Flexible Driving-stepping Locomotion and Human-like Manipulation for Disaster Response

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Autonomous Intelligent Systems

Some of our Humanoid Robots

- Developed for complex demonstration scenarios

Soccer

Interaction

Domestic service

Mobile manipulation

Motivation: Fukushima Nuclear Disaster

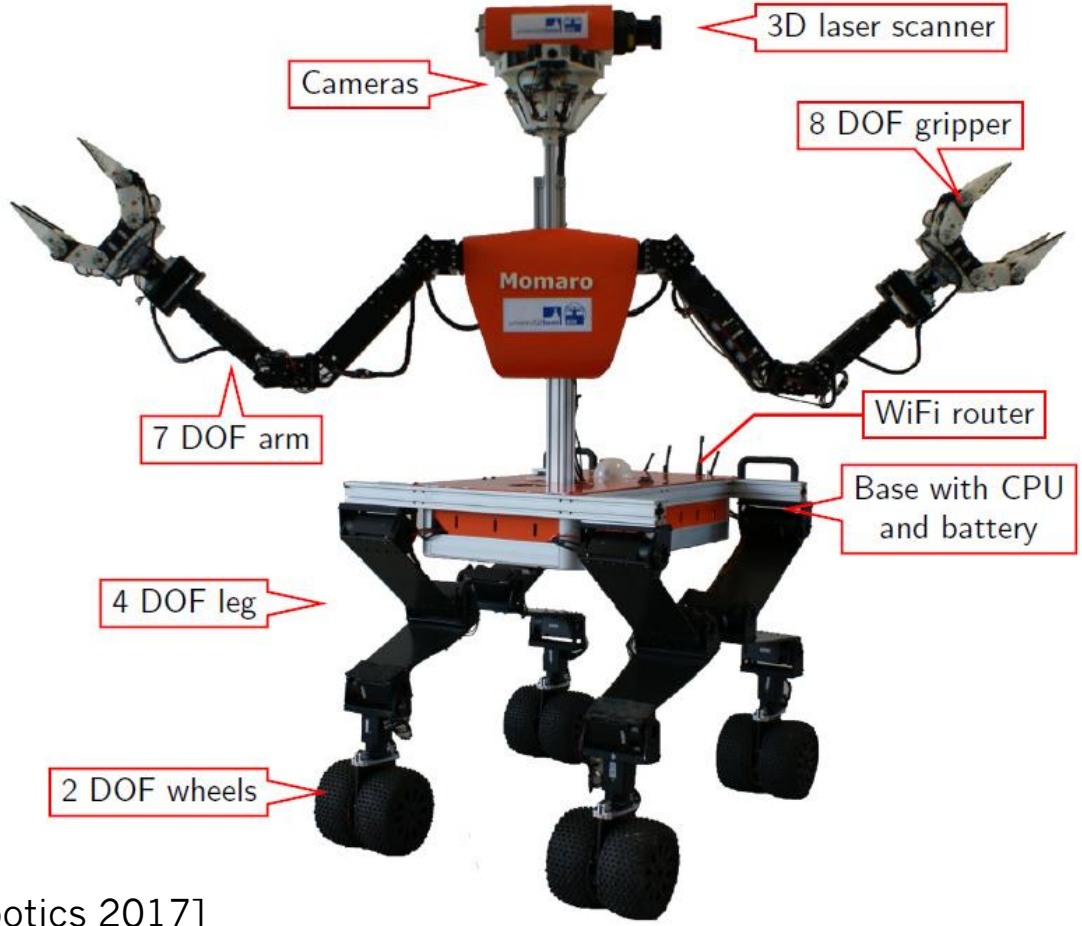
- Capabilities of disaster-response robots were insufficient for providing effective support to rescue workers.
  - Mobility: difficulties with uneven terrain, stairs, and debris
  - Manipulation: only a single actuator with simple end-effectors
  - User interface: requires extensive training, not intuitive, situation awareness problematic
- Complexity of achievable tasks and execution speed are low
- DARPA Robotics Challenge 2015

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



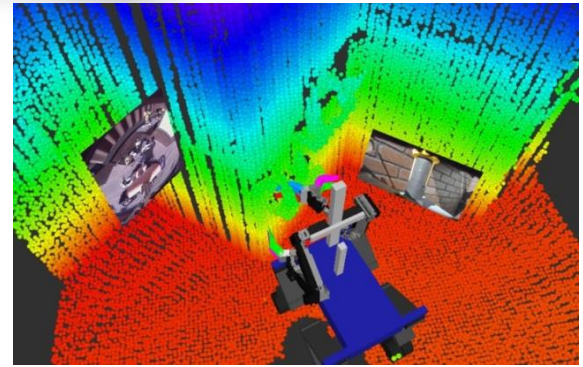
[Schwarz et al. Journal of Field Robotics 2017]

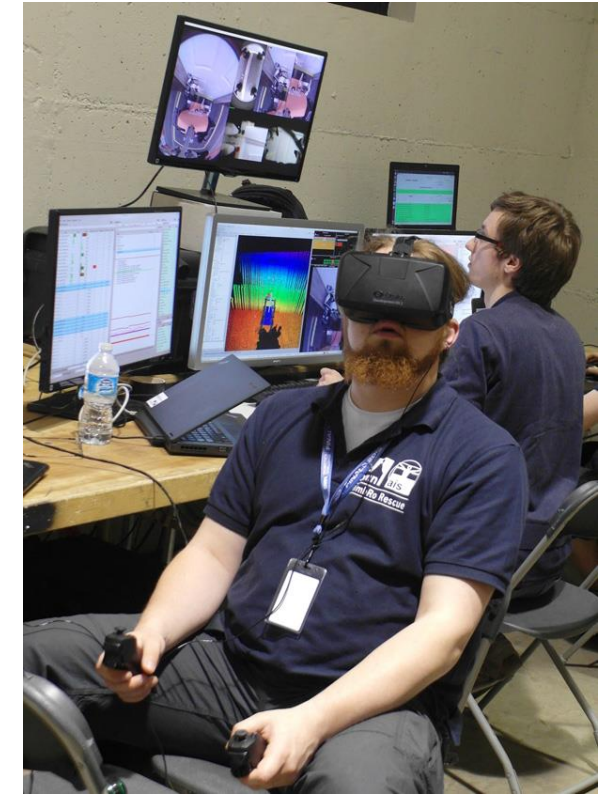

FAIRPLEX
FAIRPLEX
FAIRPLEX
23:15:03 05/06/2015 UTC
4x


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
POLAR
RANGER
XP
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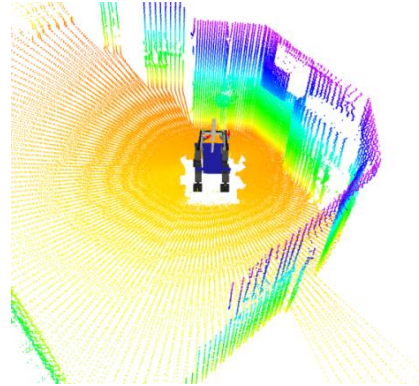
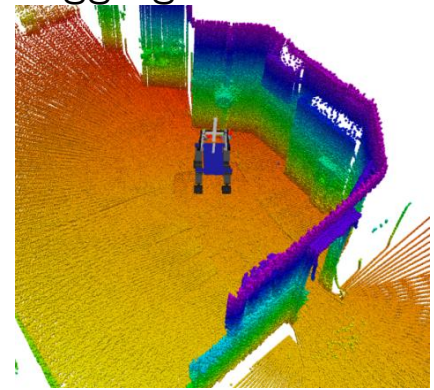
Local Multiresolution Surfel Map

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

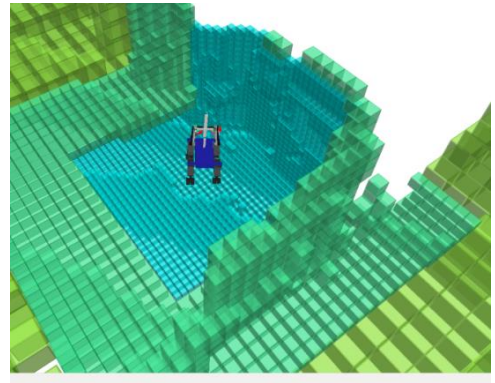
3D scan



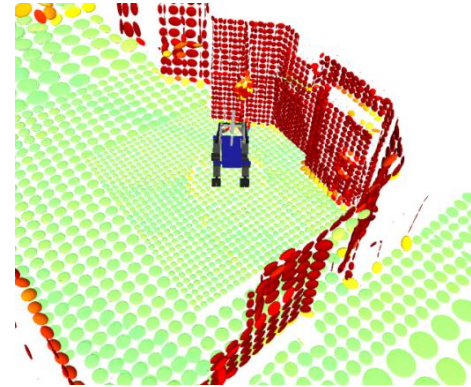
Aggregated scans



Multiresolution grid



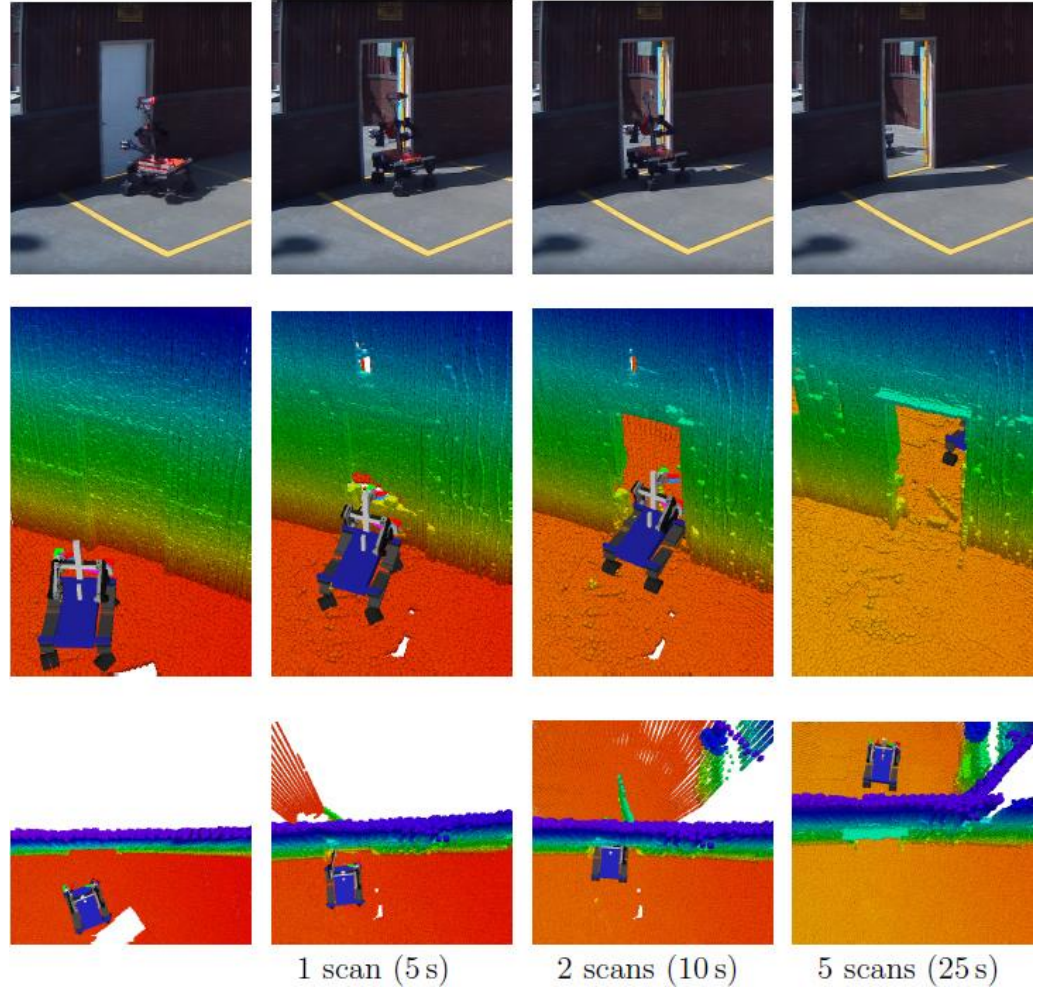
Surfels



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

Filtering Dynamic Objects

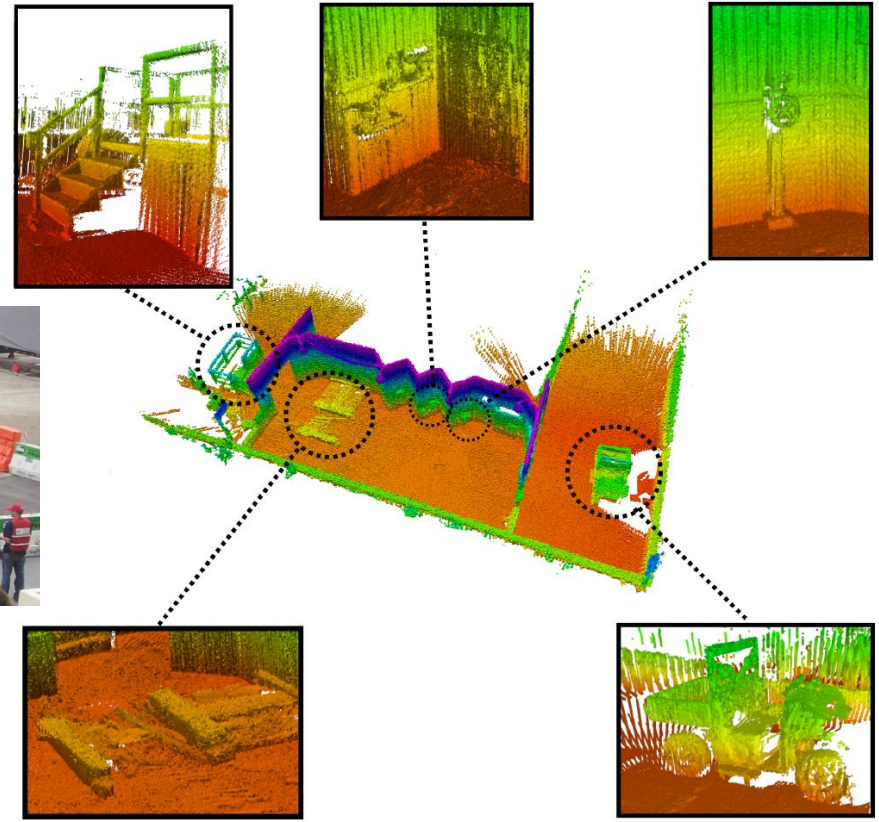
- Maintain occupancy in each cell
- Remove measurements of empty cells



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

Allocentric 3D Mapping

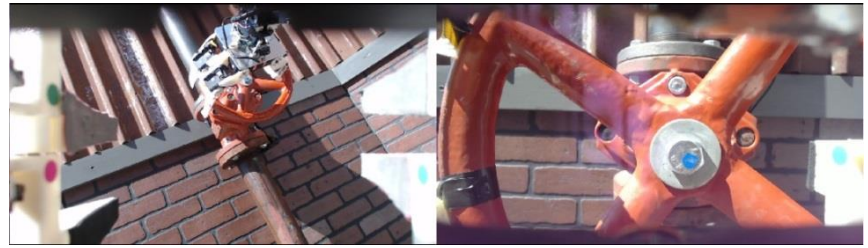
- Registration of egocentric maps by graph optimization

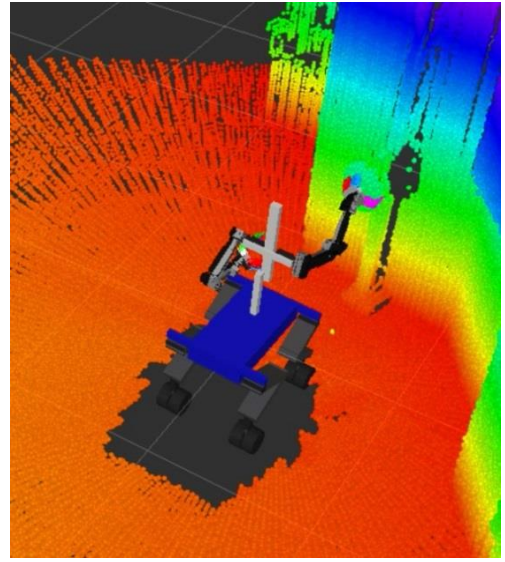


[Droeschel et al., Robotics and Autonomous Systems 2017]

Valve Turning Interface

- Align wheel model with 3D points using interactive marker





[Schwarz et al. Journal of Field Robotics 2017]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23:28:21 05/06/2015 UTC
4x


