Perception and Planning for Autonomous Locomotion and Manipulation in a Disaster-Response Robot

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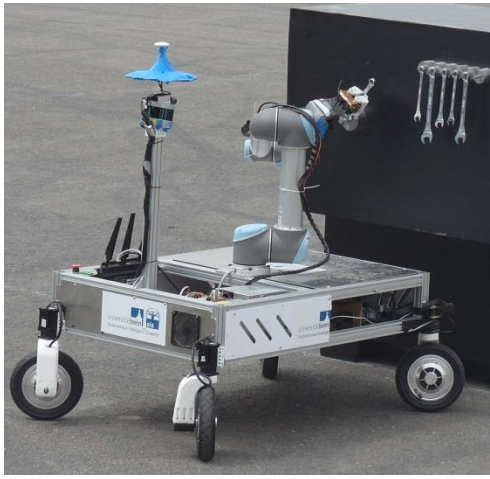
Robot Competitions

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

RoboCup @Home

DARPA Robotics Challenge

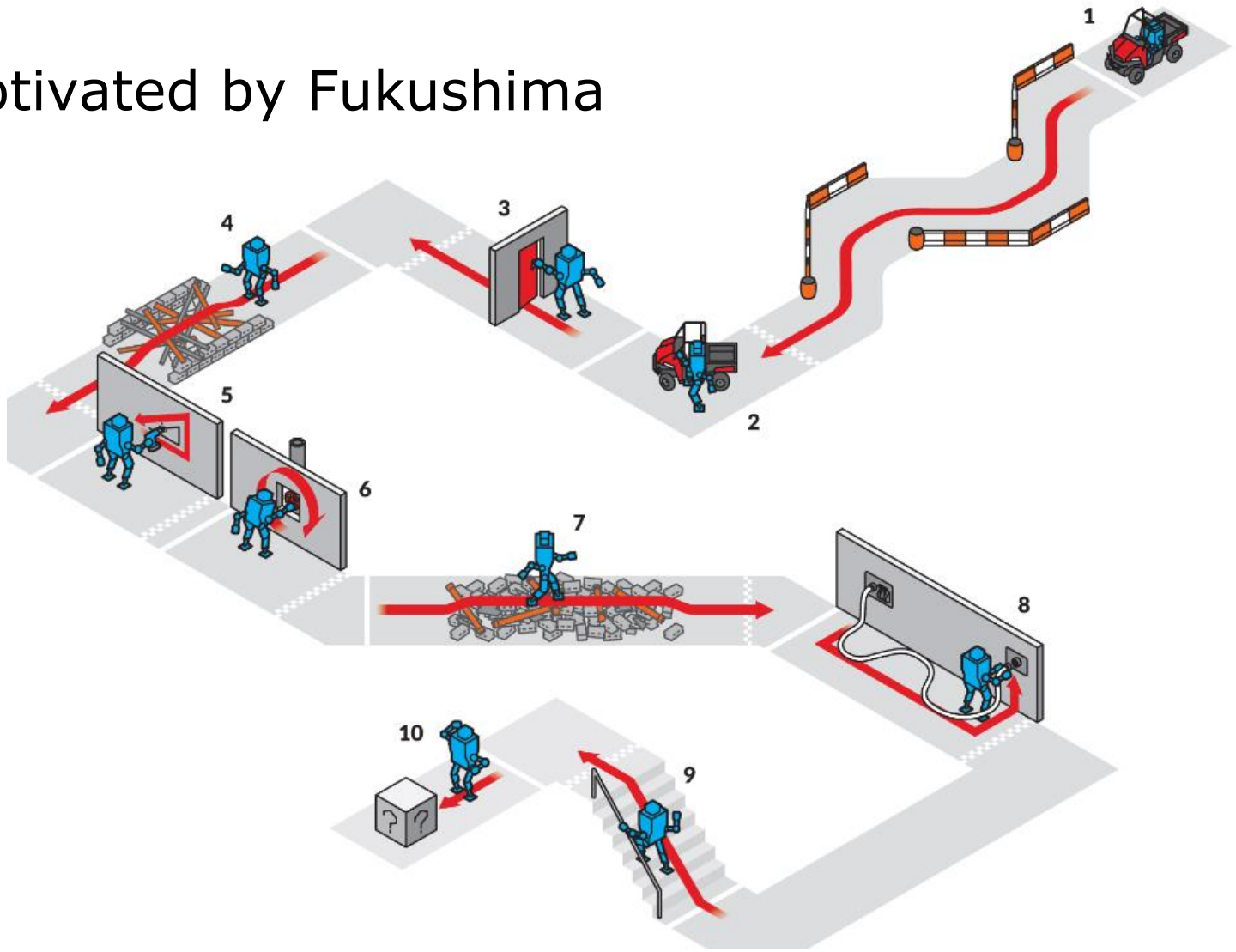
DLR SpaceBot Cup



MBZIRC

DARPA Robotics Challenge

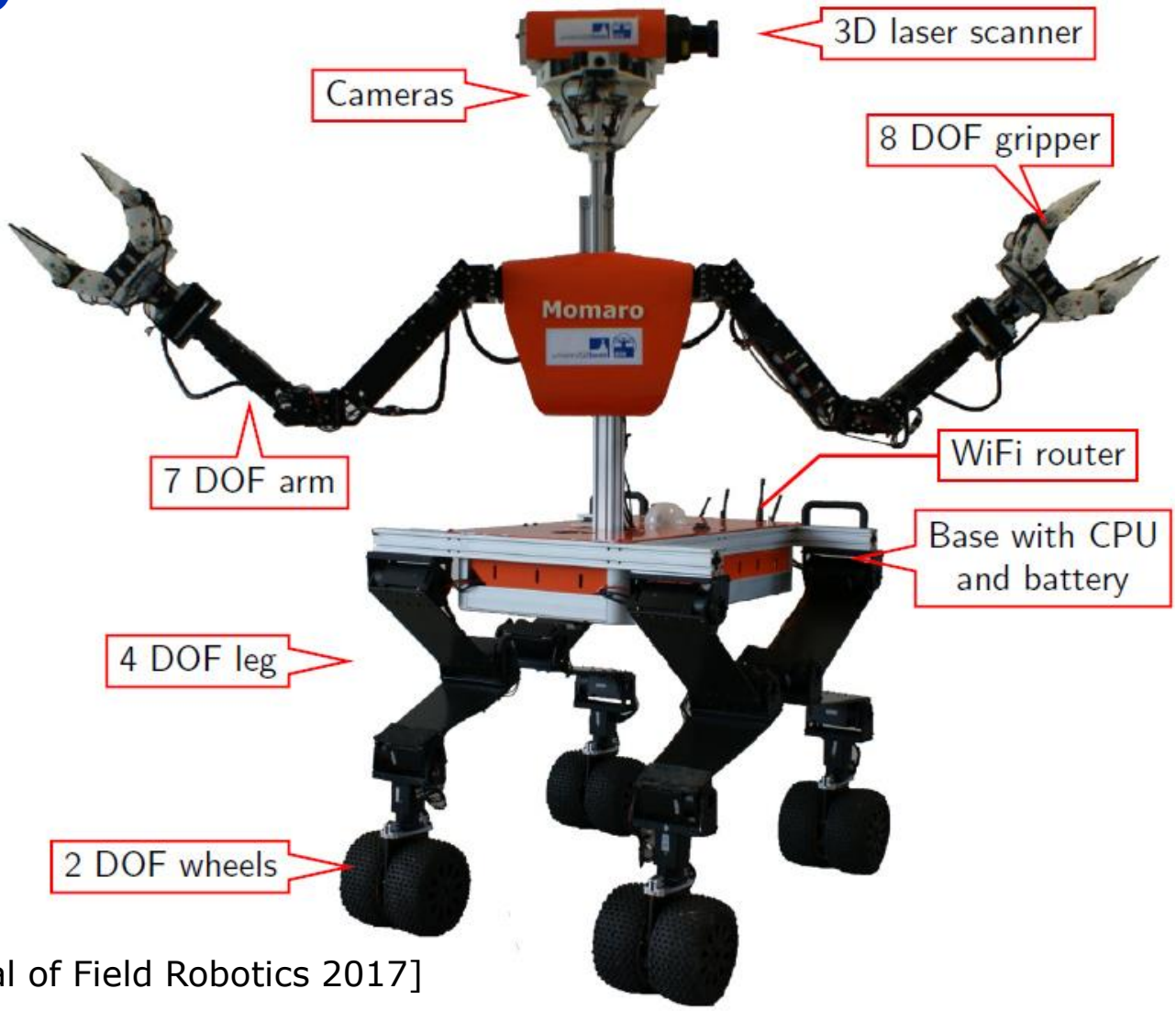
- Motivated by Fukushima



Behnke: Perception and Planning for Autonomous Locomotion and Manipulation in a Disaster-Response Robot

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 2017]

Driving a Vehicle

[Schwarz et al. Journal of Field Robotics 2017]

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

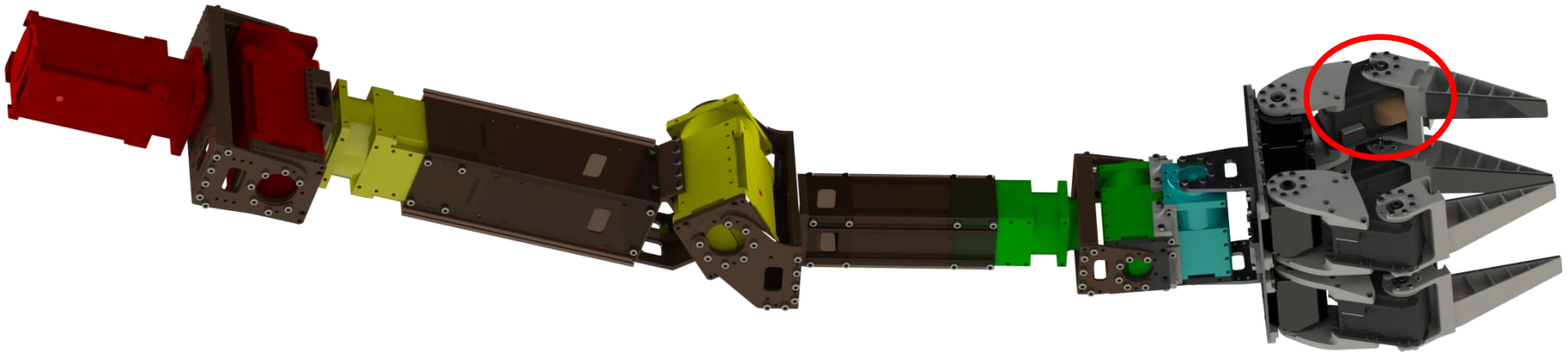
[Schwarz et al. Journal of Field Robotics 2017]

Egress

[Schwarz et al. Journal of Field Robotics 2017]

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

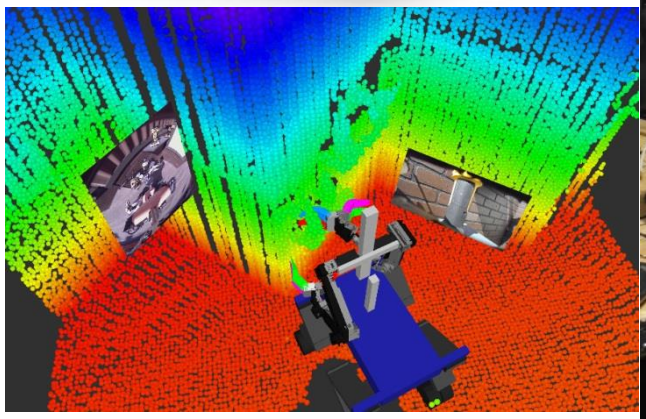


- Four fingers with two Dynamixel actuators
  - Proximal 8.4 Nm, distal 6.0 Nm
  - Bump for pushing tool trigger

[Schwarz et al. Journal of Field Robotics 2017]

Manipulation Operator Interface

- 3D head-mounted display
- 3D environment model + images
- 6D magnetic tracker



[Rodehutskors et al., Humanoids 2015]

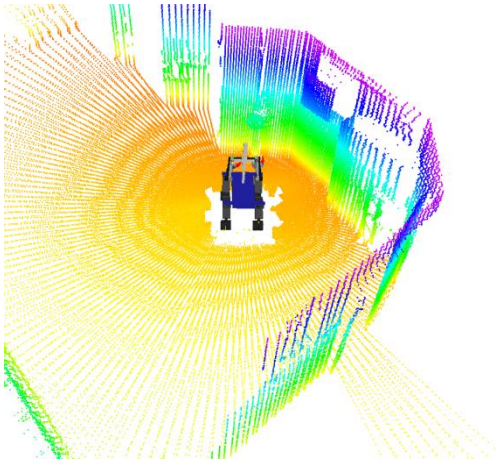
Opening a Door

[Schwarz et al. Journal of Field Robotics 2017]

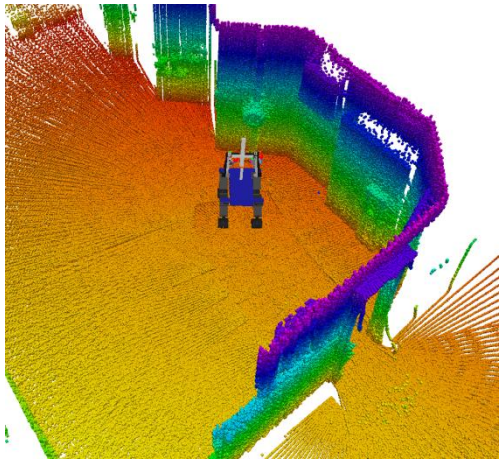
Local Multiresolution Surfel Map

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

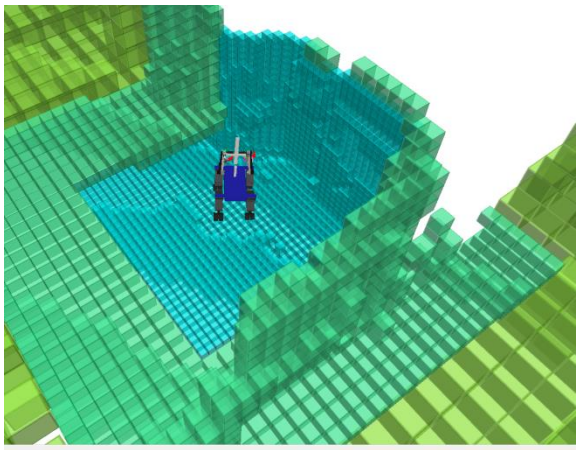
3D scan



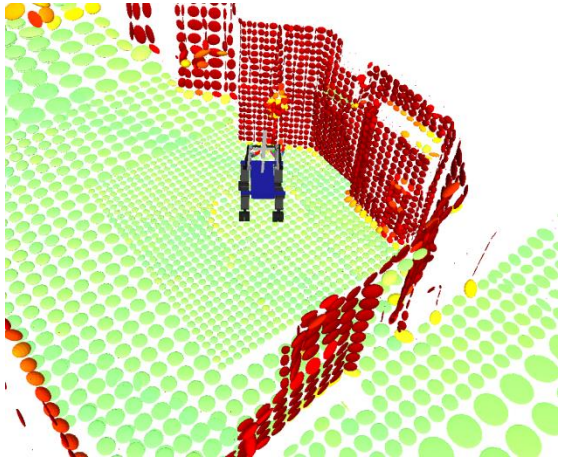
Aggregated scans



Multiresolution grid



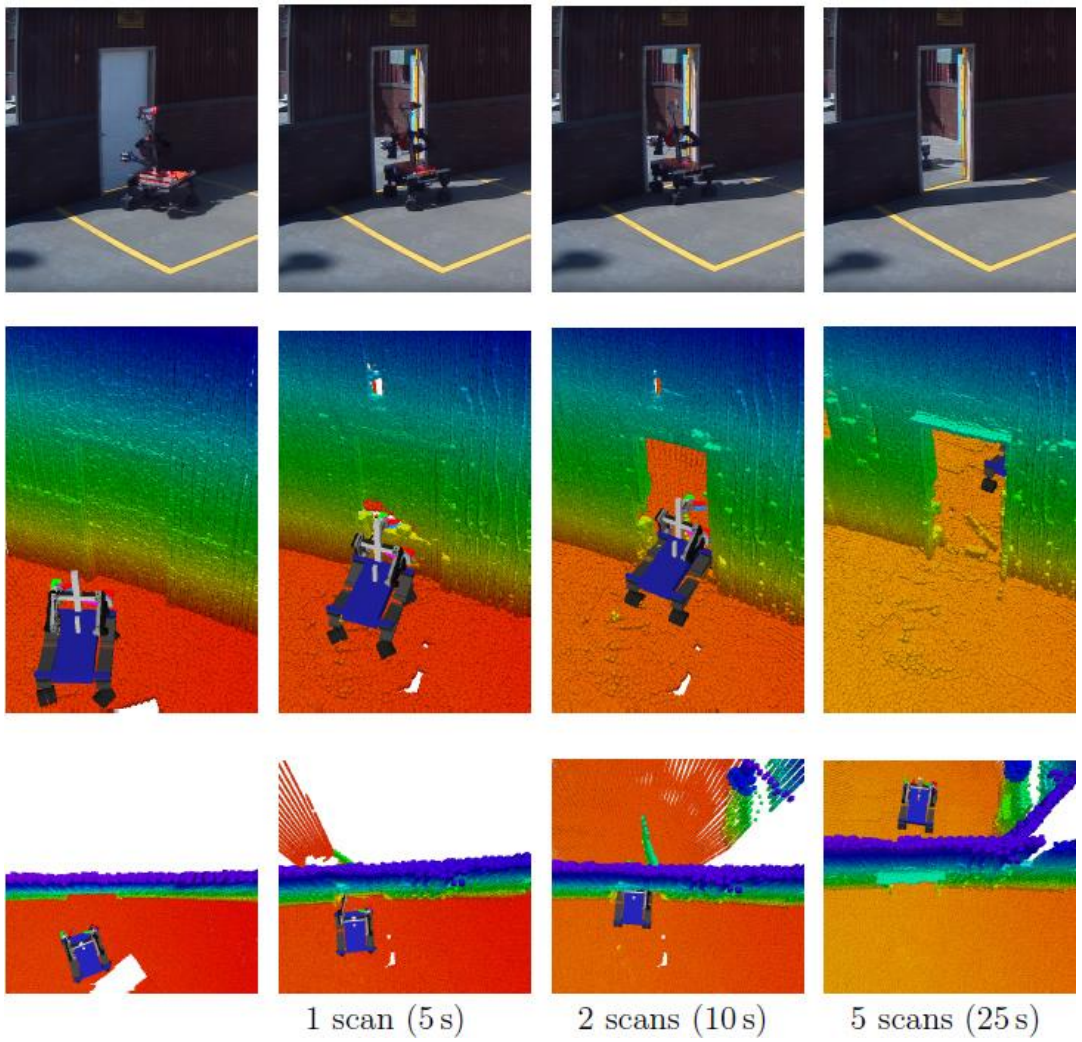
Surfels



[Droeschel et al., Robotics and Autonomous Systems 2017]

Filtering Dynamic Objects

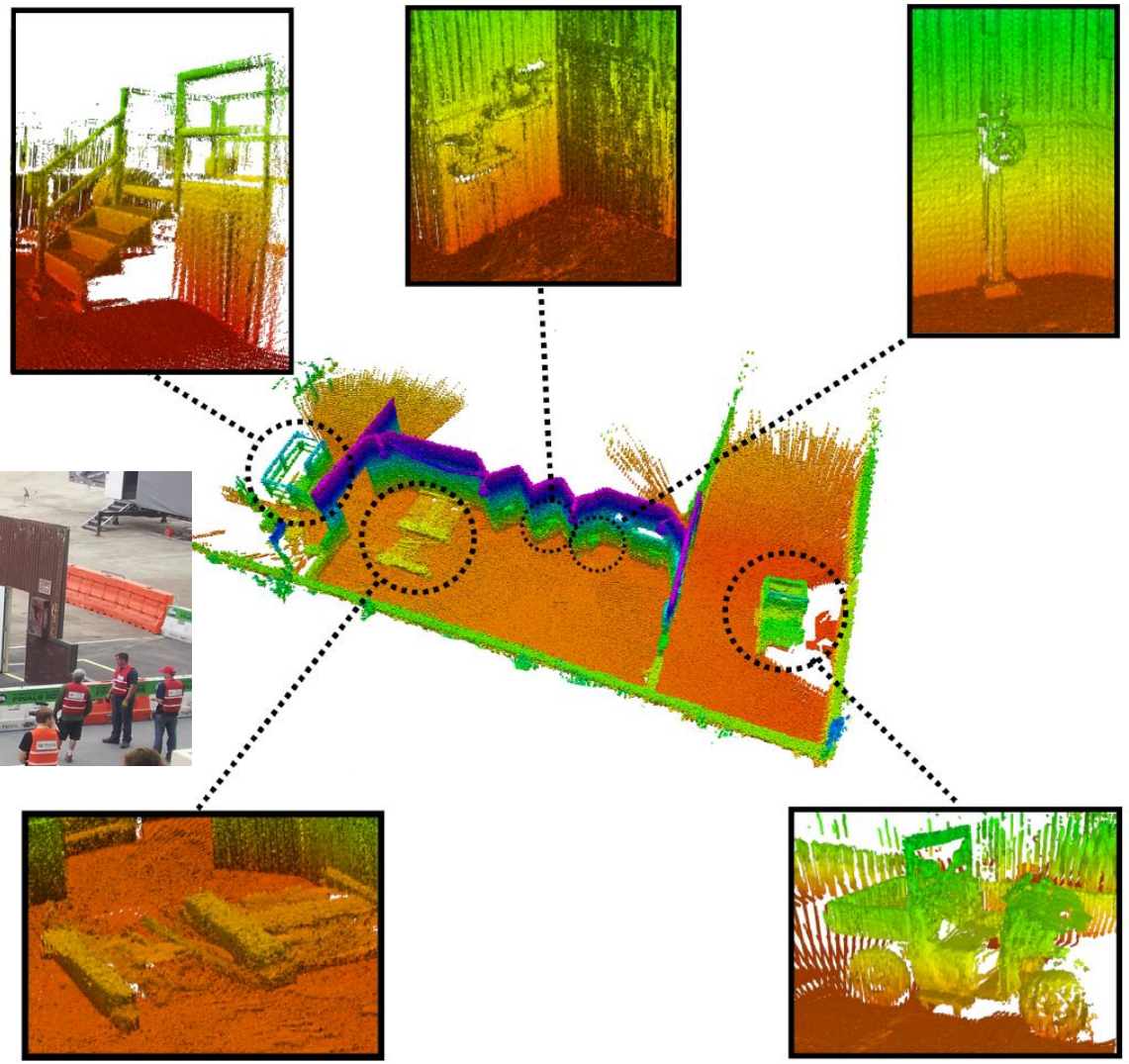
- Maintain occupancy in each cell



[Droeschel et al., Robotics and Autonomous Systems 2017]

