Perception and Planning for Humanoid Disaster-response Robots

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Autonomous Intelligent Systems

Some of our Cognitive Robots

- Equipped with numerous sensors and actuators
- Complex demonstration scenarios


Soccer

Domestic service

Mobile manipulation


Bin picking


Aerial inspection

Motivation

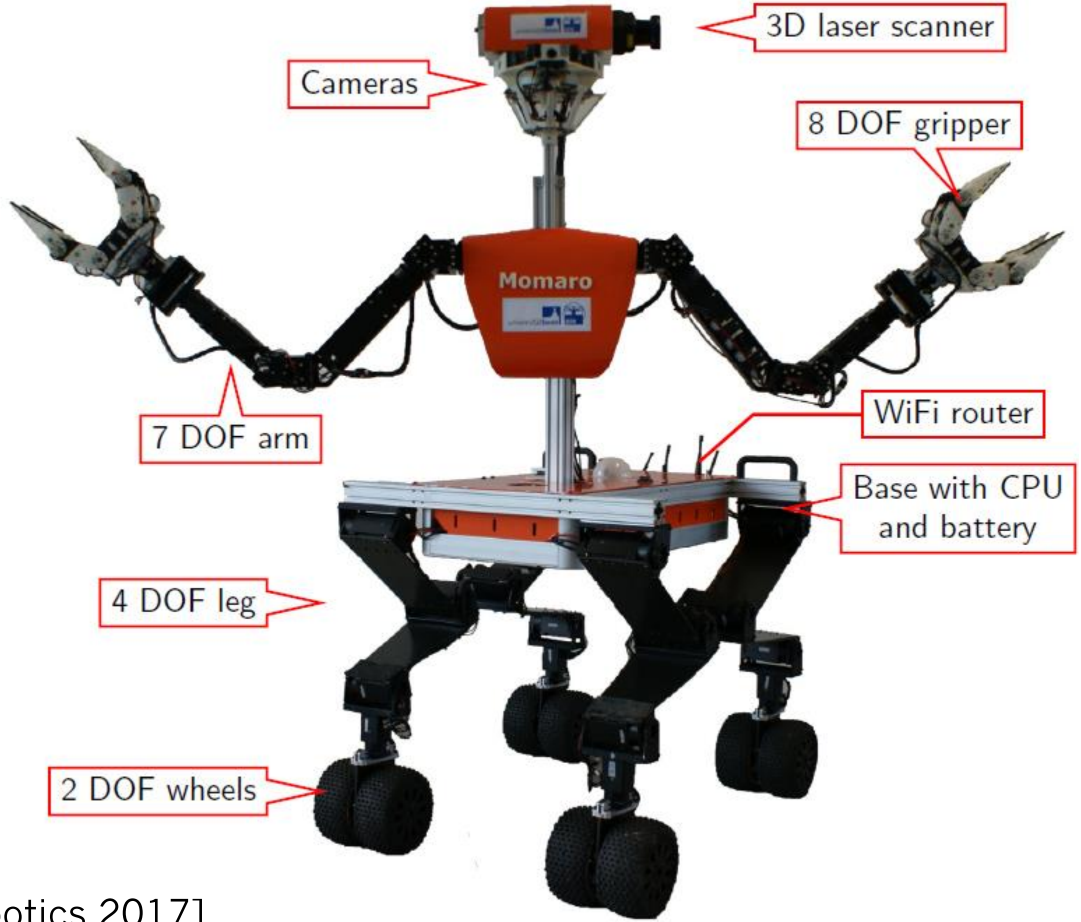
- Capabilities of disaster-response robots were insufficient for providing effective support to rescue workers.
  - Mobility: difficulties with uneven terrain, stairs, and debris
  - Manipulation: only a single actuator with simple end-effectors
  - User interface: requires extensive training, not intuitive, situation awareness problematic
- Complexity of achievable tasks and execution speed are low

Fukushima disaster 2011, Image: Digital Globe CC 3.0.

iRobot PackBot in Plant, Image: Tepco.

Mobile Manipulation Robot Momaro

- Four compliant legs ending in pairs of steerable wheels
- Anthropomorphic upper body
- Sensor head
  - 3D laser scanner
  - IMU, cameras



[Schwarz et al. Journal of Field Robotics 2017]

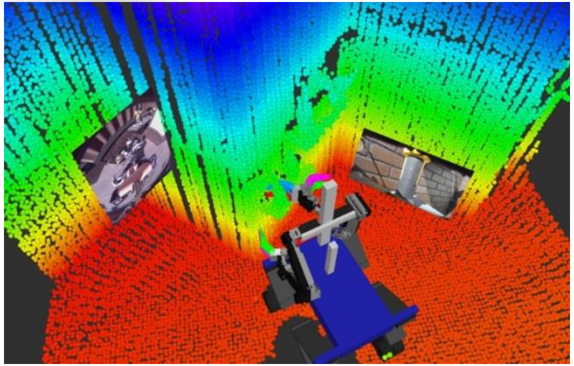

FAIRPLEX
FAIRPLEX
FAIRPLEX
POLARIS
23:15:03 05/06/2015 UTC
4x


CAUTION
POLARIS
23:16:59 05/06/2015 UTC
4x

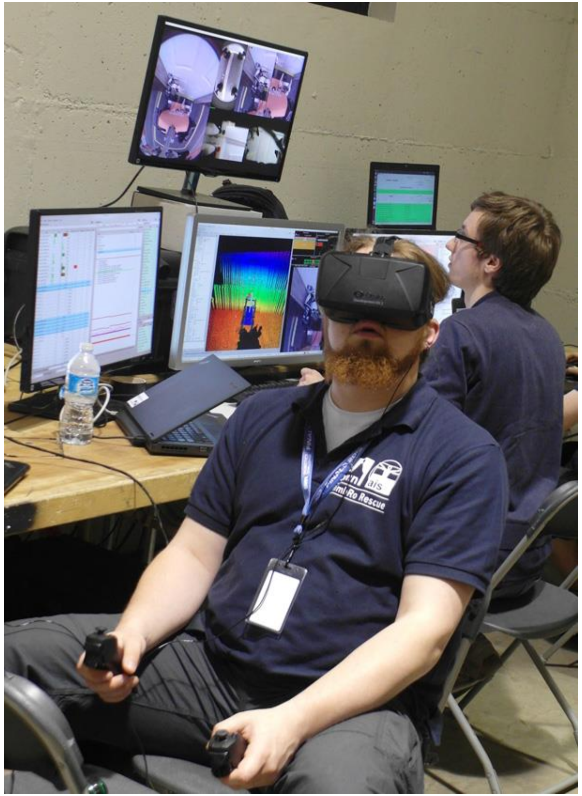
Manipulation Operator Interface

- 3D head-mounted display

- 3D environment model
  +
  images



- 6D magnetic tracker



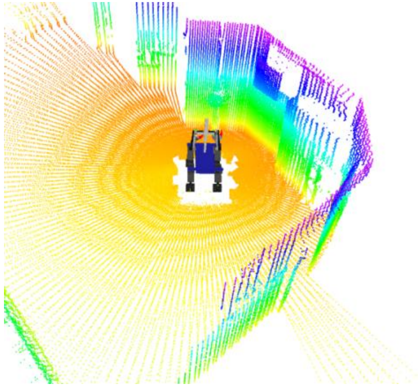
[Rodehutskors et al., Humanoids 2015]


FAIRPLEX
Momaro
23:20:32 05/06/2015 UTC
4x

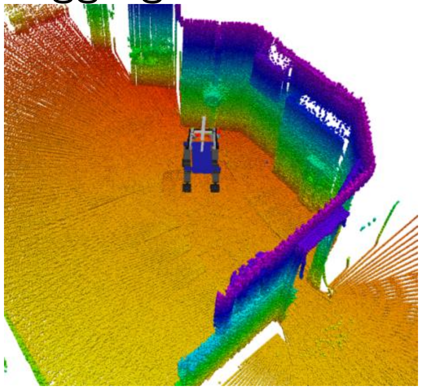
Local Multiresolution Surfel Map

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

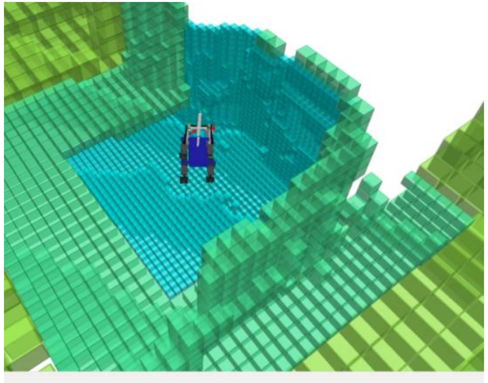
3D scan



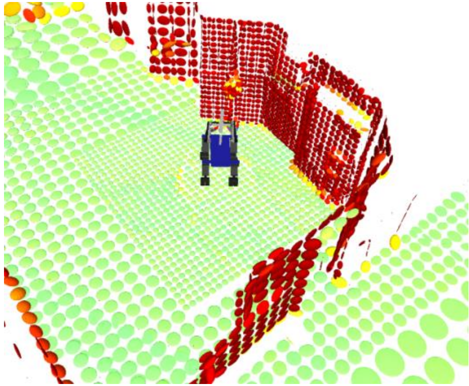
Aggregated scans



Multiresolution grid



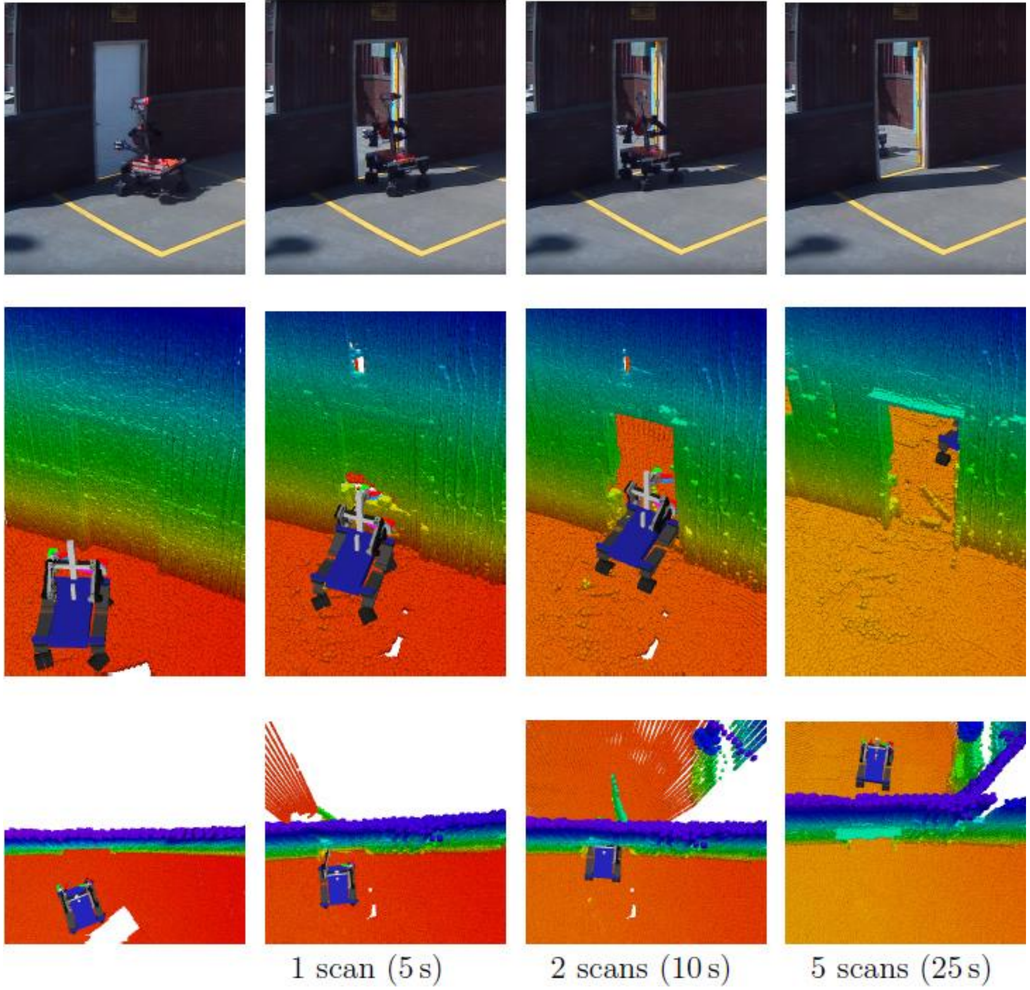
Surfels



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

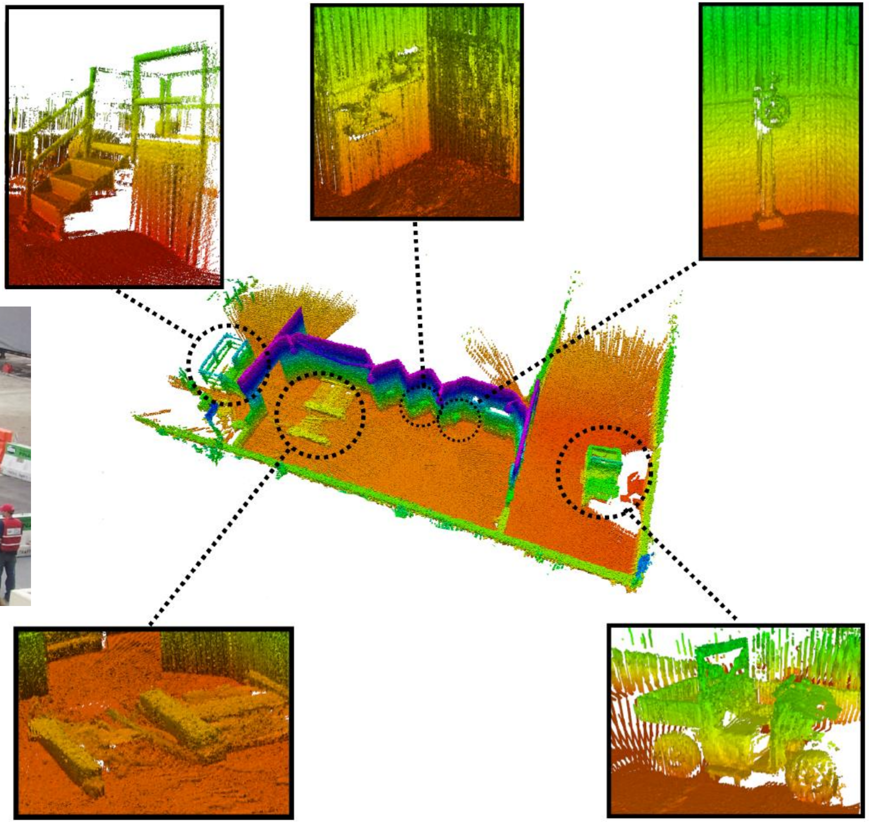
Filtering Dynamic Objects

- Maintain occupancy in each cell
- Remove measurements of empty cells



Allocentric 3D Mapping

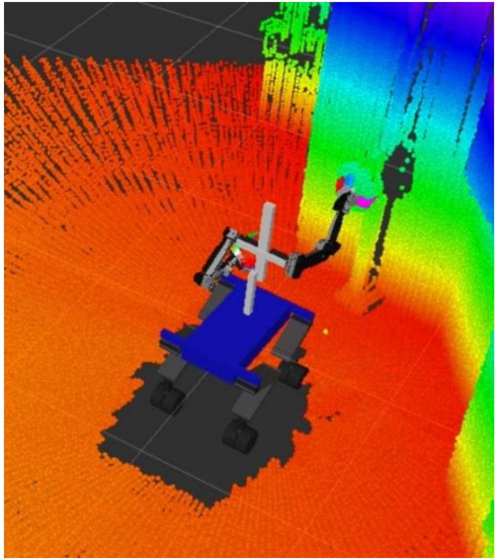
- Registration of egocentric maps by graph optimization



