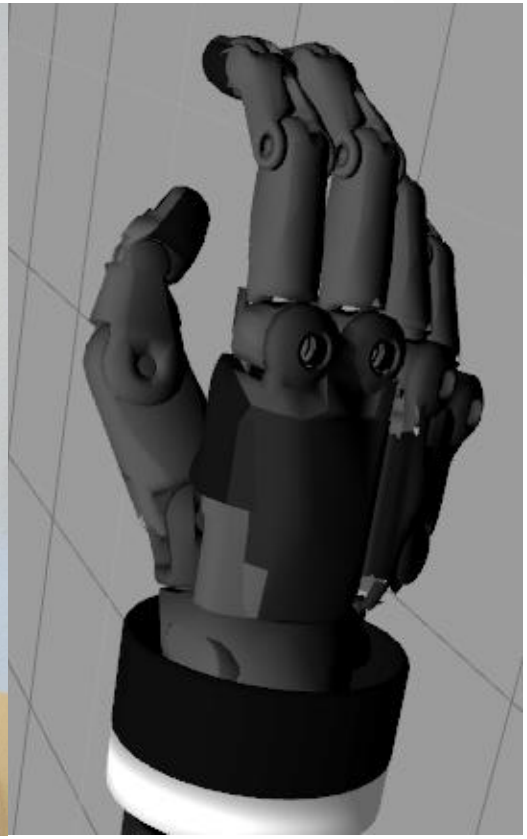




[Aldoma et al., ICRA 2013]

# Schunk SVH

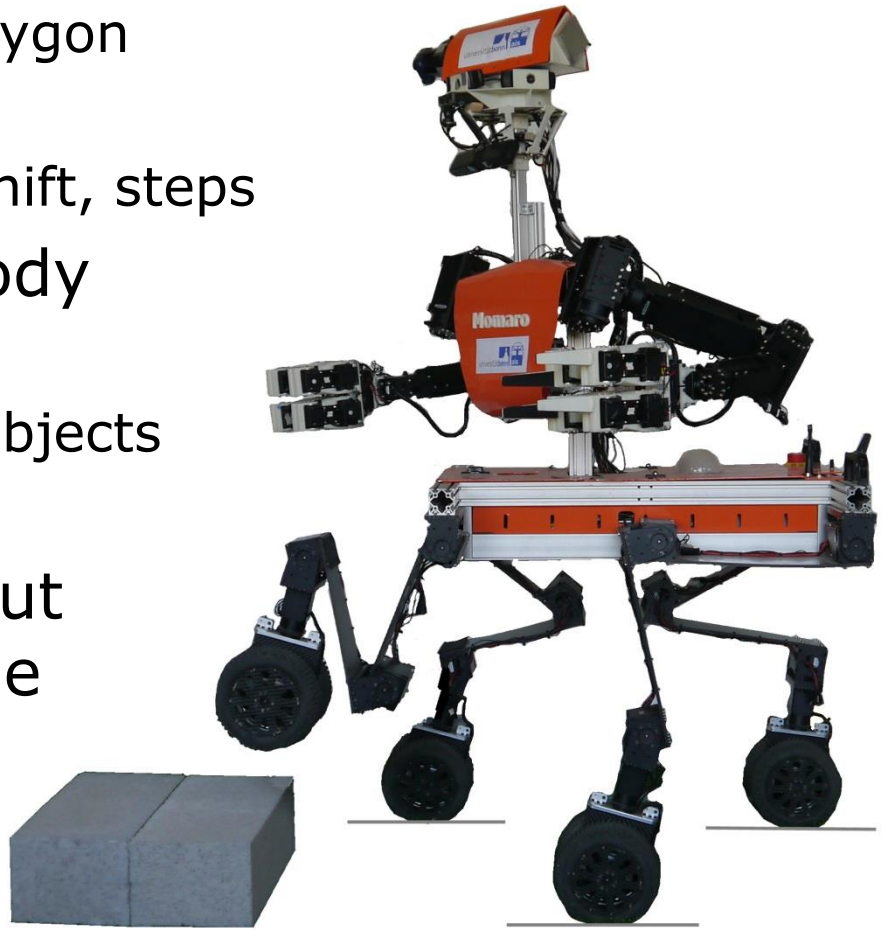
- Anthropomorphic hand
- 9 DoF



# CENTAURO

# Conclusion

- Compliant wheeled-legged base
  - Large adjustable support polygon
  - Omnidirectional driving
  - Terrain adaptation, weight shift, steps
- Anthropomorphic upper body
  - Human-like manipulation
  - Bimanual handling of large objects
  - Tool use
- Teleoperation is flexible, but demanding and error-prone
- Developing autonomy for common navigation and manipulation tasks



# Questions?