02:23:20 07/06/2015 UTC
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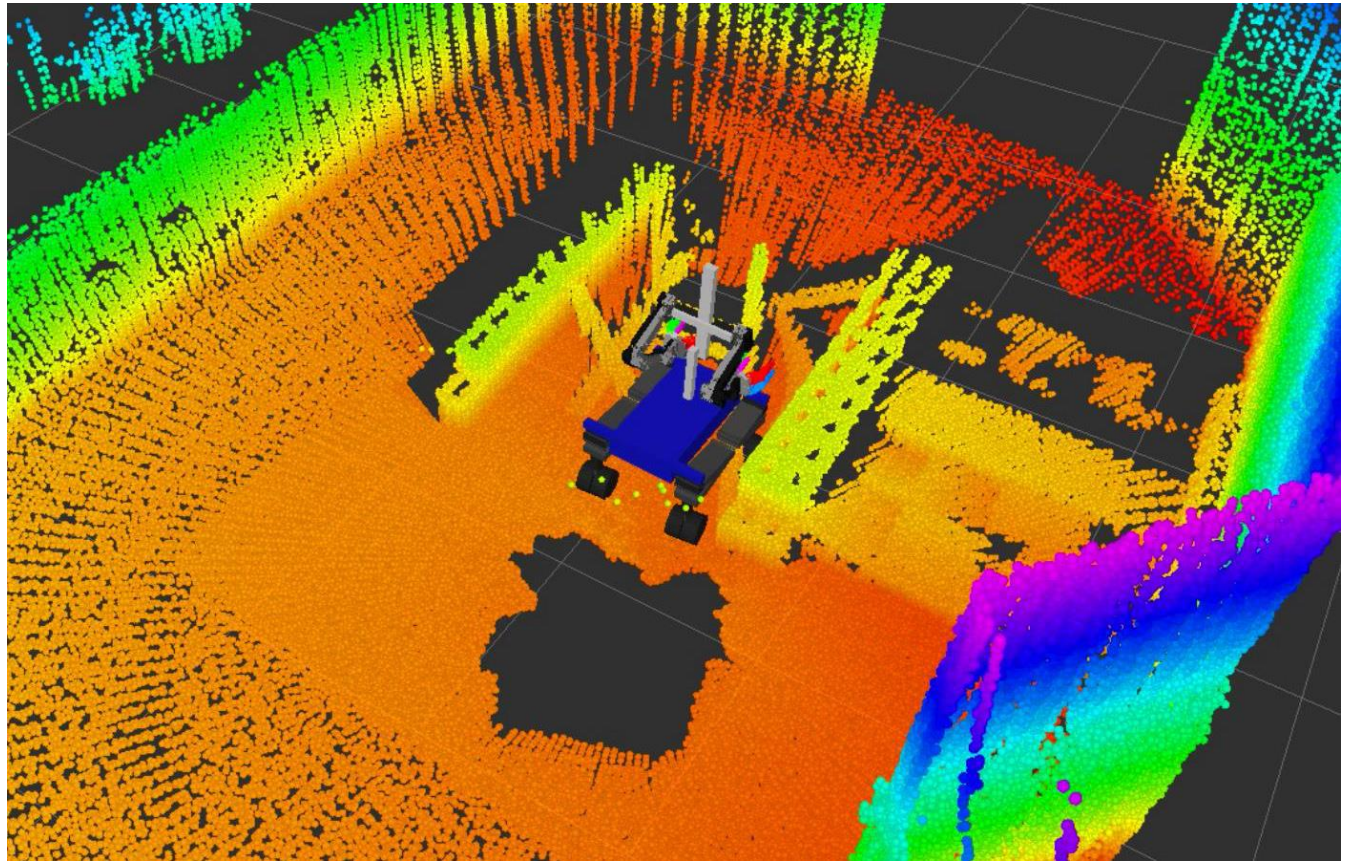
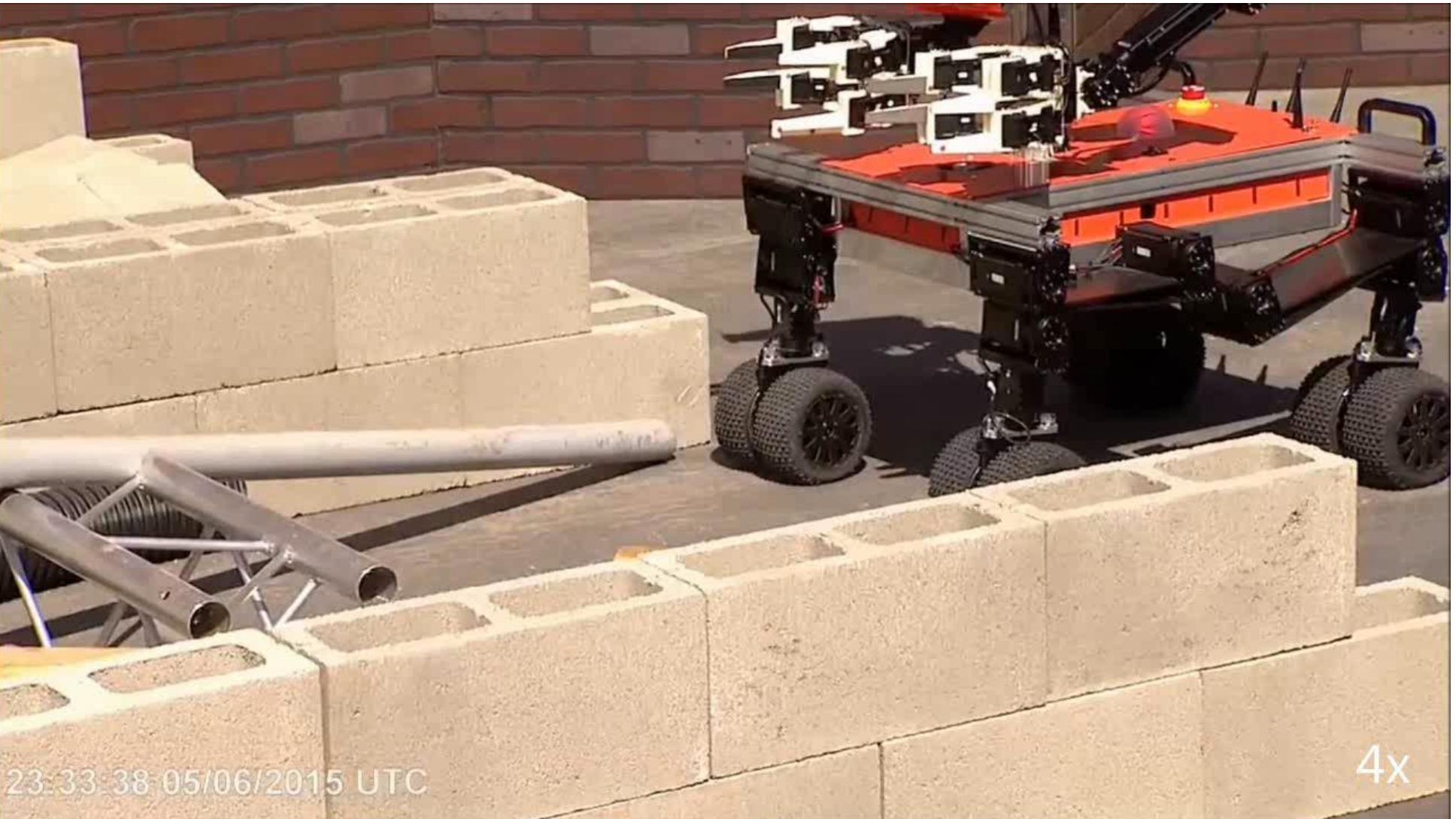
Debris Tasks

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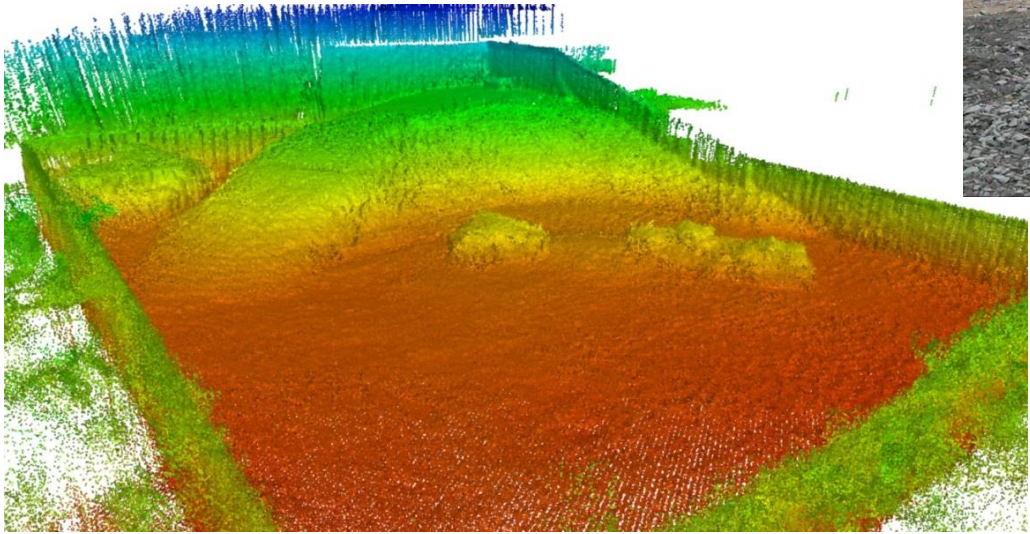
DARPA
CHALLENGE
2015
23:36:46 05/06/2015 UTC
4x

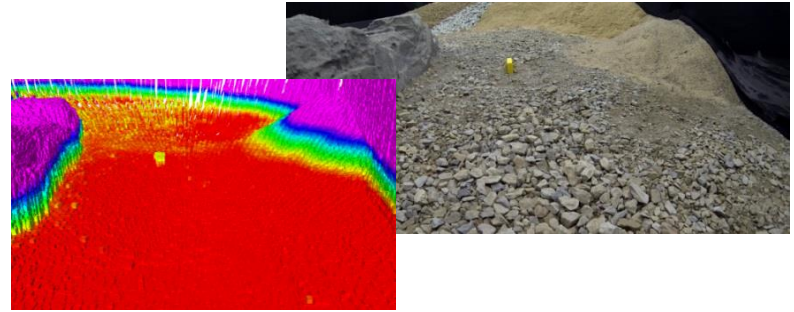
Team NimbRo Rescue

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

DLR SpaceBot Cup 2015

- Mobile manipulation in rough terrain



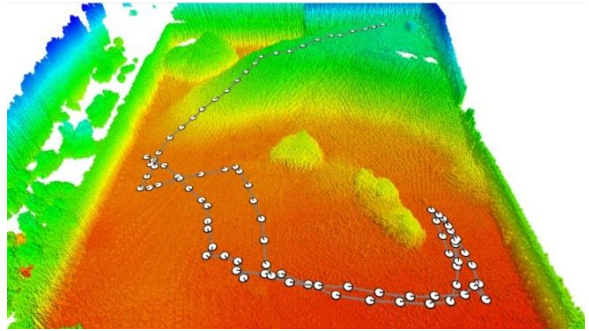


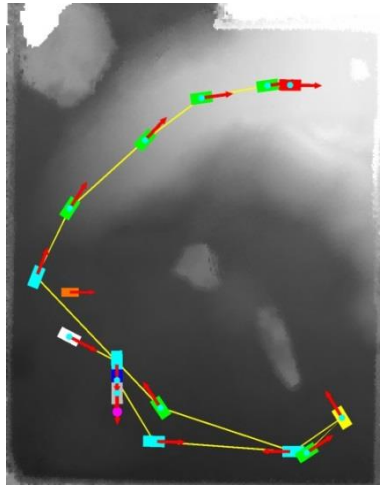
[Schwarz et al., Frontiers on Robotics and AI 2016]

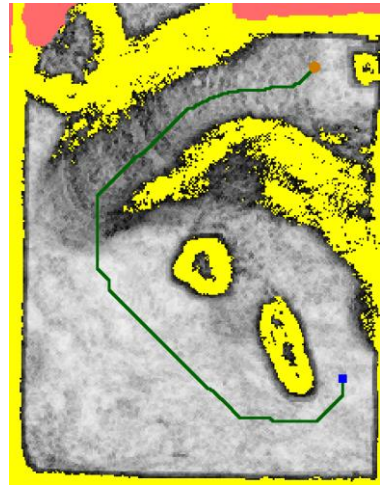

8X

Autonomous Mission Execution

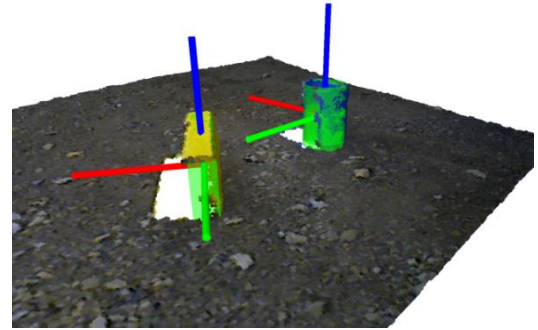
- 3D mapping, localization, mission and navigation planning

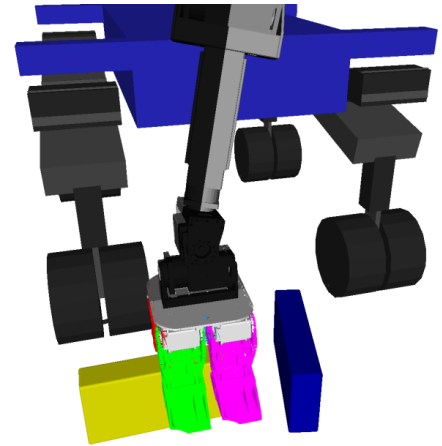






- 3D object perception and grasping

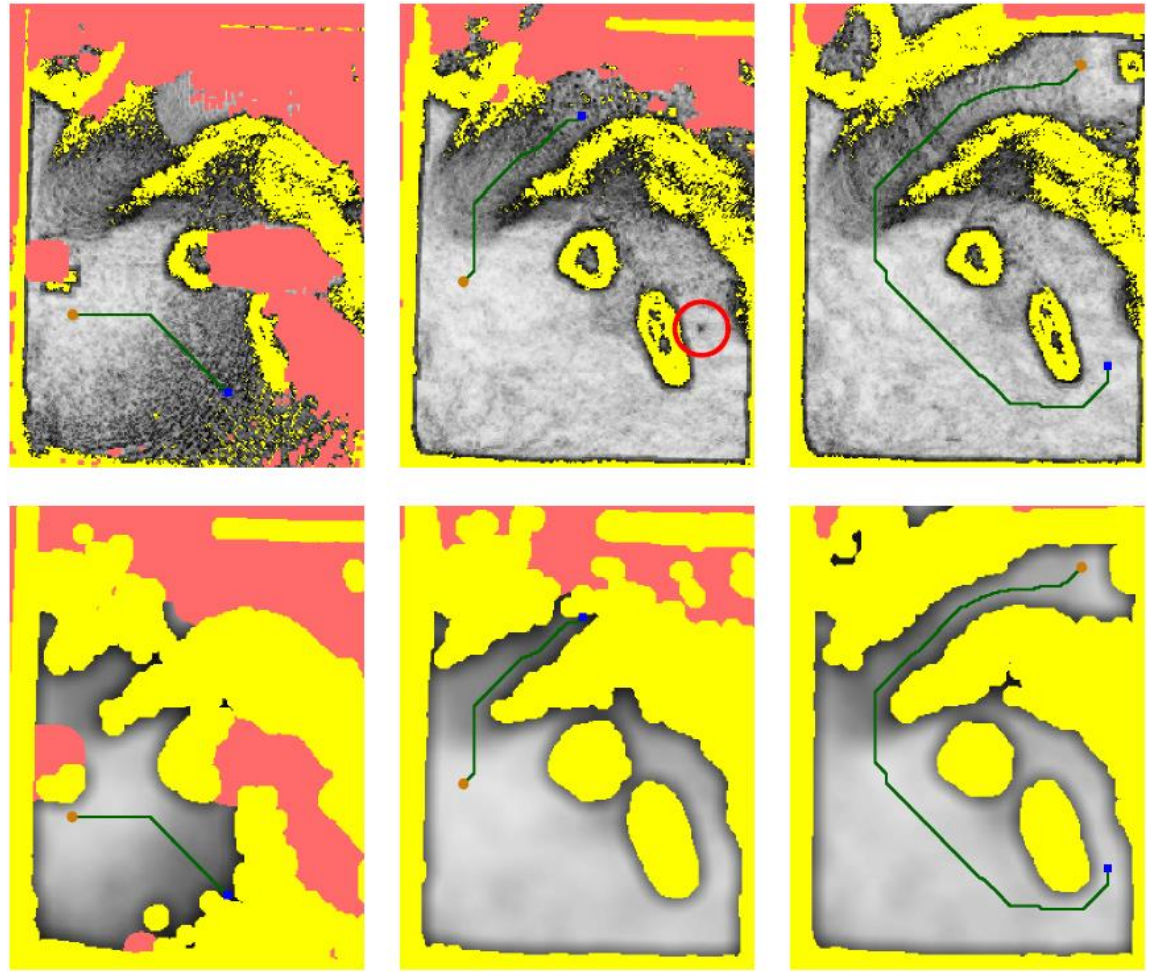




[Schwarz et al. Frontiers 2016]