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

Valve Turning Interface

- Align wheel model with 3D points using interactive marker



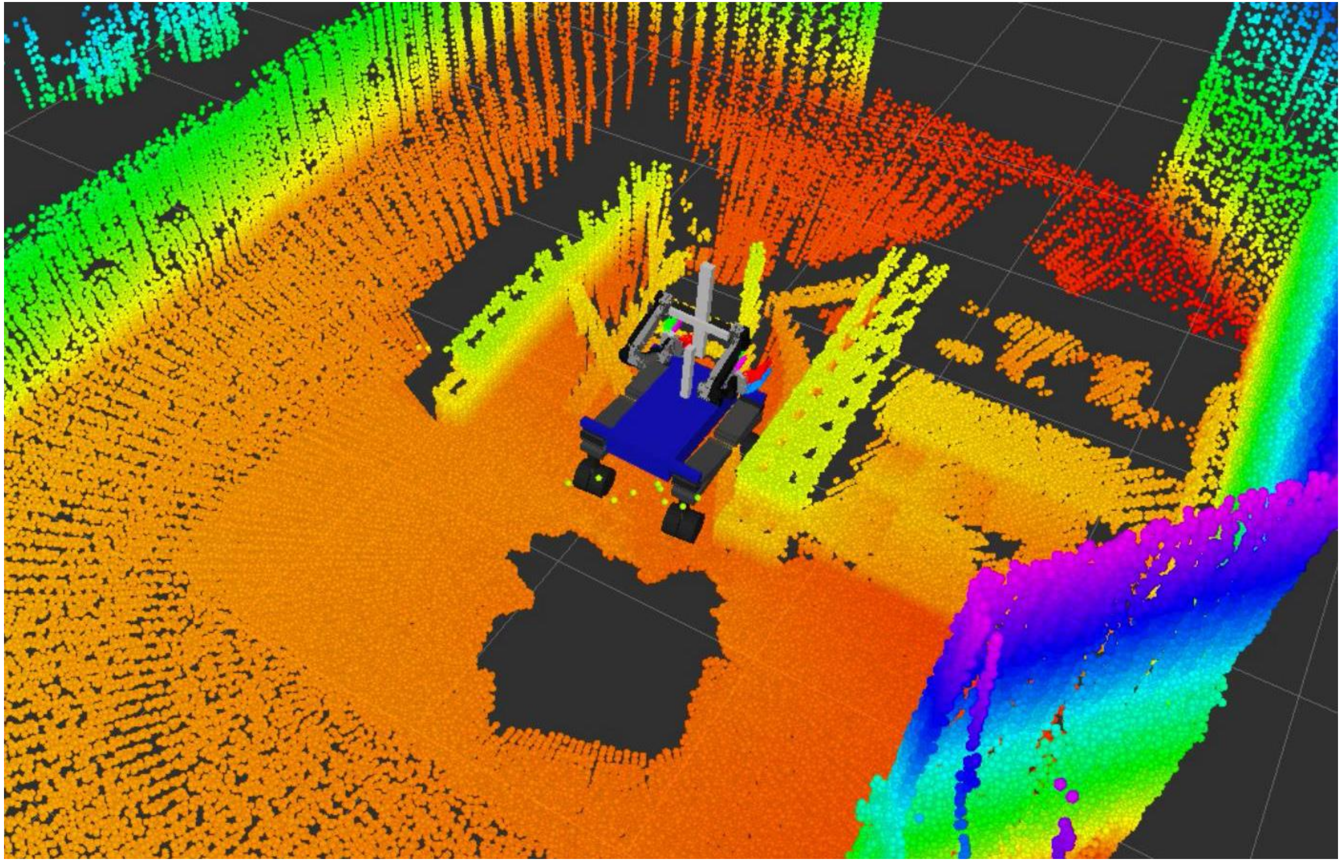
[Schwarz et al. Journal of Field Robotics 2017]

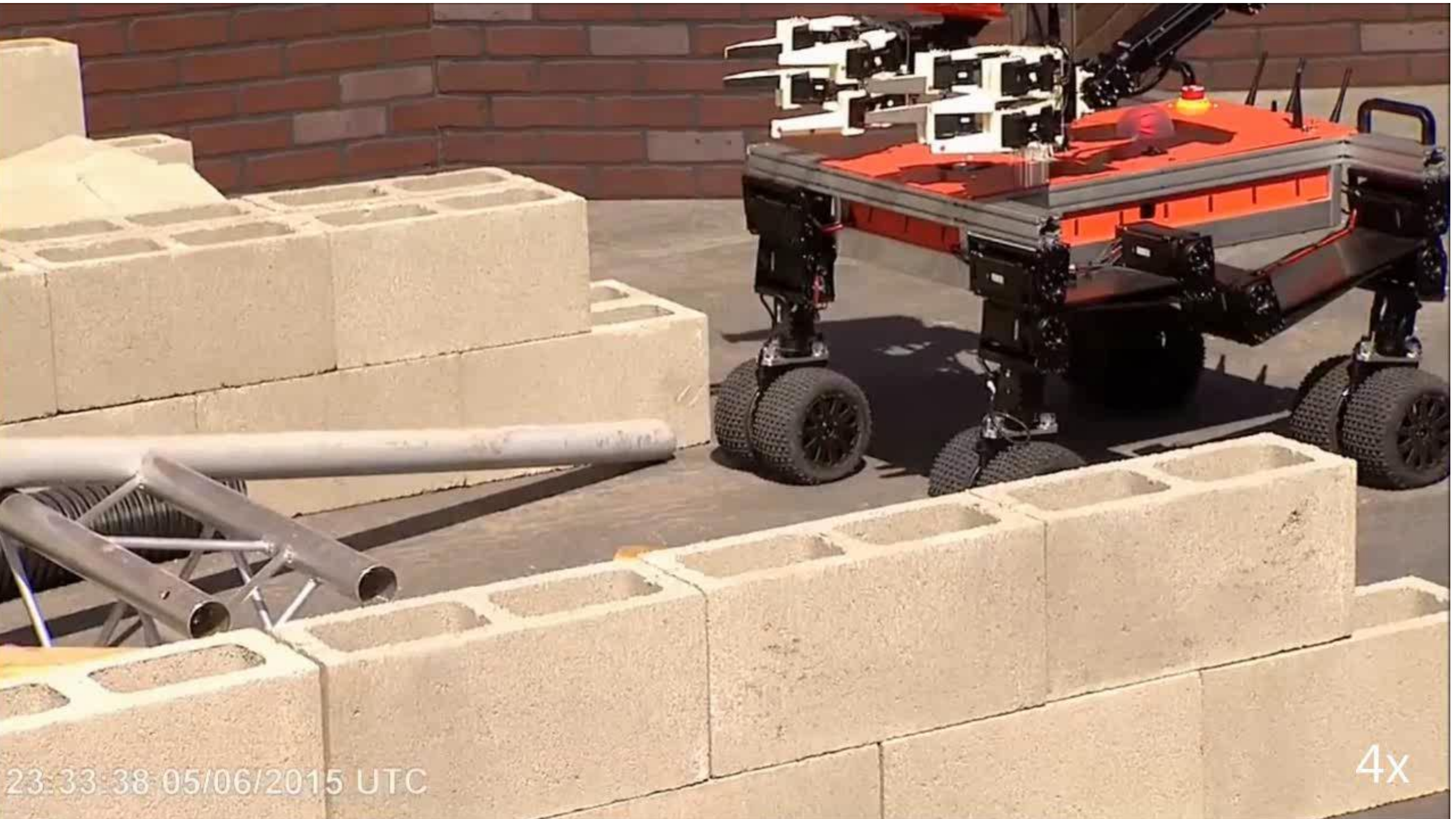

23:25:56 05/06/2015 UTC
4x


23:28:21 05/06/2015 UTC
4x


02:23:20 07/06/2015 UTC
4X

Debris Tasks




23:33:38 05/06/2015 UTC
4x

DARPA
CHALLENGE
2015
23:36:46 05/06/2015 UTC
4x

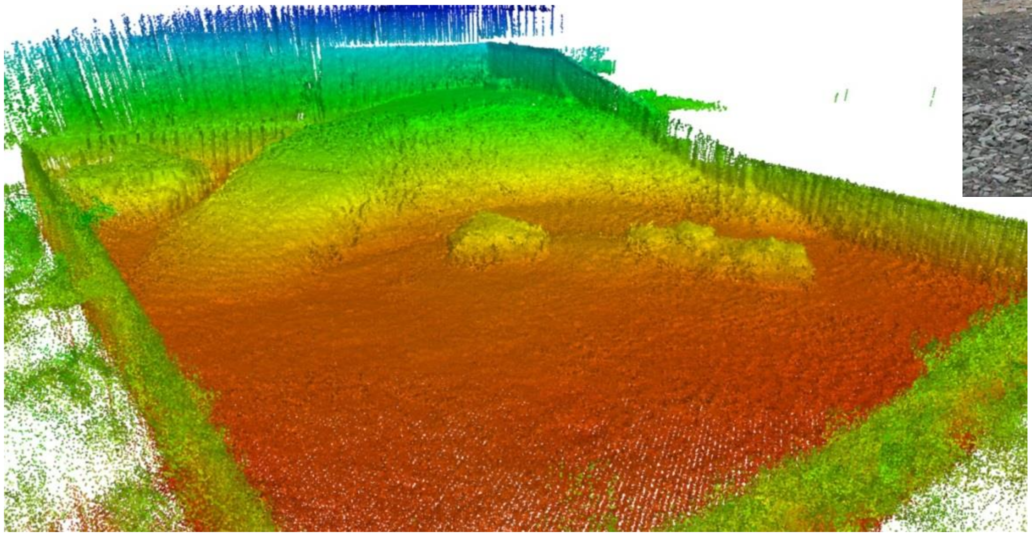
Team NimbRo Rescue

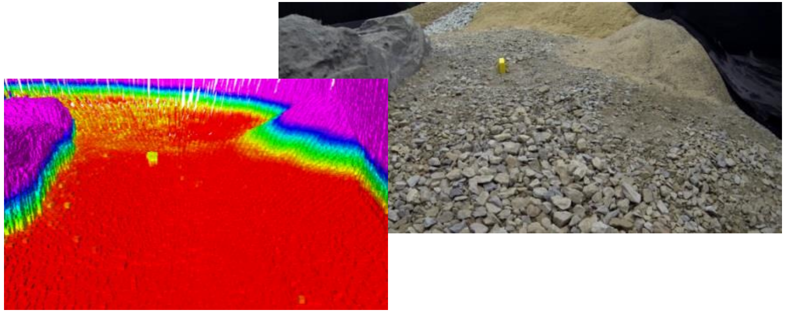
Best European Team (4th place overall), solved seven of eight tasks in 34 minutes

DLR SpaceBot Cup 2015

- Mobile manipulation in rough terrain

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

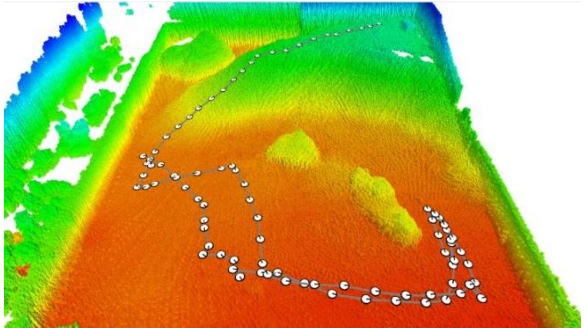




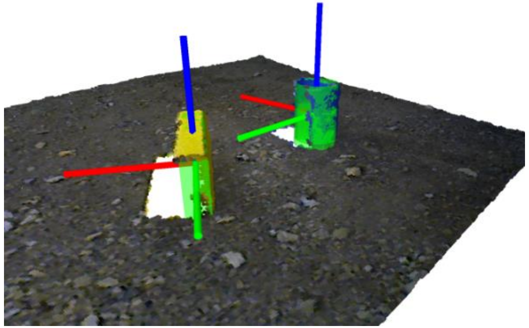

8X

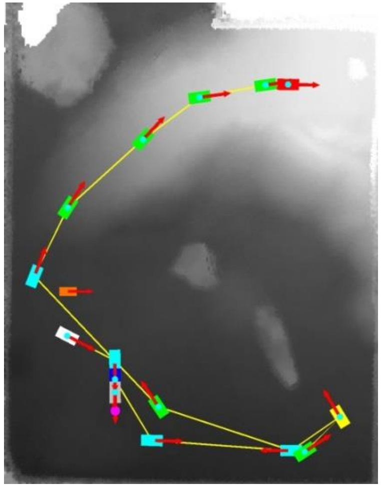
Autonomous Mission Execution

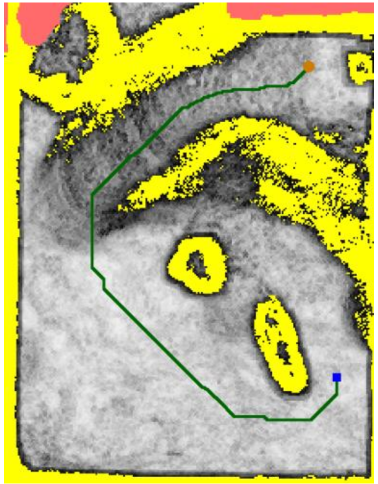
- 3D mapping, localization, mission and navigation planning