Allocentric 3D Mapping

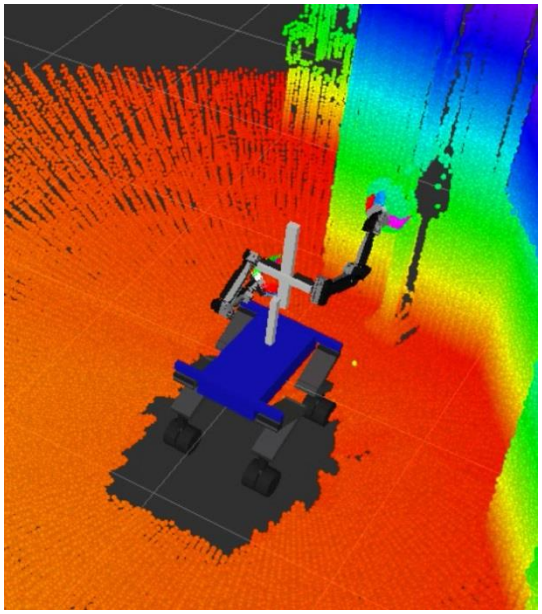
- Registration of egocentric maps by graph optimization



[Droeschel et al., Robotics and Autonomous Systems 2017]

Valve Turning Interface

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



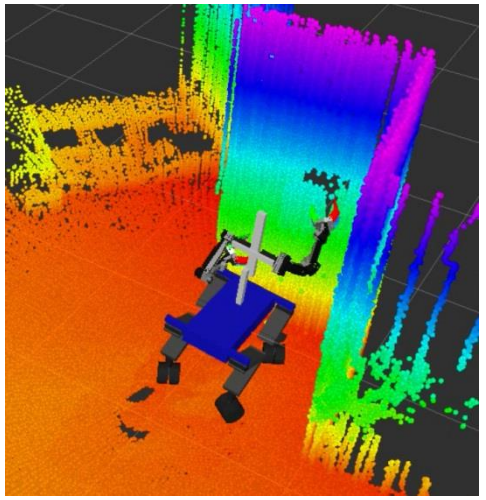
[Schwarz et al. Journal of Field Robotics 2017]

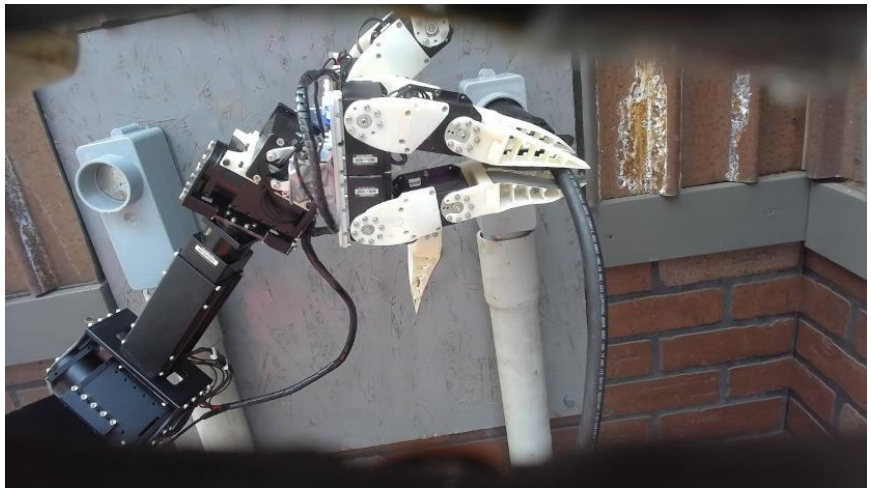
Turning a Valve

[Schwarz et al. Journal of Field Robotics 2017]

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 2017]

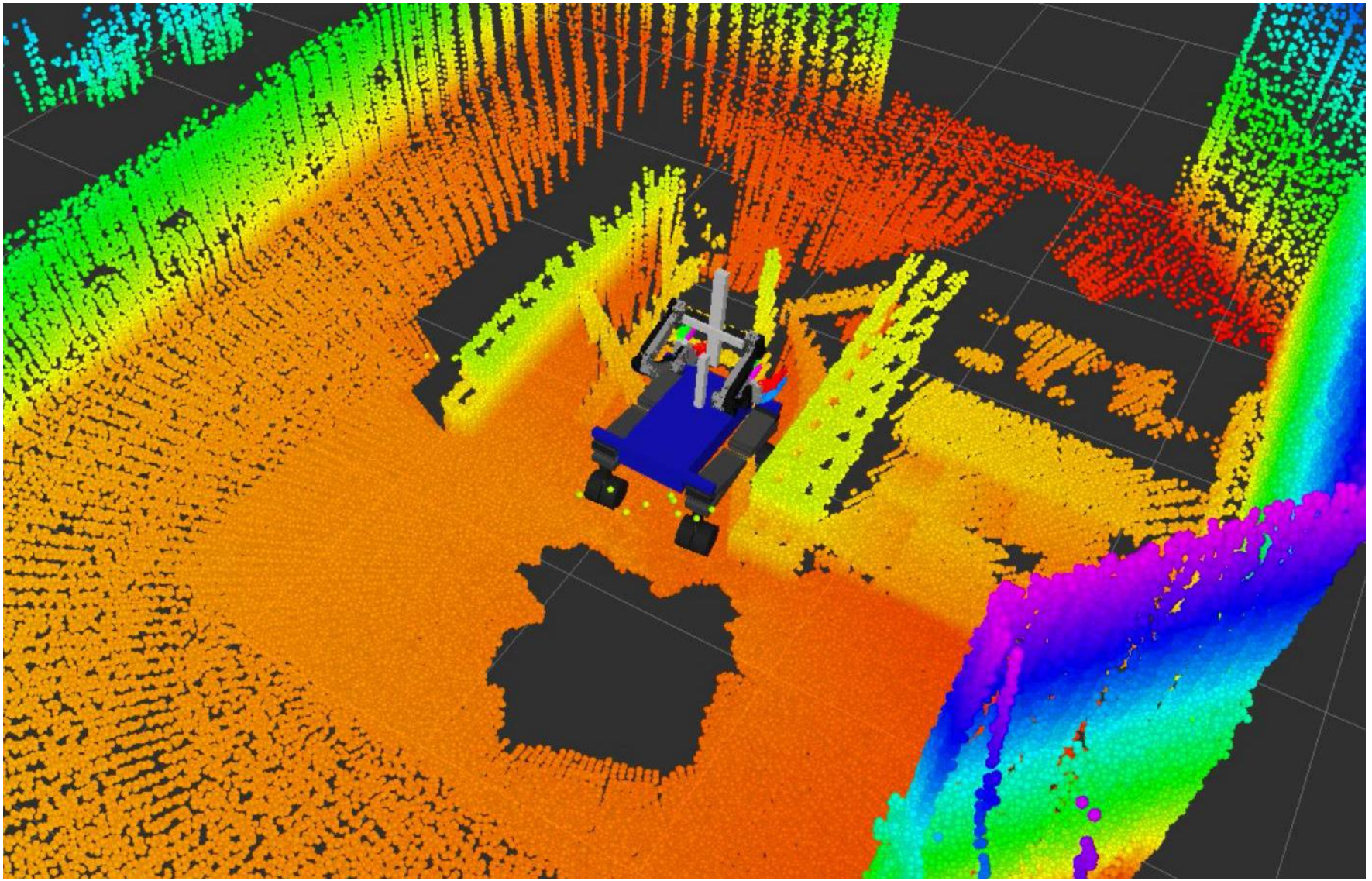
Operating a Switch

[Schwarz et al. Journal of Field Robotics 2017]

Plug Task at DRC

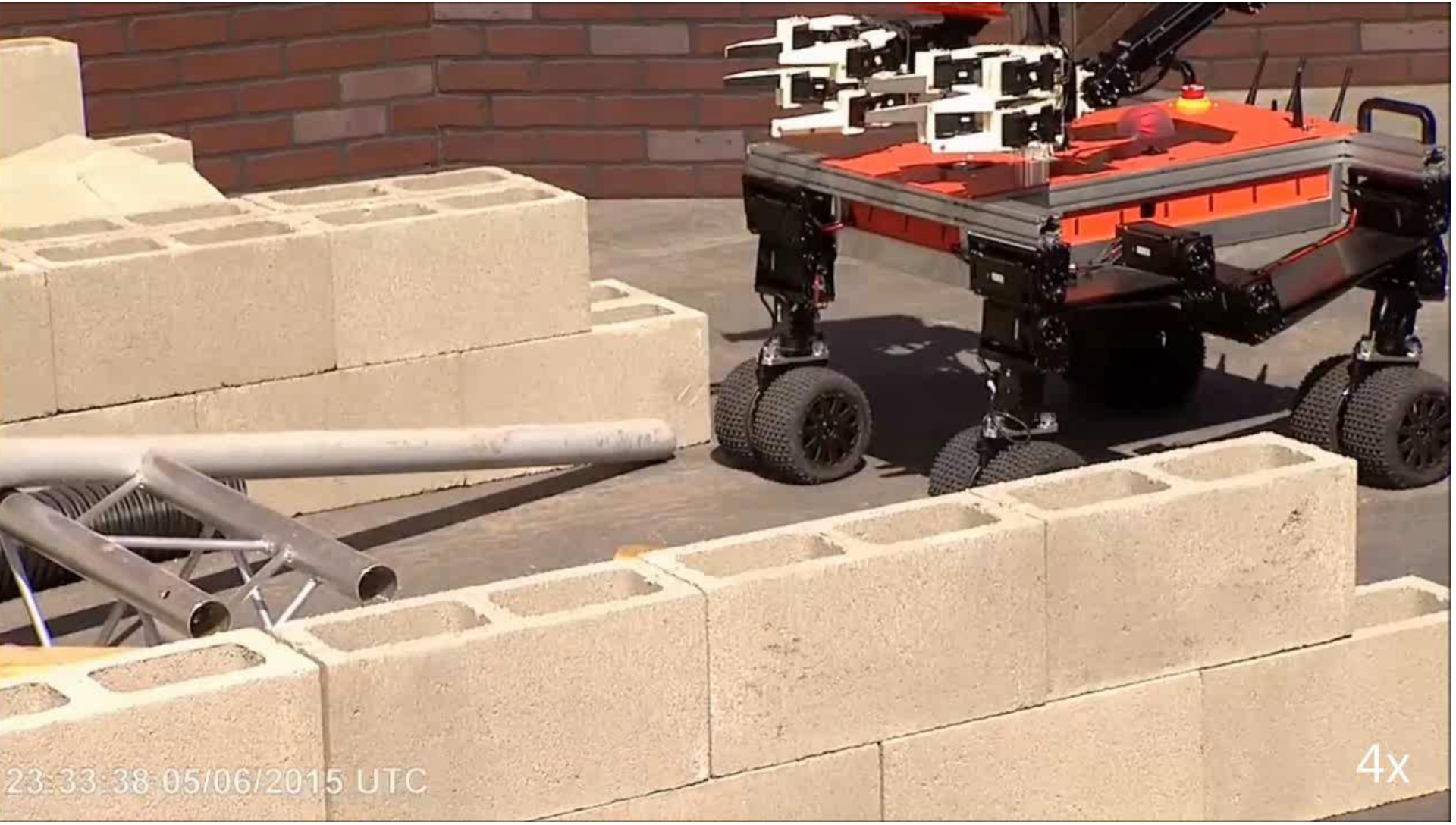
[Schwarz et al. Journal of Field Robotics 2017]

Debris Task



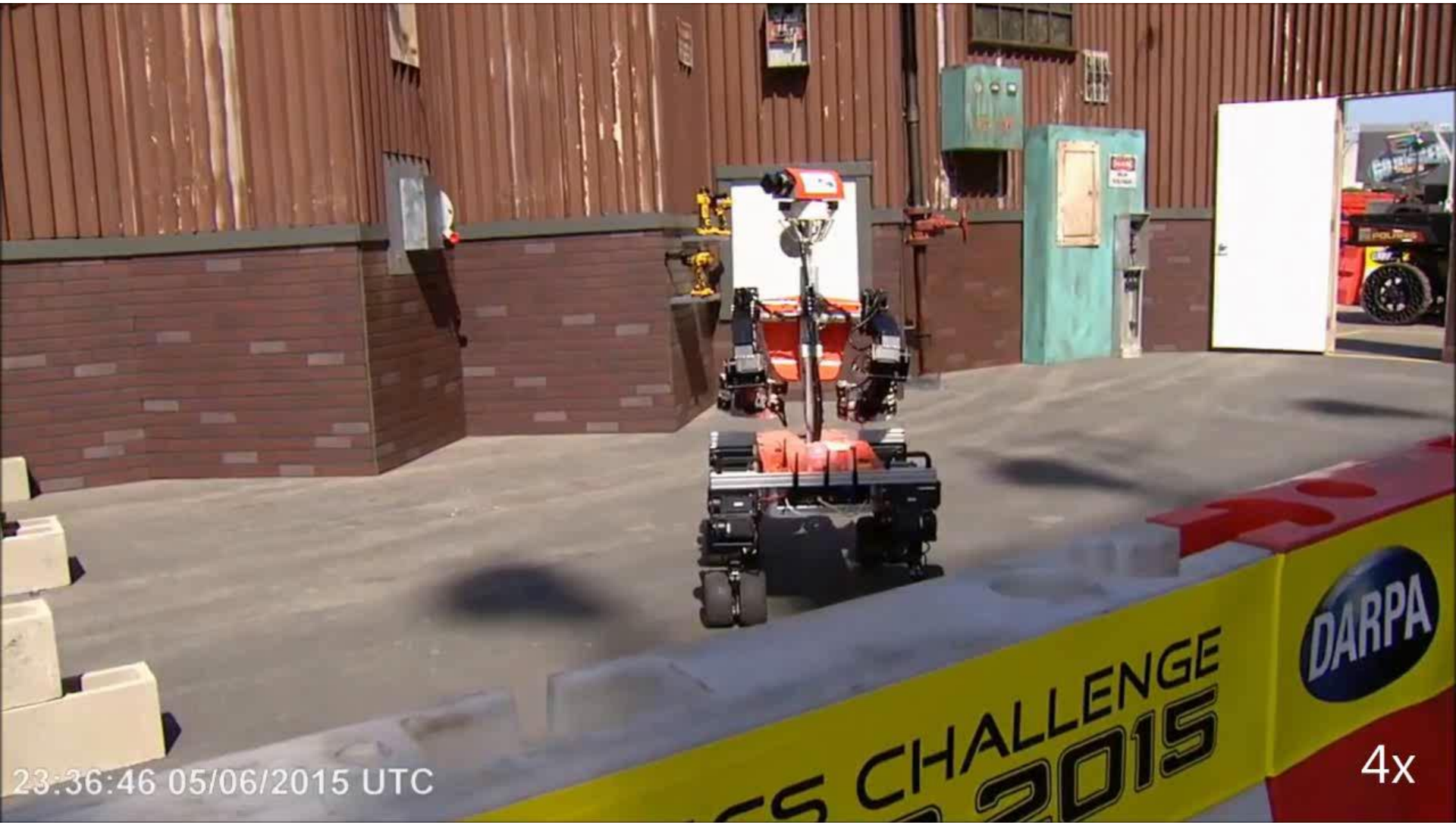
[Schwarz et al. Journal of Field Robotics 2017]

Drive Through Debris



[Schwarz et al. Journal of Field Robotics 2016]

Cutting Drywall



[Schwarz et al. Journal of Field Robotics 2016]

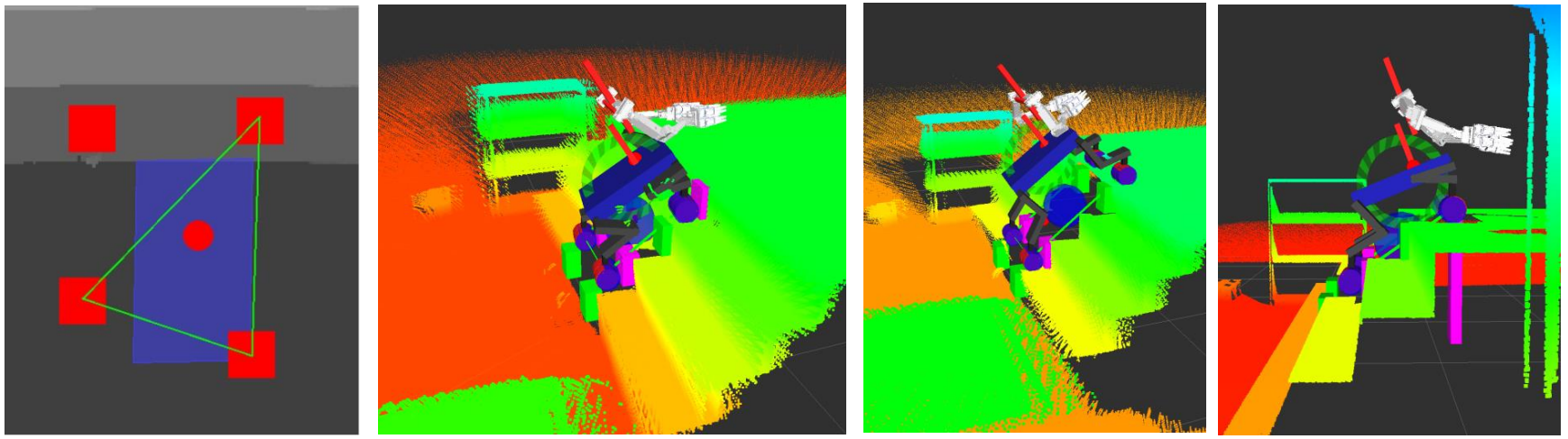
Team NimbRo Rescue

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



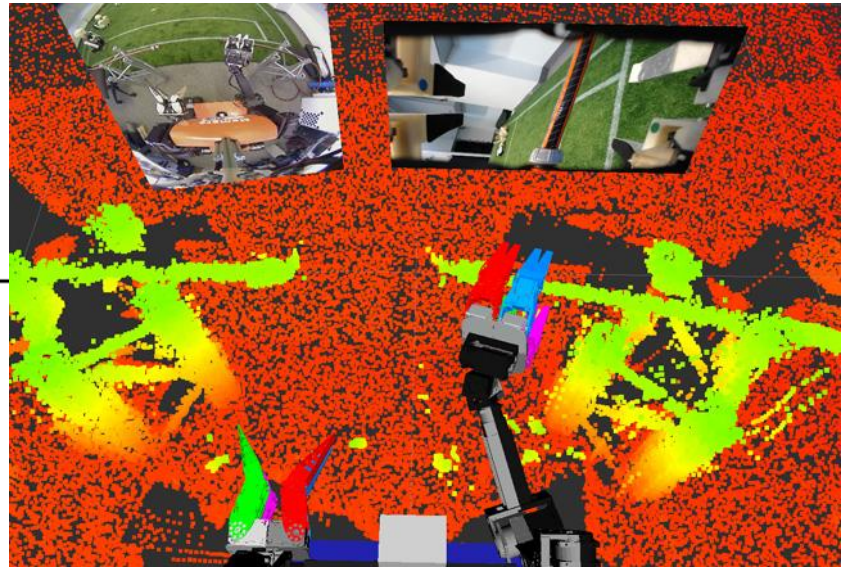
[Schwarz et al., ICRA 2016]