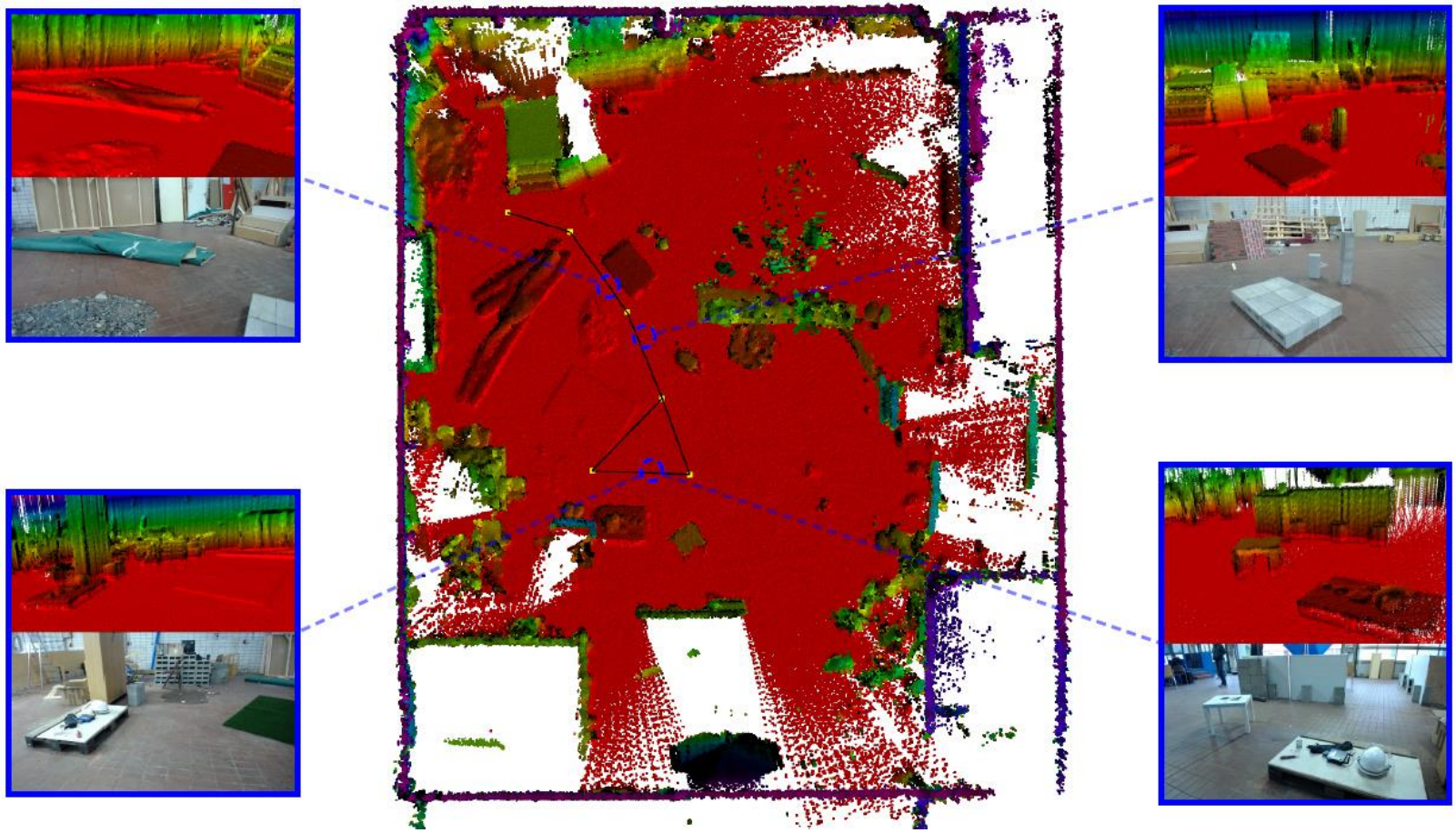
Navigation Planning

- Costs from local height differences
- A* path planning



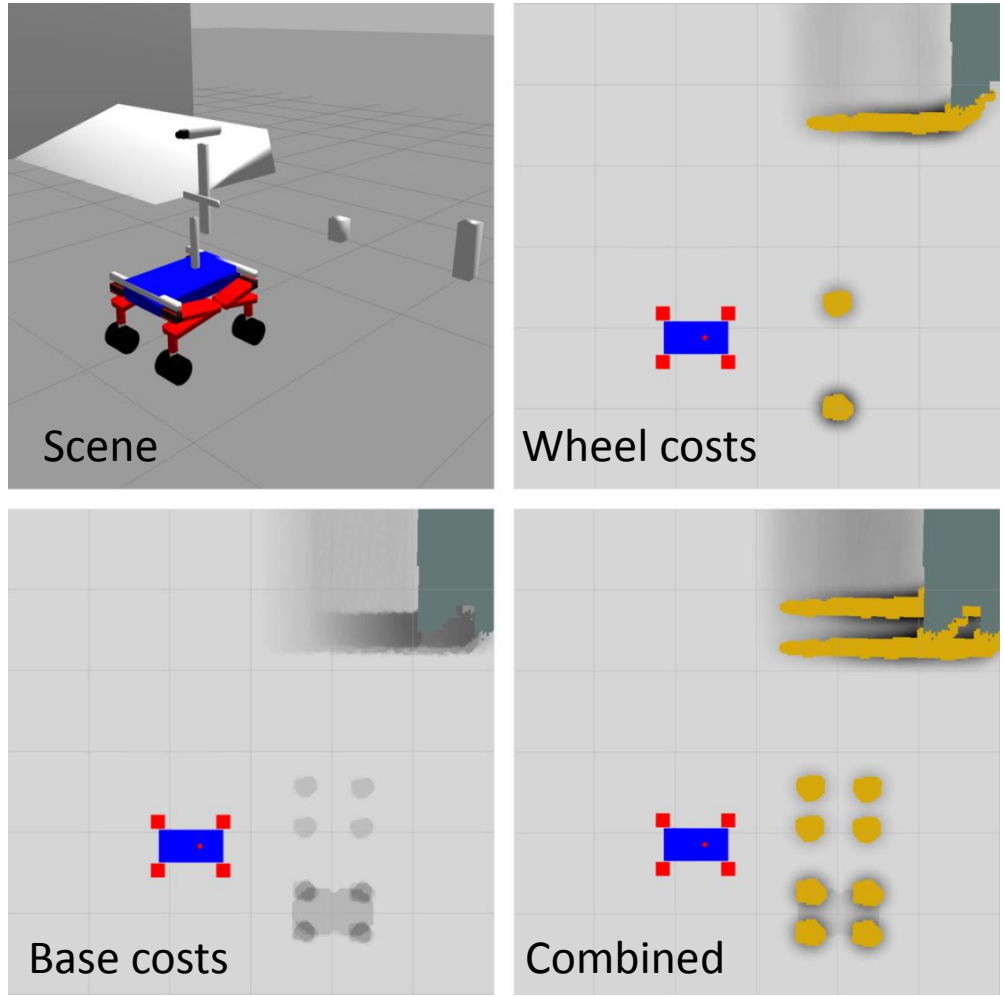
[Schwarz et al., Frontiers in Robotics and AI 2016]

3D Map



Considering Robot Footprint

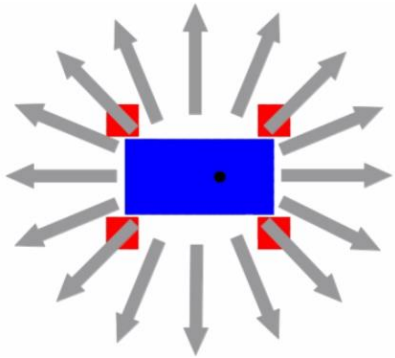
- Costs for individual wheel pairs from height differences
- Base costs
- Non-linear combination yields 3D (x, y, θ) cost map



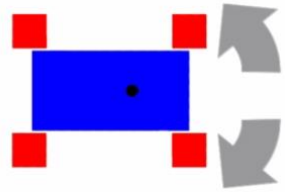
[Klamt and Behnke, IROS 2017]

3D Driving Planning (x, y, θ): A*

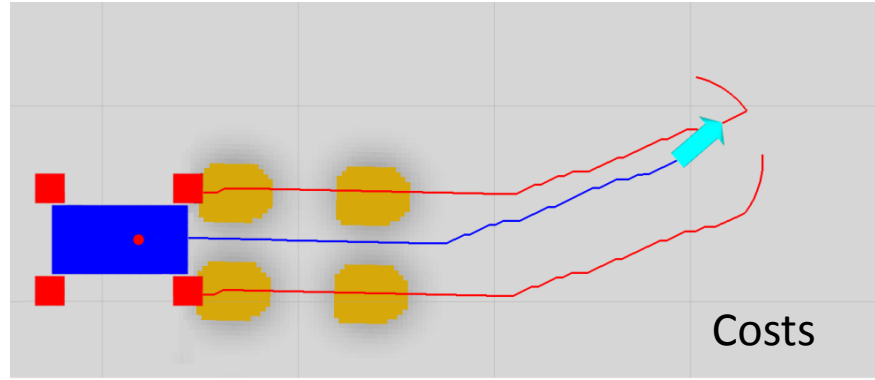
- 16 driving directions

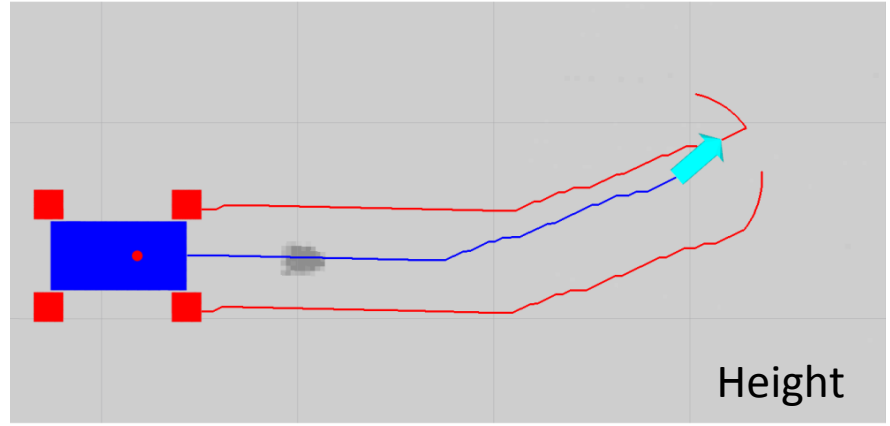


- Orientation changes



=> Obstacle between wheels

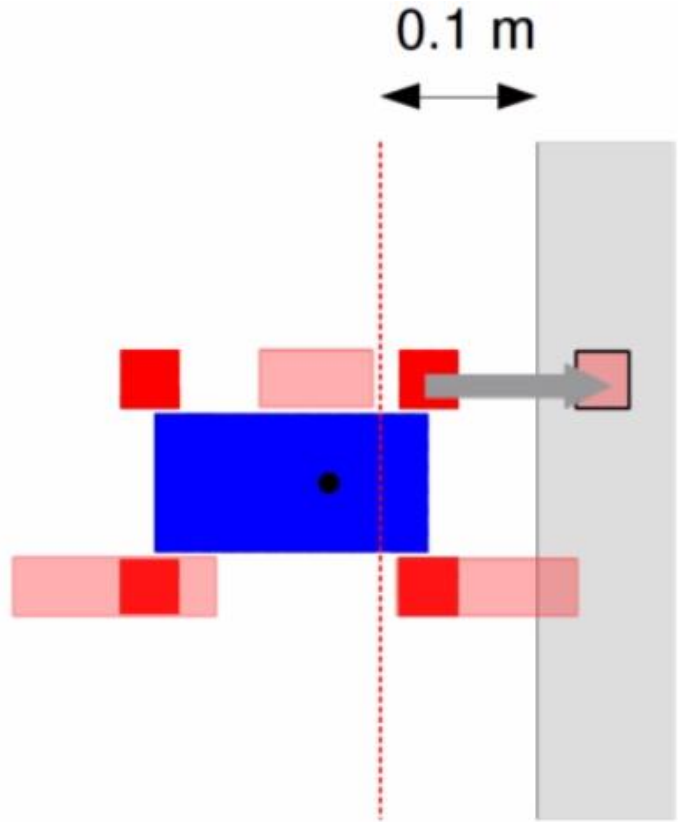




[Klamt and Behnke, IROS 2017]

Making Steps

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

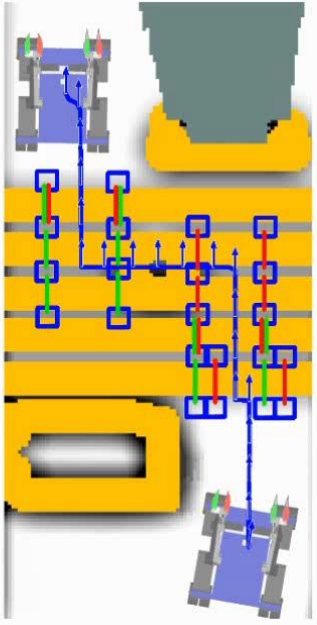


[Klamt and Behnke: IROS 2017]

Expanding Abstract Steps to Detailed Motion Sequences

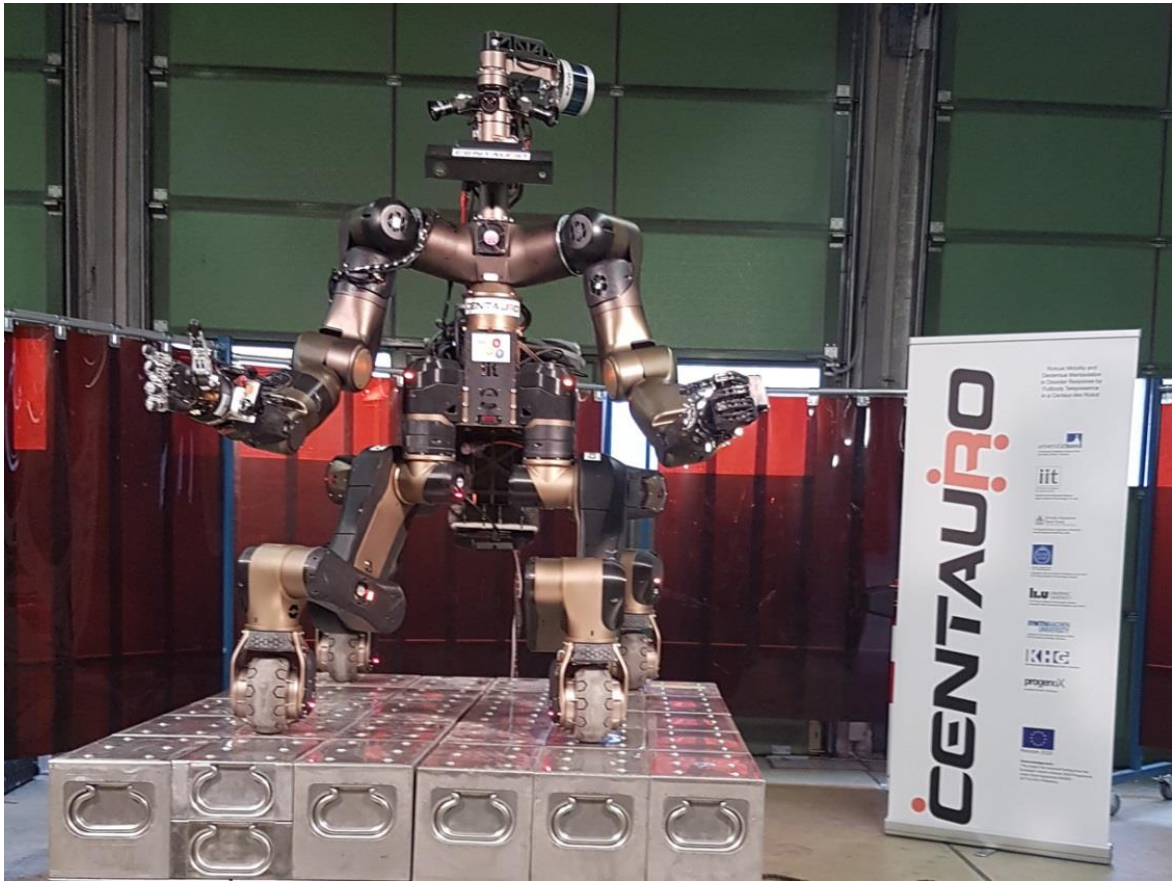
[Klamt and Behnke: IROS 2017]

Planning for Challenging Scenarios



[Klamt and Behnke: IROS 2017]

Centauro Robot



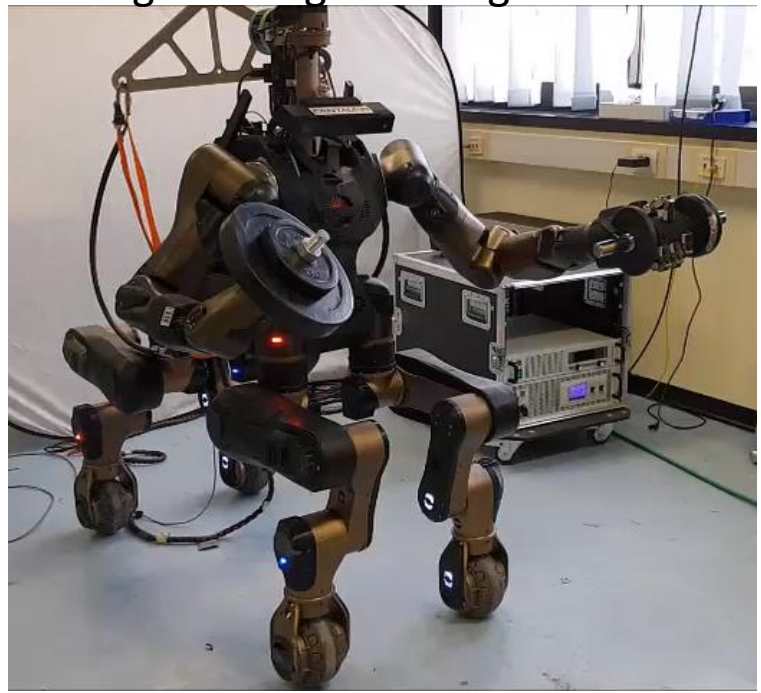
- Serial elastic actuators
- 42 main DoFs
- Schunk hand
- 3D laser
- RGB-D camera
- Color cameras
- Two GPU PCs

[Tsagarakis et al., IIT 2017]