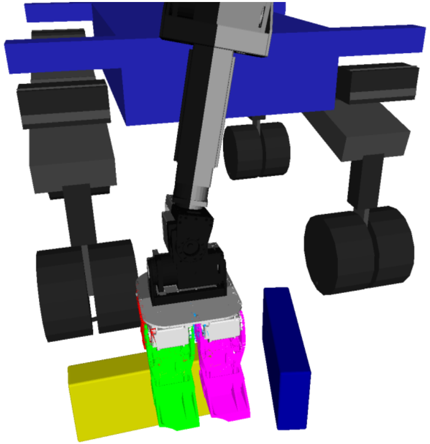


- 3D object perception and grasping









[Schwarz et al. Frontiers 2016]

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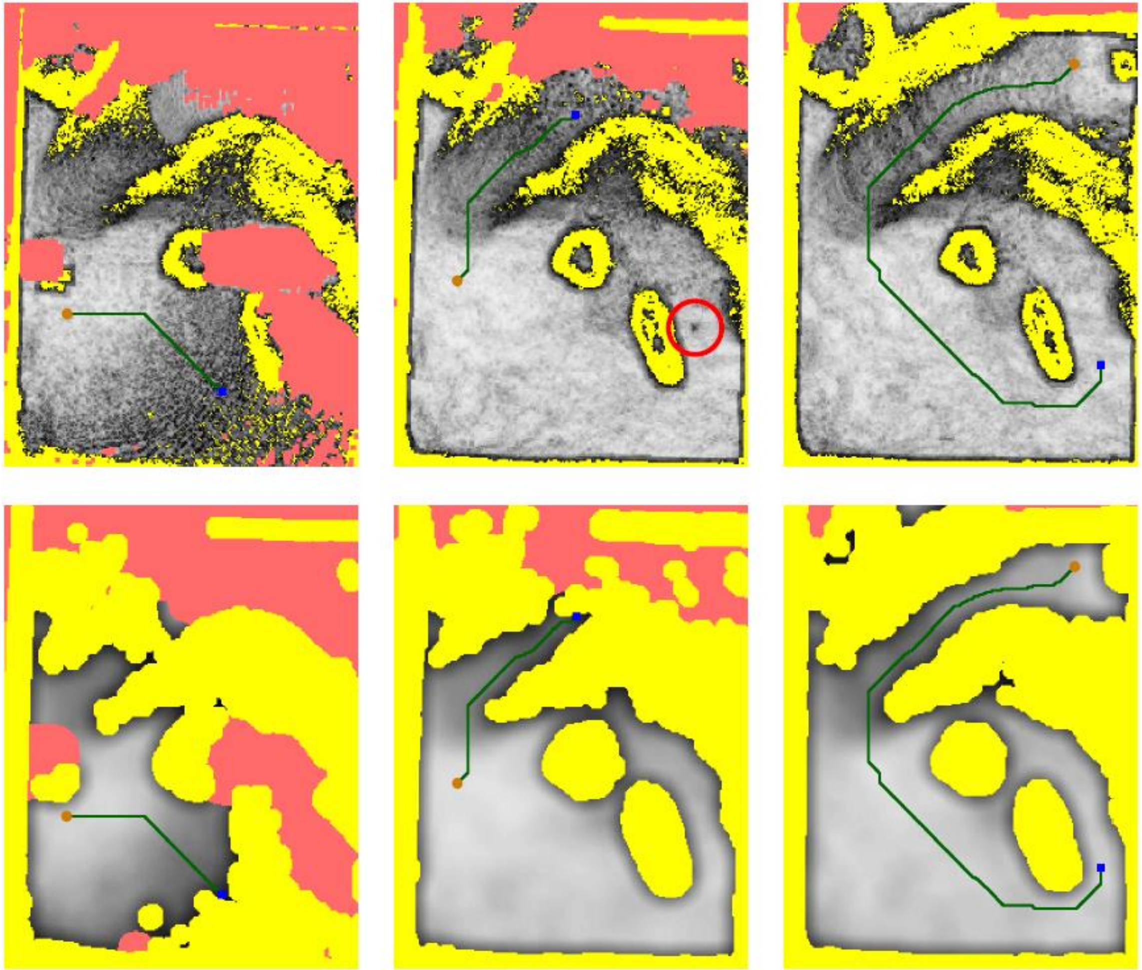
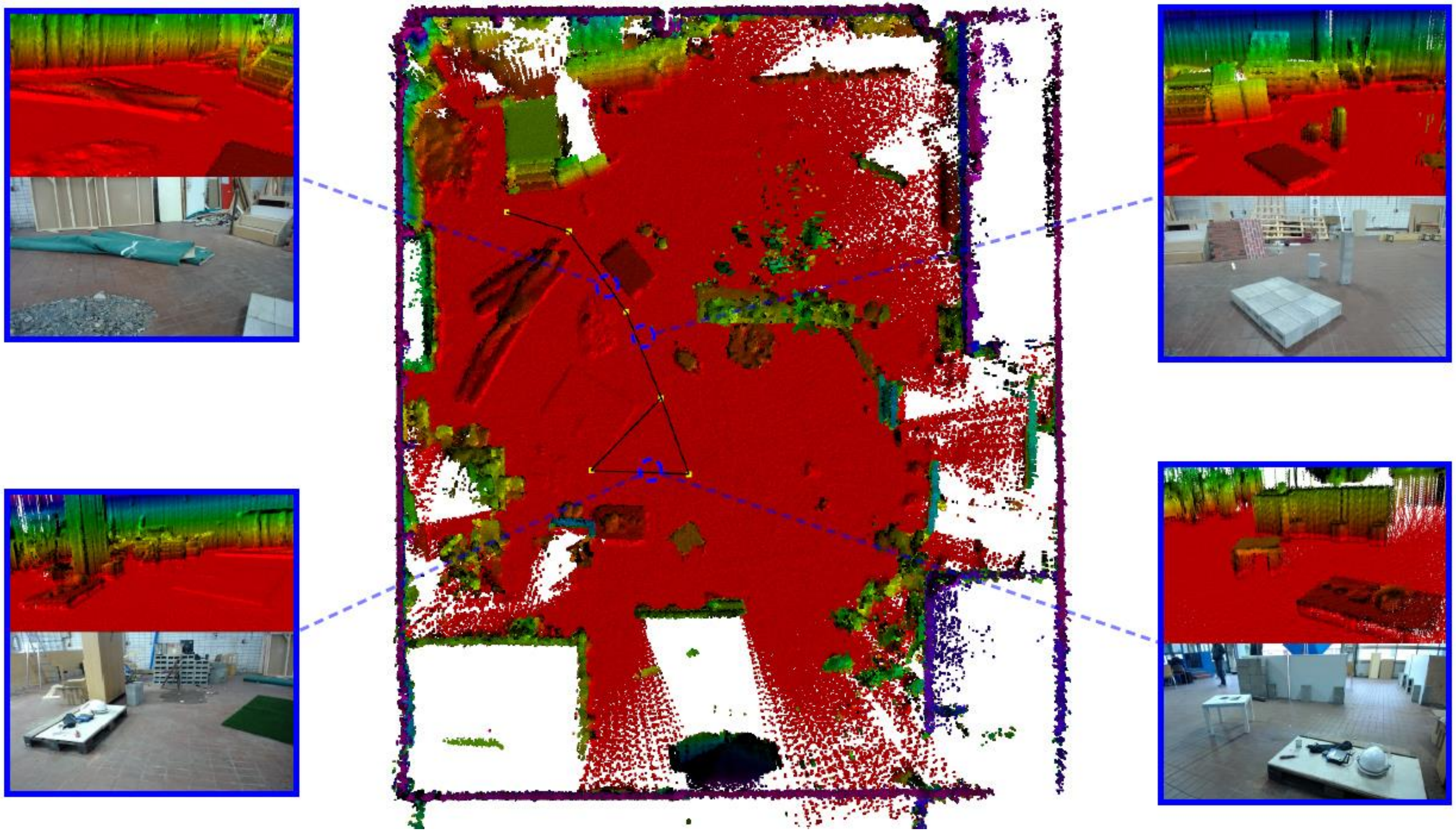
Navigation Planning

- Costs from local height differences
- A* path planning



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

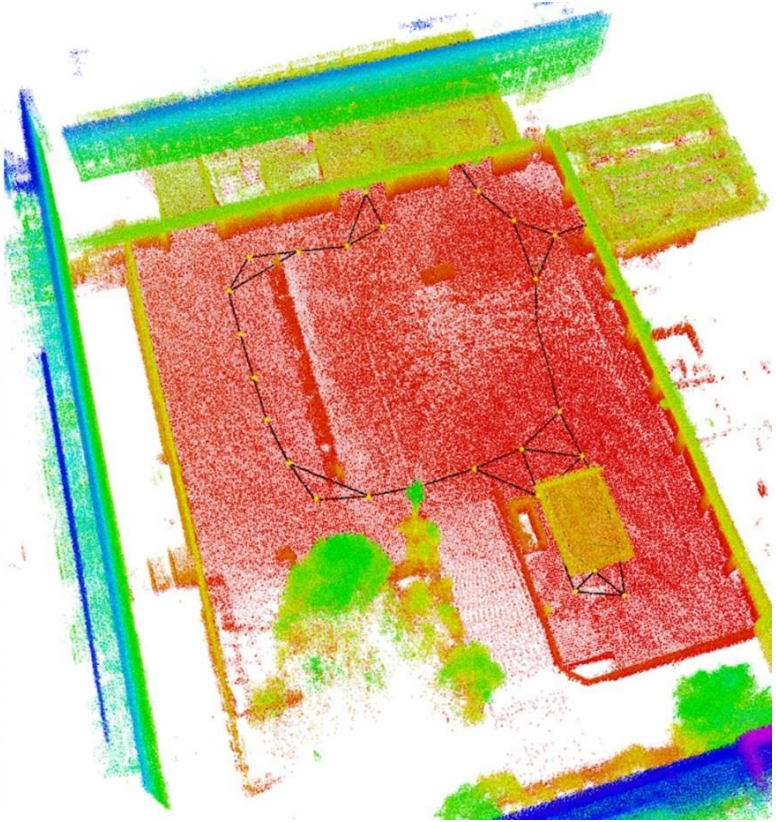
3D Map



Improved 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

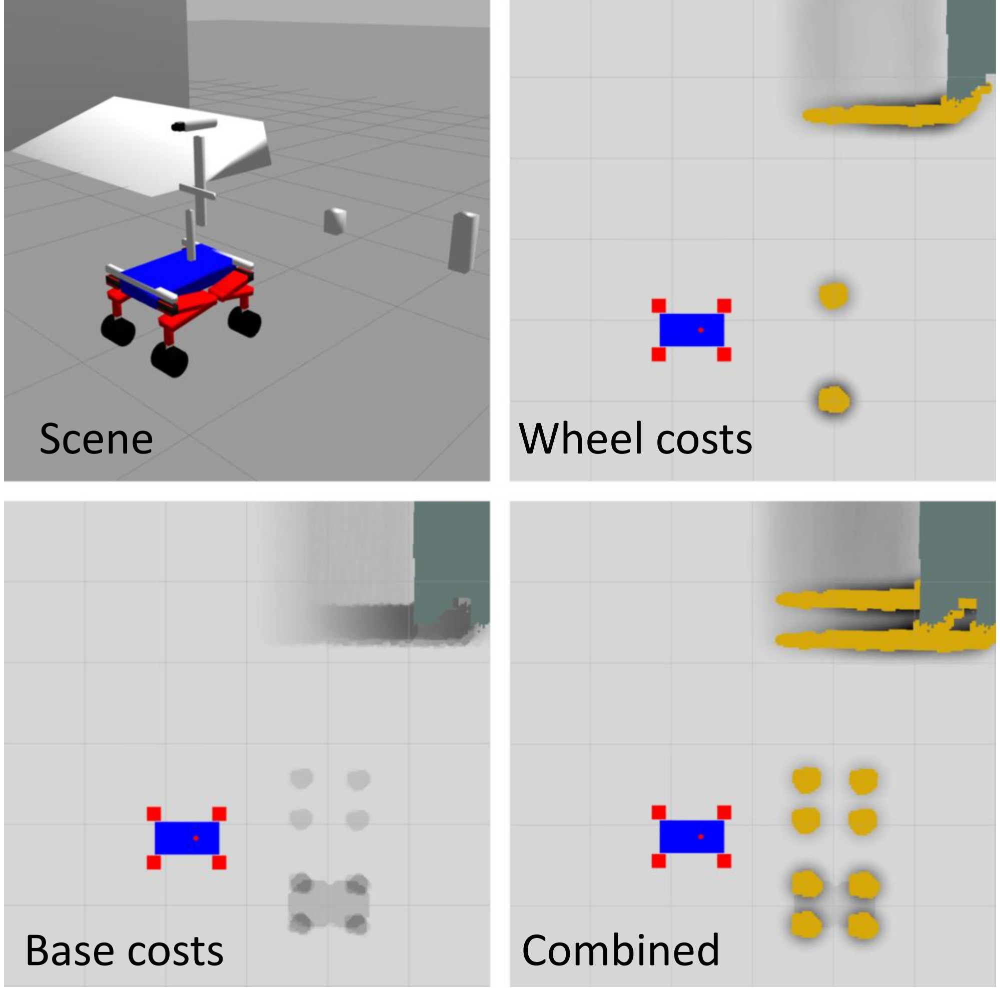
3D Map of Indoor+Outdoor Scene



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

Considering Robot Footprint

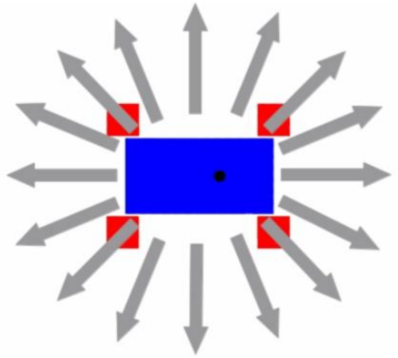
- Costs for individual wheel pairs from height differences
- Base costs
- Non-linear combination yields 3D (x, y, θ) cost map



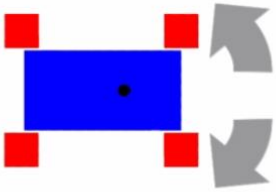
[Klamt and Behnke, IROS 2017]