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



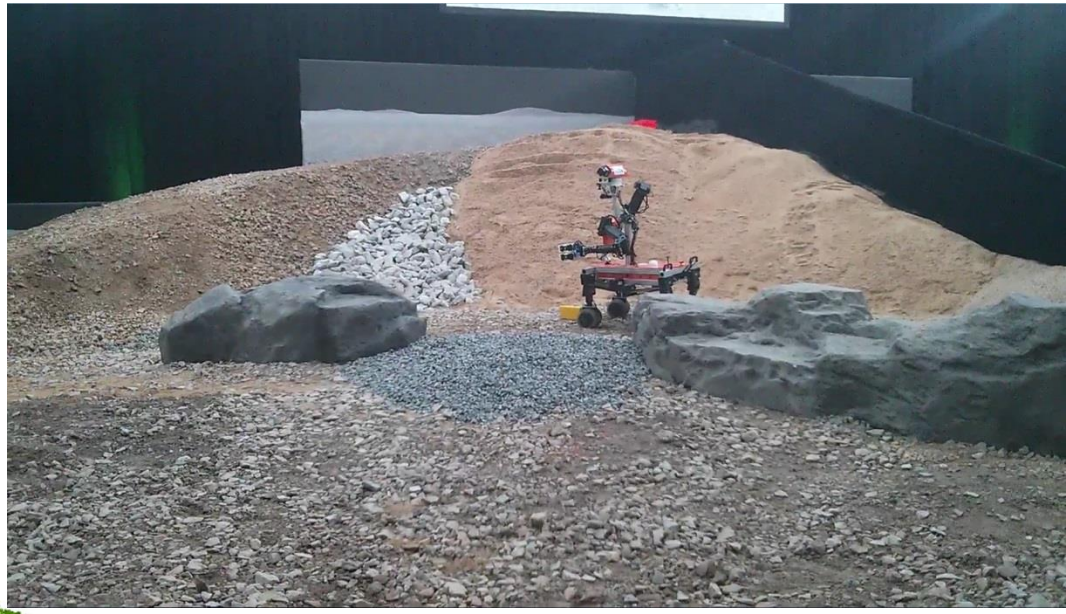
Task	Time [min:s]				
	Avg.	Median	Min.	Max.	Std. Dev.
Left grasp	0:44	0:38	0:27	1:20	0:16
Right grasp	0:45	0:40	0:34	1:04	0:10
Connect	1:36	1:32	1:07	2:04	0:21
Total	3:04	2:57	2:21	3:51	0:28

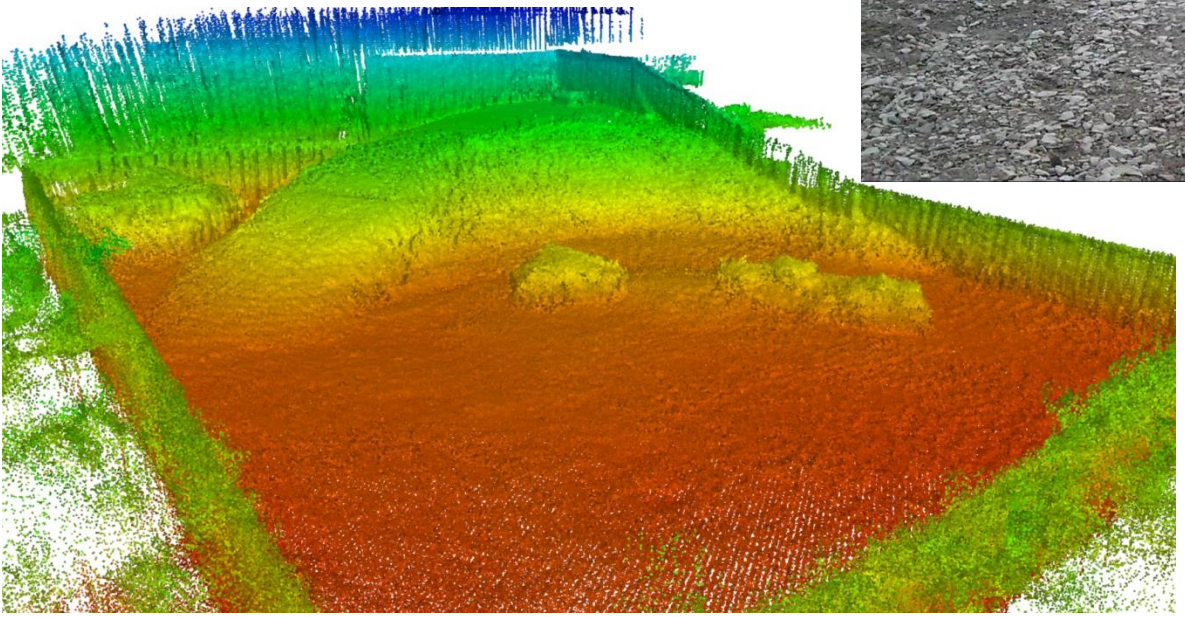
[Rodehutskors et al., Humanoids 2015]

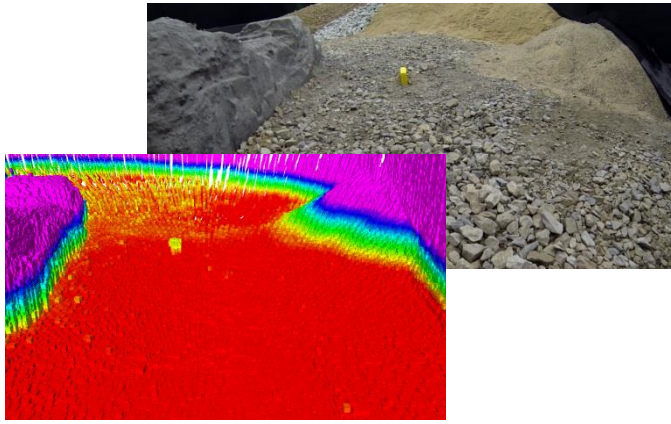
DLR SpaceBot Cup 2015

- Mobile manipulation in rough terrain

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





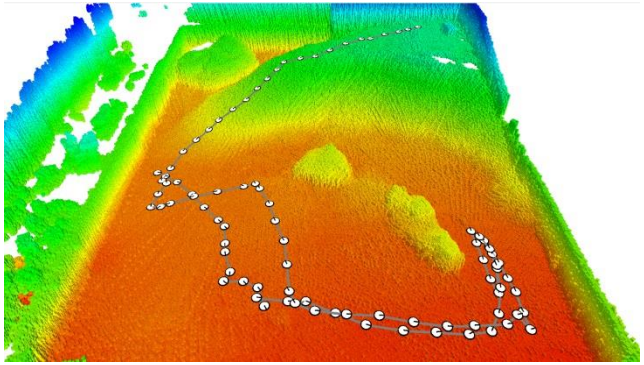


DLR SpaceBot Camp 2015

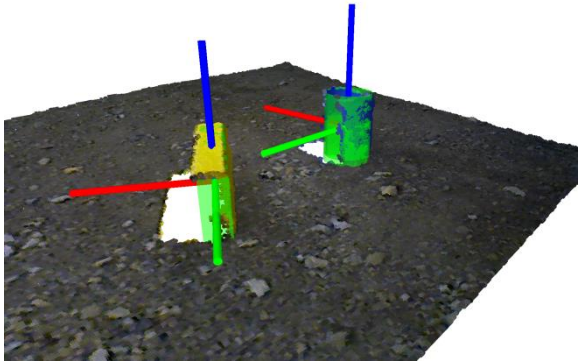
[Schwarz et al., Frontiers in Robotics and AI 2016]

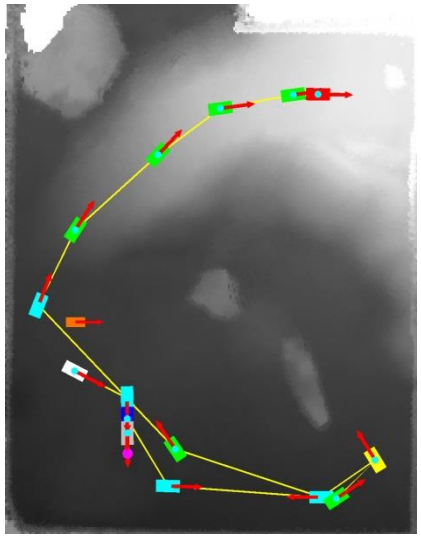
Autonomous Mission Execution

3D Mapping & Localization

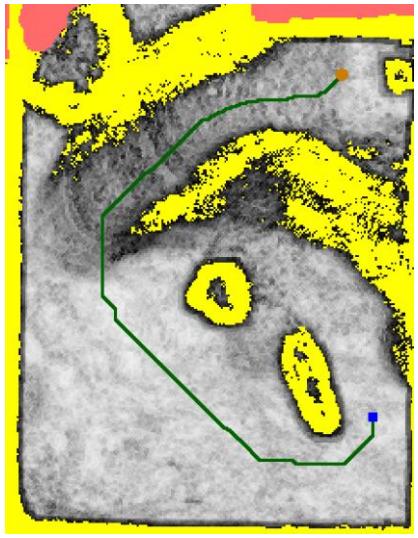


Object perception

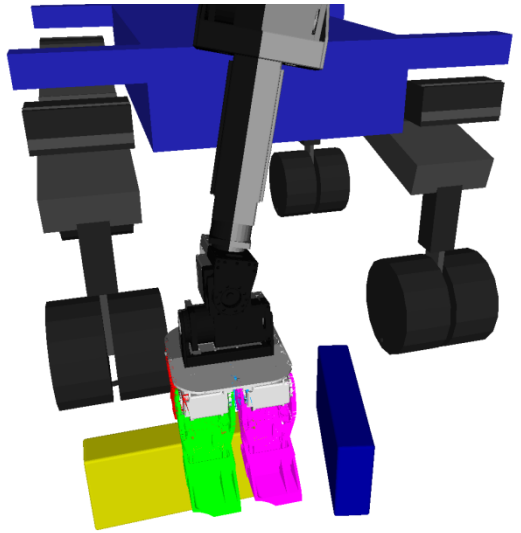




Mission plan



Navigation plan

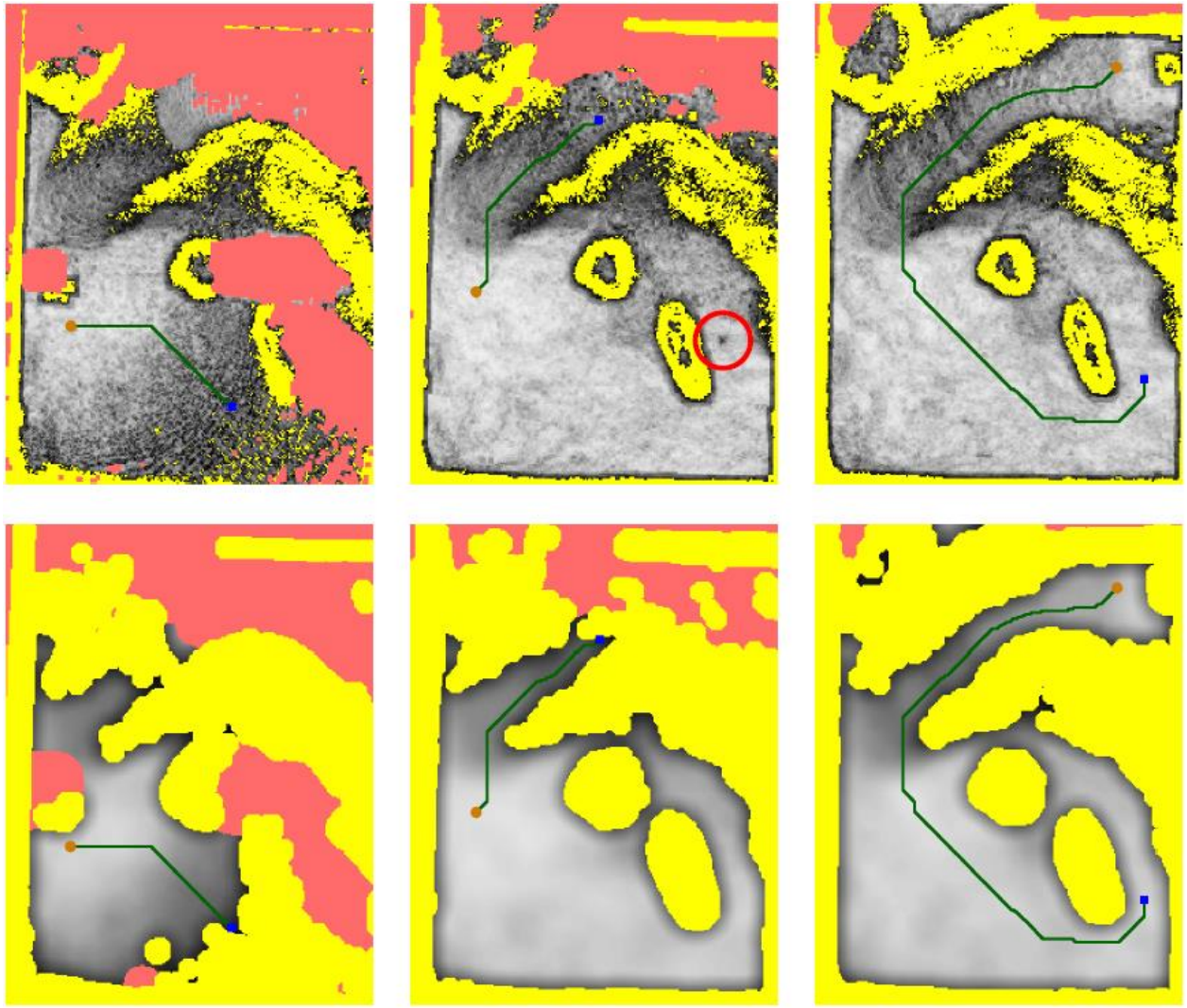


Grasping

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

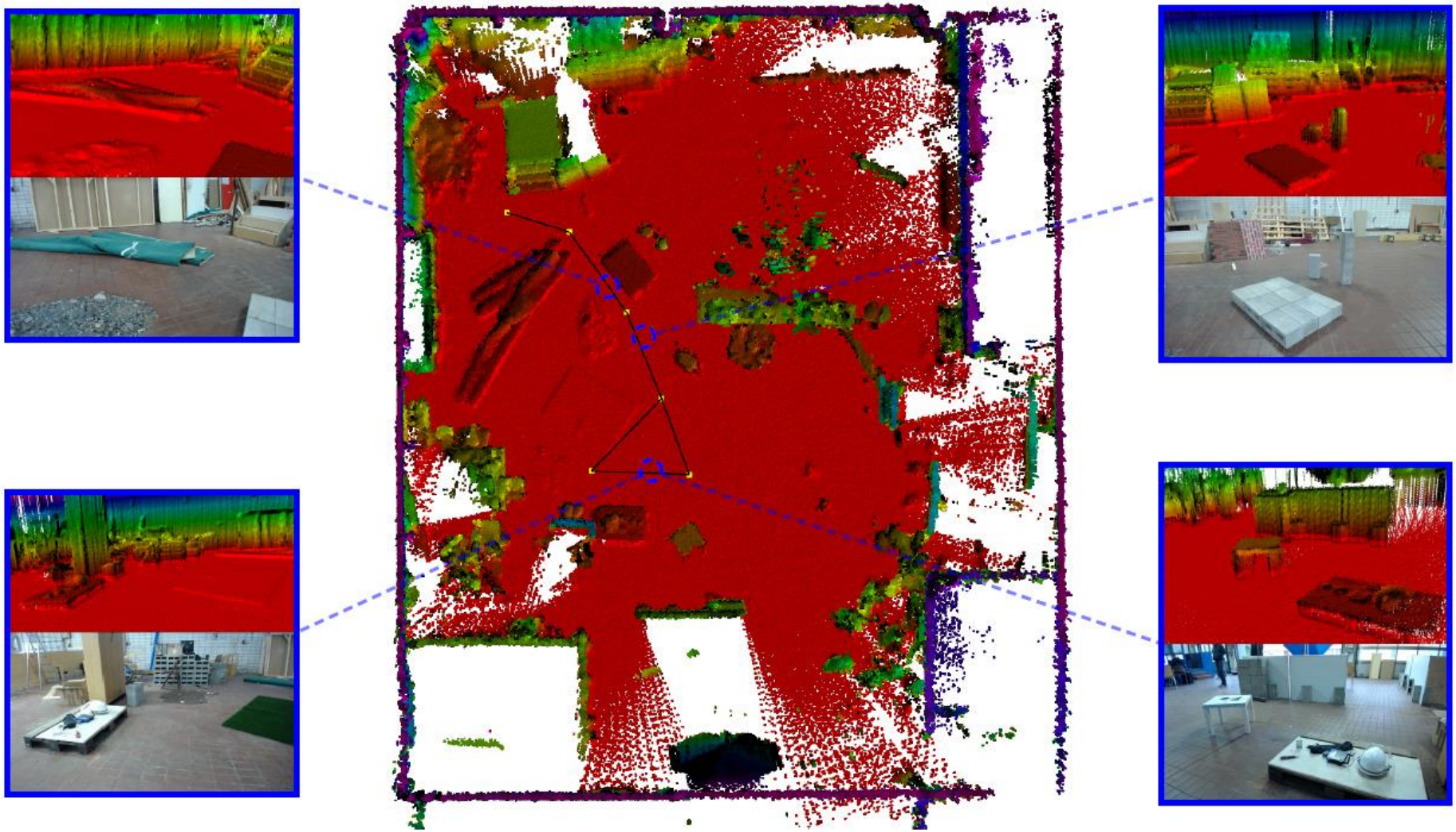
Navigation Planning

- Costs from local height differences
- A* path planning



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

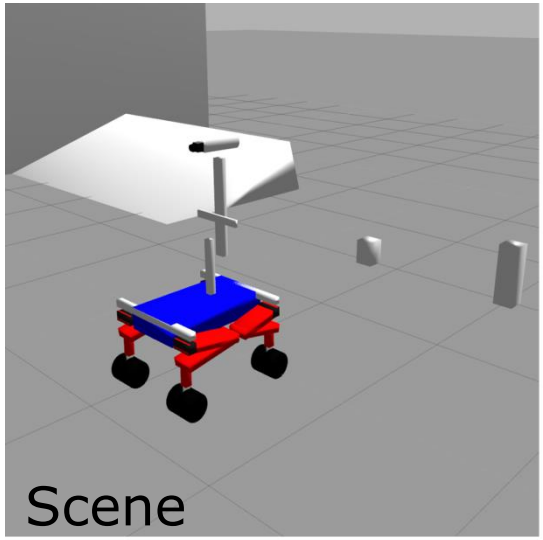
3D Map of Disaster-like Scene

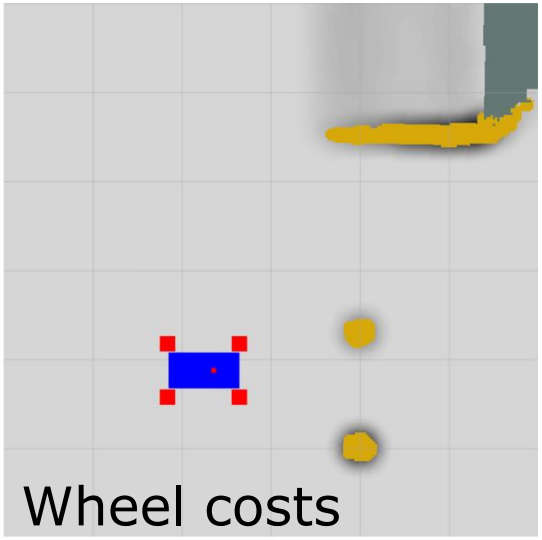


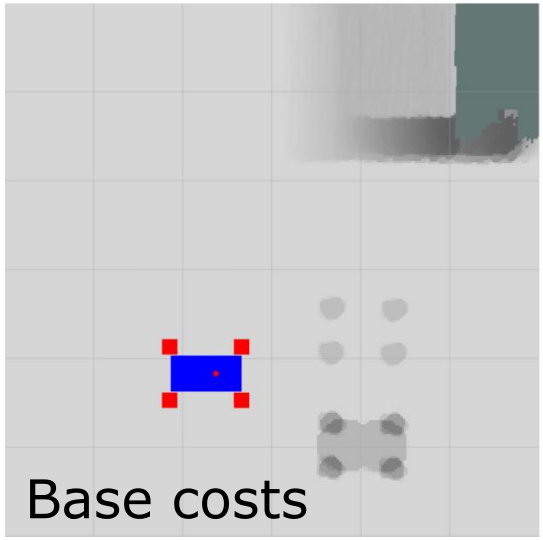
[Droeschel et al., Robotics and Autonomous Systems 2017]

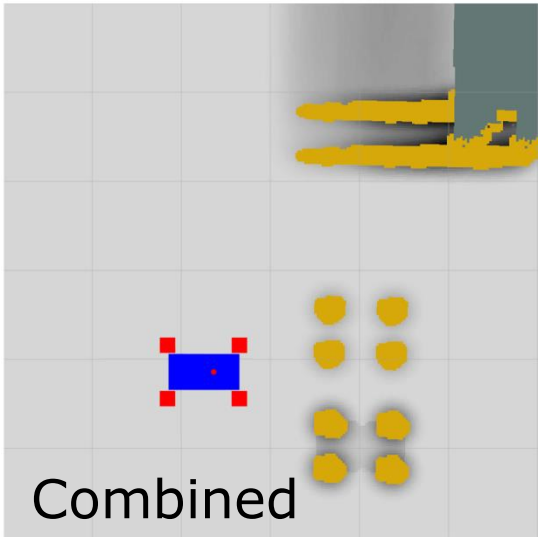
Considering Robot Footprint

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





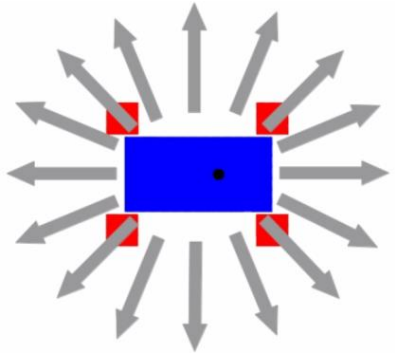




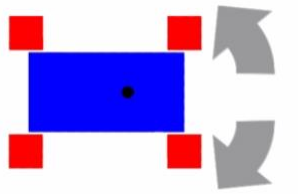
[Klamt and Behnke, under review]