Strong Actuators

Pushing 45 Kg

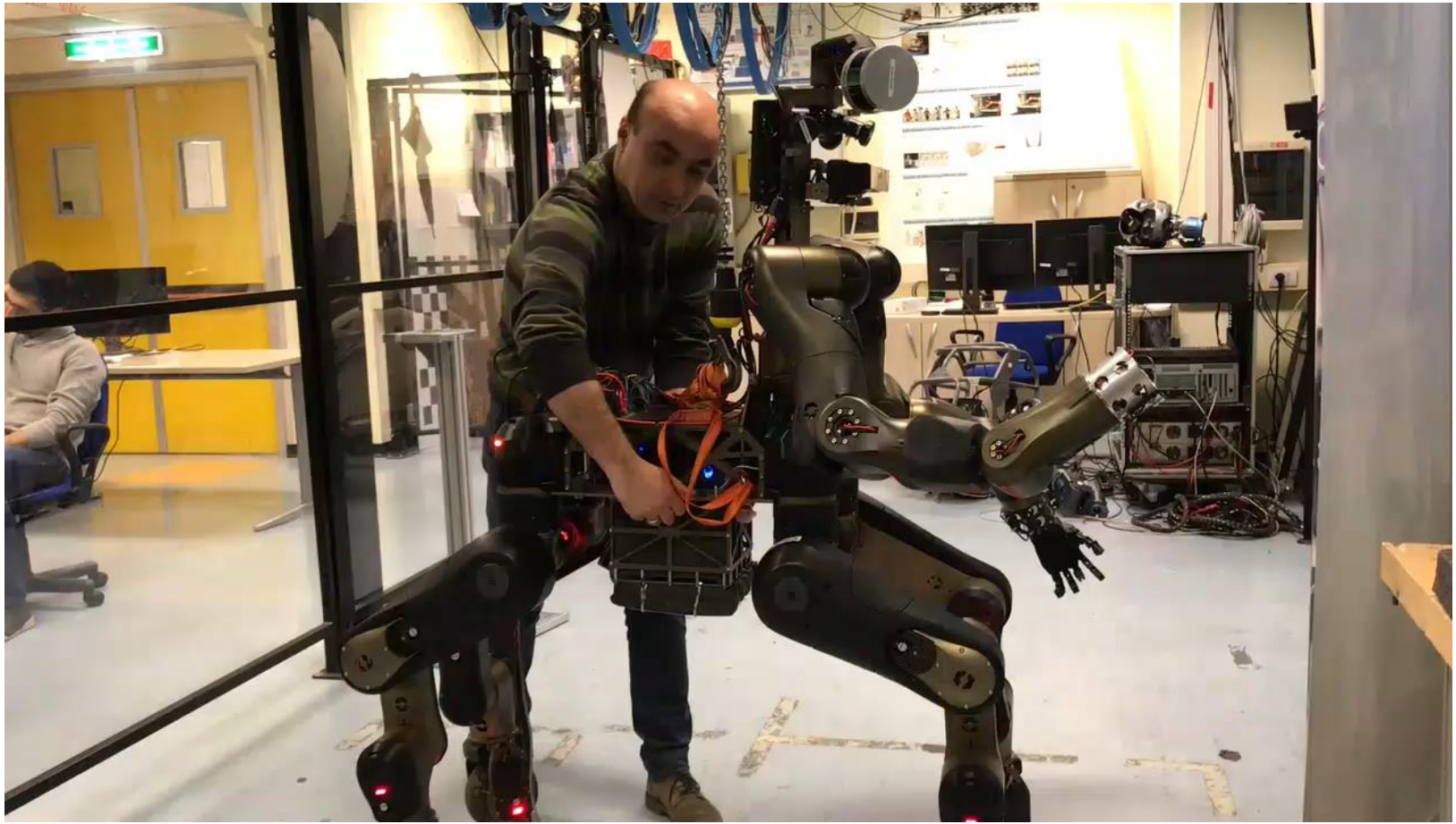
Right: 12 Kg left: 5 Kg load



60 Kg load on pelvis

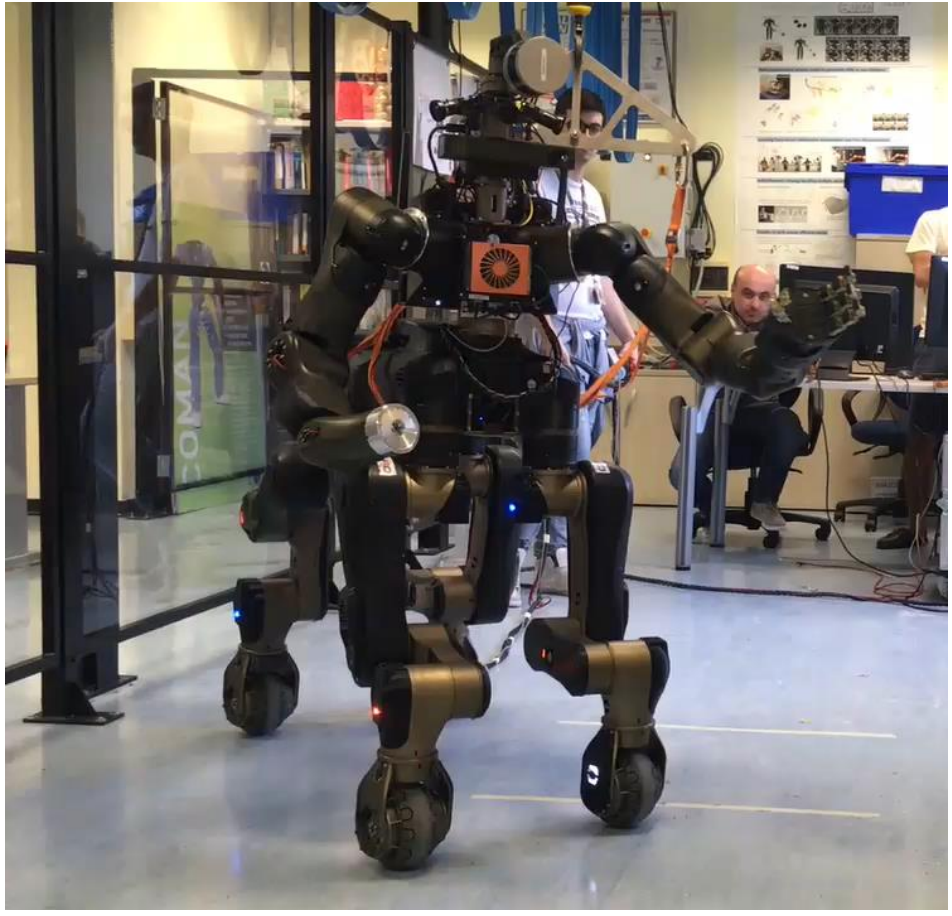
[Tsagarakis et al., IIT 2018]

Compliant



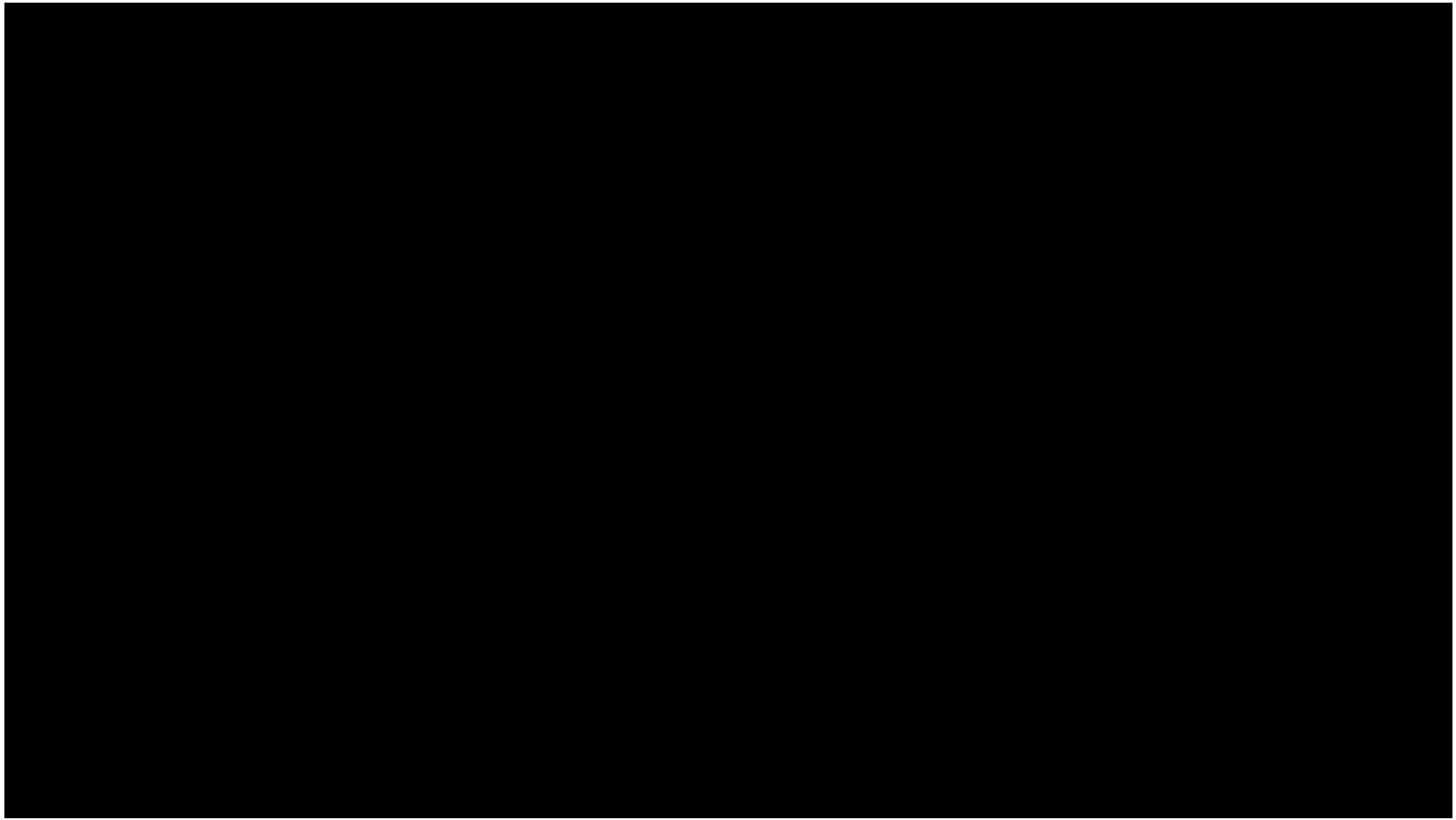
[Tsagarakis et al., IIT 2018]

Full-body Motion Control



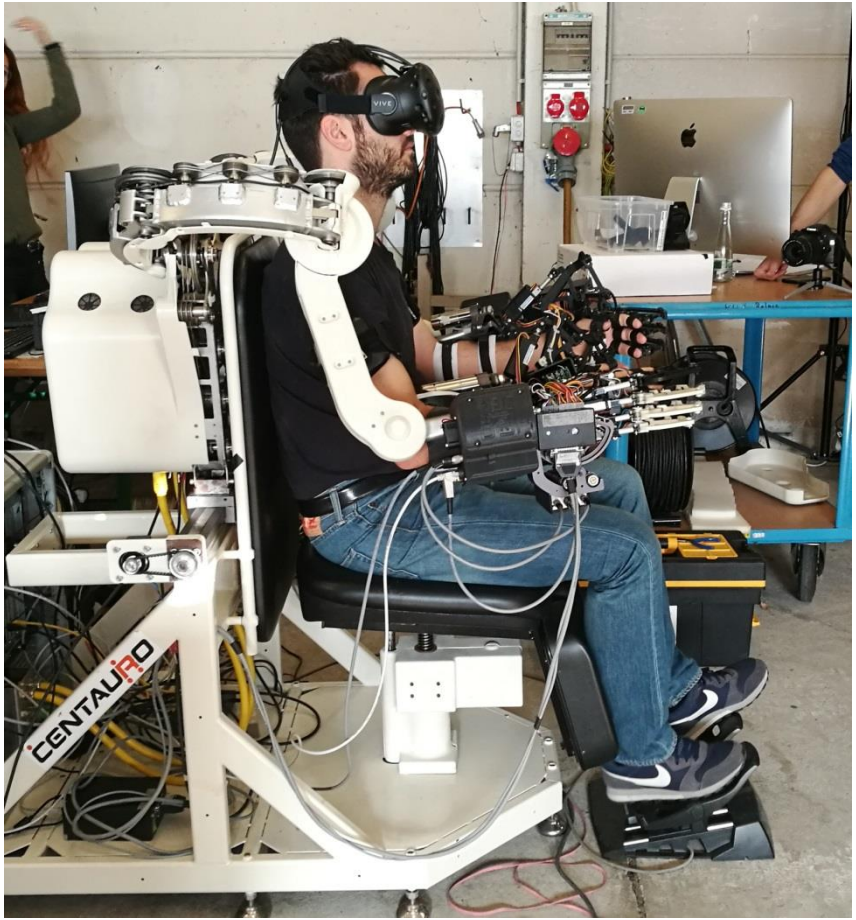
[Tsagarakis et al., IIT 2018]

Quadruped Walking



[Tsagarakis et al., IIT 2018]

Immersive Control via Exoskeleton and HMD



Stereo Visual and Audio Feedback
- Head-Mounted Display
- Audio Headset

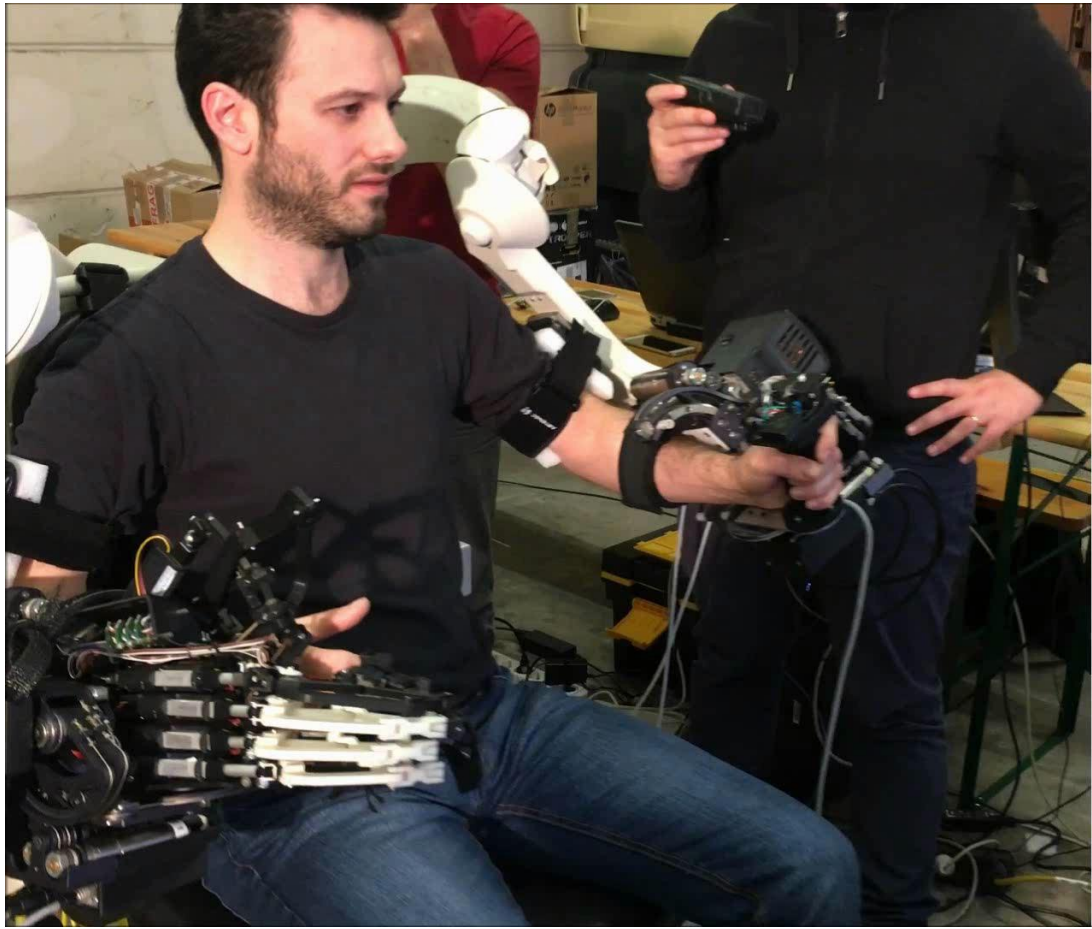
Arm-Hand Movements
- Arm and wrist exoskeleton
- 7 DoFs, wide workspace
- Force and torque feedback

Grasping Control
- Hand exoskeleton
- Independent Fingers
- Force feedback

Navigation
- 3 DoFs Pedals

[Frisoli et al., SSSA 2018]

Main Operator Control



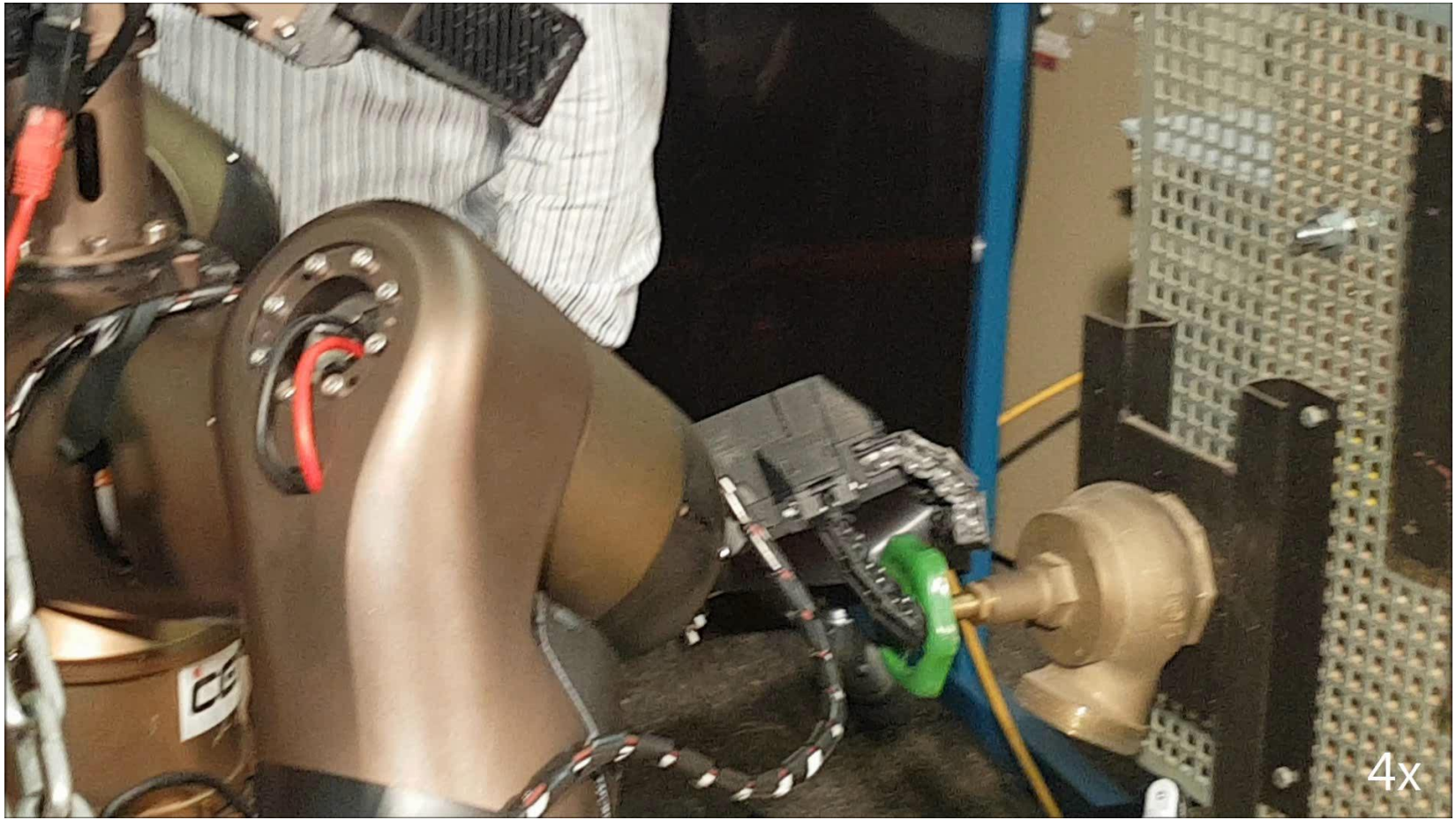
Manipulation Tasks

- Surface
- Valve (lever)
- Valve (gate)
- Snap hook
- Fire hose
- 230V connector
- Cutting tool
- Driller
- Screw driver
- Grasping