3D Driving Planning (x, y, θ): A*

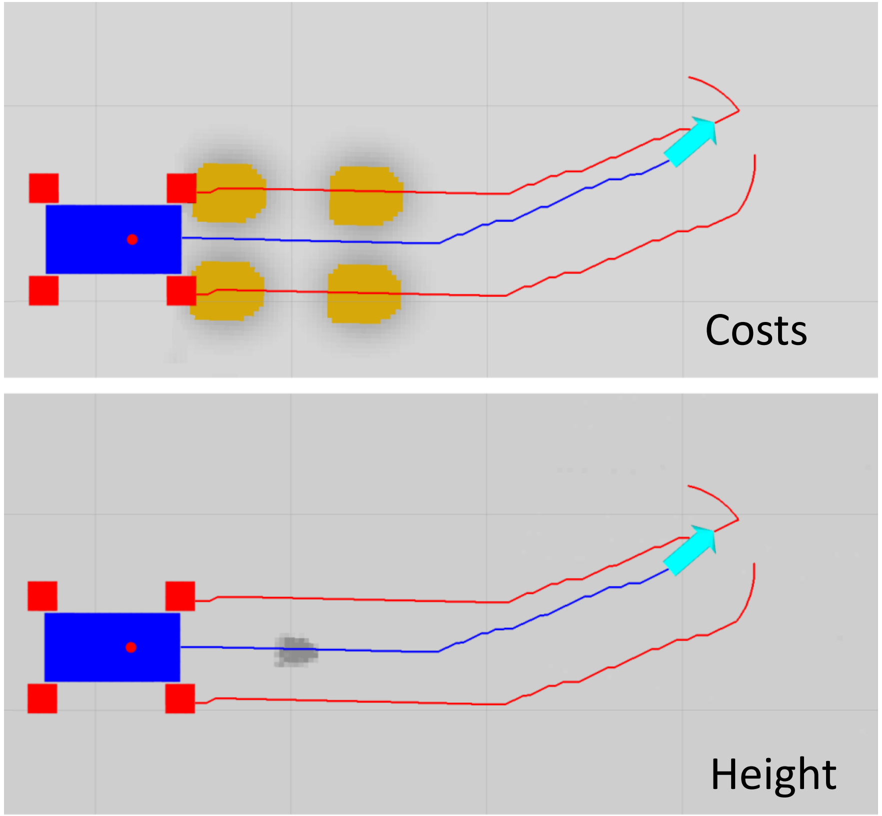
- 16 driving directions



- Orientation changes



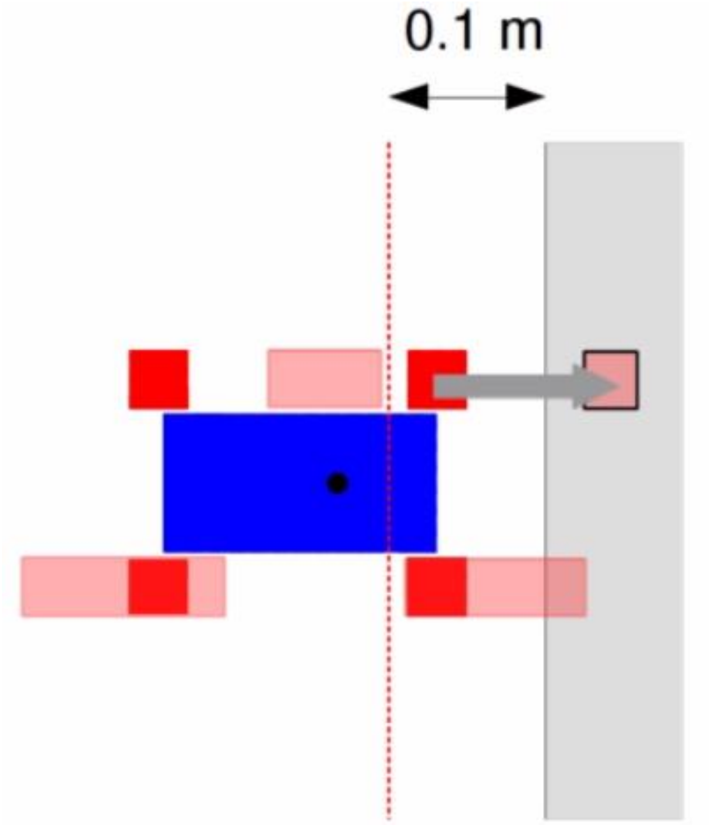
=> Obstacle between wheels



[Klamt and Behnke, IROS 2017]

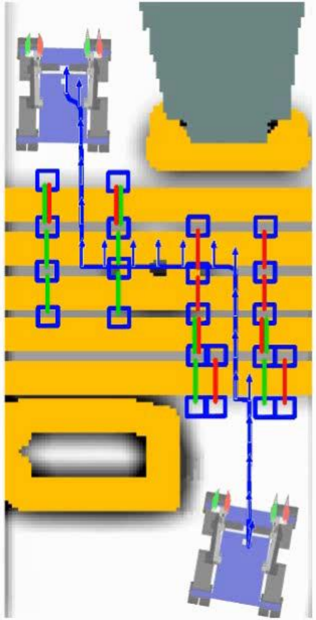
Making Steps

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



[Klamt and Behnke: IROS 2017]

Planning for Challenging Scenarios



[Klamt and Behnke: IROS 2017]

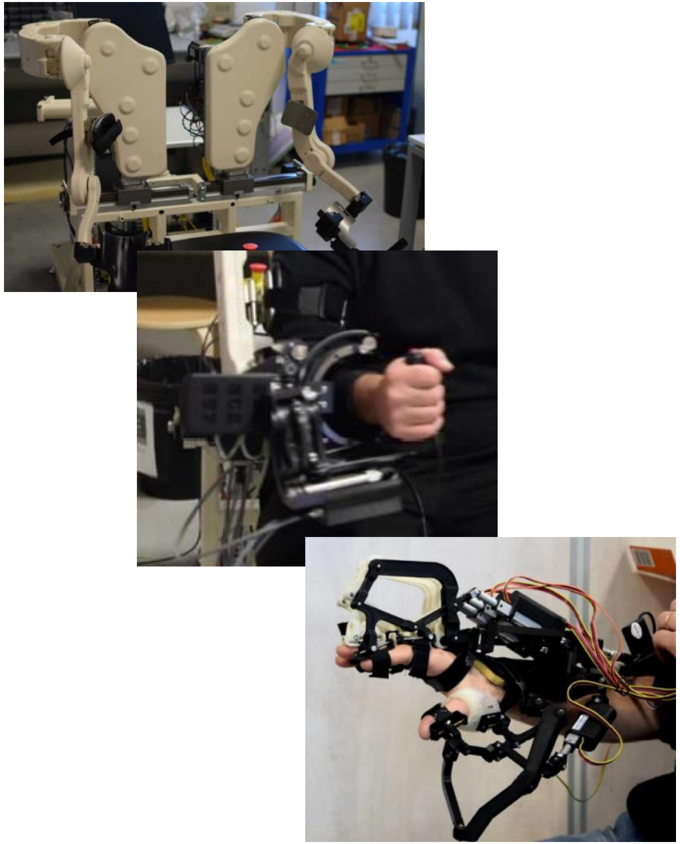
Centauro Robot

- Serial elastic actuators
- 42 main DoFs
- Schunk hand
- 3D laser
- RGB-D camera
- Color cameras
- Two GPU PCs

[Tsagarakis et al., IIT 2017]

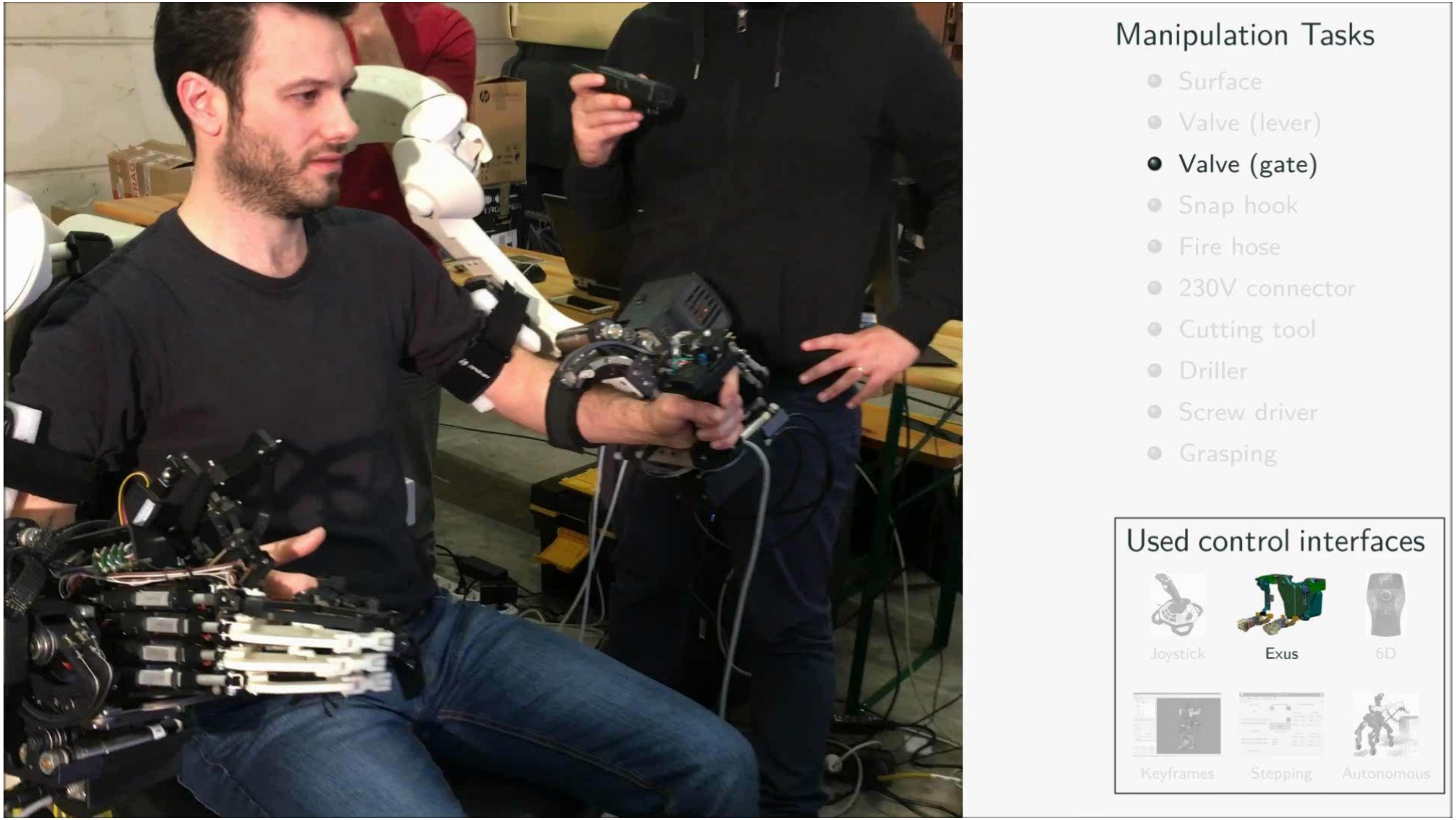
Main Operator Telepresence Interface

- Tendon-driven dual-arm exoskeleton
- Active wrist with differential tendon transmission
- Underactuated hand exoskeleton
- Head-mounted display
- Foot pedals

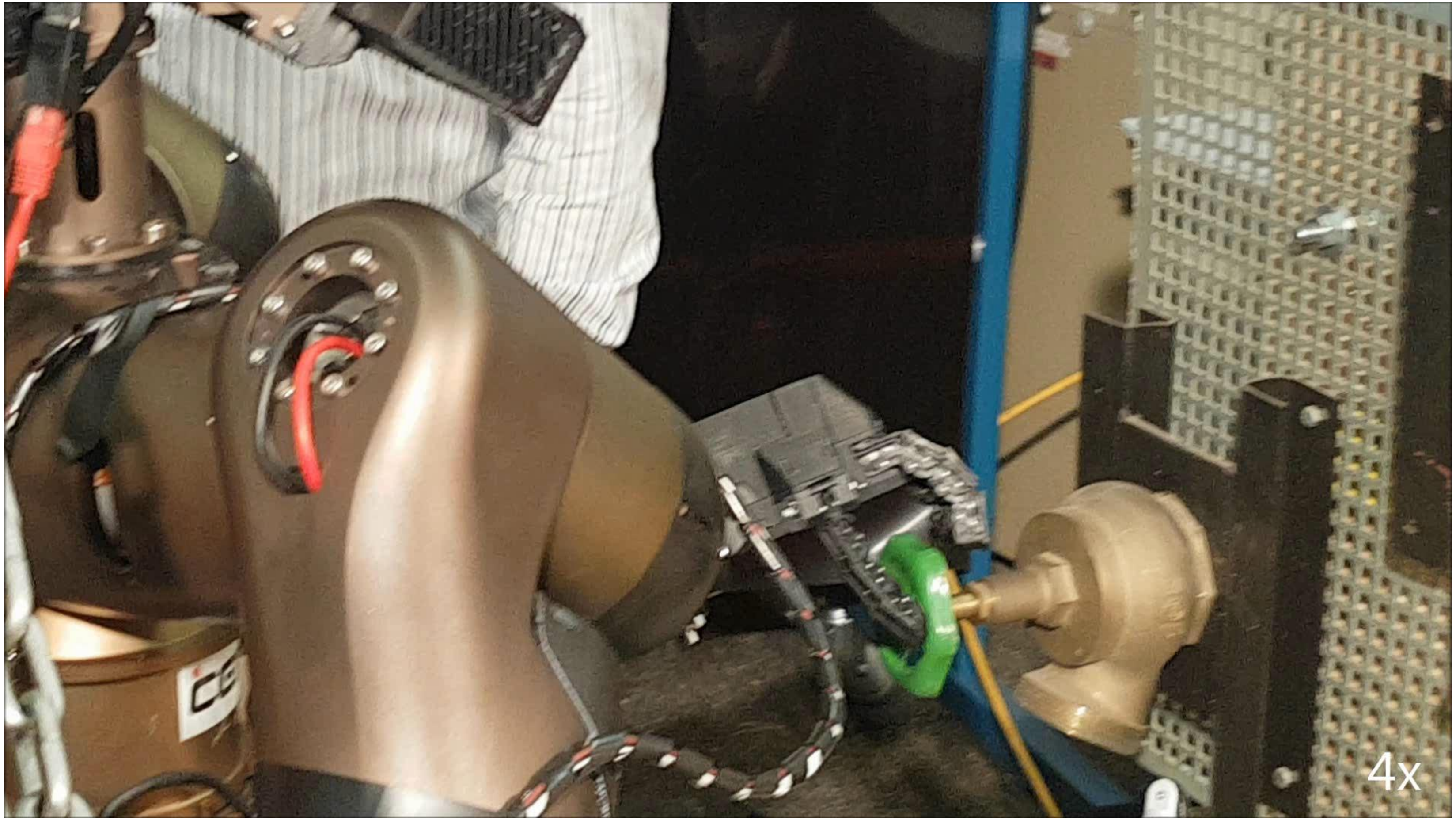


[Frisoli et al., SSSA 2017]