3D Driving Planning (x, y, θ): A*

- 16 driving directions

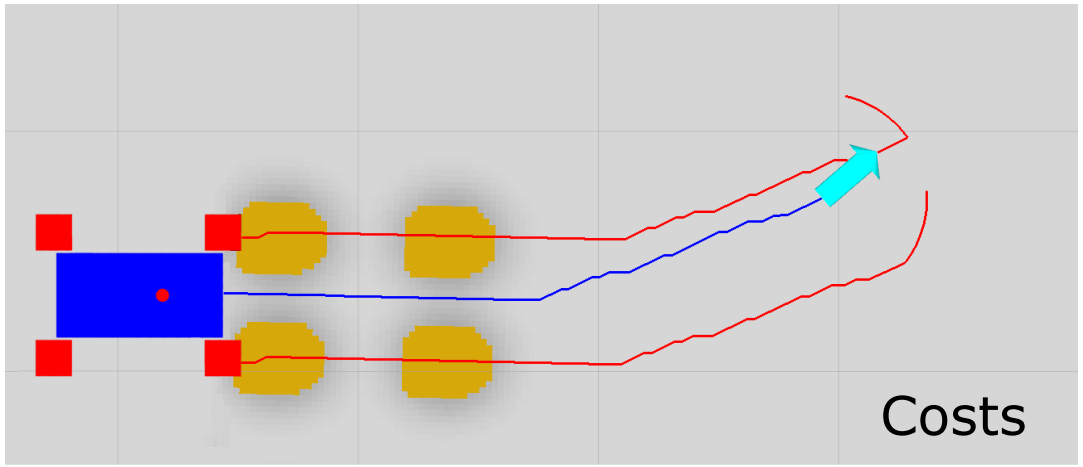


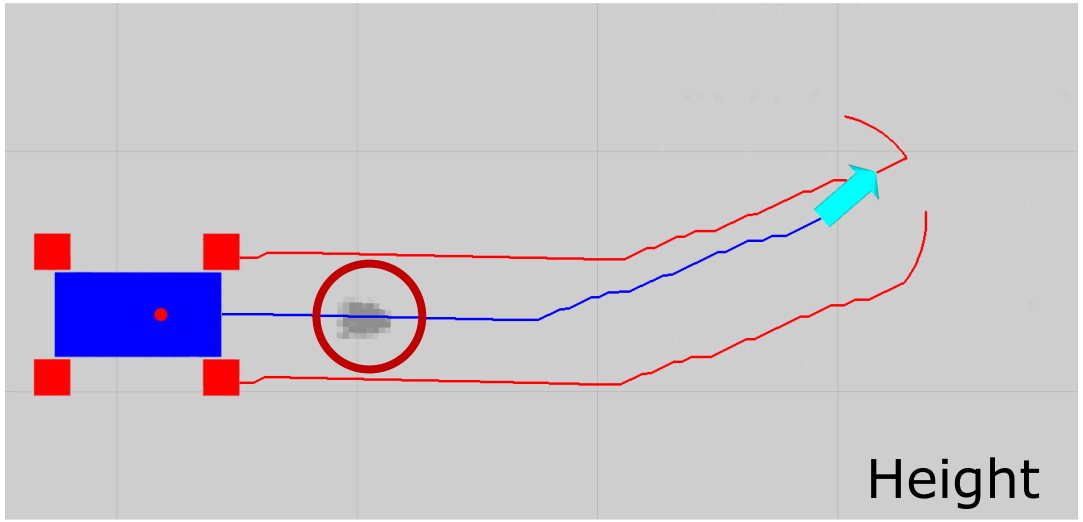
- Orientation changes



=> Obstacle between wheels

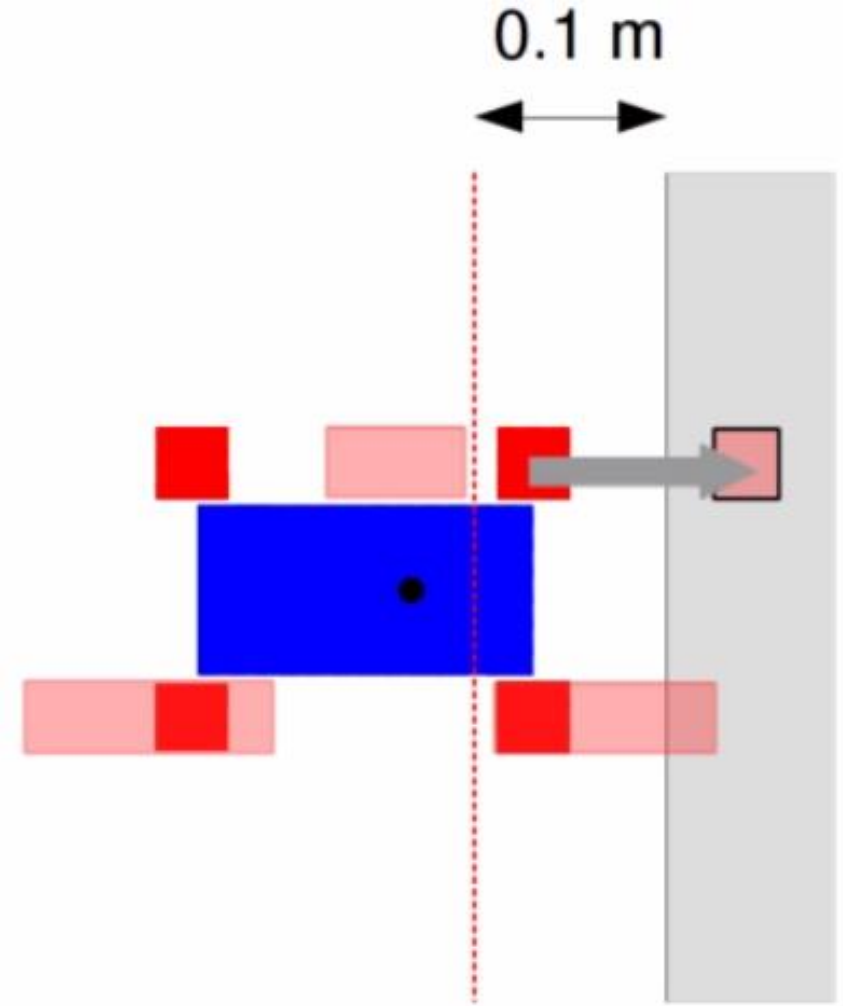
[Klamt and Behnke, under review]





Making Steps

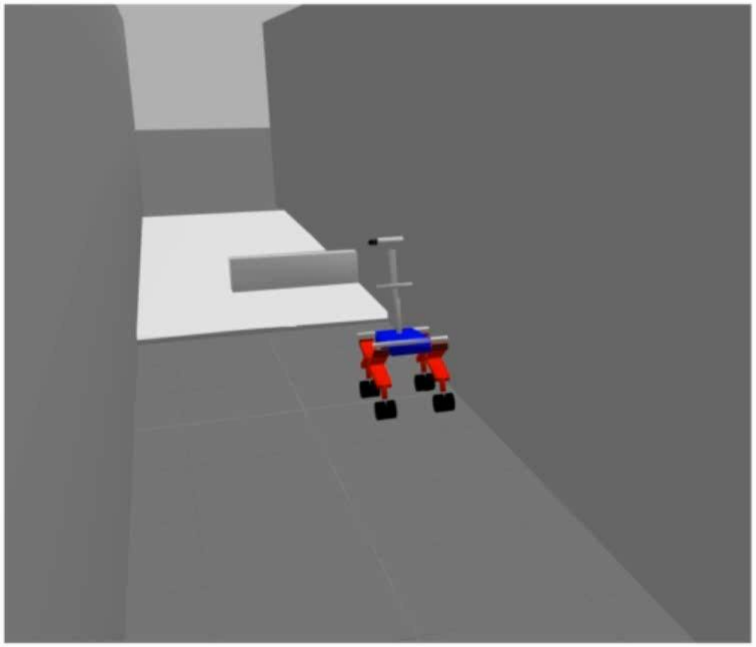
- If not drivable obstacle in front of a wheel
- Step landing must be drivable
- Support leg positions must be drivable



[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.

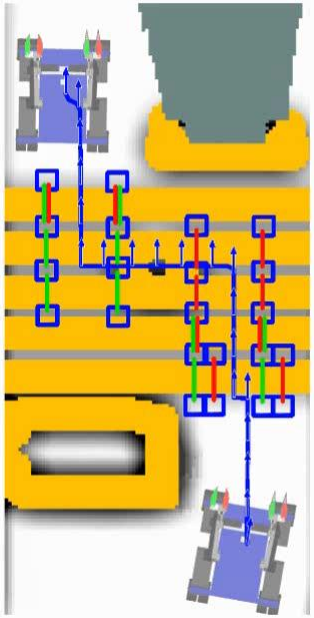
[Klamt and Behnke, under review]

Detailed Realization of Steps

Expanding Abstract Steps to Detailed Motion Sequences

[Klamt and Behnke, under review]

Stairs with Additional Obstacles

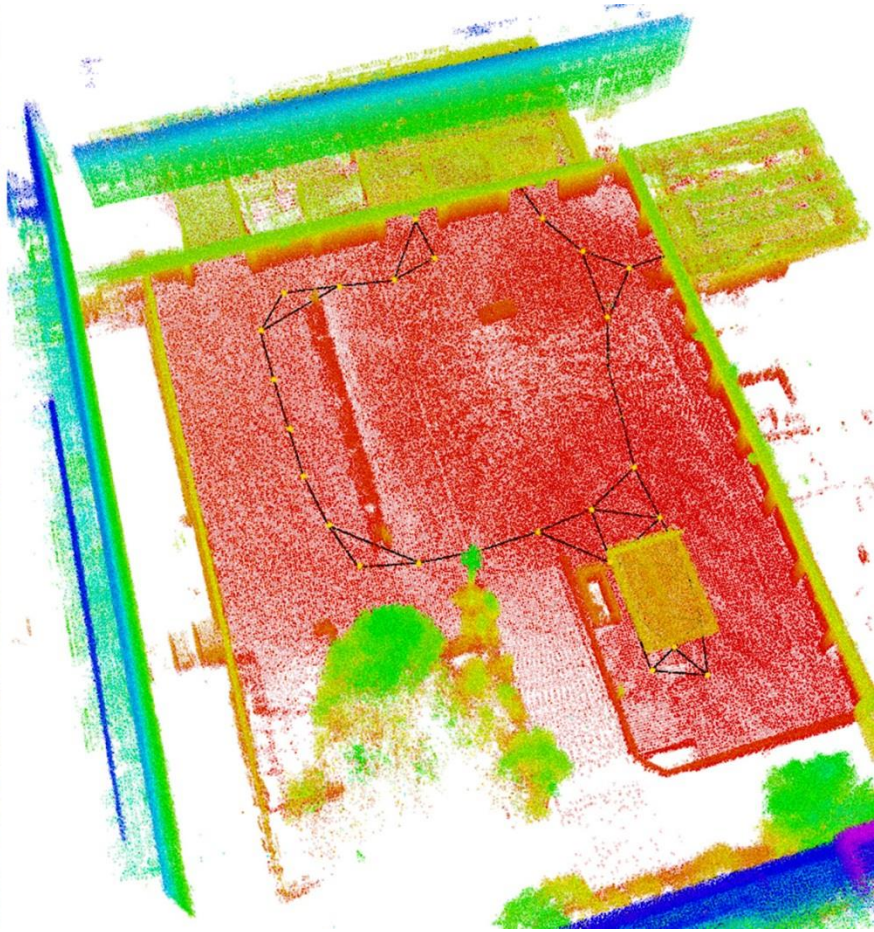


[Klamt and Behnke, under review]

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



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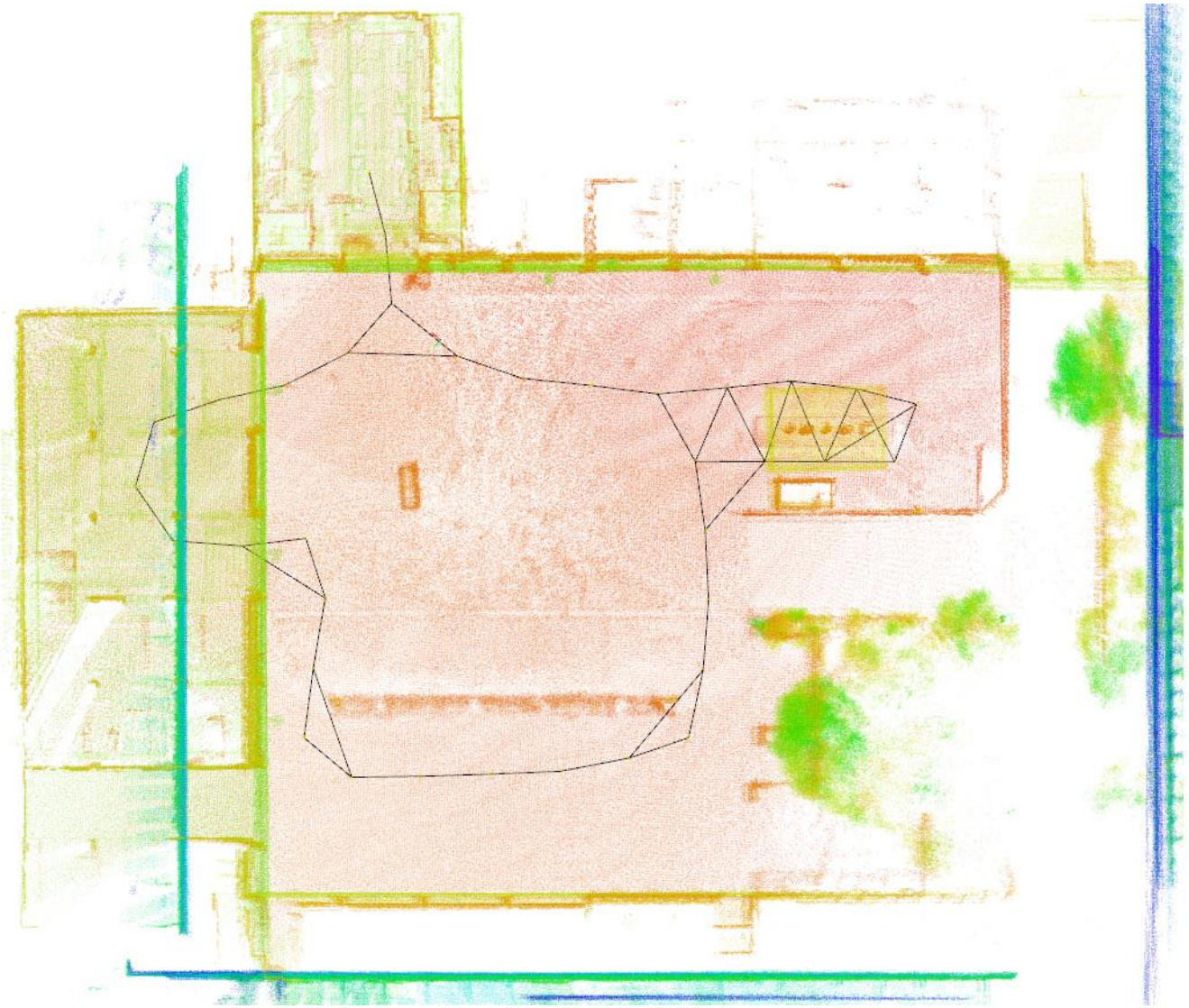
3D Map of Indoor+Outdoor Scene



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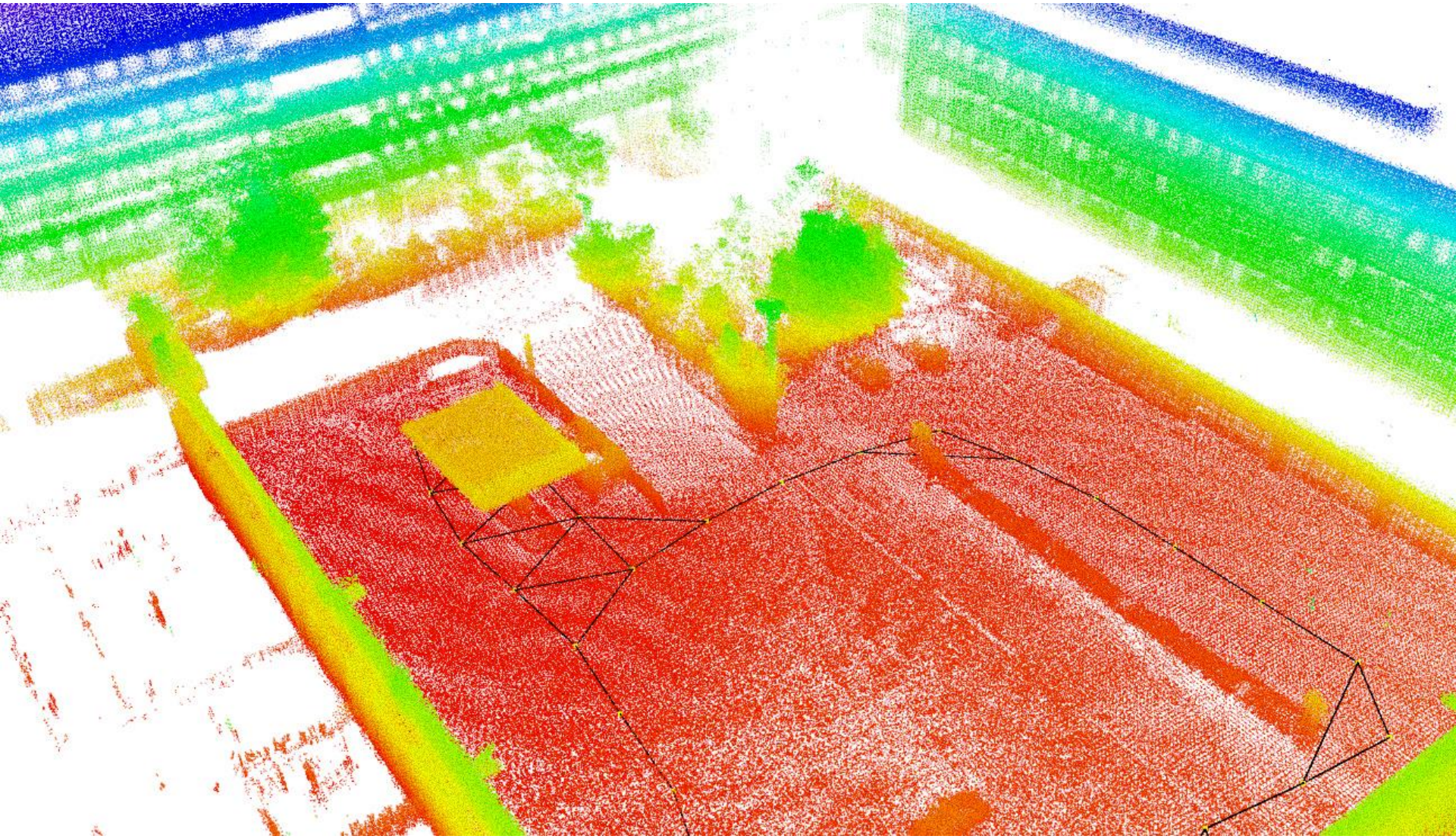
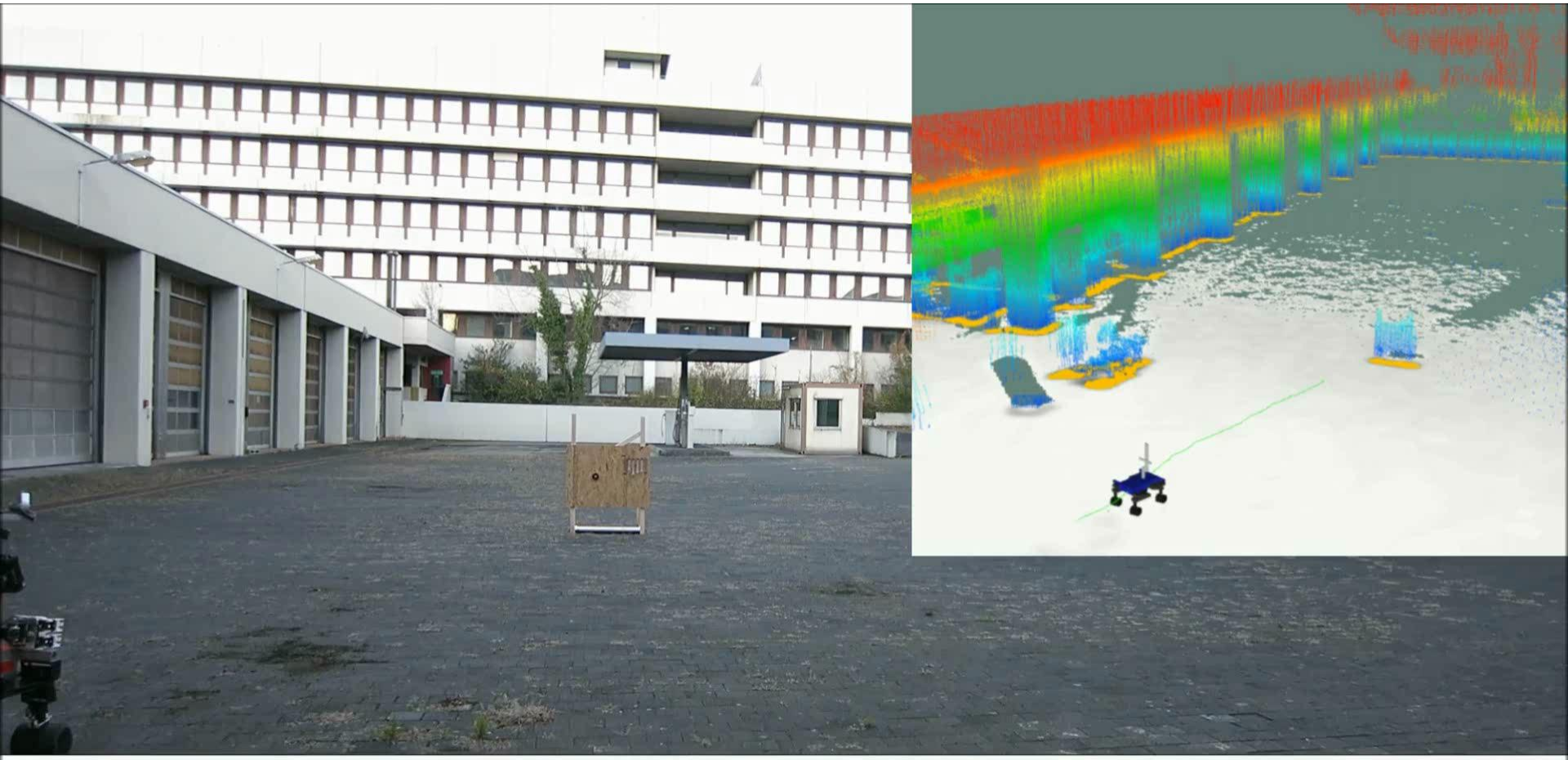