Used control interfaces

[Frisoli et al., SSSA 2017]

Turning a Valve

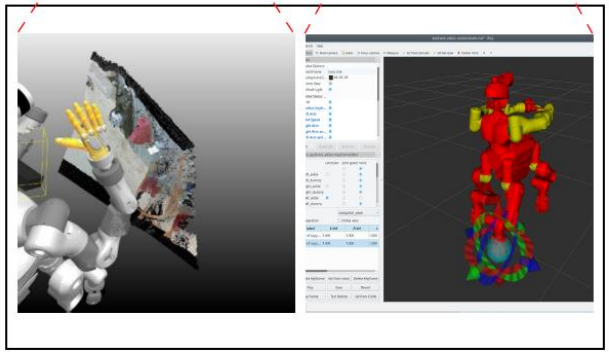


[Frisoli et al., SSSA 2017]

Support Operator Interfaces

3D VEROSIM visualization

Robot state & Keyframe editor

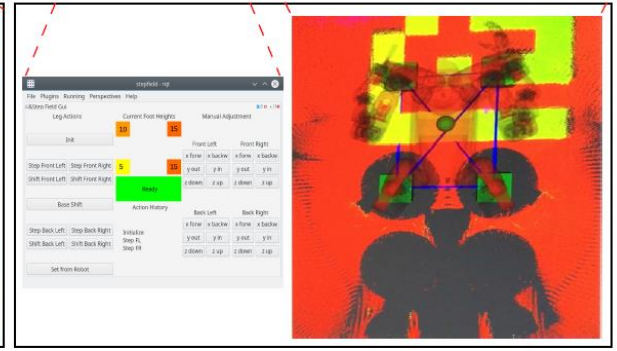


Foot cameras

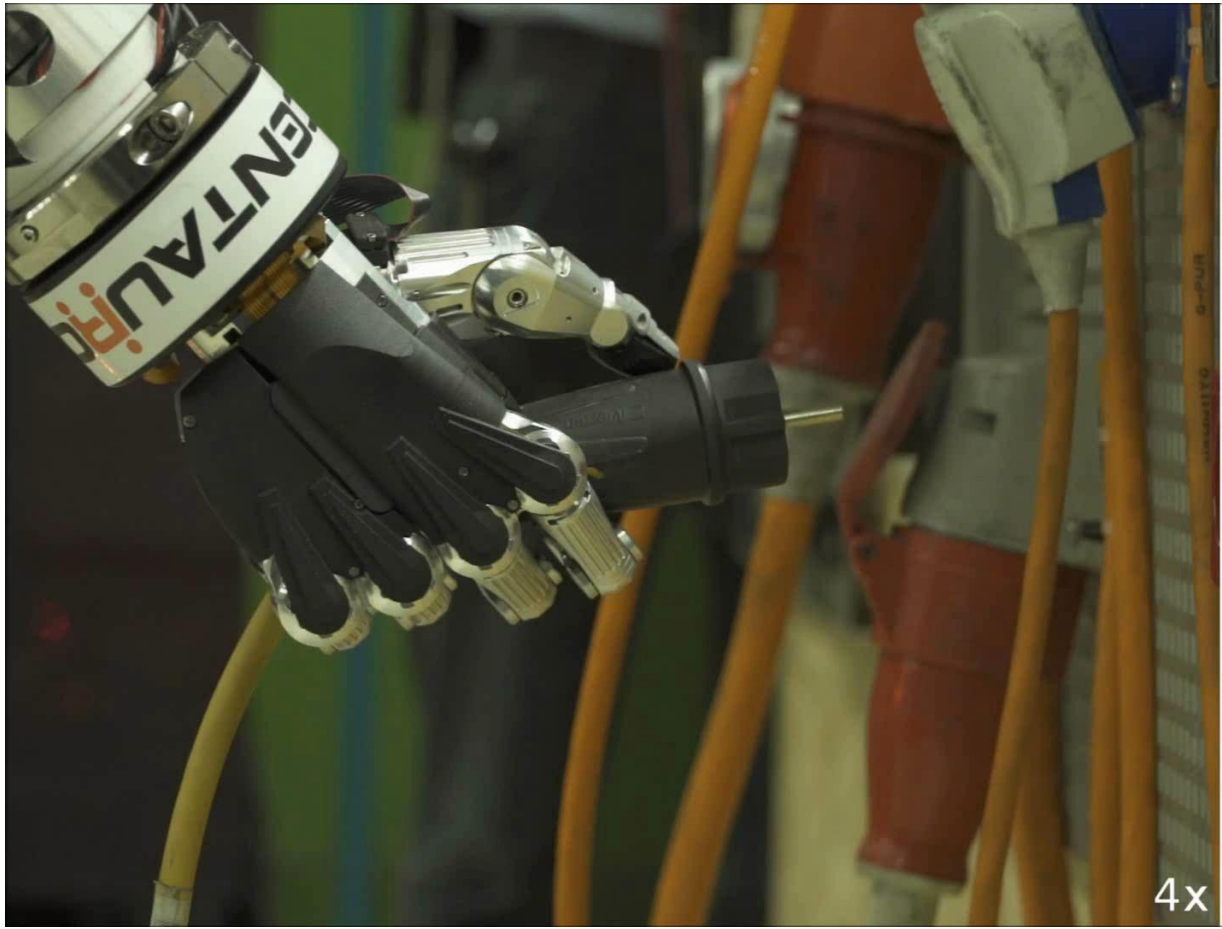
Panoramic view & RGB Kinect image

Task specific GUI

Pointcloud, ground contact & COM markers



Connecting a Plug



Manipulation Tasks

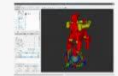
- Surface
- Valve (lever)
- Valve (gate)
- Snap hook
- Fire hose
- 230V connector
- Cutting tool
- Driller
- Screw driver
- Grasping

Used control interfaces


Joystick


Exus


6D

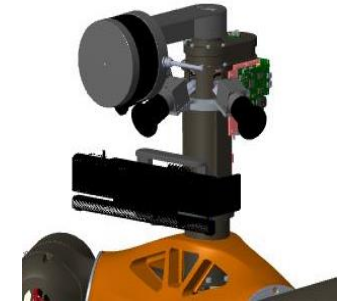

Keyframes

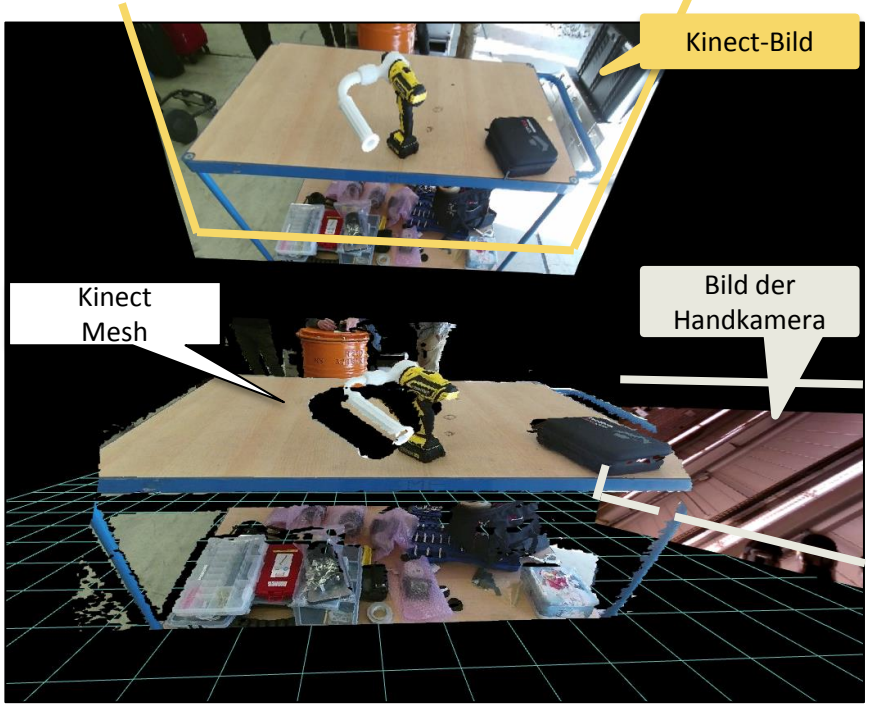

Stepping


Autonomous

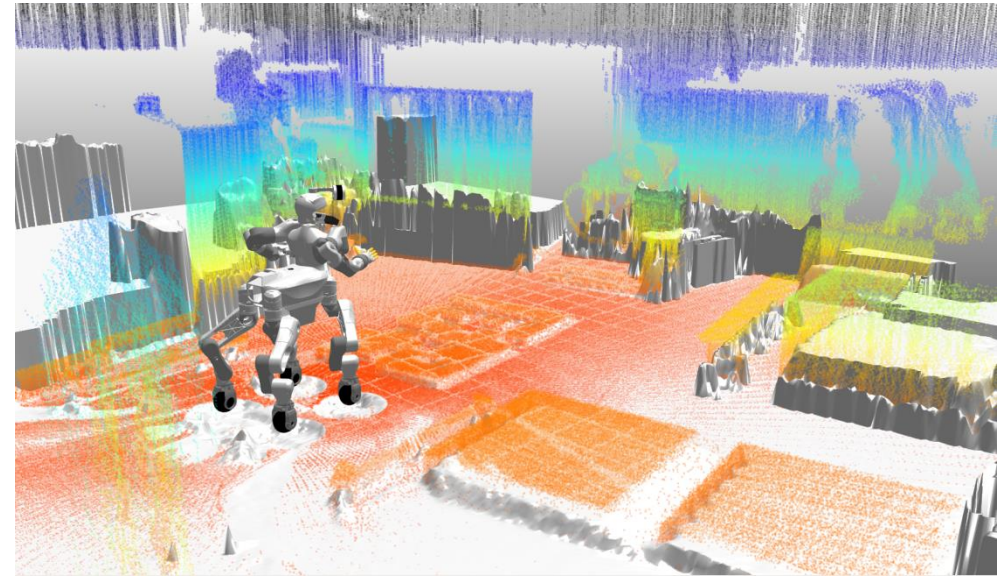
3D Environment Visualization

- Measurements of 3D lidar, cameras, RGB-D cameras
- Immersive visualization through HMD (head tacking)





Immersive 3D visualization for main operator



Visualization for third-person operator

[Cichon et al., RWTH 2018]

Opening and Going Through a Door

Locomotion Tasks

- Ramp
- Small door
- Regular door
- Gap
- Step field
- Stairs

Used control interfaces


Joystick


Exus

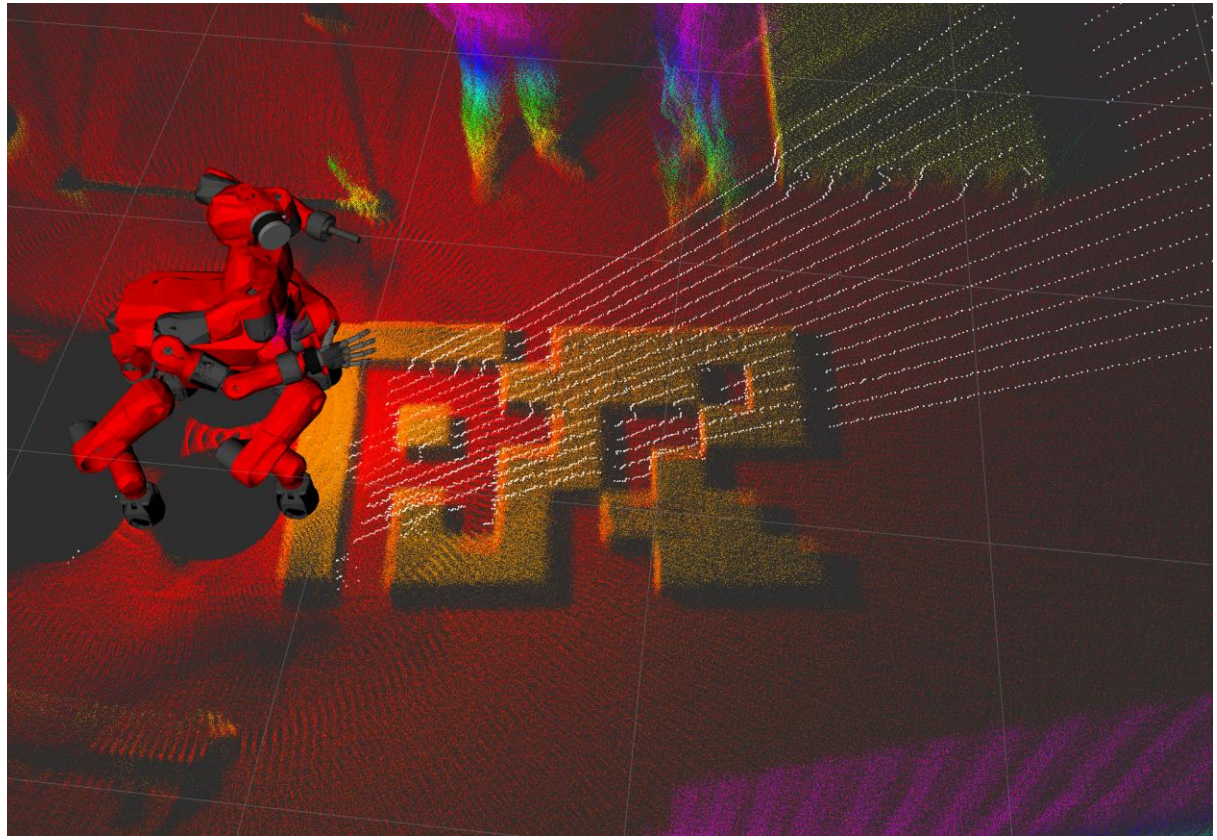

6D


Keyframes


Stepping


Autonomous

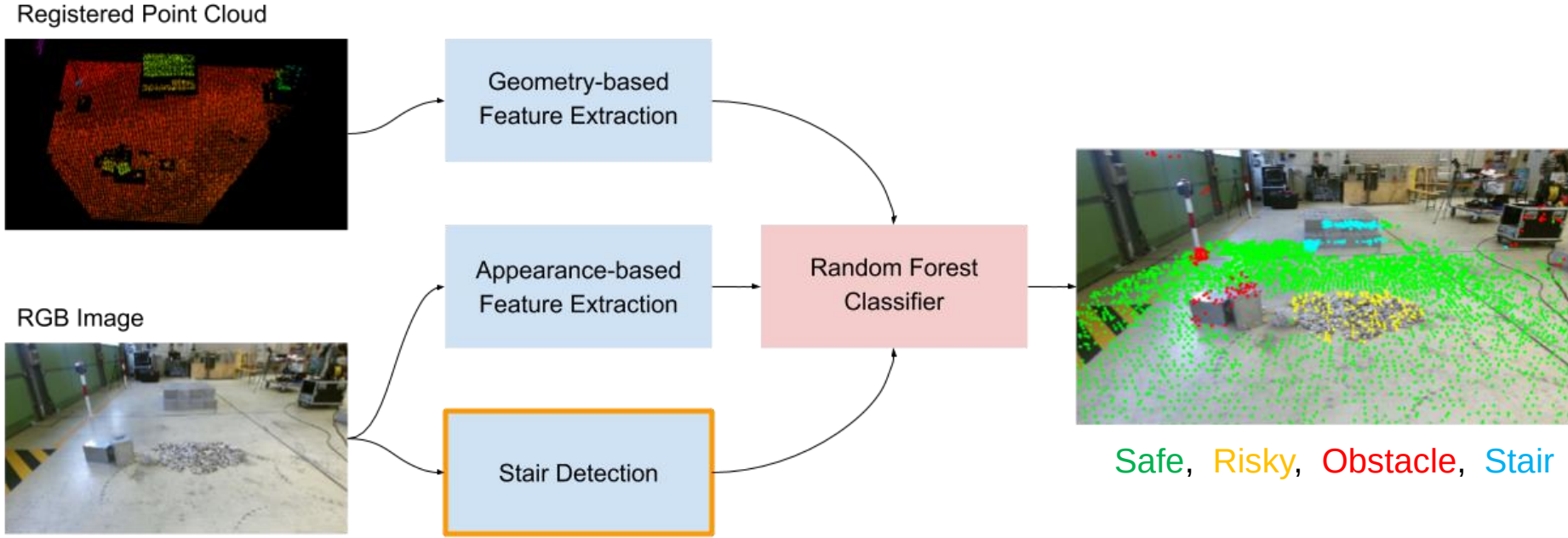
3D Mapping and Localization



Walking over a Step Field

Terrain Classification

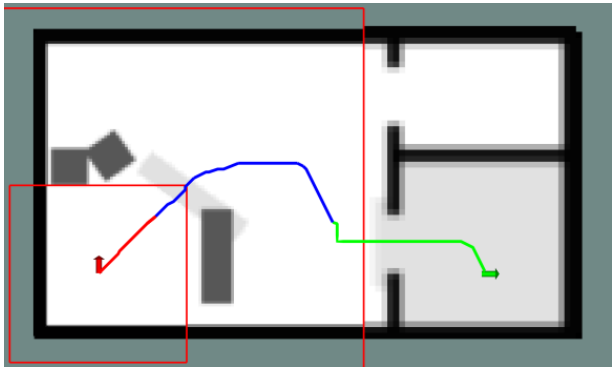
- Based on 3D lidar and color images
- Detection of uneven ground, obstacles, stairs

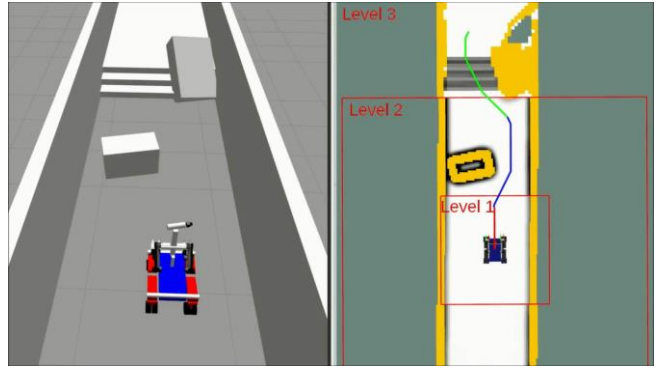


[Chen et al. KTH 2018]