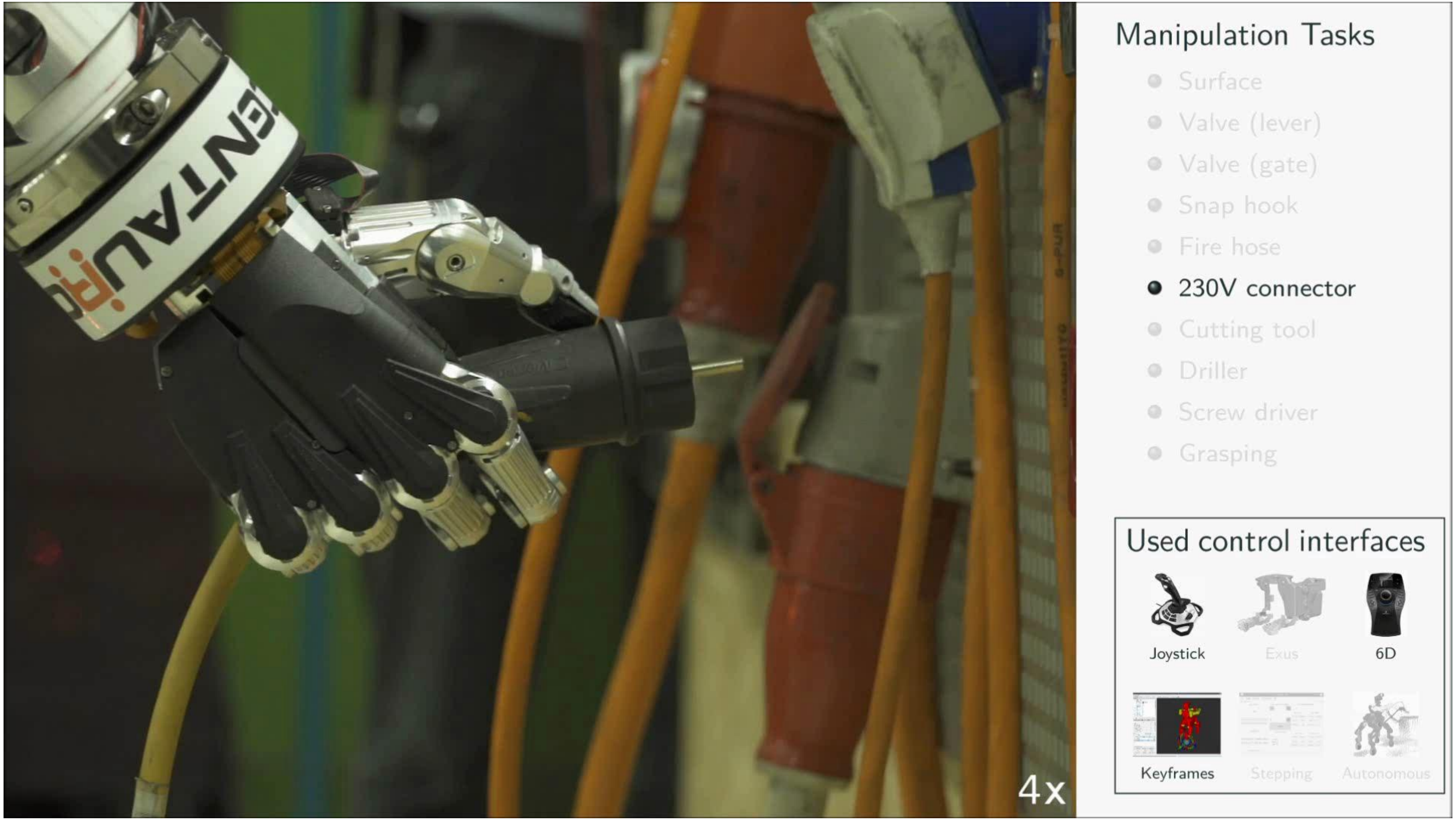
Main Operator Control



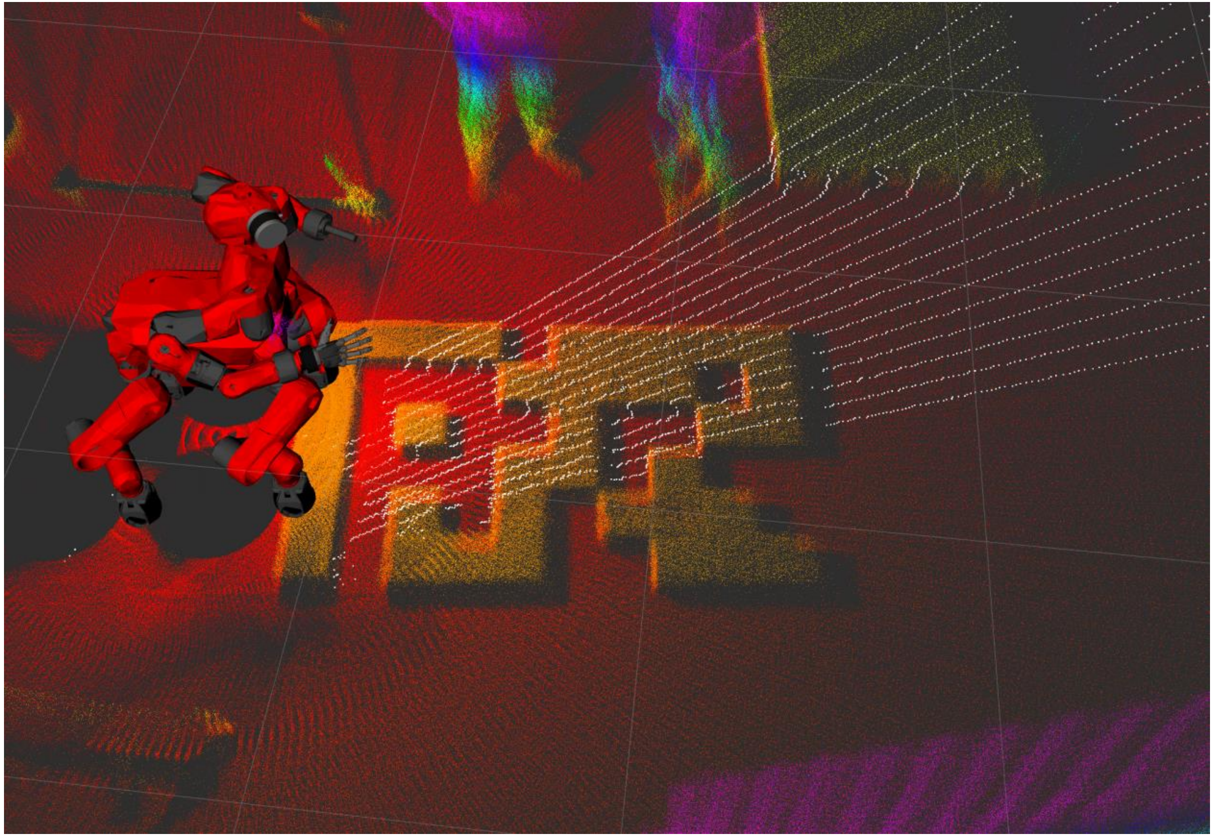
Turning a Valve



Connecting a Plug



3D Mapping and Localization



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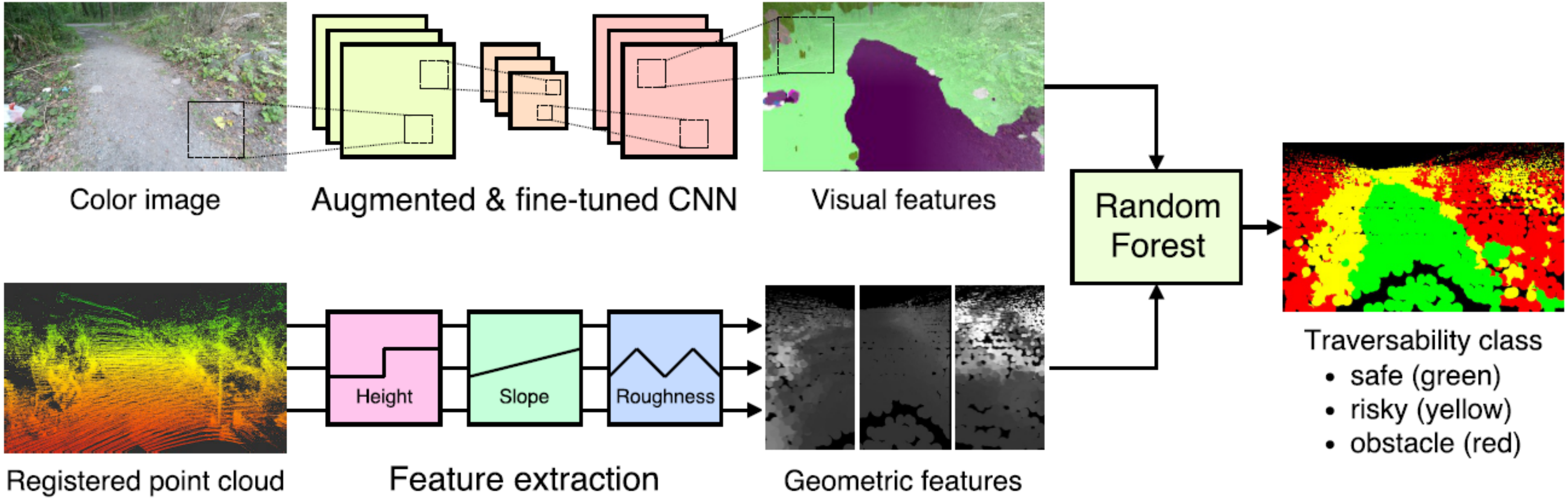
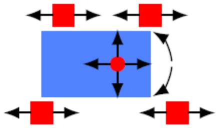
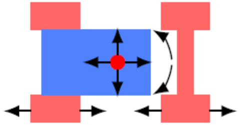
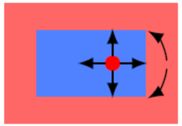
Walking over a Step Field

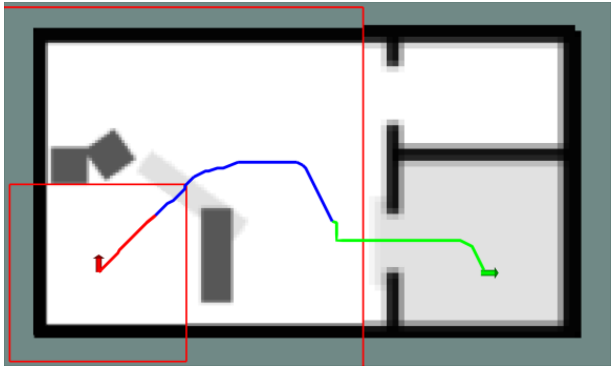
Terrain Classification

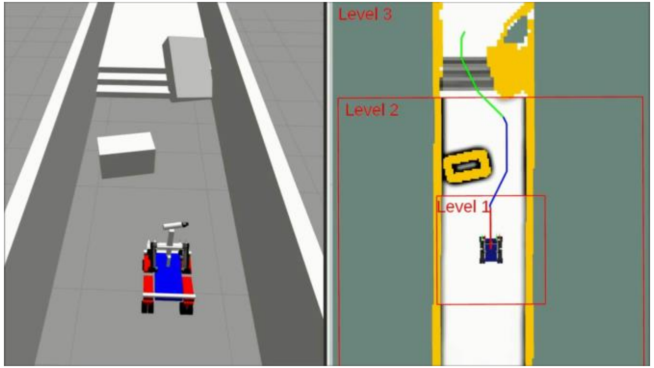


[Schilling et al., IROS 2017]

Hybrid Driving-Stepping Locomotion Planning: Abstraction

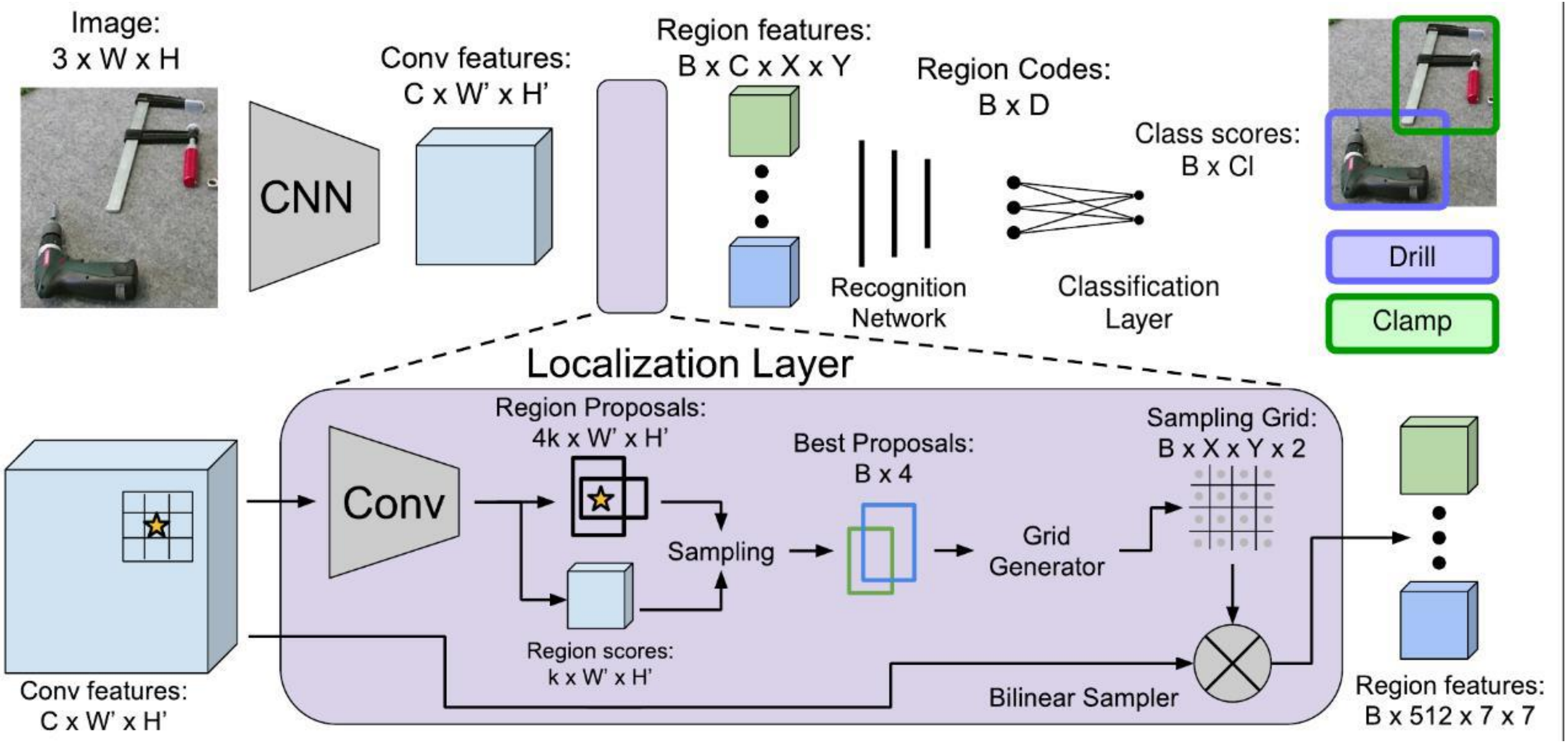
Level	Map Resolution	Map Features	Robot Representation	Action Semantics
1	• 2.5 cm • 64 orient.	• Height		• Individual Foot Actions
2	• 5.0 cm • 32 orient.	• Height • Height Difference		• Foot Pair Actions
3	• 10 cm • 16 orient.	• Height • Height Difference • Terrain Class		• Whole Robot Actions