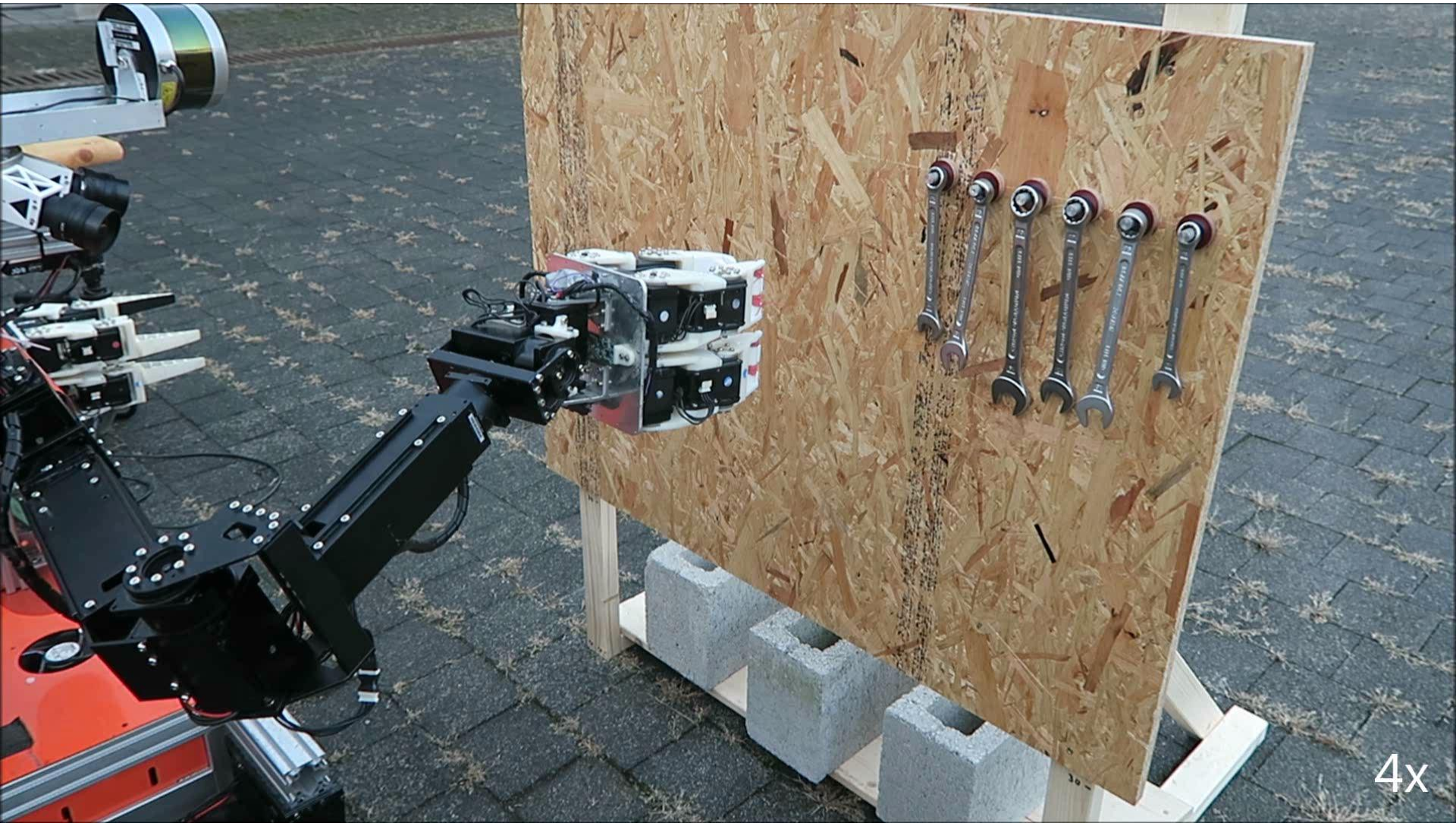
[Droeschel et al., Robotics and Autonomous Systems 2017]

Global and Local Navigation



Navigation in allocentric laser map (colored points)

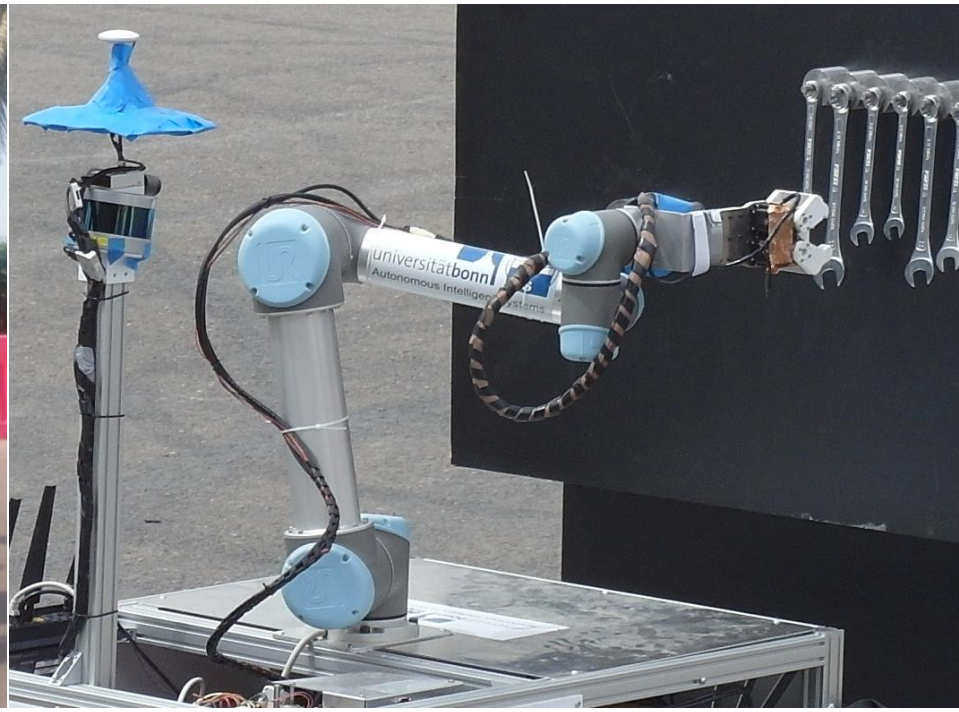
Using a Wrench to Turn a Valve



MBZIRC Challenge 2

Robot Manipulator

- 6DoF arm (UR5)
- Stereo cameras (Pointgray)
- ToF camera (PMD picoflexx)
- Two-finger gripper

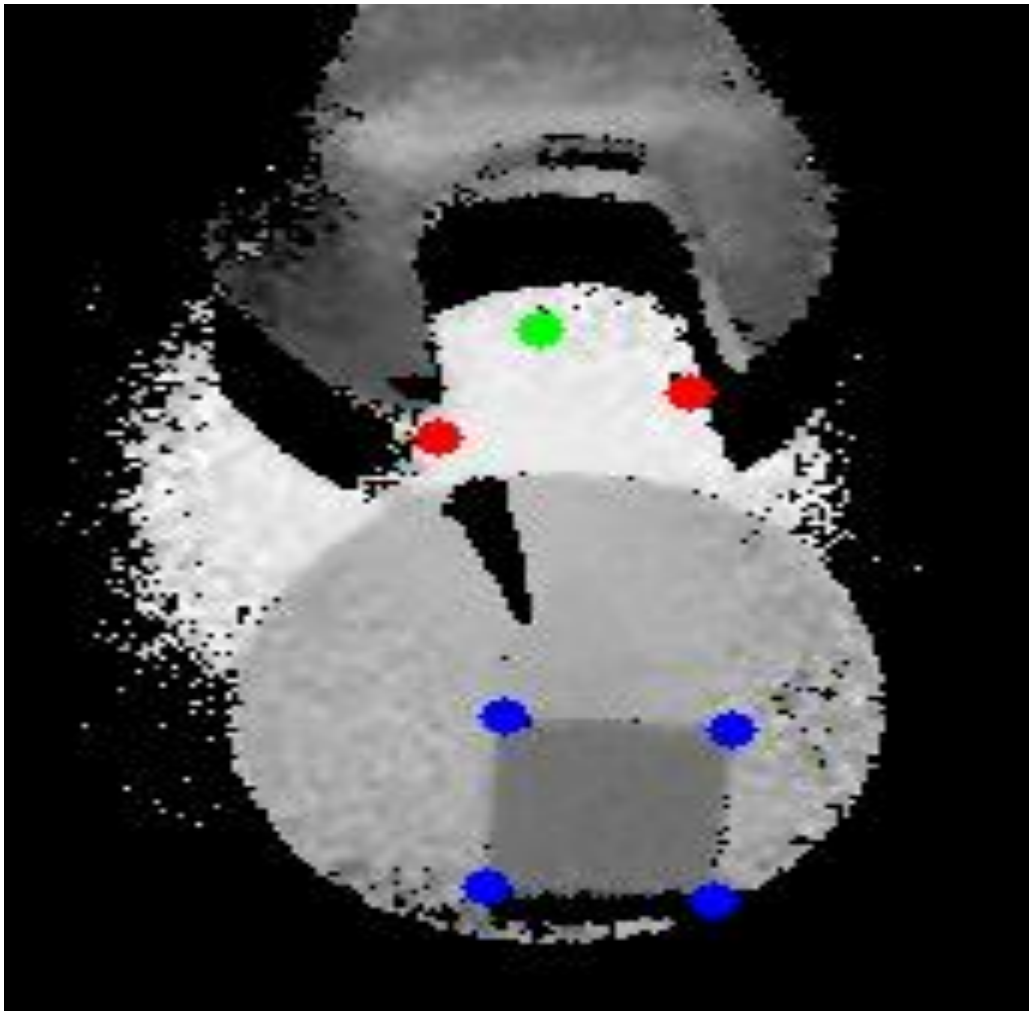


Wrench Selection

- Deep learning object detection
- Training set: 100 stereo pairs

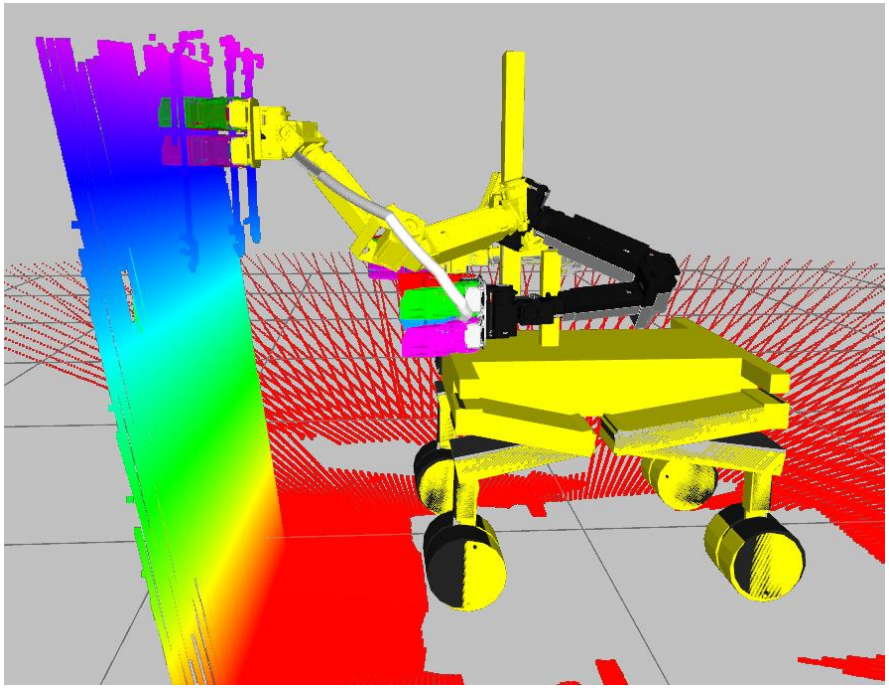
Valve Registration

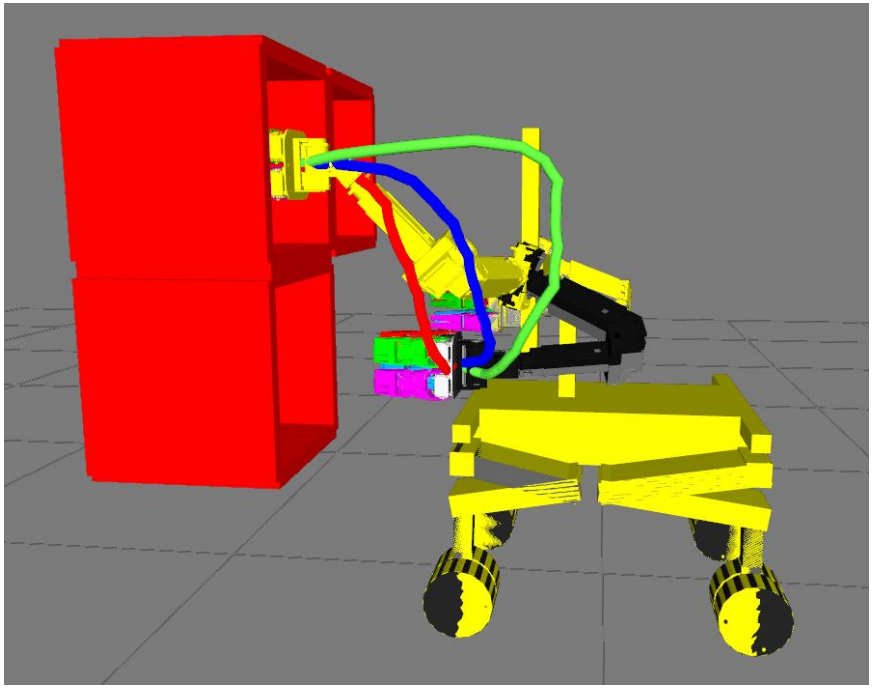
- Picoflexx depth
- Euclidean clustering
- Rotating calipers for estimating valve stem angle and size



Manipulation Trajectory Optimization

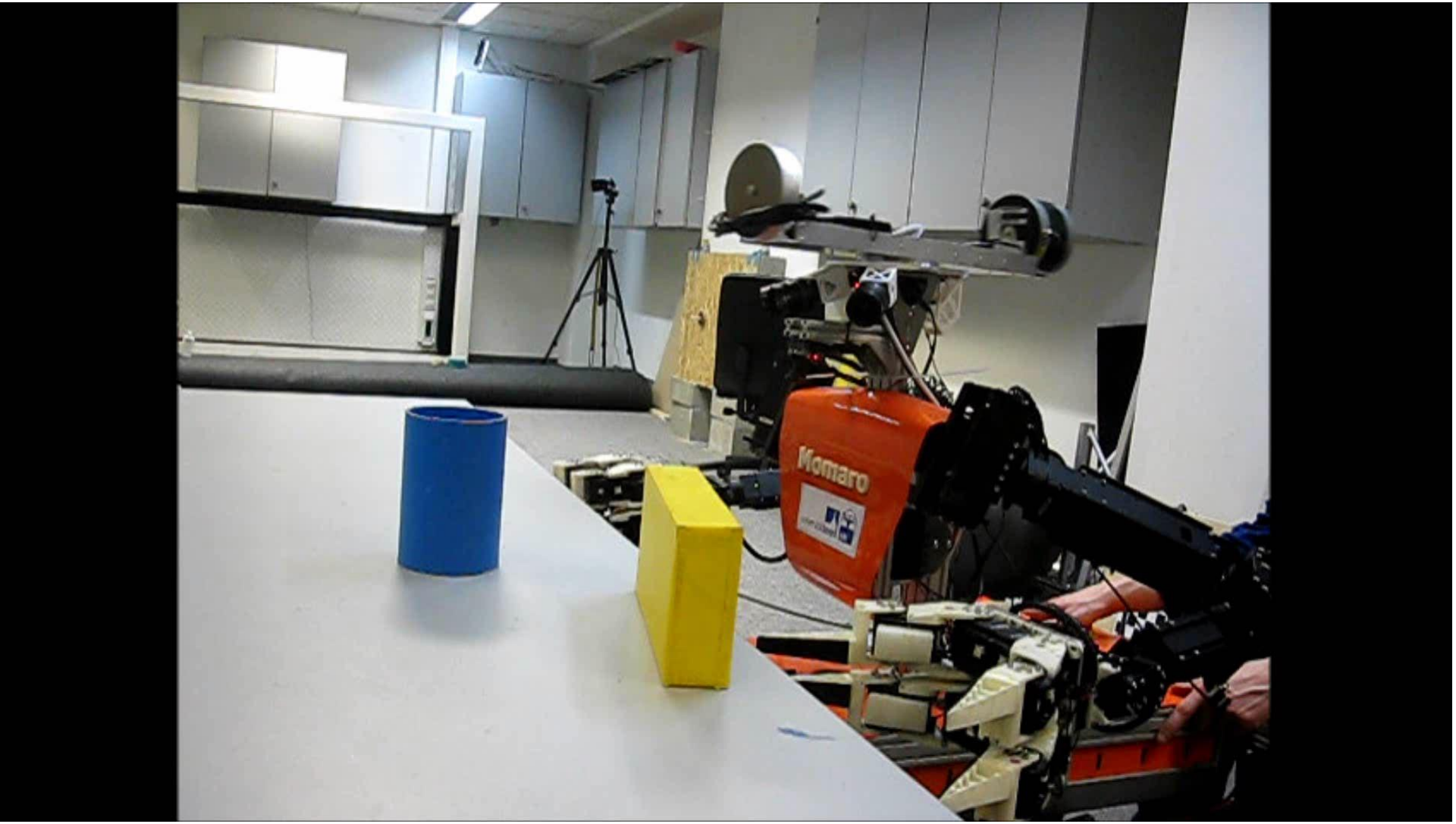
- Extended stochastic trajectory optimization (STOMP)
- 8 DoF (including torso yaw)
- Weighting multiple objectives
- Speed limits depend on distance to obstacles





[Pavlichenko et al. under review]

Momaro Reaching for an Object

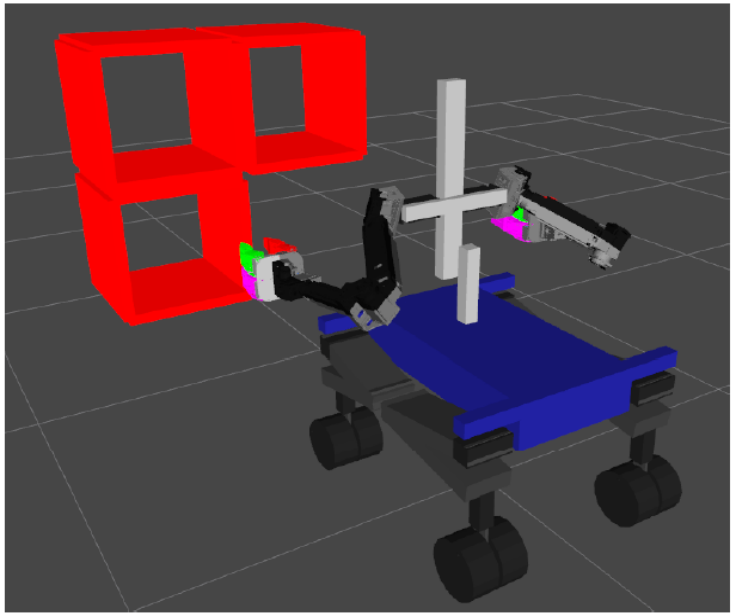


[Pavlichenko et al.]

Behnke: Perception and Planning for Autonomous Locomotion and Manipulation in a Disaster-Response Robot

Shelf Experiment

- Four configurations
  - 12 planning tasks
  - 100 executions for each task
- 3 difficulty levels:
  - Easy
  - Hard (gripper deeper)
  - Hard constrained (endeffector orient.)