Hybrid Driving-Stepping Locomotion Planning: Abstraction

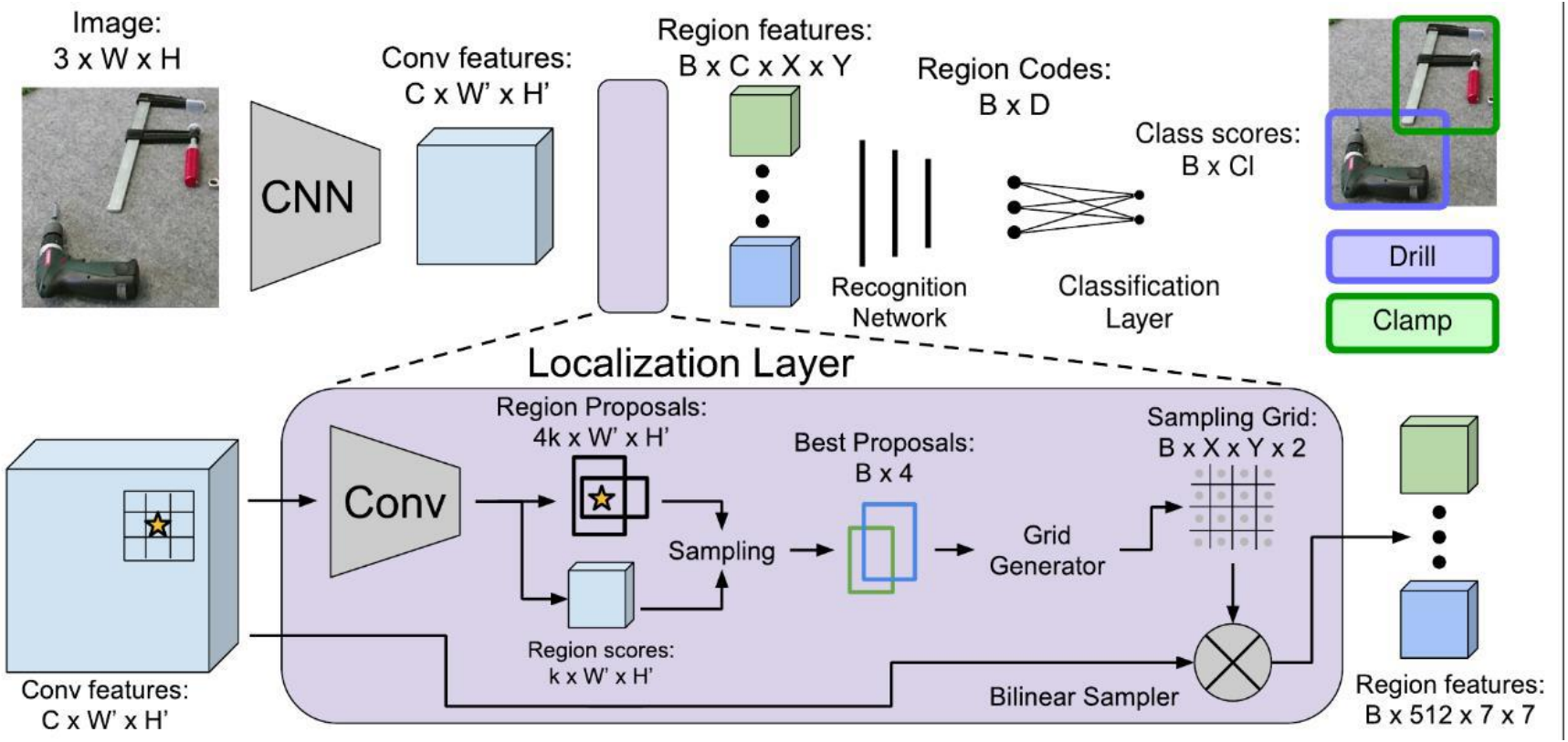
Level	Map Resolution	Map Features	Robot Representation	Action Semantics
1	• 2.5 cm • 64 orient.	• Height		• Individual Foot Actions
2	• 5.0 cm • 32 orient.	• Height • Height Difference		• Foot Pair Actions
3	• 10 cm • 16 orient.	• Height • Height Difference • Terrain Class		• Whole Robot Actions





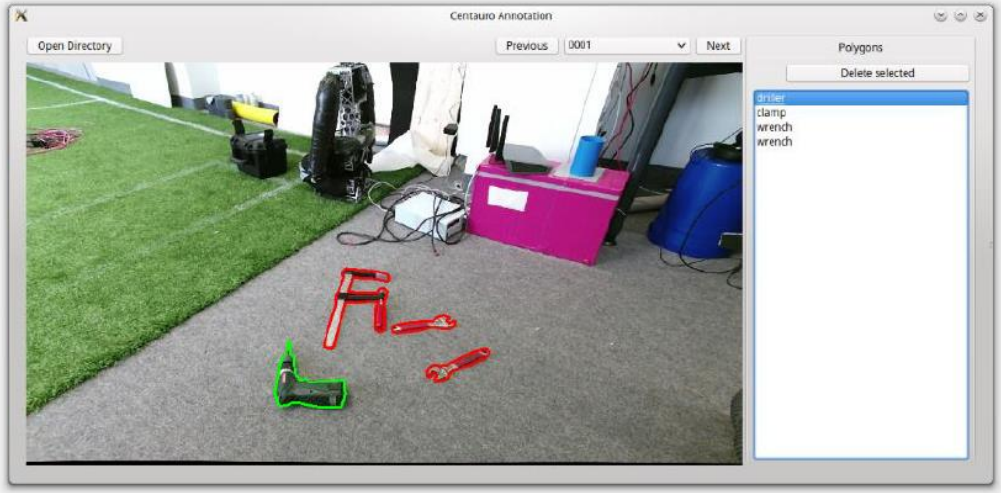
[Klamt and Behnke, IROS 2017, ICRA 2018]

Deep Learning Object Detection



[Johnson et al. 2015]

CENTAURO Workspace Perception Data Set



129 frames, 6 object classes

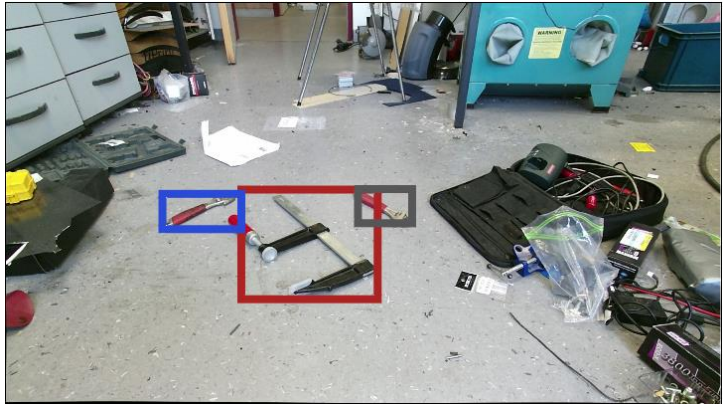
https://www.centauro-project.eu/data_multimedia/tools_data

Tool Detection Results

[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

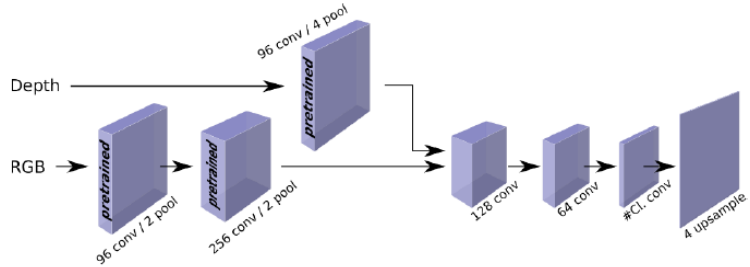
Tools Detection Examples



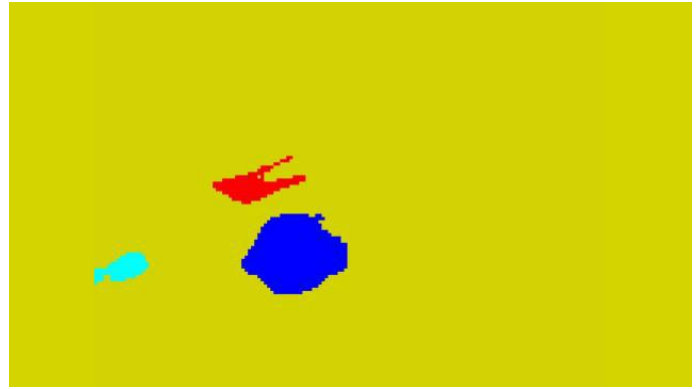
[Schwarz et al. IJRR 2017]

Semantic Segmentation

- Deep CNN



[Husain et al. RA-L 2016]

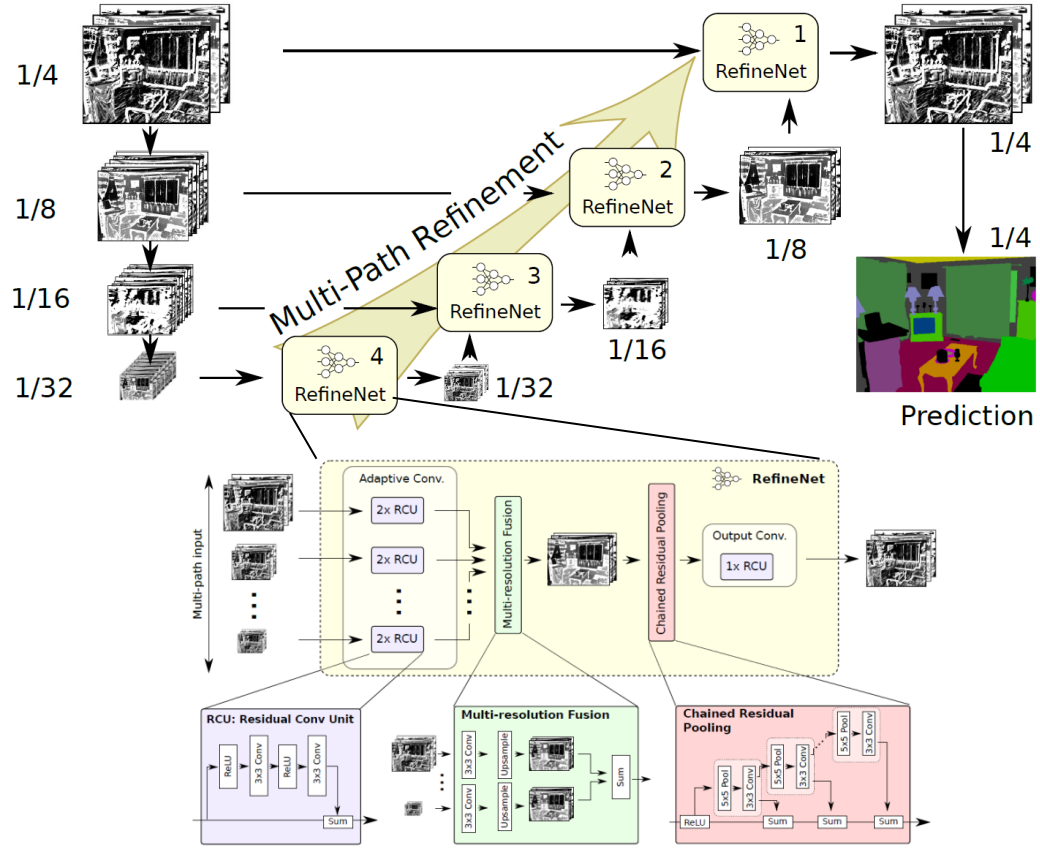


Pixel-wise accuracy:

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

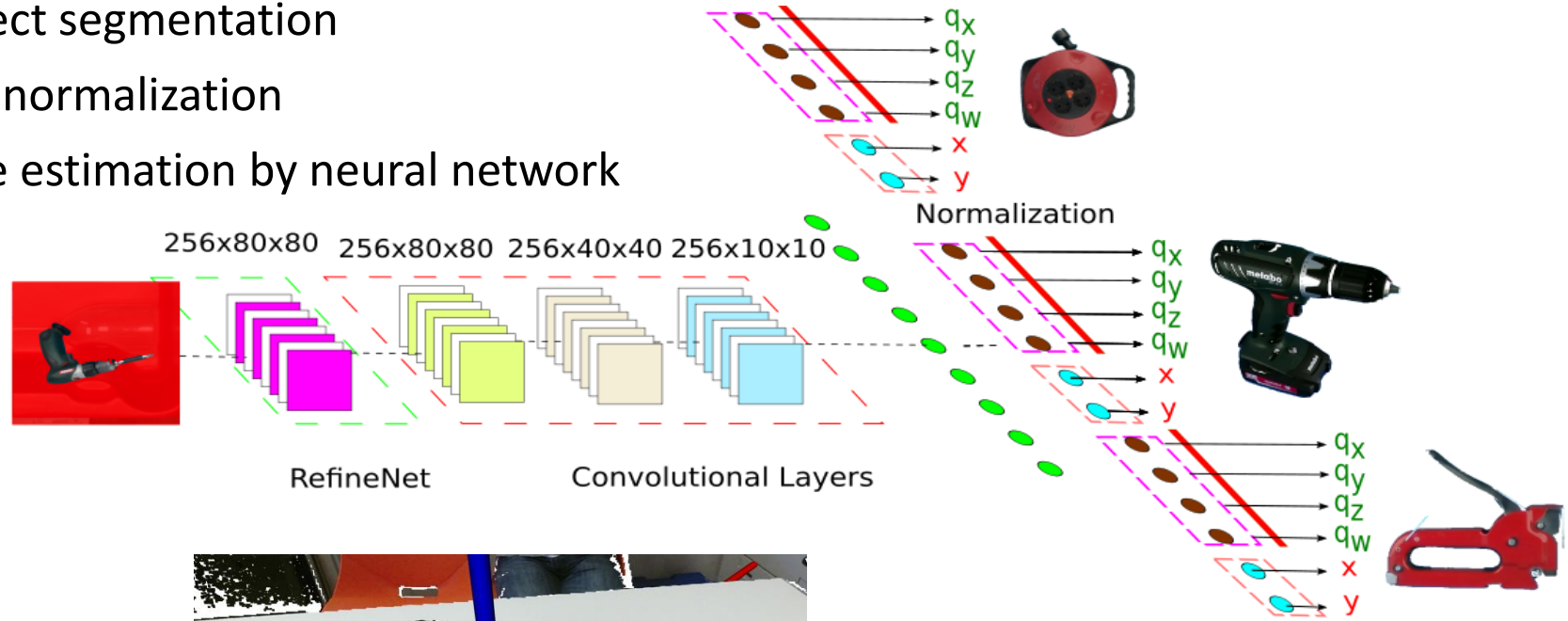
2. **Improving generalization**:
   Object-centered models,
   deformable registration,
   transfer learning,
   semi-supervised learning

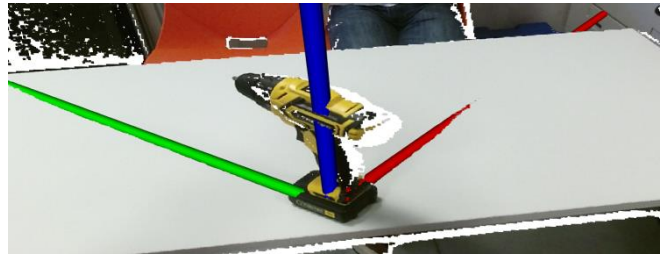
Object Capture and Scene Rendering

- Object capture on turn table
- Rendering in scenes with complex backgrounds
- => Ground truth without human annotation

6D Pose Estimation

- Object segmentation
- Size normalization
- Pose estimation by neural network





[Periyasamy et al. IROS 2018]

Transfer of Manipulation Skills

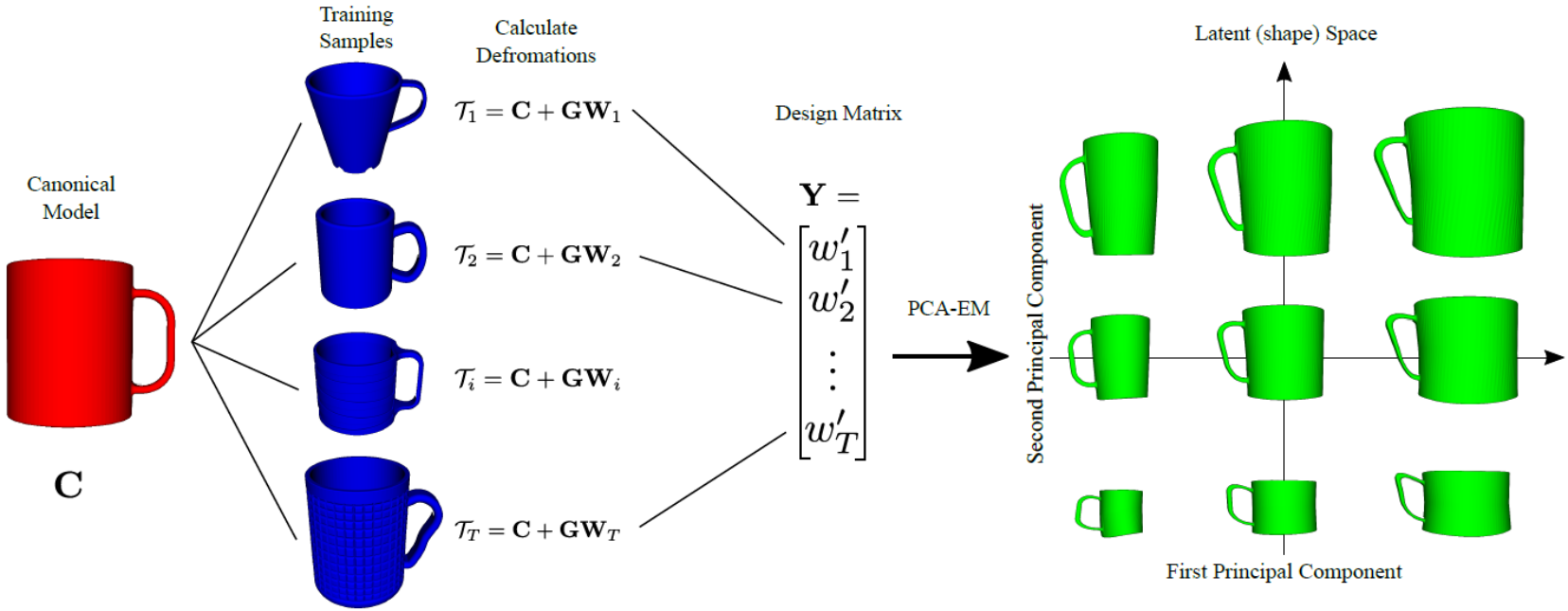
- Objects belonging to the same **category** can be handled in a very similar manner.