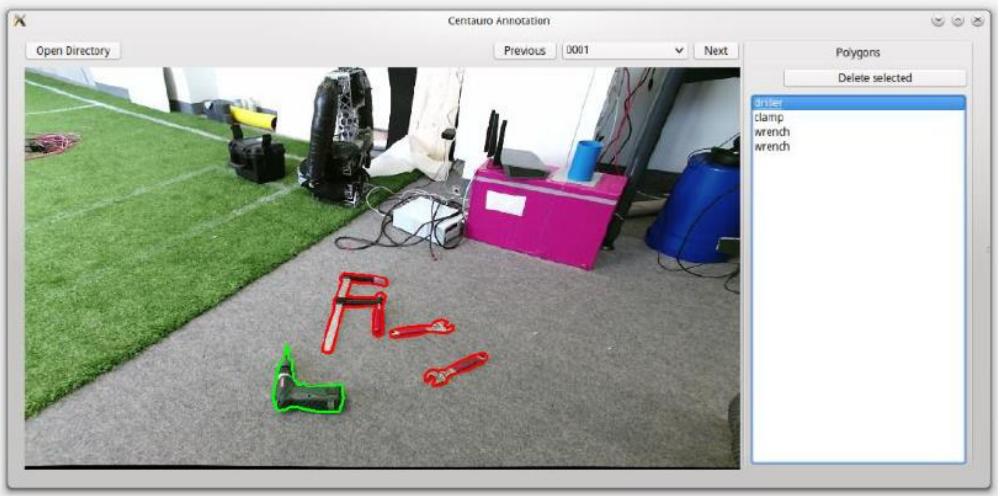
[Klamt and Behnke, IROS 2017, ICRA 2018]

Deep Learning Object Detection



[Johnson et al. 2015]

CENTAURO Workspace Perception Data Set



129 frames, 6 object classes

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

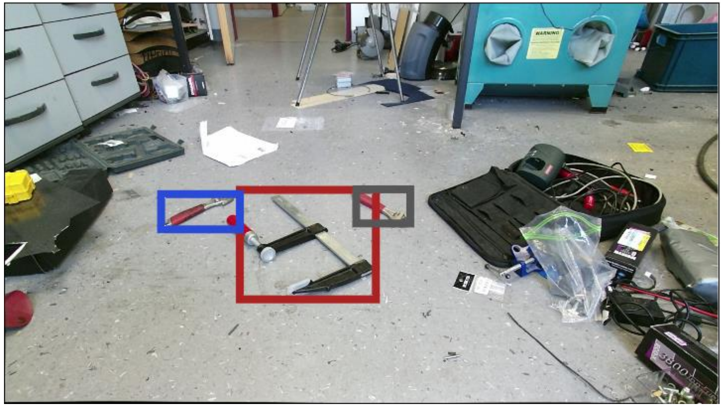
Tool Detection Results

extension_box stapler driller clamp [background]

[Schwarz et al. IJRR 2017]

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

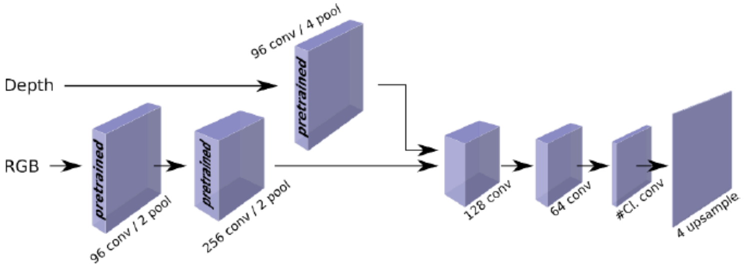
Tools Detection Examples



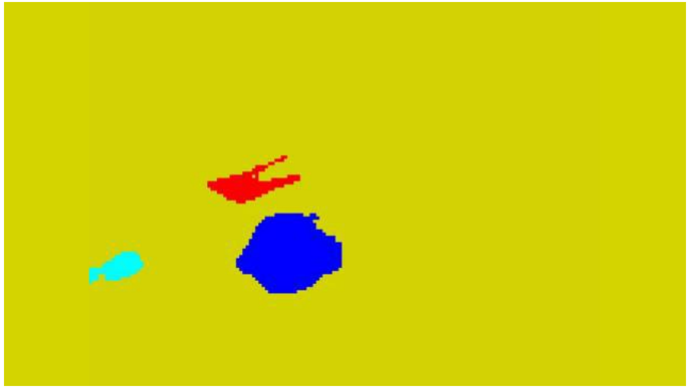
[Schwarz et al. IJRR 2017]

Semantic Segmentation

- Deep CNN



[Husain et al. RA-L 2016]

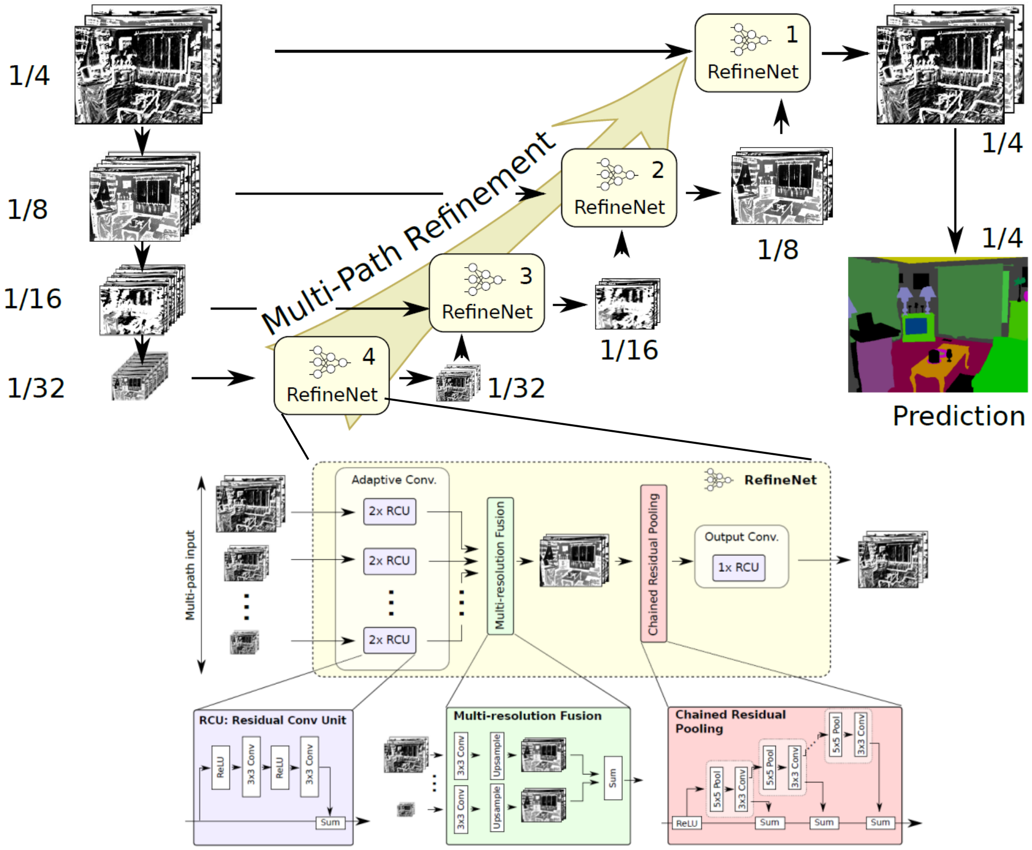


Pixel-wise accuracy:

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

RefineNet for Semantic Segmentation

- Scene represented as feature hierarchy
- Corse-to-fine semantic segmentation
- Combine higher-level features with missing details

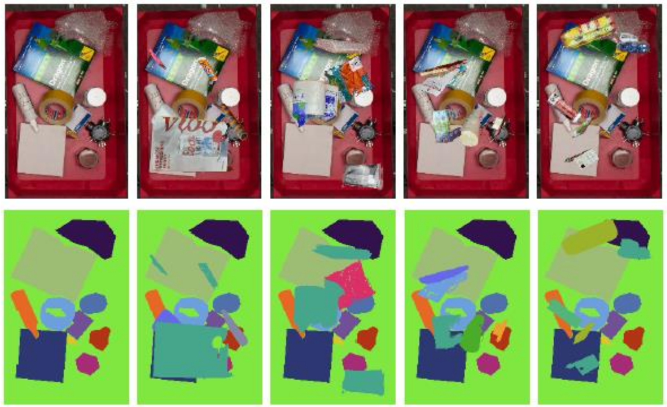


[Lin et al. CVPR 2017]

The Data Problem

- Deep Learning in robotics (still) suffers from shortage of available examples
- We address this problem in two ways:

1. **Generating data**:
   Automatic data capture,
   online mesh databases,
   scene synthesis



2. **Improving generalization**:
   Object-centered models,
   deformable registration,
   transfer learning,
   semi-supervised learning

Object Capture and Scene Rendering

- Turntable + DLSR camera

- Rendered scenes

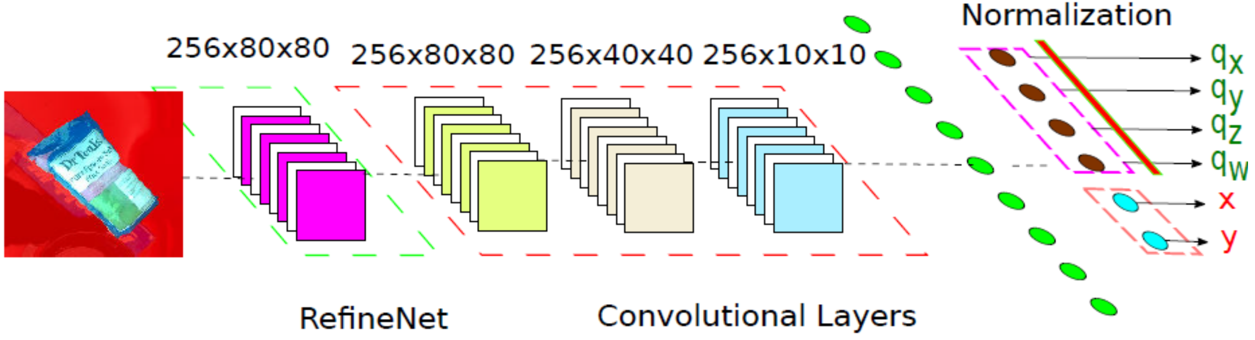
[Schwarz et al. ICRA 2018]

Semantic Segmentation Example

[Schwarz et al. ICRA 2018]

Object Pose Estimation

- Cut out individual segments
- Use upper layer of RefineNet as input
- Predict pose coordinates



Input

Predicted pose

[Schwarz et al. ICRA 2018, Periyasamy et al. IROS 2018]

From Turntable Captures to Textured Meshes

Fused & textured result

Transfer of Manipulation Skills

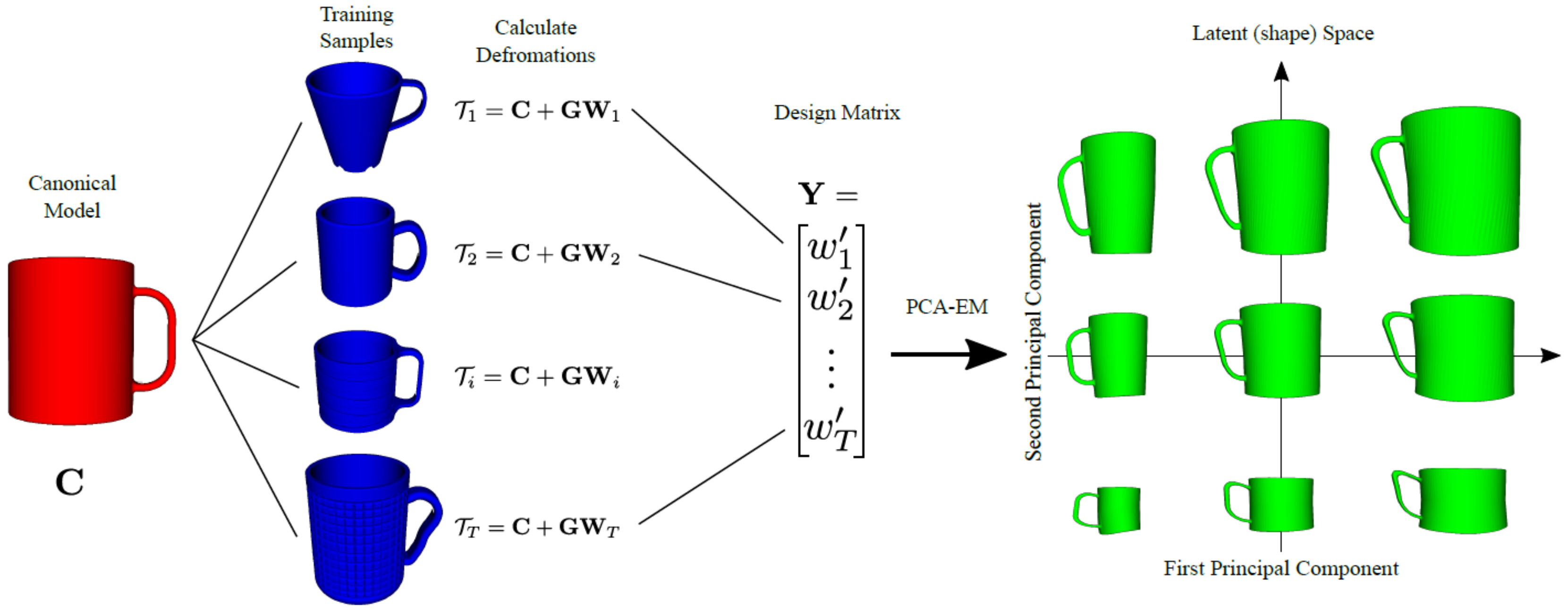
- Objects belonging to the same **category** can be handled in a very similar manner.