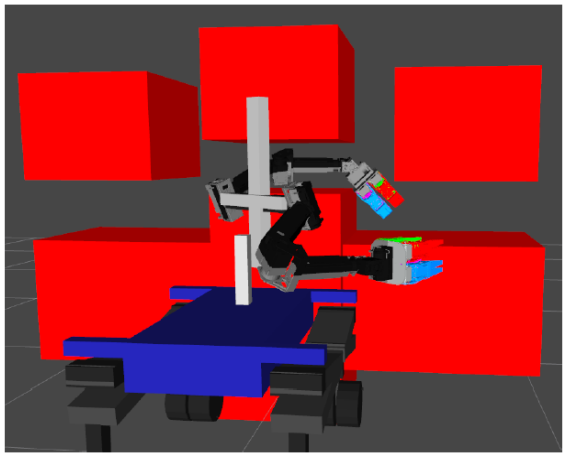


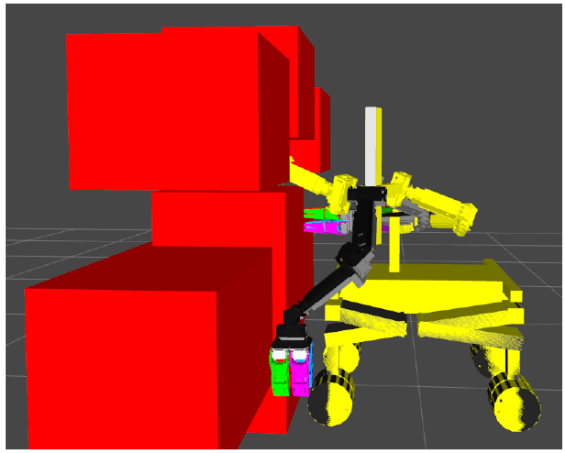
	Difficulty level					
	Easy		Hard		Hard constrained	
Algorithm	success rate	runtime [s]	success rate	runtime [s]	success rate	runtime [s]
LBKPIECE	0.94	2.47 ± 1.08	0.93	2.46 ± 0.85	-	-
STOMP-Industrial	0.87	0.87 ± 0.86	0.76	1.47 ± 1,01	-	-
RRTConnect	0.97	0.29 ± 0.18	0.96	0.85 ± 0.58	0.97	1.22 ± 1.04
STOMP-New	1.0	0.09 ± 0.02	1.0	0.18 ± 0.11	0.99	0.28 ± 0.21

Corridor Experiment

- Two difficulty levels:
  - Easy
  - Hard
- 100 trials each

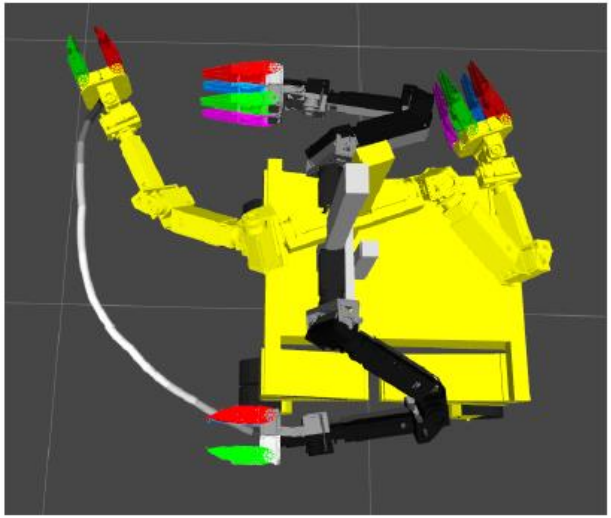
[Pavlichenko et al. under review]

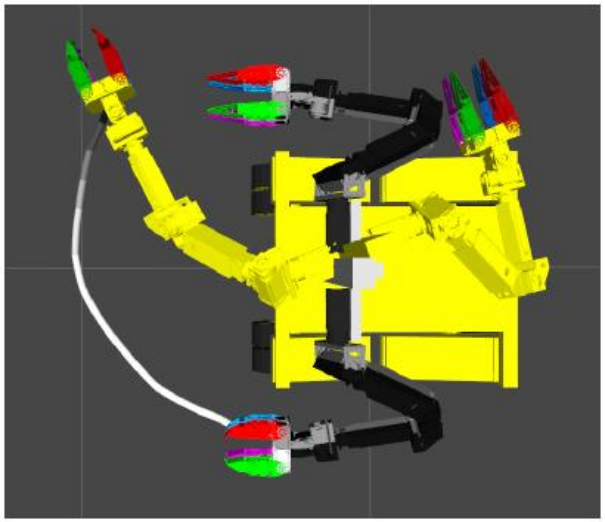


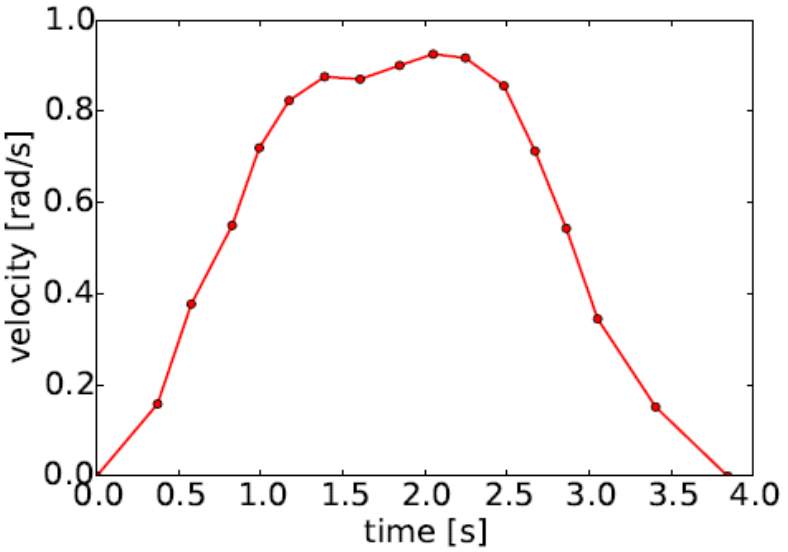


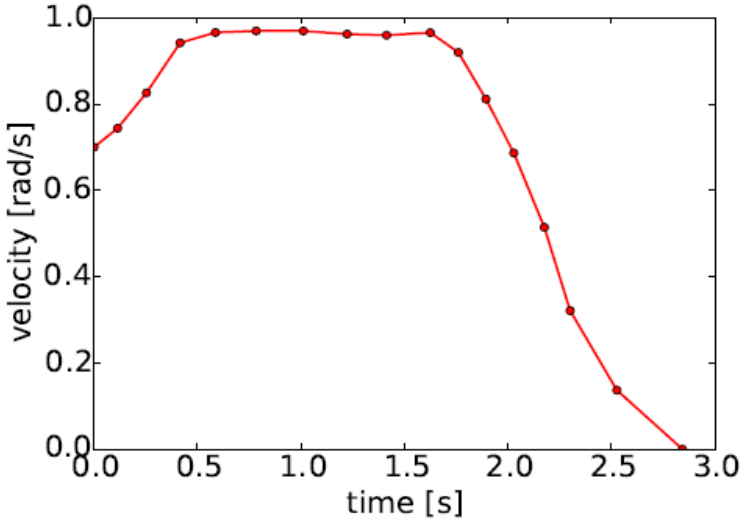
	Difficulty level			
	Easy		Hard	
Algorithm	success rate	runtime [s]	success rate	runtime [s]
LBKPIECE	0.65	6.97 ± 2.58	0.50	7.82 ± 2.58
RRTConnect	0.08	9.64 ± 1.27	0.06	9.71 ± 1.56
STOMP-Industrial	0.00	2.82 ± 0.07	0.00	2.85 ± 0.08
STOMP-New	0.78	1.89 ± 1.44	0.18	3.64 ± 1.29

Velocity Profiles

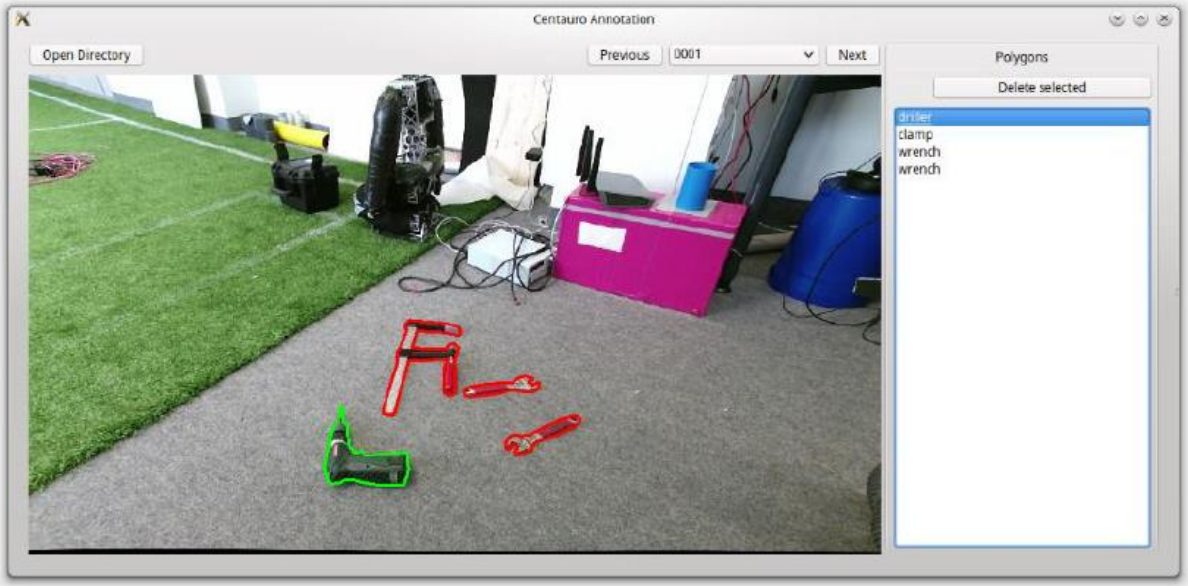








Workspace Perception Data Set

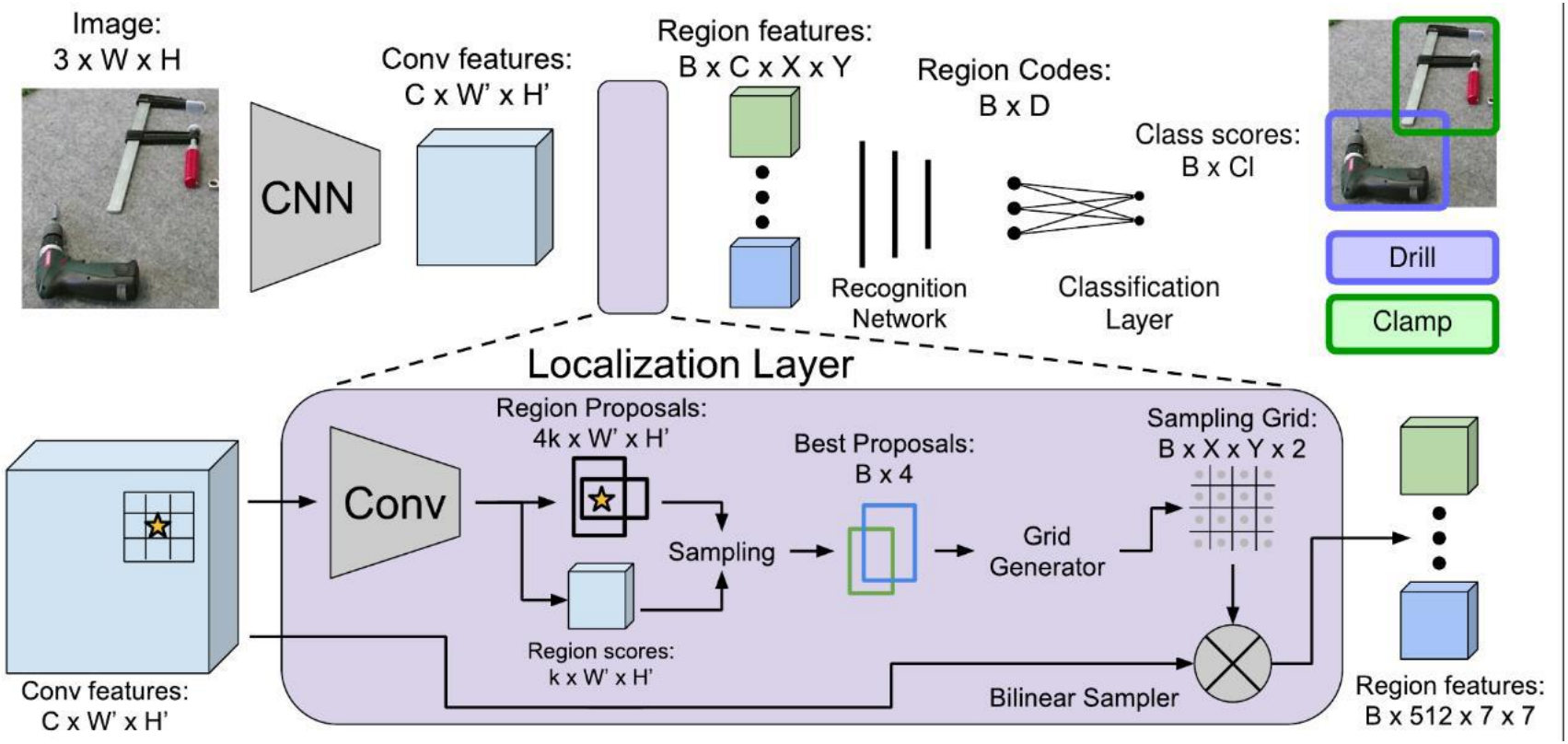


129 frames, 6 object classes

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

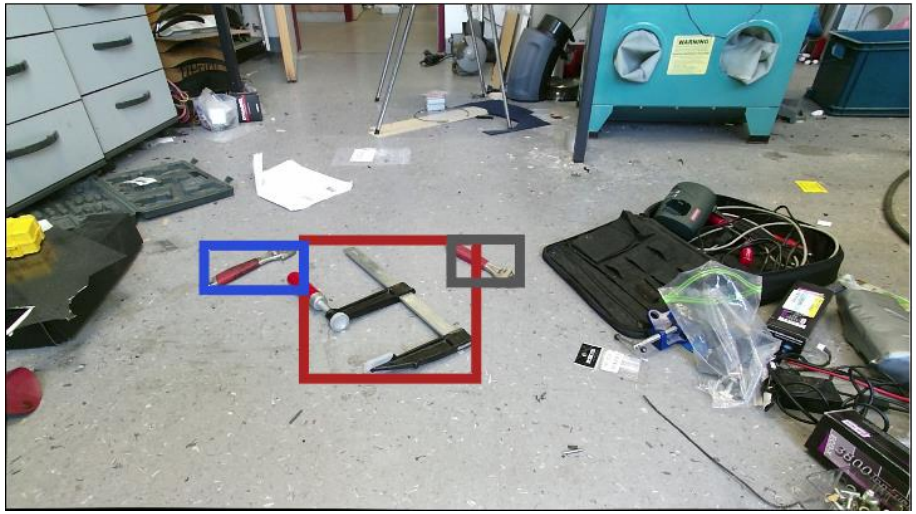
[Schwarz et al. IJRR 2017]

Tool Detection Results

Resolution	Clamp	Door handle	Driller	Extension	Stapler	Wrench	Mean
	AP / F1	AP / F1	AP / F1	AP / F1	AP / F1	AP / F1	AP / F1
720×507	0.881/0.783	0.522/0.554	0.986/0.875	1.000/0.938	0.960/0.814	0.656/0.661	0.834/0.771
1080×760	0.926/0.829	0.867/0.632	0.972/0.893	1.000/0.950	0.992/0.892	0.927/0.848	0.947/0.841
1470×1035	0.913/0.814	0.974/0.745	1.000/0.915	1.000/0.952	0.999/0.909	0.949/0.860	0.973/0.866

[Schwarz et al. IJRR 2017]

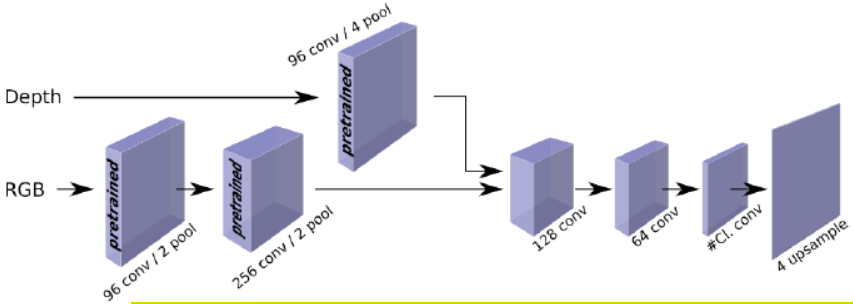
Tool Detection Examples

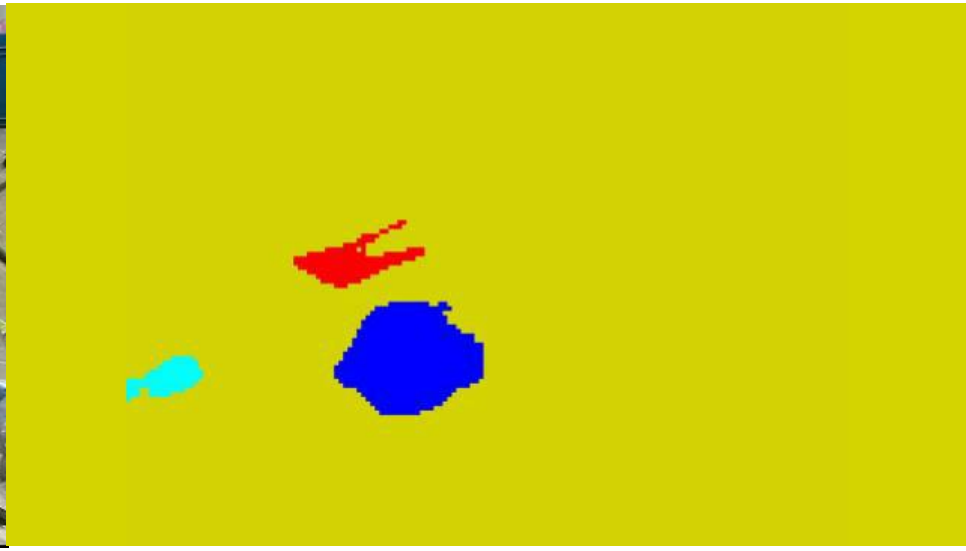


Semantic Segmentation

- Deep CNN

[Husain et al. RA-L 2016]



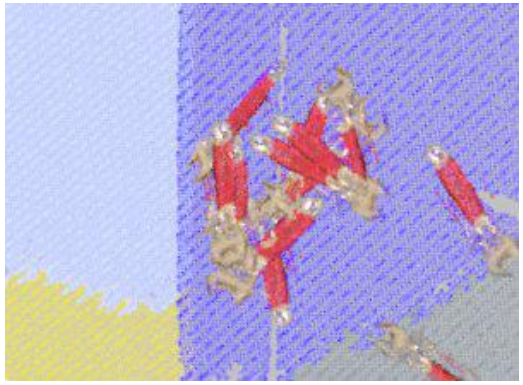


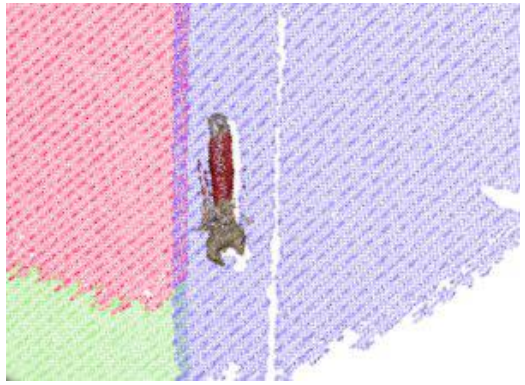
Pixel-wise accuracy:

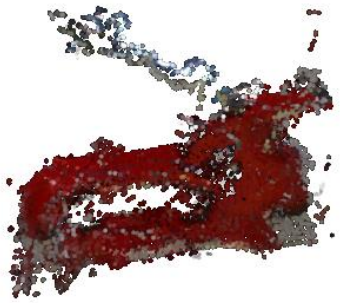
Clamp	Door handle	Driller	Extension	Stapler	Wrench	Background	Mean
0.727	0.751	0.769	0.889	0.775	0.734	0.992	0.805

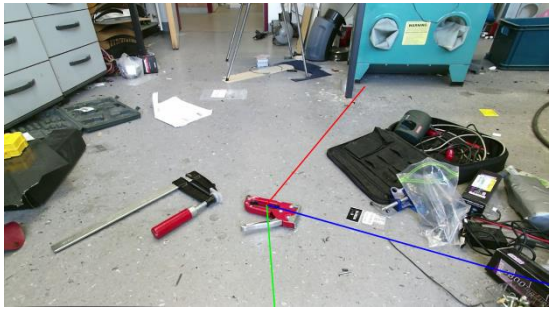
3D Object Modeling and 6D Pose Estimation