Transfer of Manipulation Skills

Knowledge Transfer

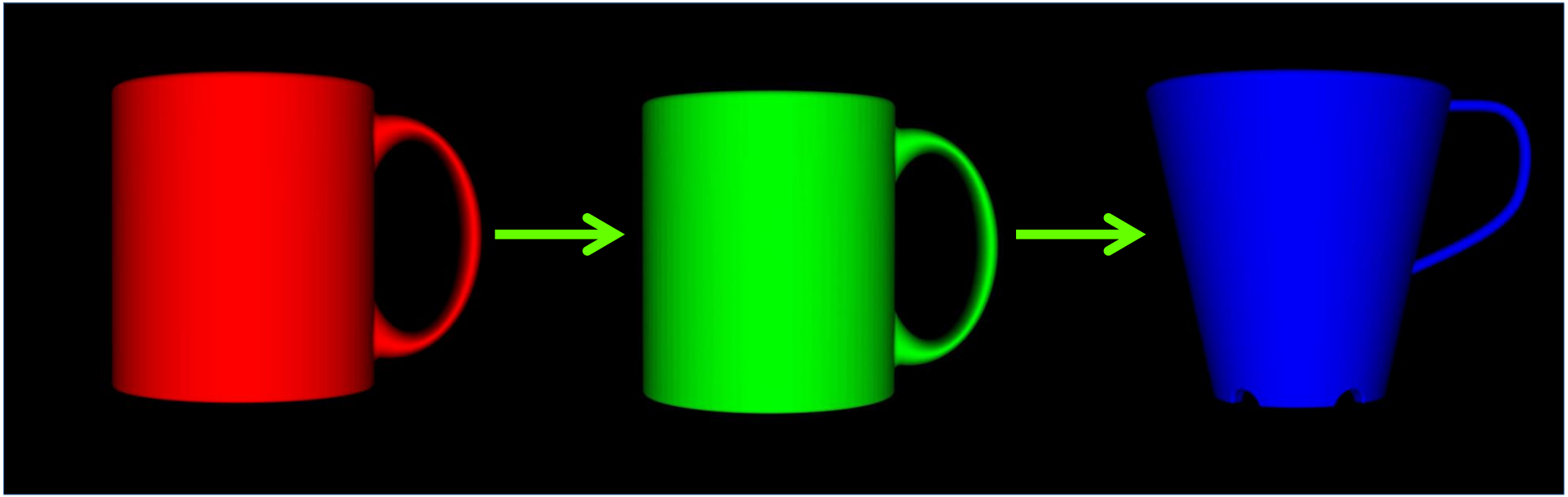
Learning a Latent Shape Space

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



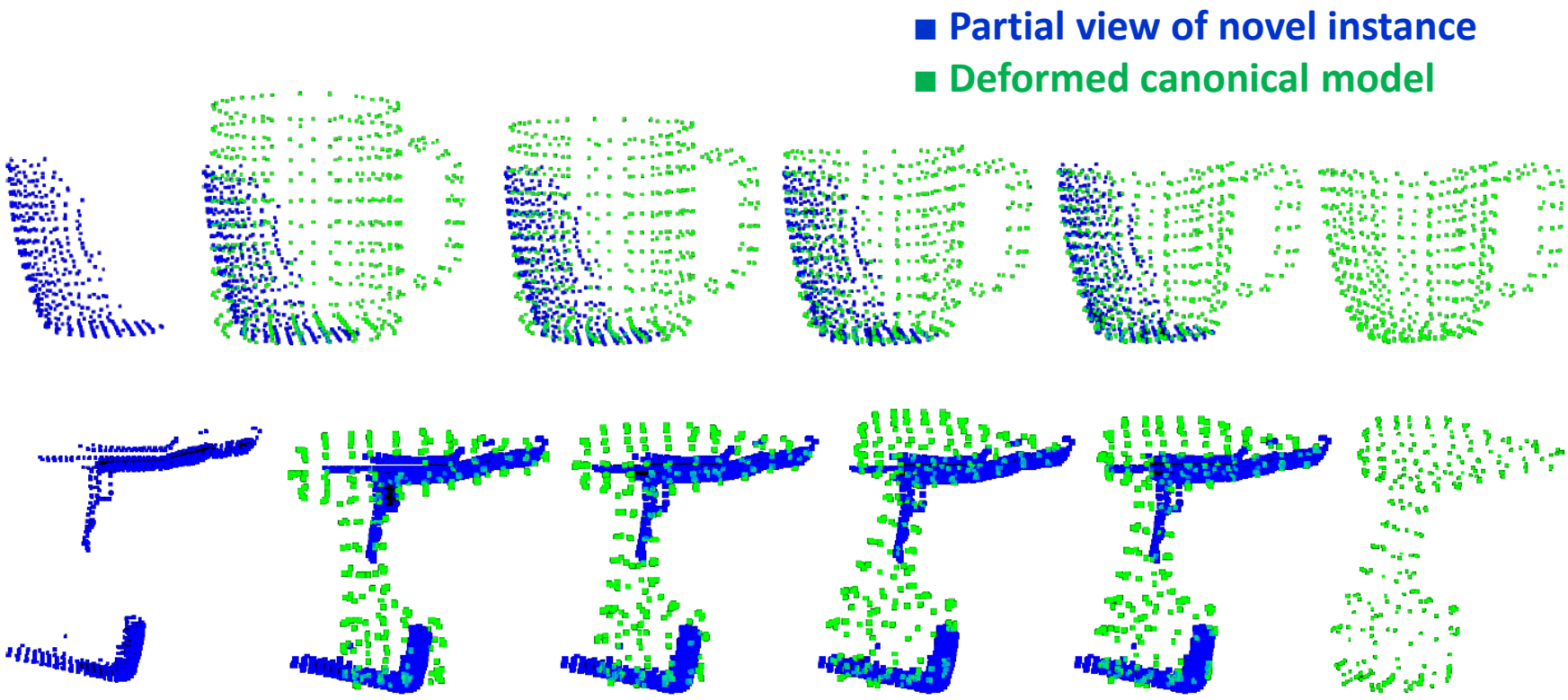
[Rodriguez and Behnke ICRA 2018]

Interpolation in Shape Space



[Rodriguez and Behnke ICRA 2018]

Shape-aware Non-rigid Registration



[Rodriguez and Behnke ICRA 2018]

Shape-aware Registration for Grasp Transfer

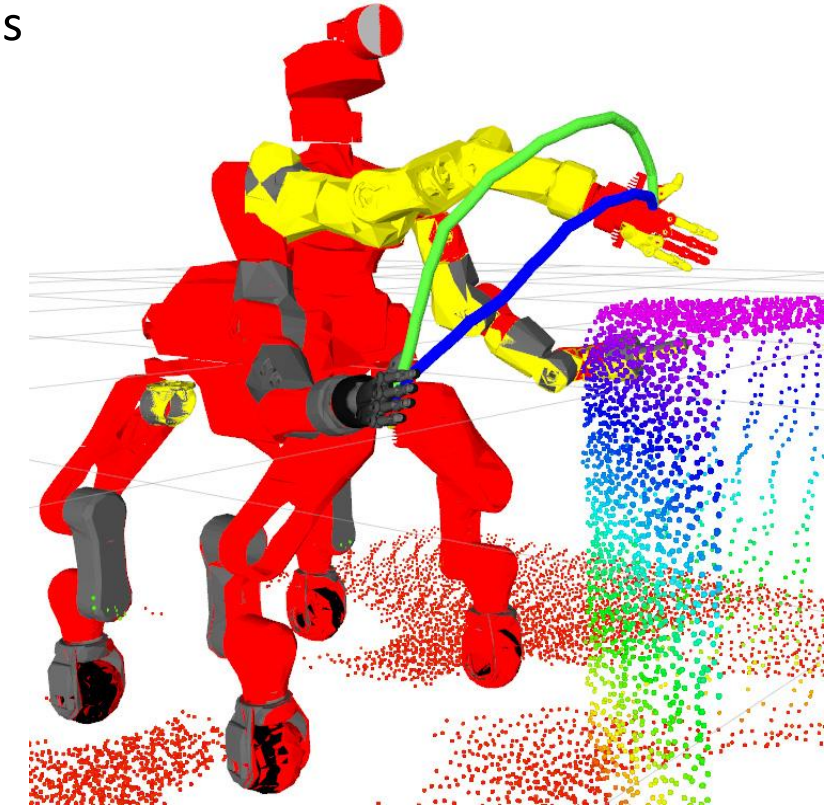
- Full point cloud

- Partial view

[Rodriguez and Behnke ICRA 2018]

Obstacle Avoidance and Trajectory Optimization

- Stochastic optimization of arm trajectory considering the measured obstacles
- Modular, weighted cost function
  - Obstacle avoidance
  - Joint limits
  - Duration
  - Torques
  - Orientation constraints

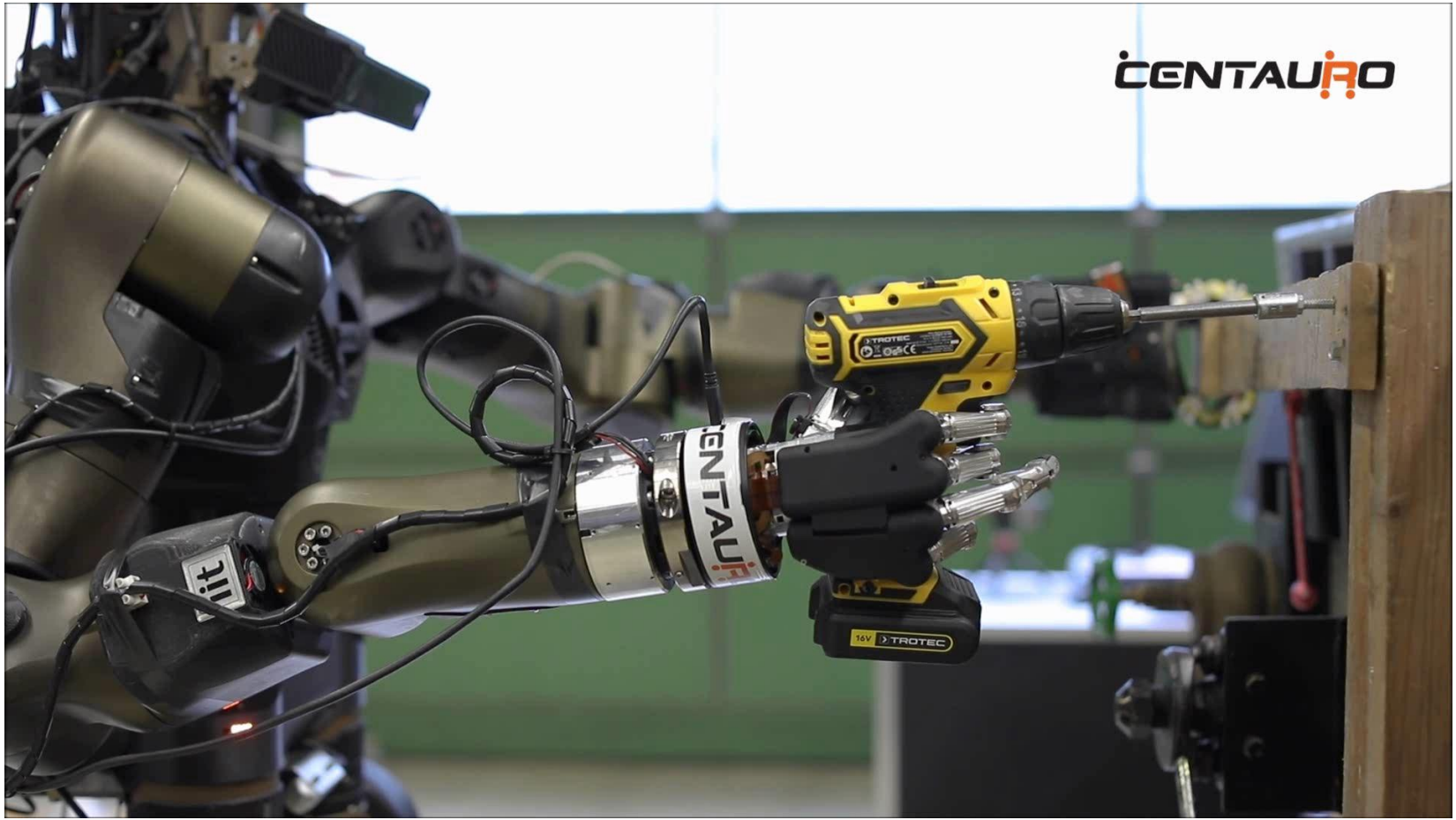


[Pavlichenko and Behnke: IROS 2017]