Transfer of Manipulation Skills

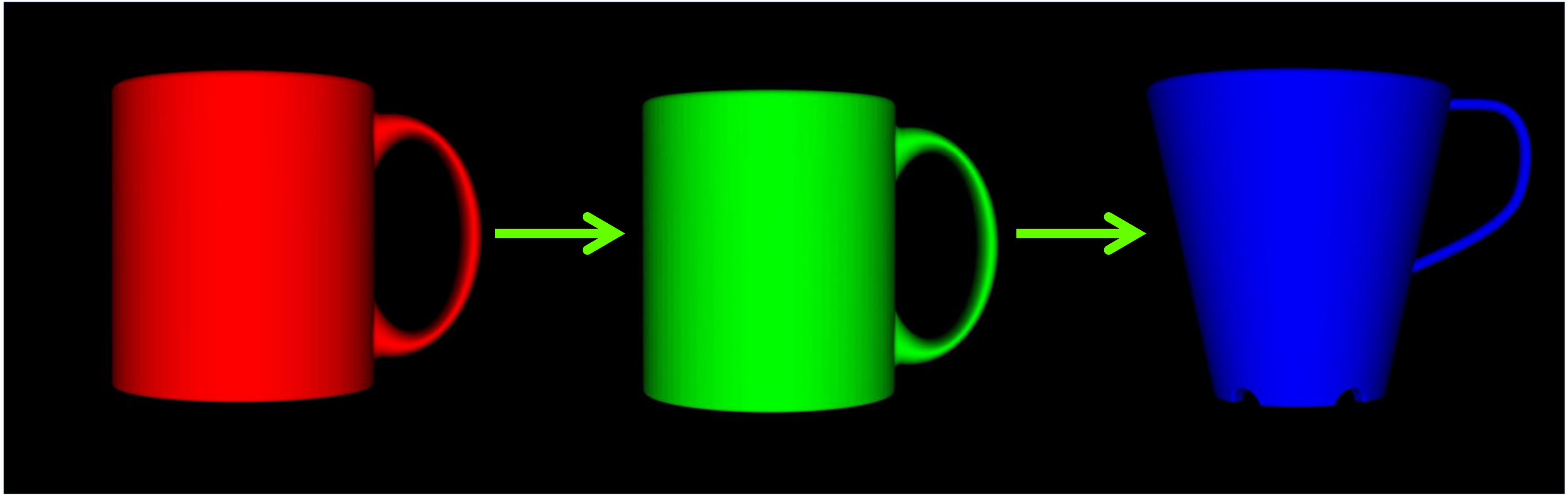
Knowledge Transfer

Learning a Latent Shape Space

- Non-rigid registration of instances and canonical model
- Principal component analysis of deformations



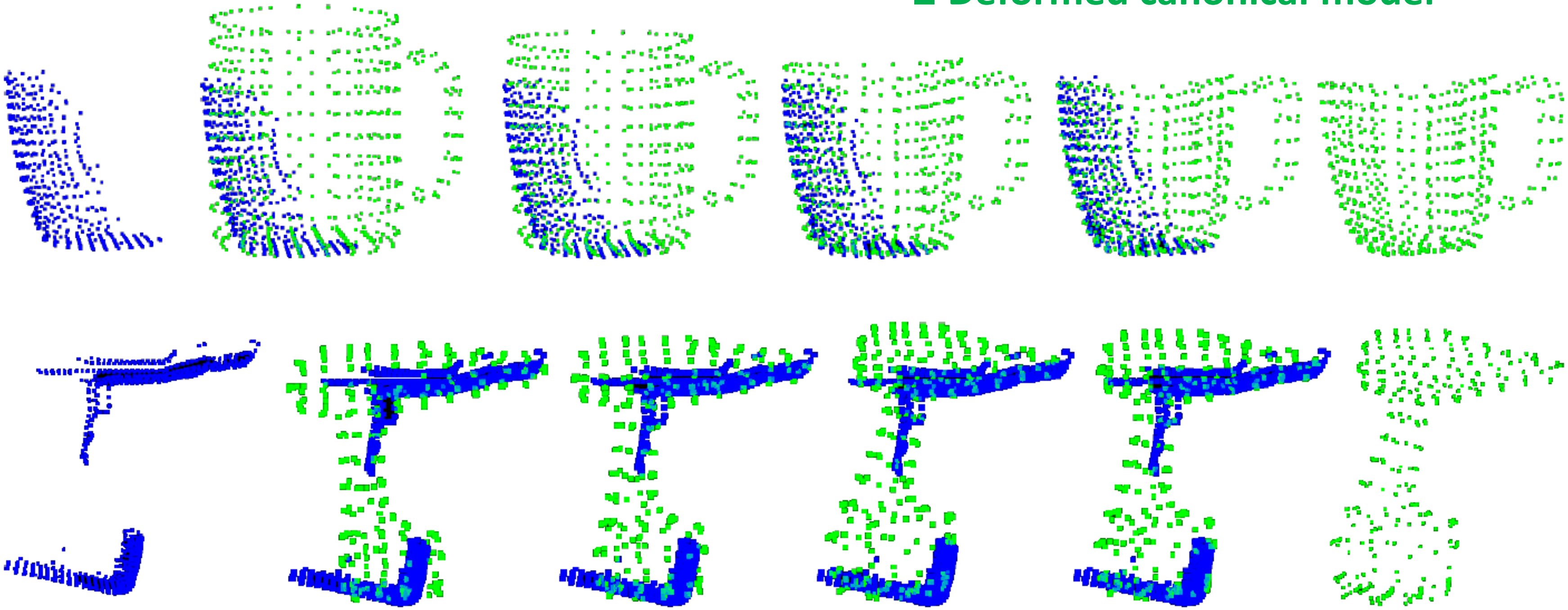
Interpolation in Shape Space



[Rodriguez and Behnke ICRA 2018]

Shape-aware Non-rigid Registration

- Partial view of novel instance
- Deformed canonical model

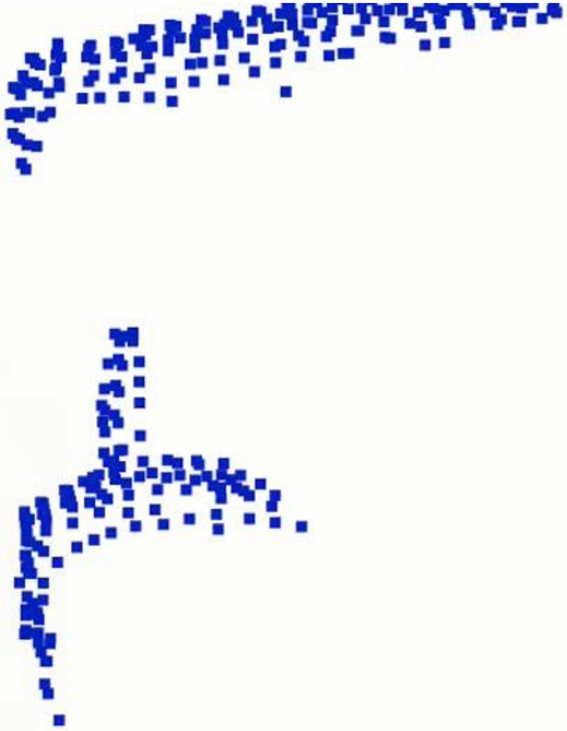


[Rodriguez and Behnke ICRA 2018]

Shape-aware Registration for Grasp Transfer

- Full point cloud

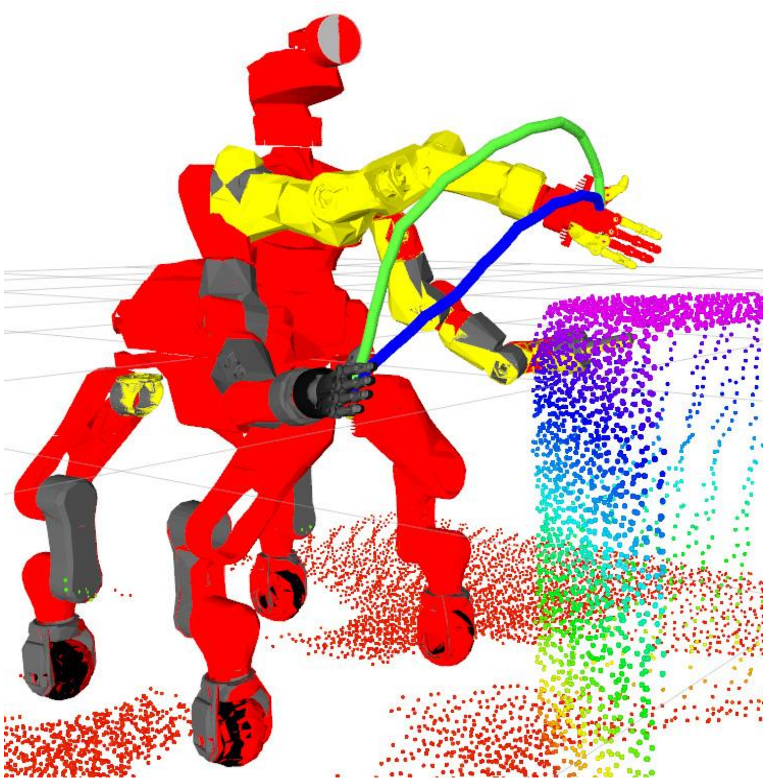
- Partial view



Collision-aware Motion Generation

Constrained Trajectory Optimization:

- Collision avoidance
- Joint limits
- Time minimization
- Torque optimization

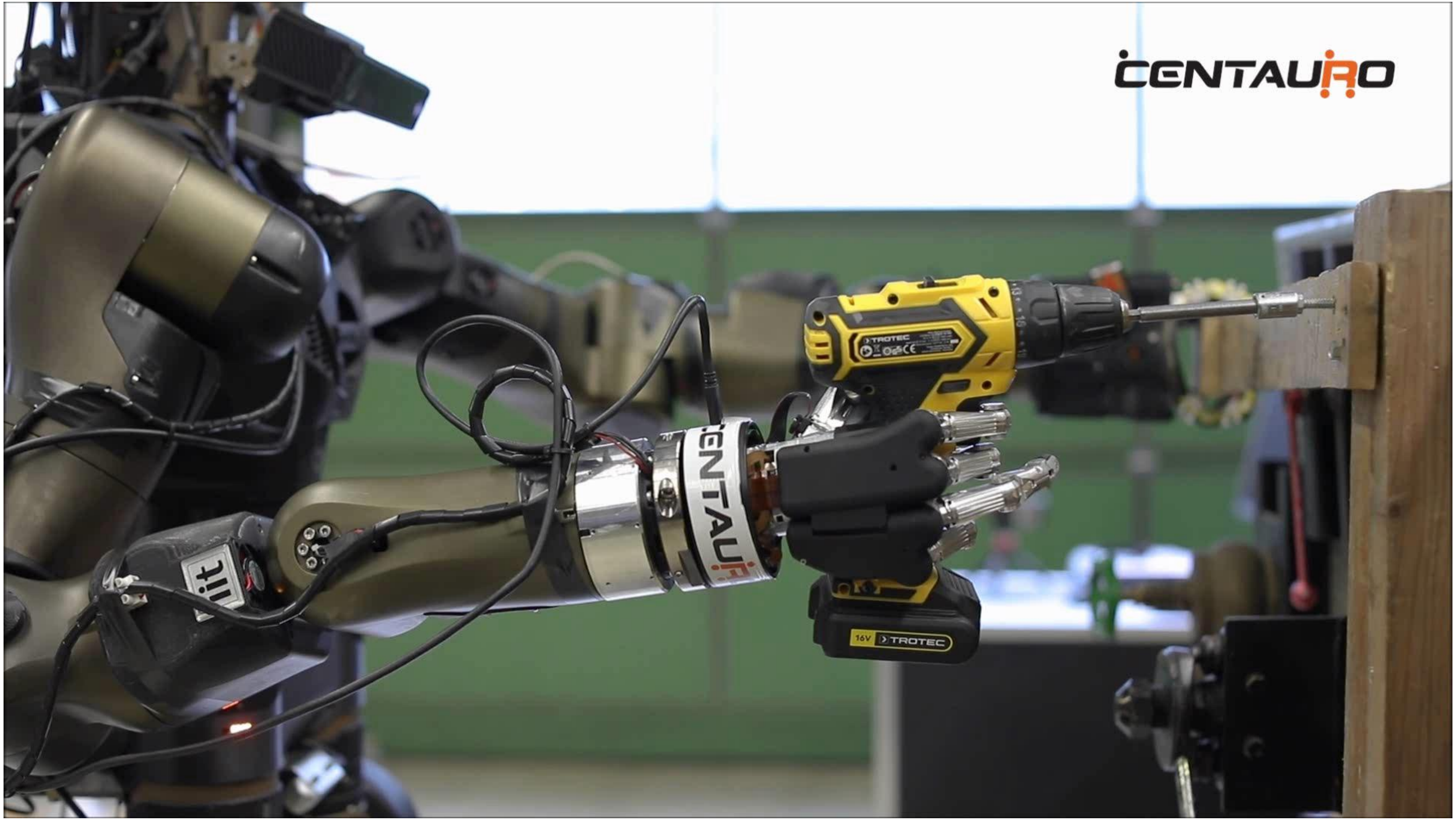


[Pavlichenko et al., IROS 2017]