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







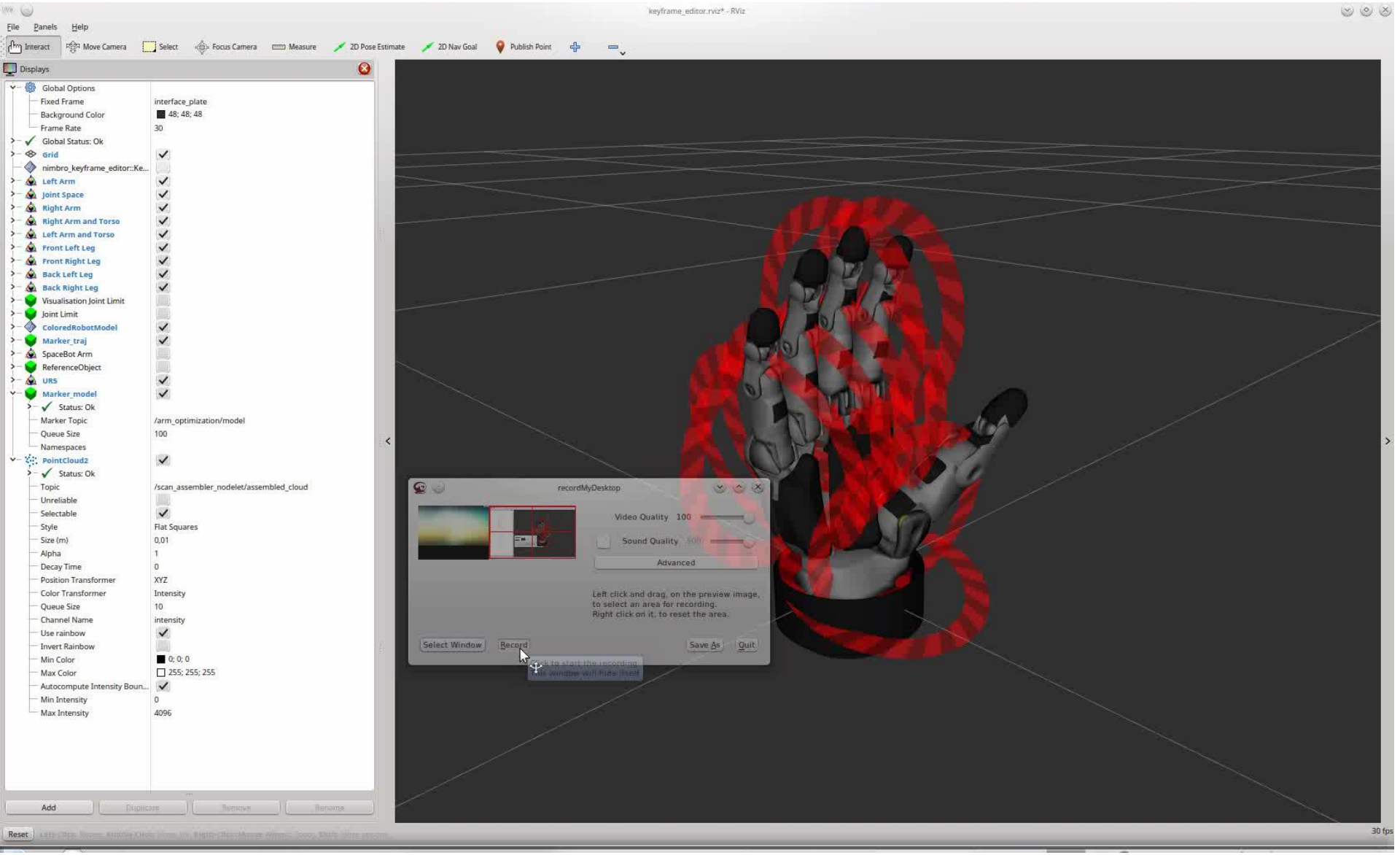


[Aldoma et al., ICRA 2013]

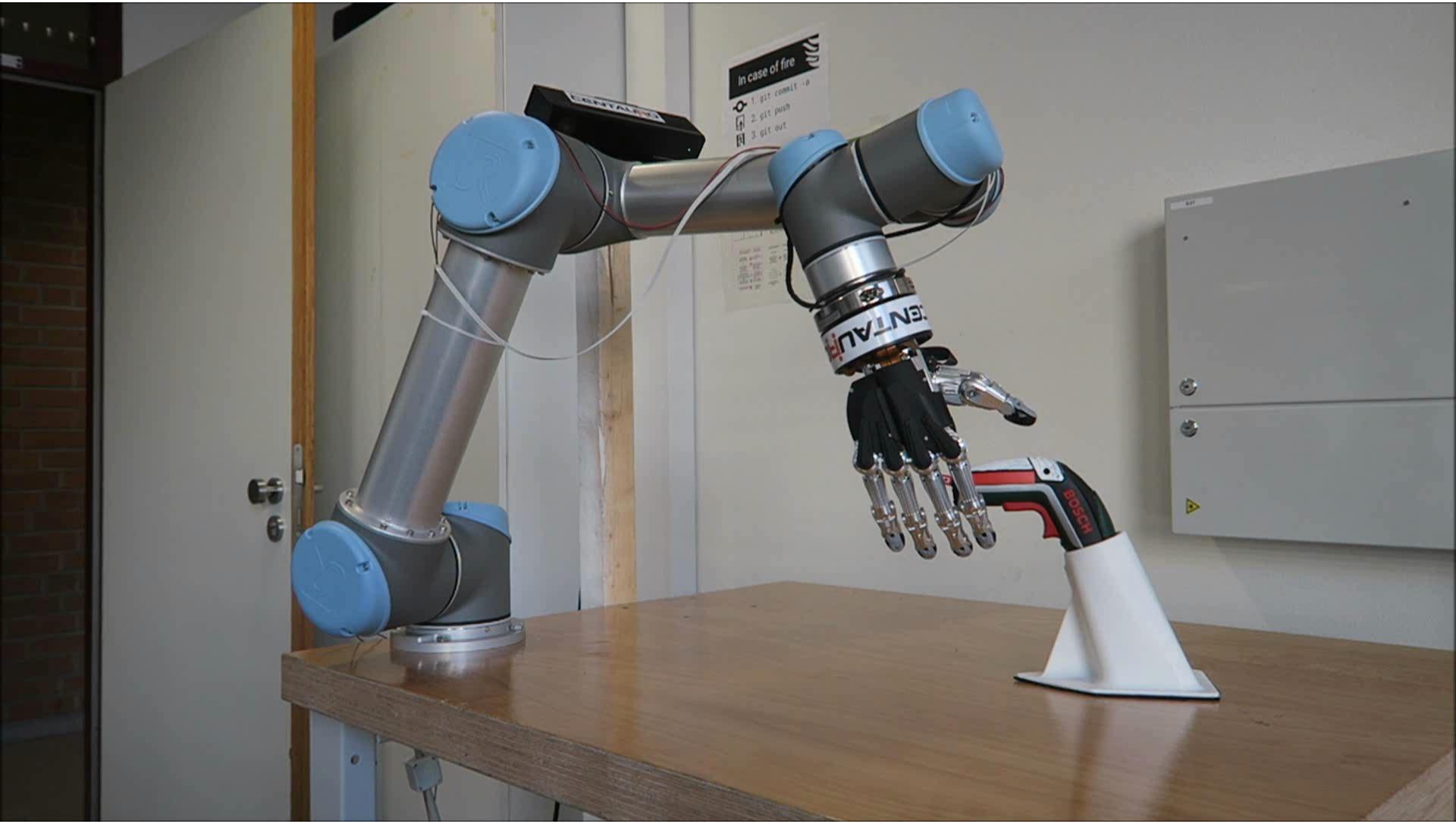
Schunk SVH

- Anthropo-morphic hand
- 9 DoF

Rviz Interface with Interactive Markers



Grasping the Drill



Transfer of Manipulation Skills

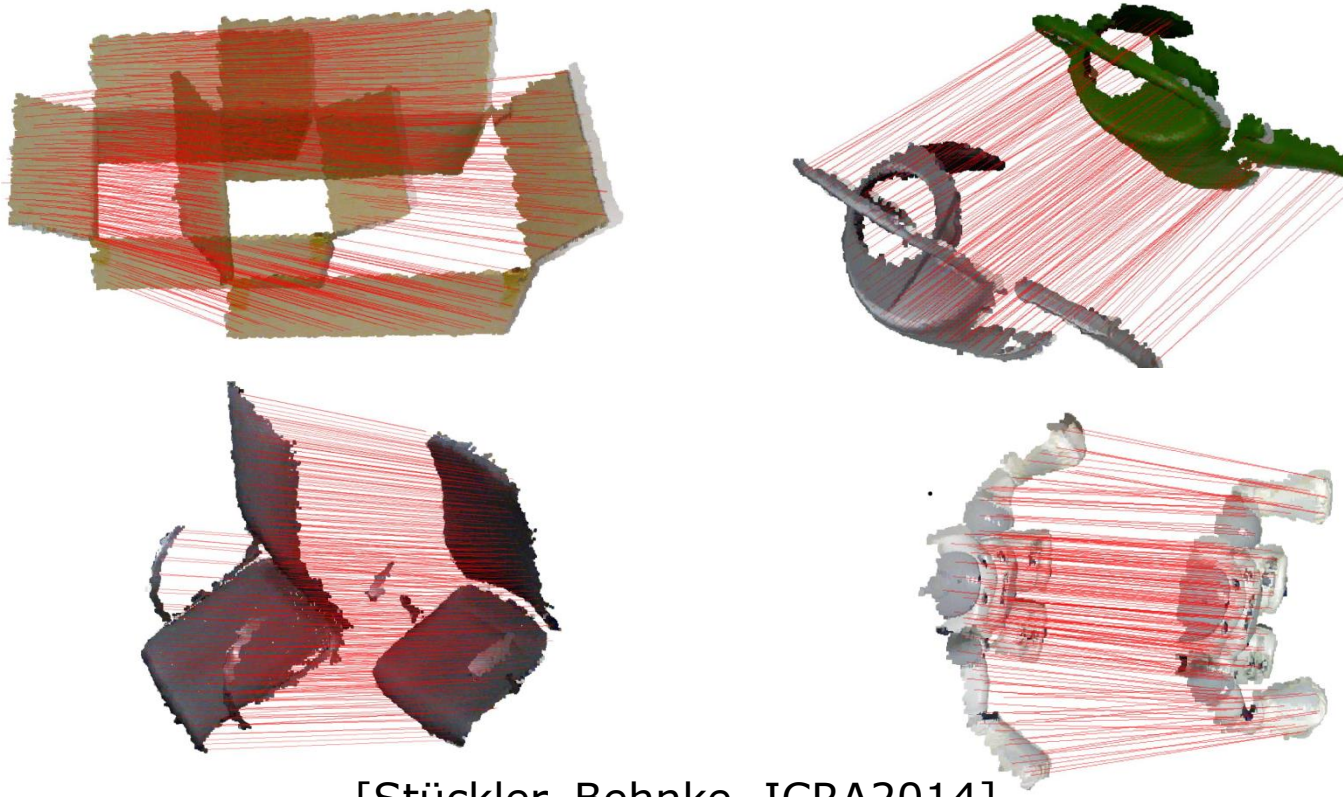
- Objects belonging to the same **category** can be manipulated in a similar manner

Transfer of Manipulation Skills

- **Knowledge Transfer**

Deformable RGB-D Registration

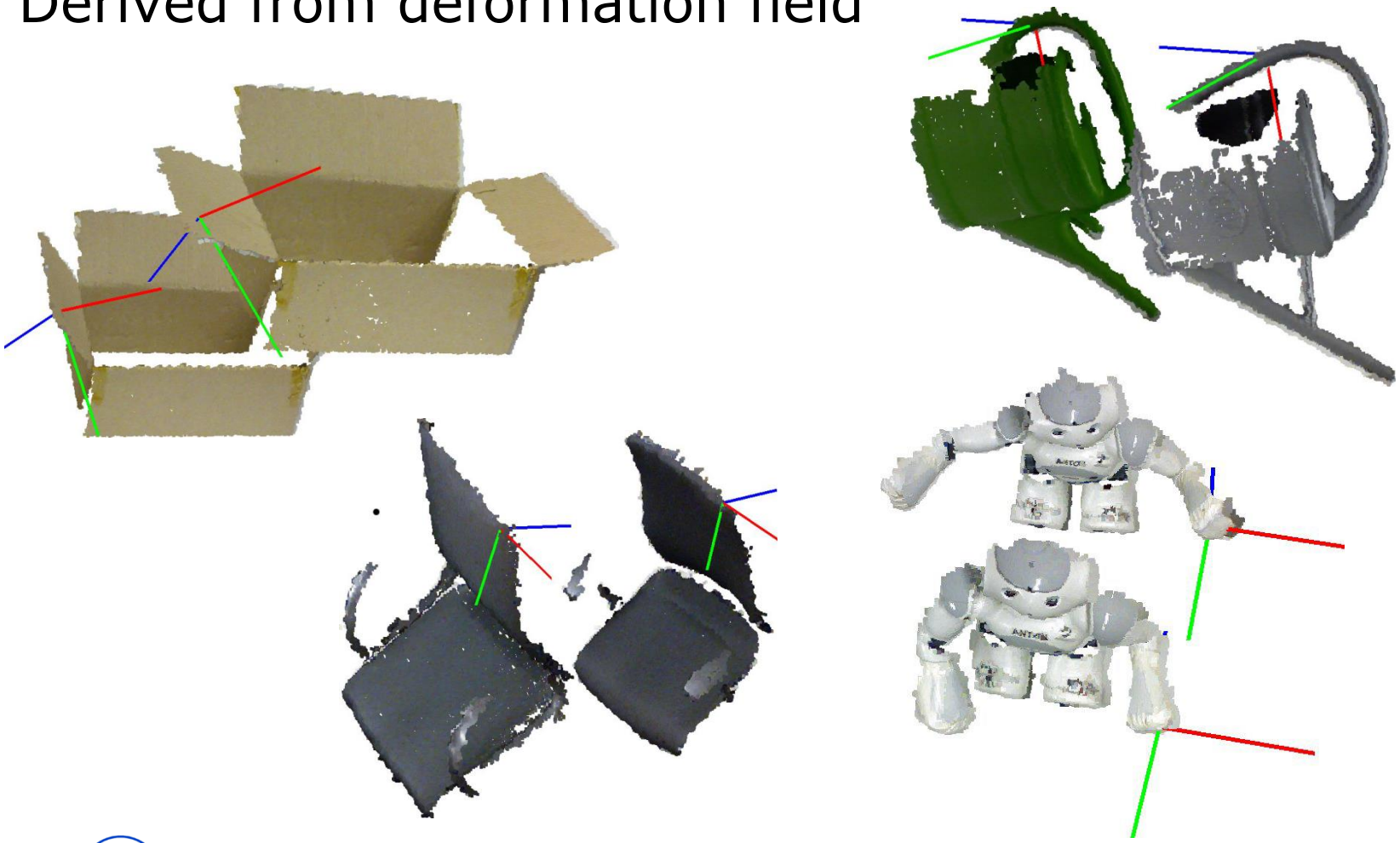
- Based on Coherent Point Drift method [Myronenko & Song, PAMI 2010]
- Multiresolution Surfel Map allows real-time registration



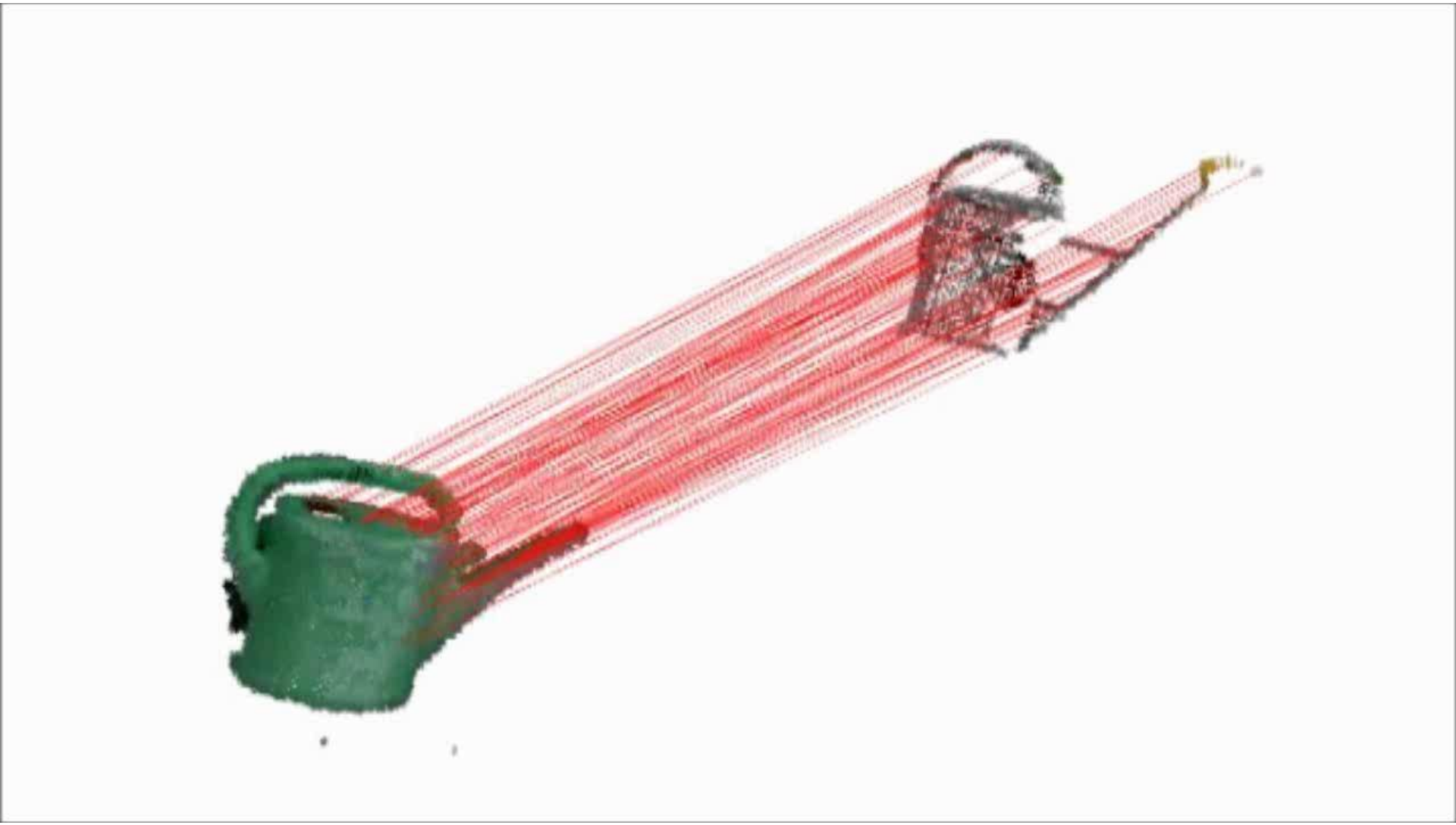
[Stückler, Behnke, ICRA2014]