Grasping an Unknown Power Drill

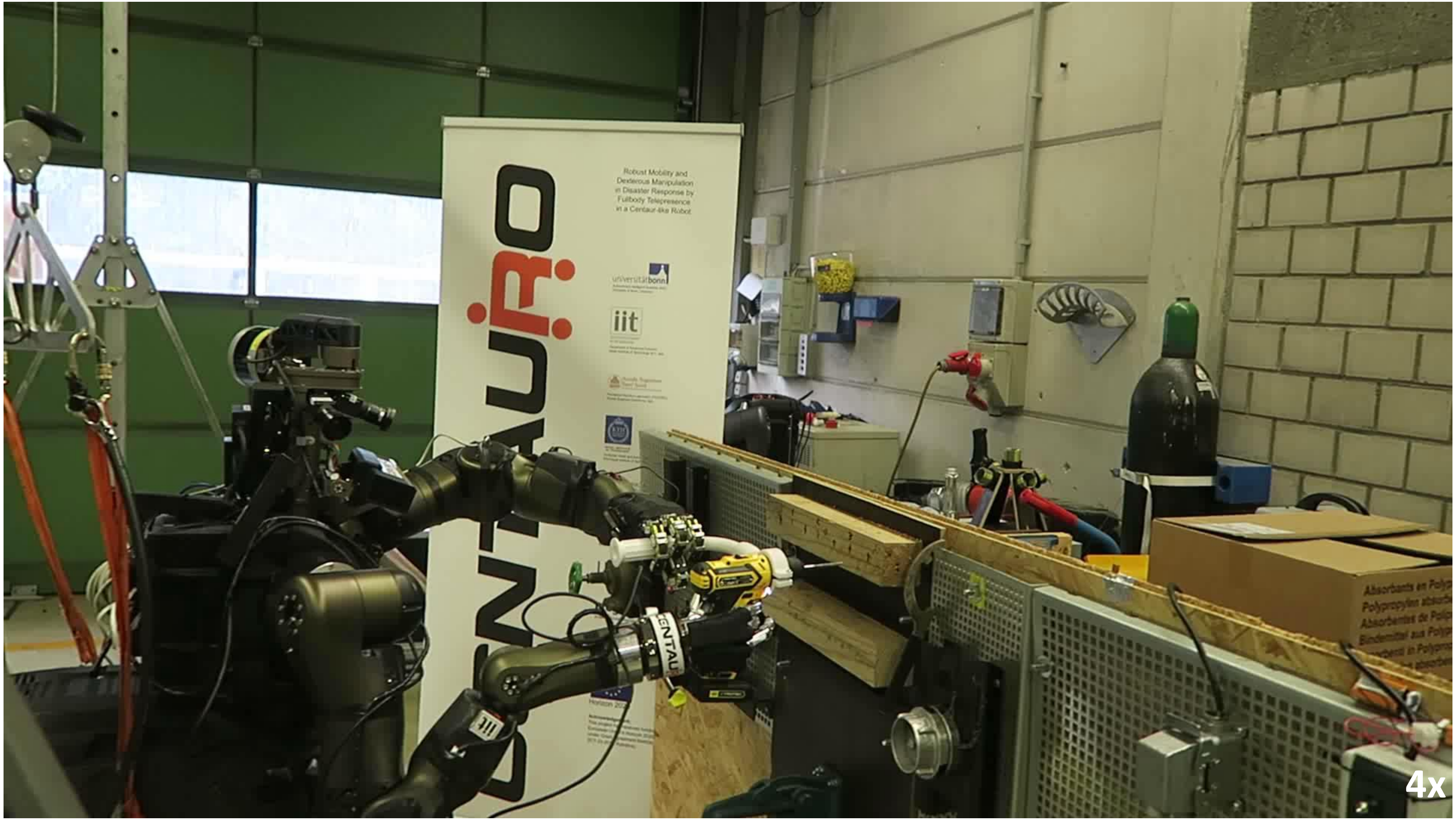
Fastening a Screw

Bimanual Fastening Task

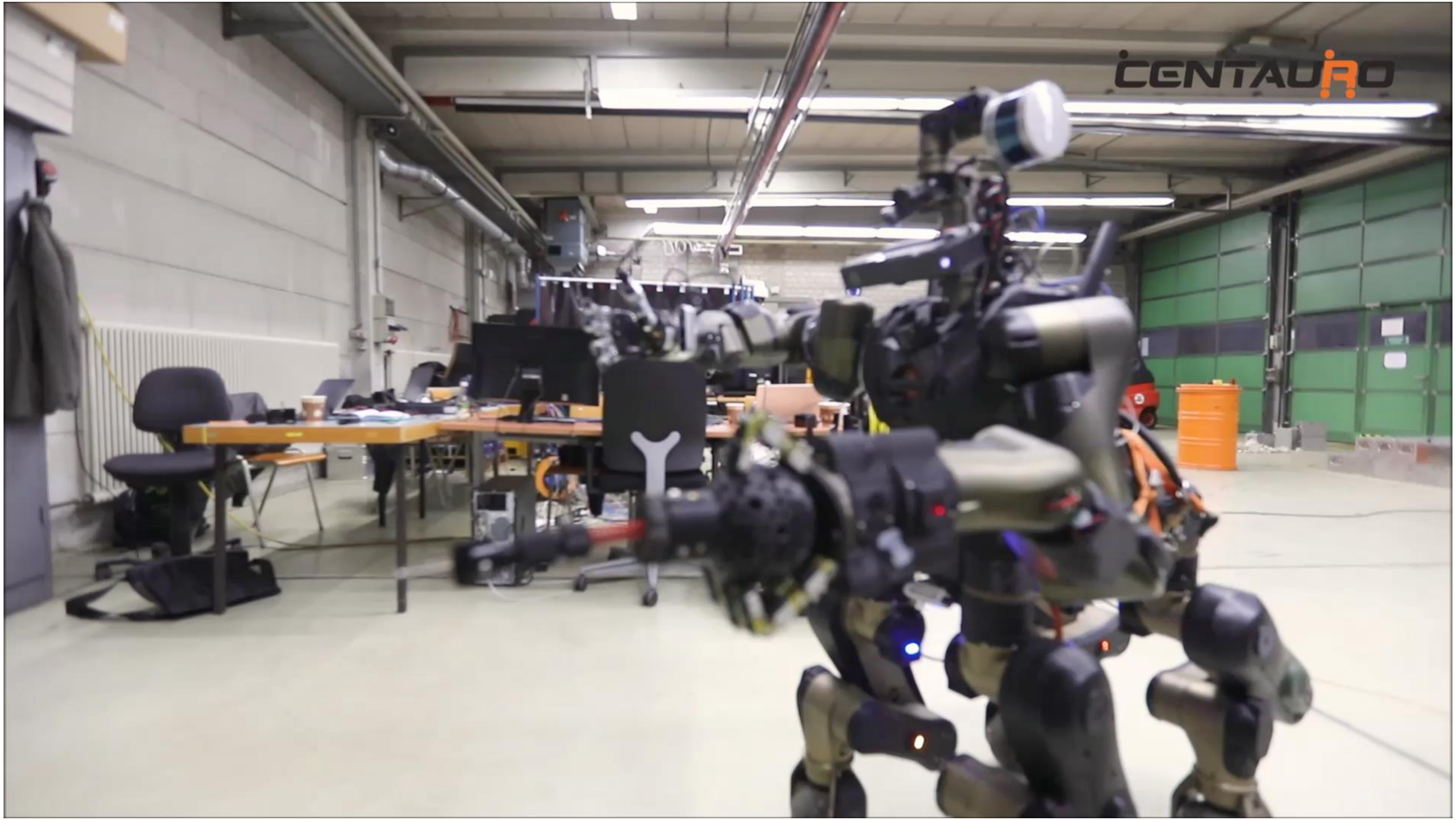


Bimanual Grasping

Bimanual Drilling

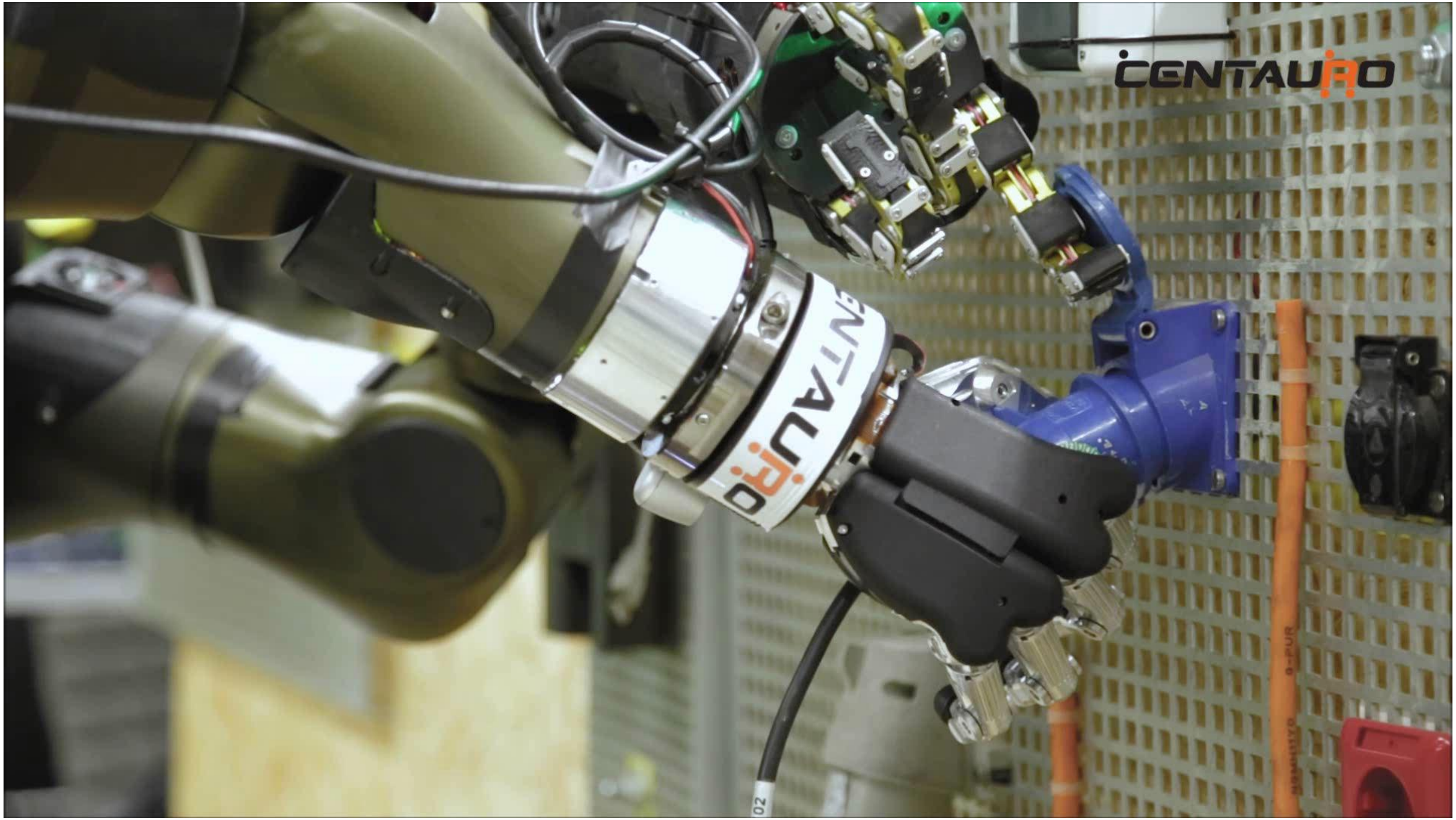


Opening a Door with a Key



Closing a Shackle

Bimanual Plug Tasks



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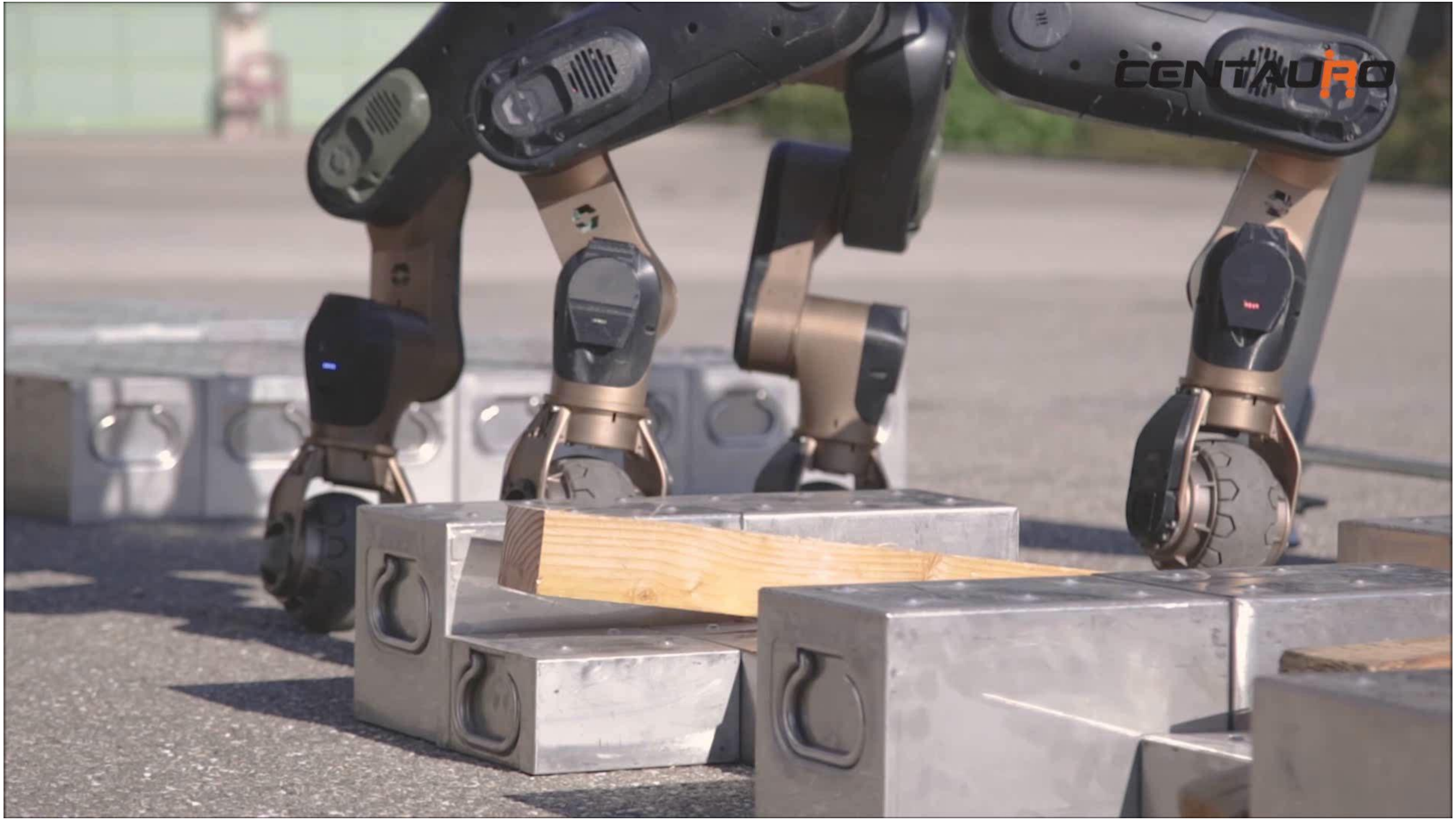
Step Field with Debris



Autonomous Navigation

CENTAURO Team

Conclusions

- Developed capable humanoid robot systems for disaster-response scenarios
- Teleoperation is flexible, but demanding and error-prone
- Autonomy for common navigation and manipulation tasks needed
- Challenges include
  - Capable and affordable robot platforms
  - 4D semantic perception
  - High-dimensional motion planning
- Promising approaches
  - Shared autonomy
  - Structured learning