Transformation of Poses on Object

- Derived from deformation field

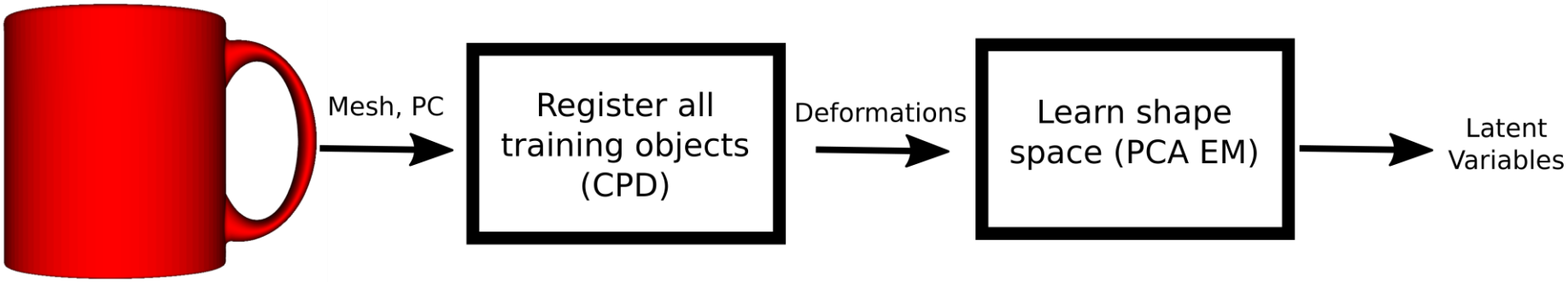


Grasp & Motion Skill Transfer

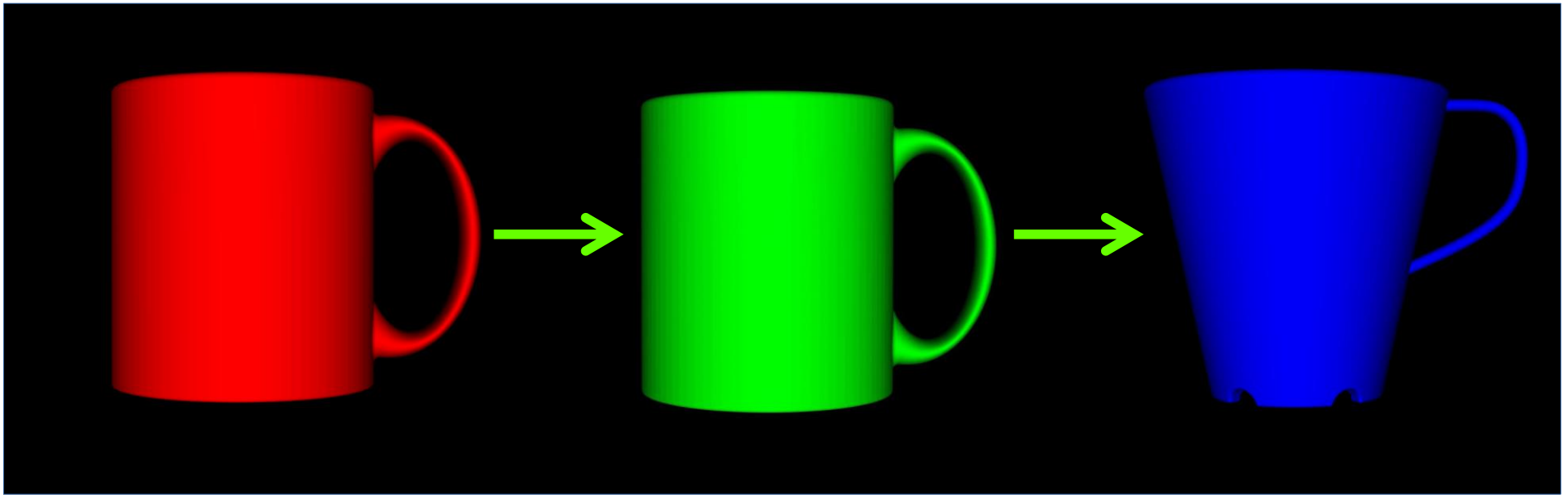


Transfer of Manipulation Skills

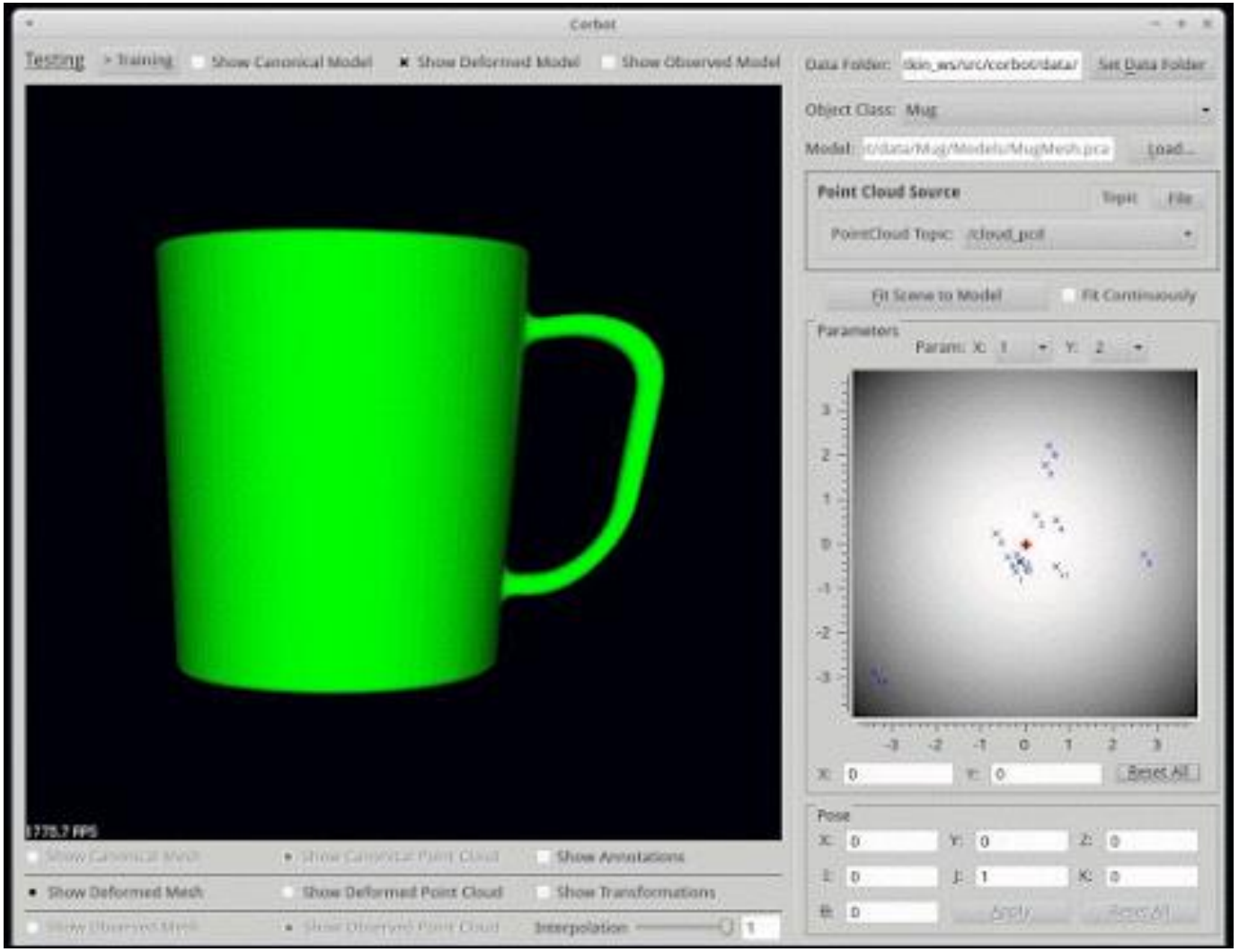
- Find shape variations of the objects within a class.
- Define the canonical model
  - Register all training objects (CPD)
  - Learn the shape space of the category using deformations and grasping data only of the canonical model (PCA EM)



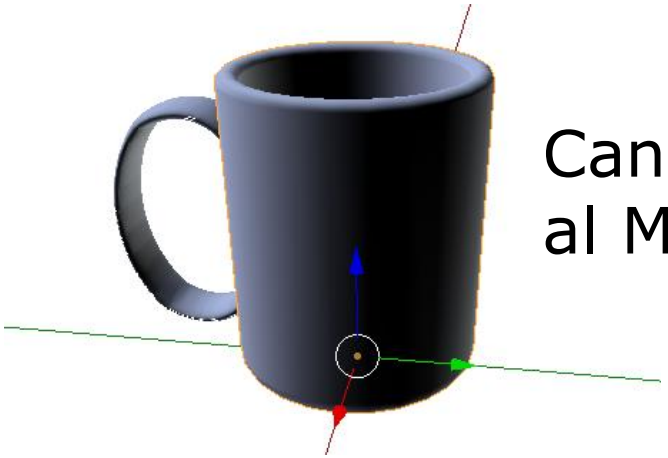
Deformations



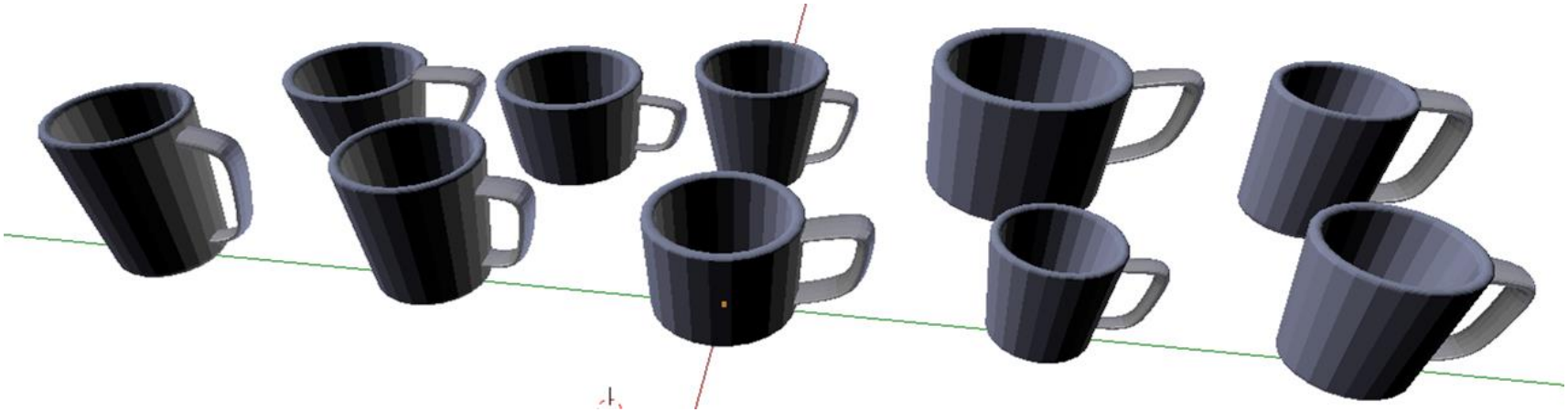
Interpolation in Shape Space



Generation of New Instances

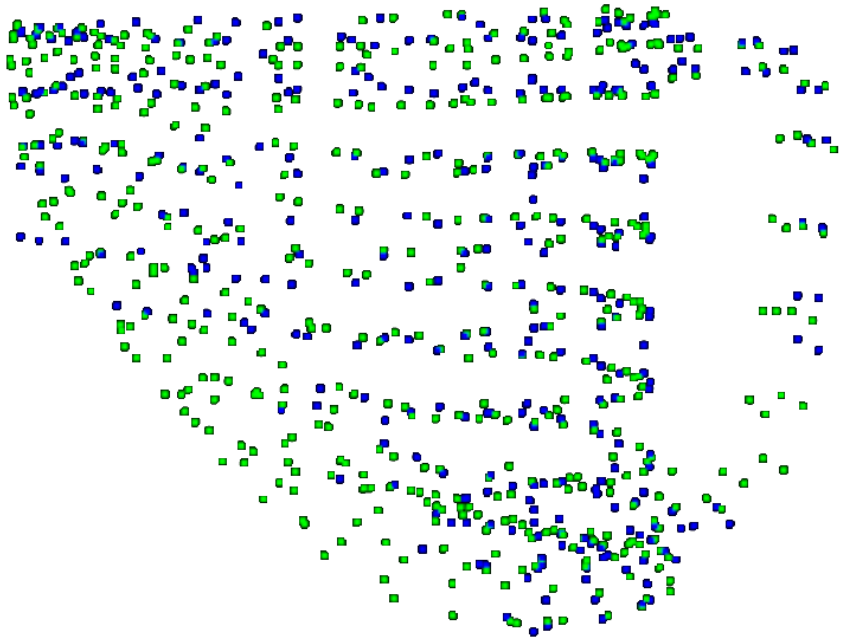


Canonic
al Model

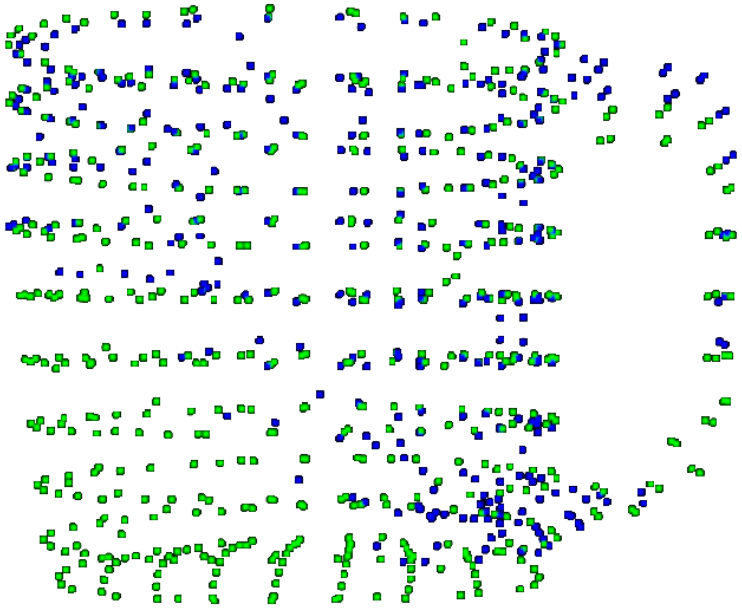


Object Inference

CPD



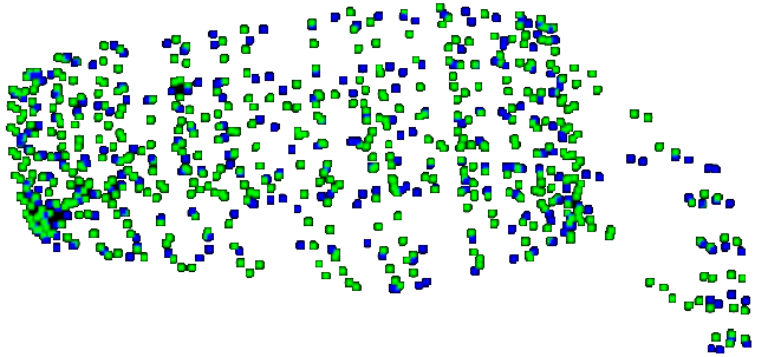
Our Approach



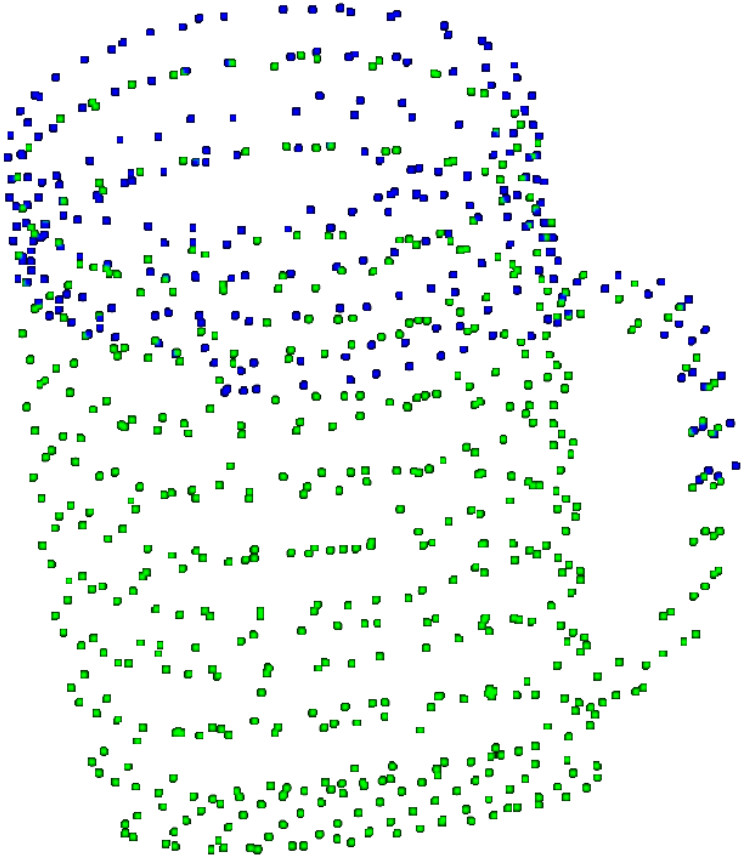
- Input Point Cloud
- Generated object

Object Inference

CPD

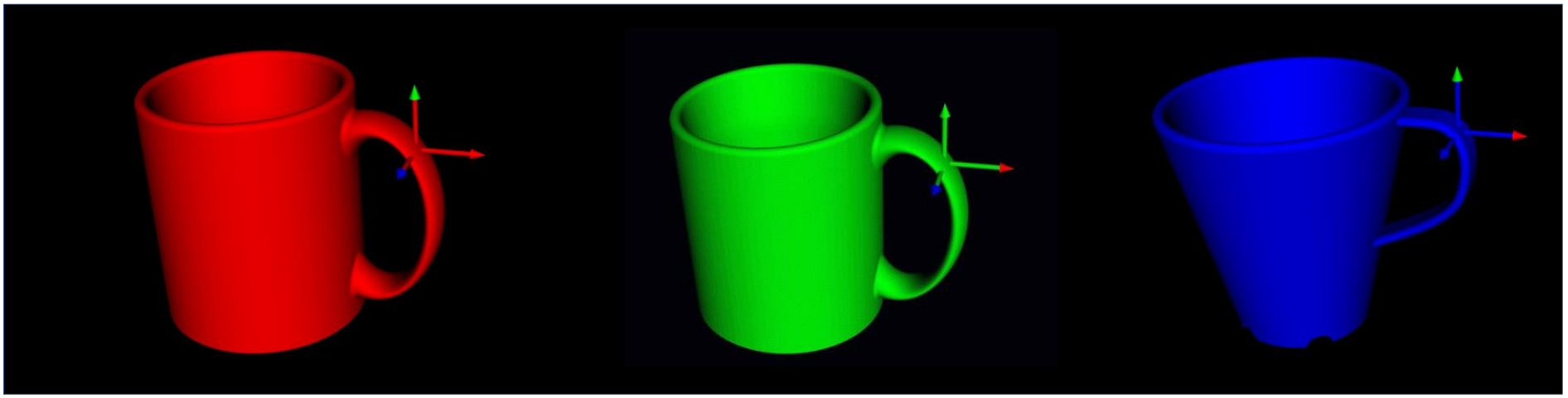


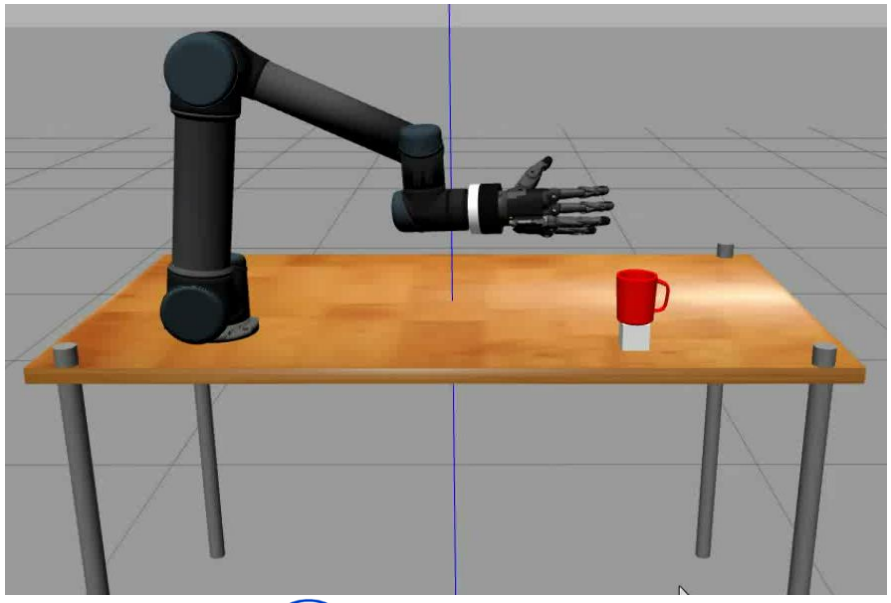
Our Approach

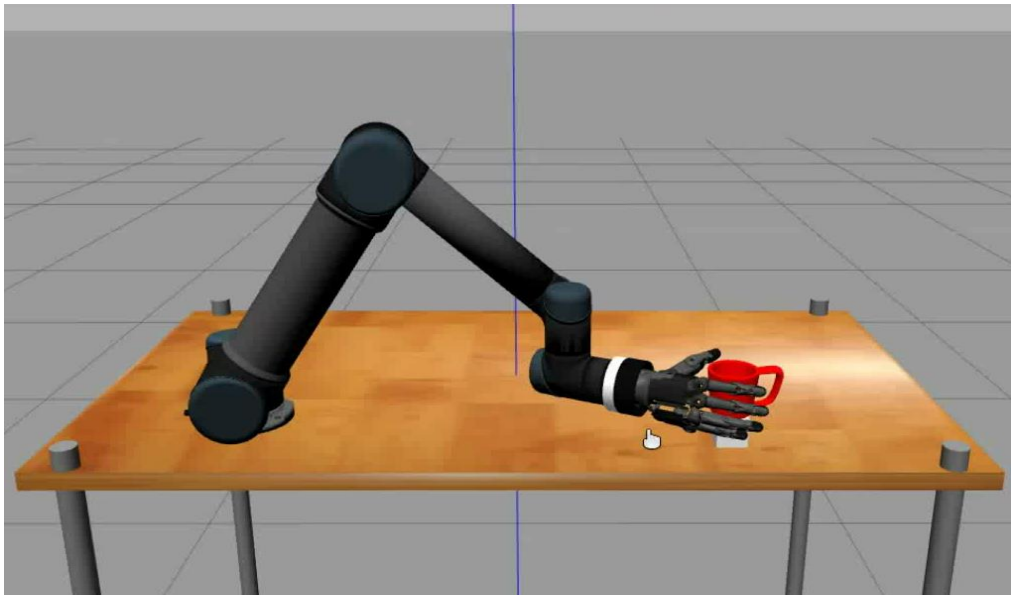


- Input Point Cloud
- Generated object

Grasping Information Transfer



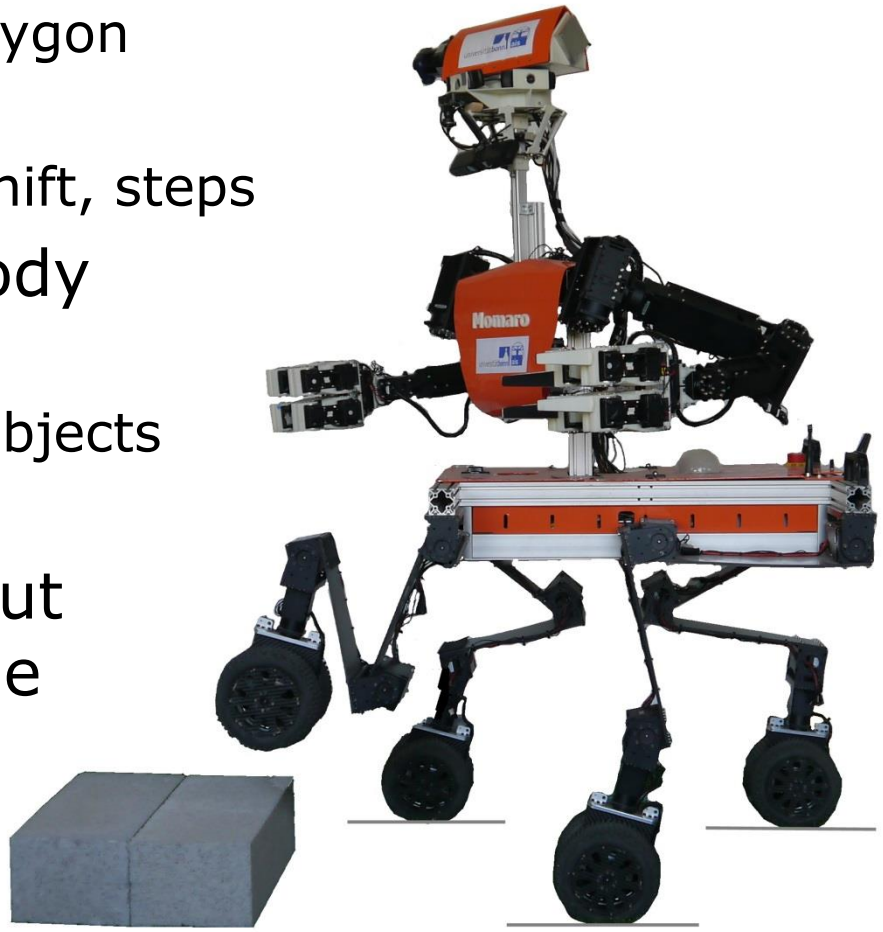




CENTAURO

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?