Grasping an Unknown Power Drill

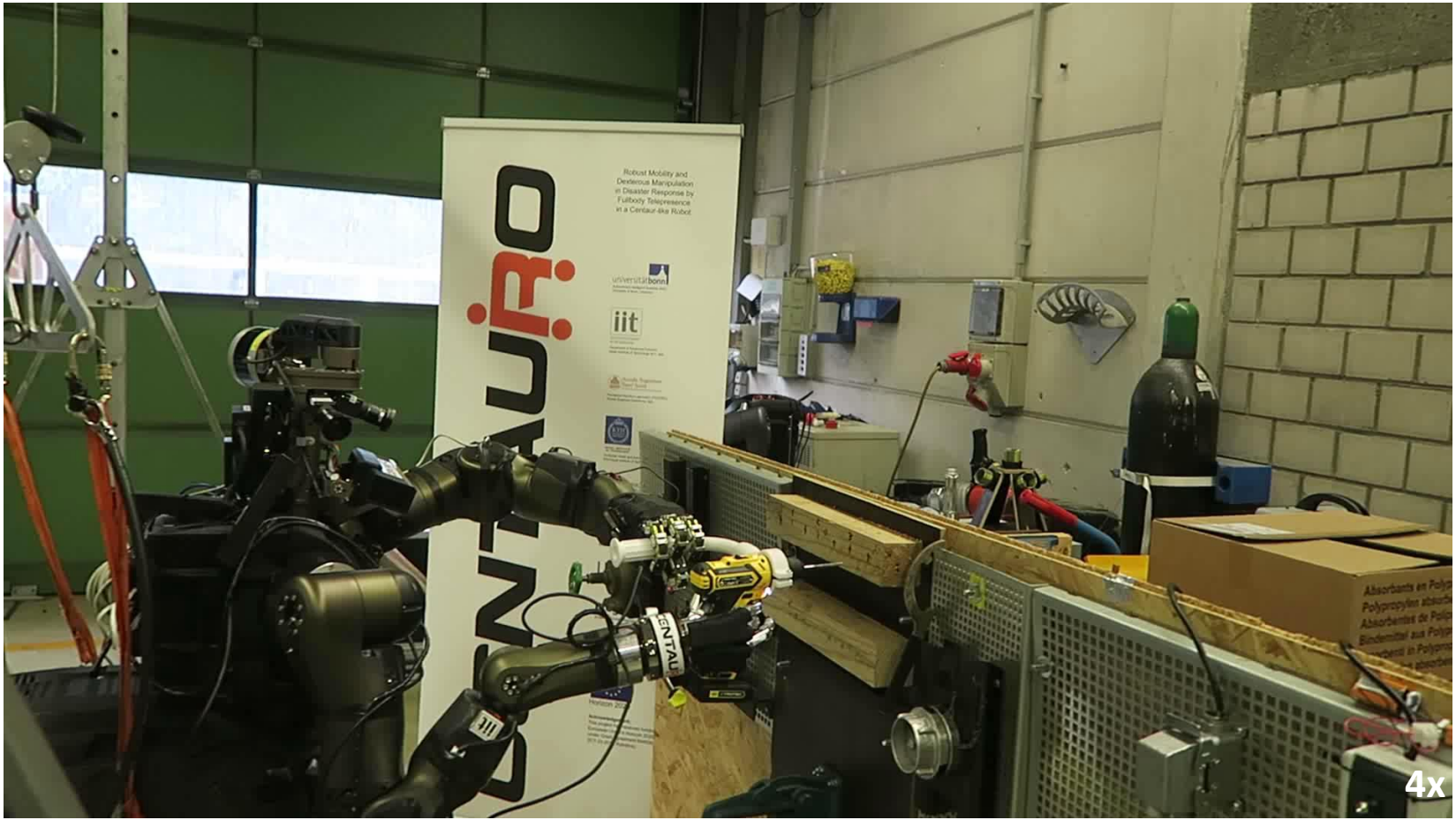
Fastening a Screw

Bimanual Fastening Task

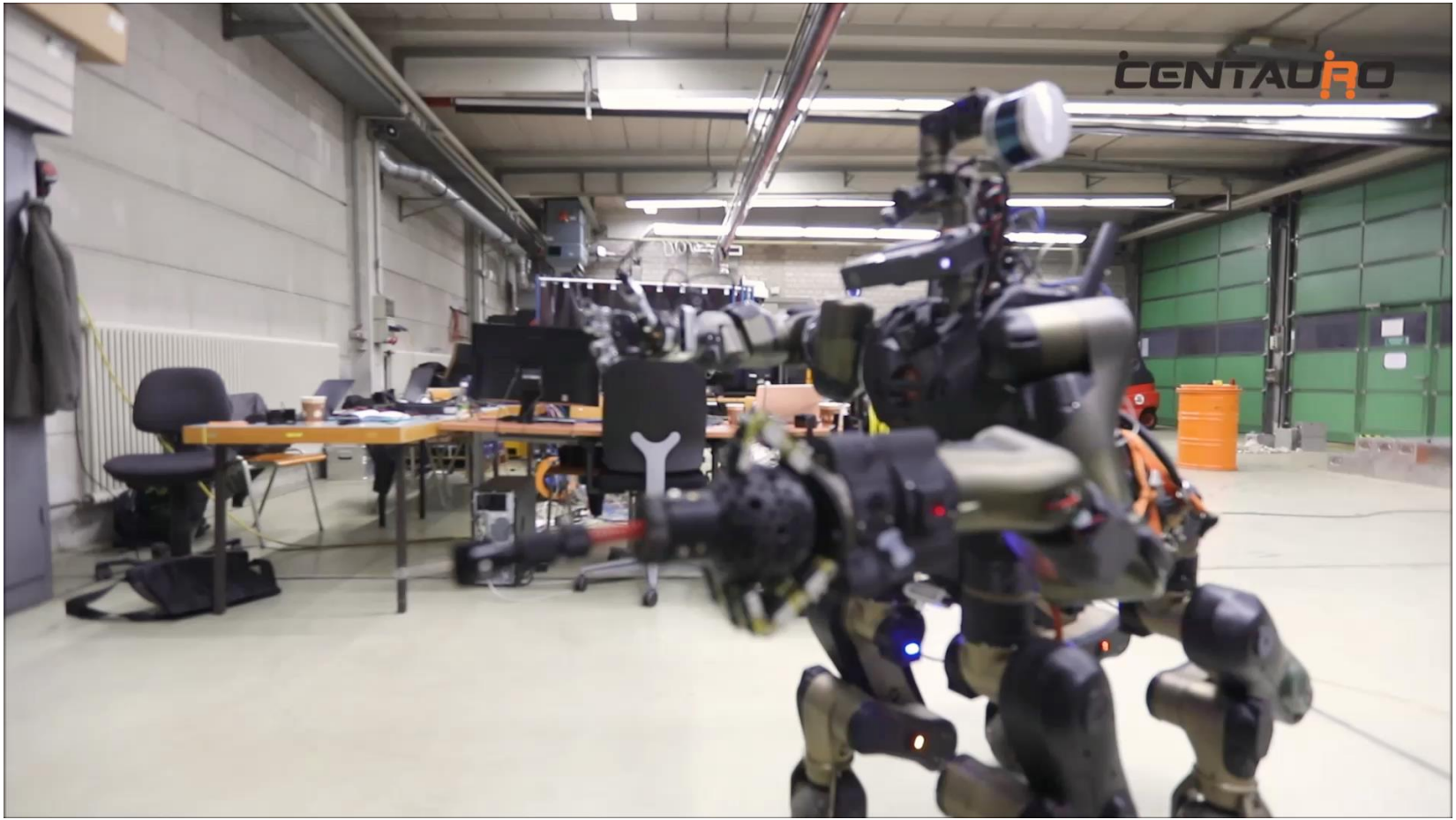


Autonomous Bimanual Grasping

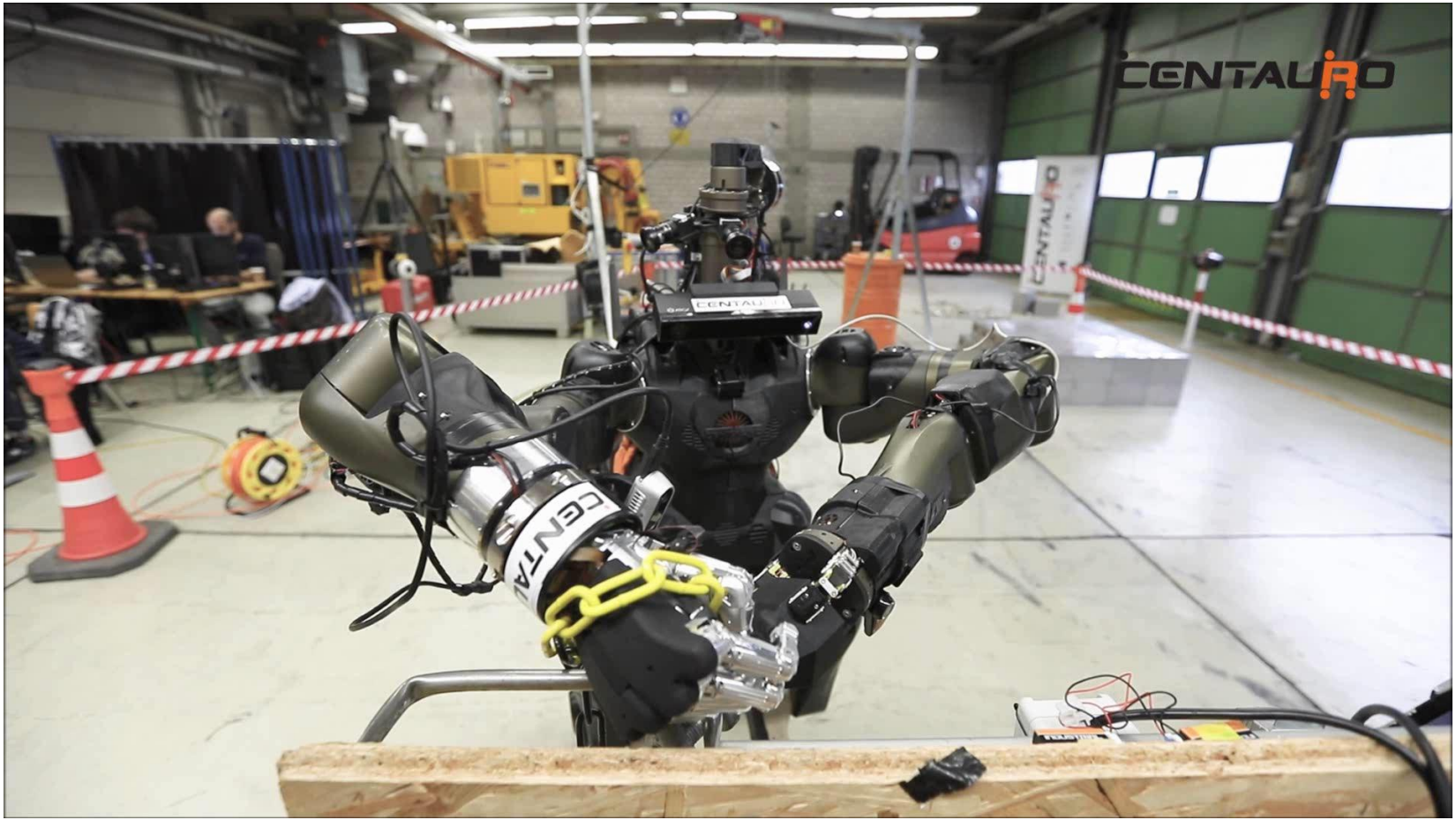
Bimanual Drilling



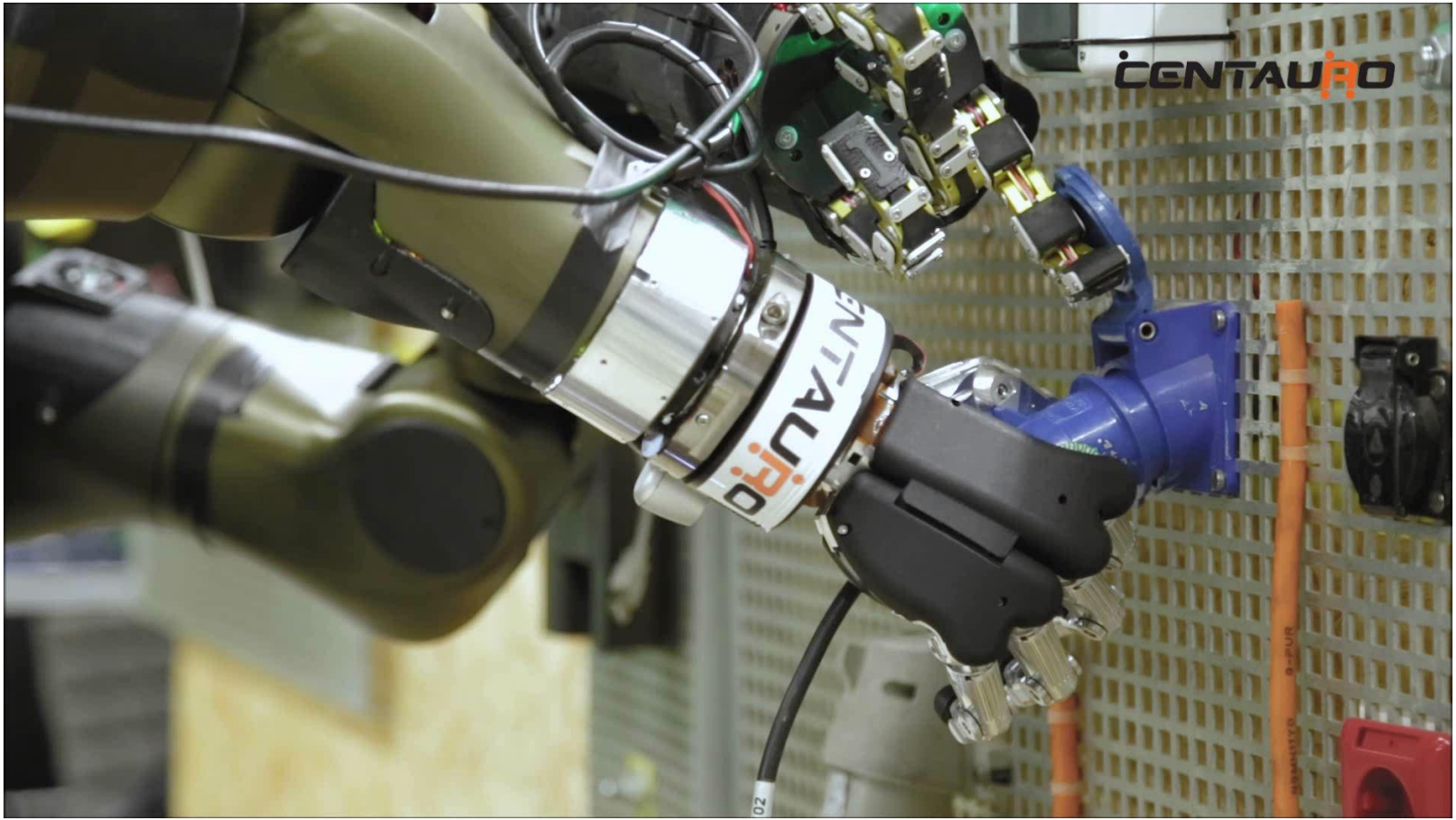
Opening a Door with a Key



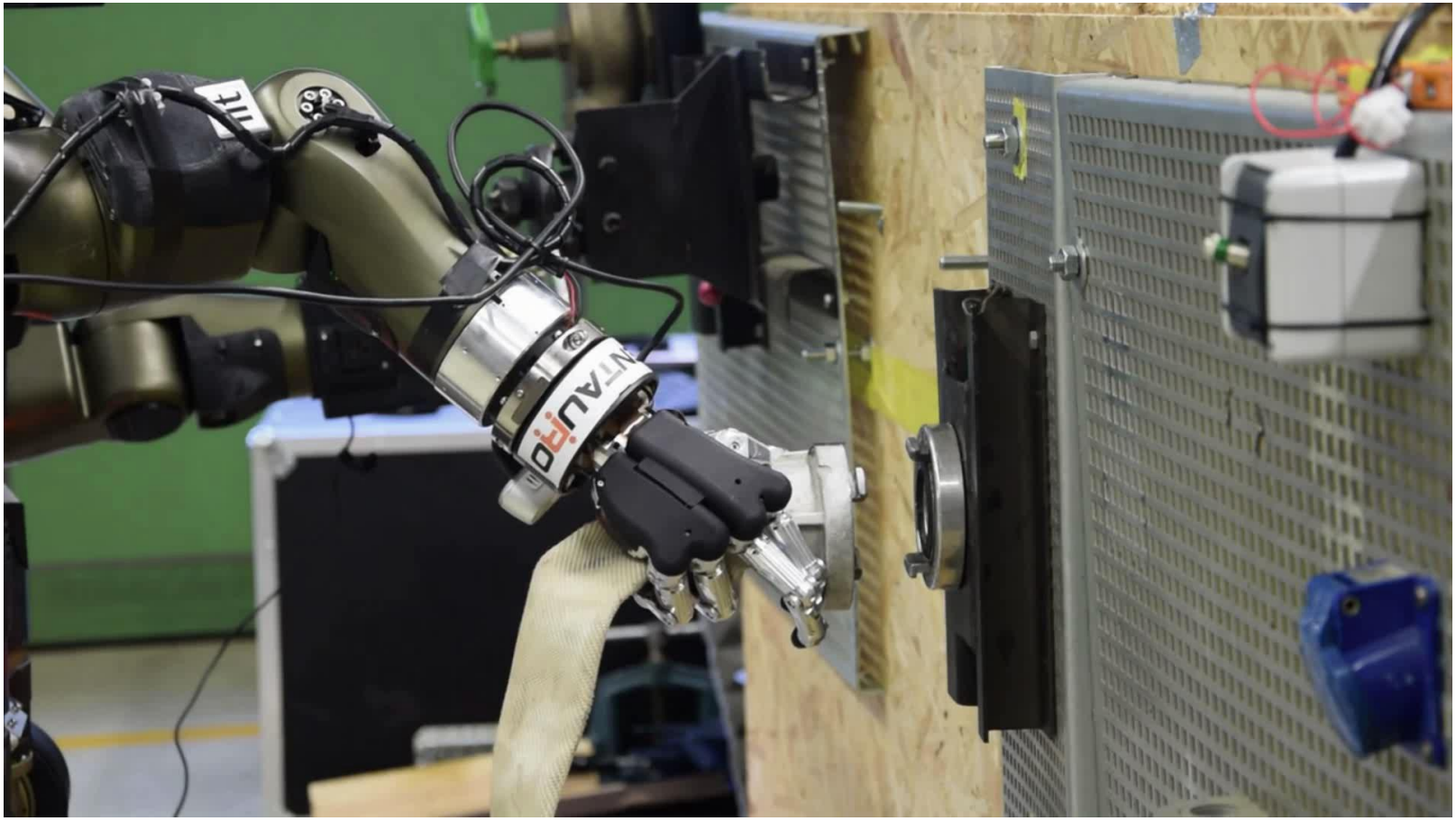
Closing a Shackle



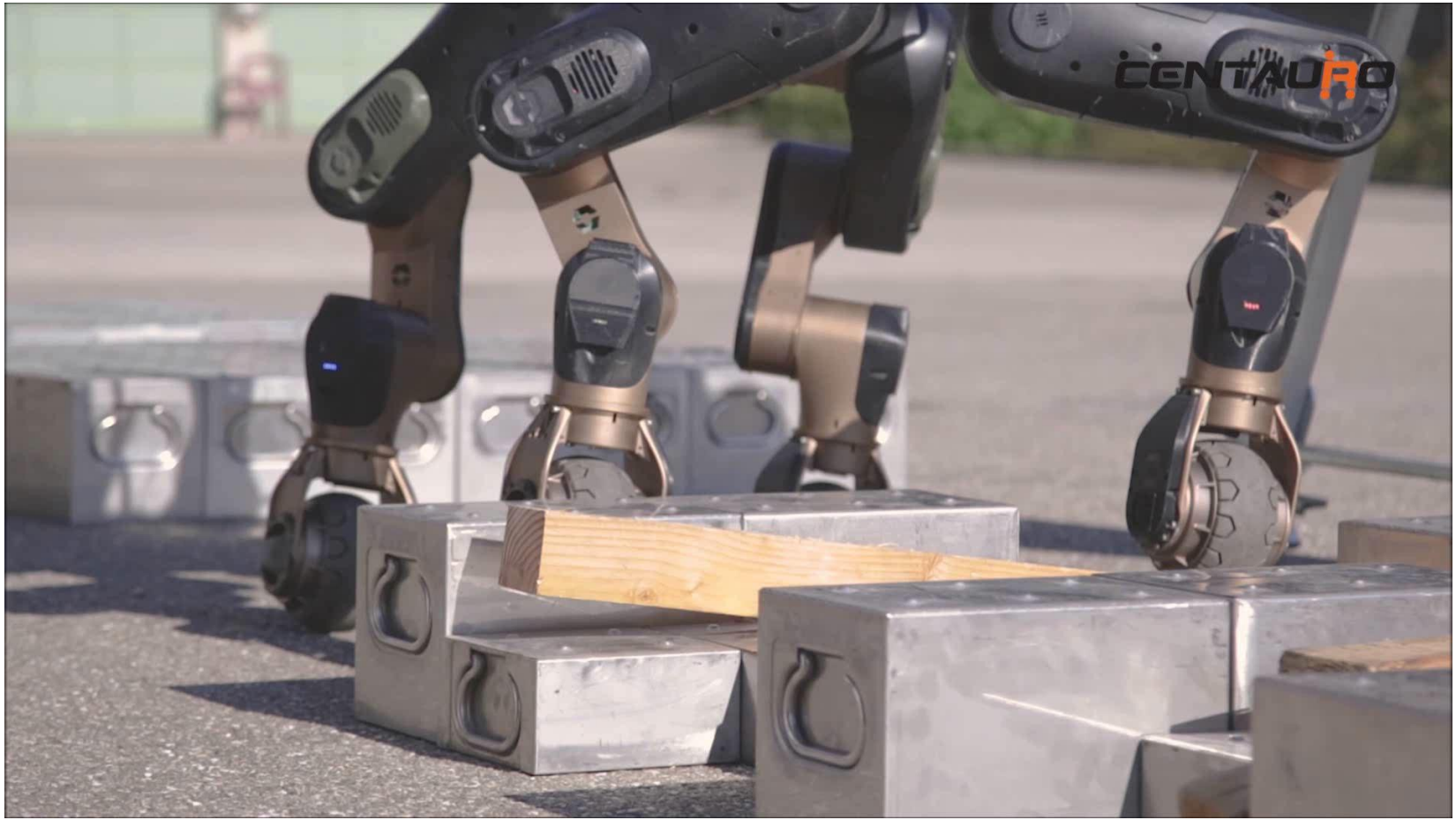
Bimanual Plug Tasks: Socket with Lid, Loose Socket



Connecting a Fire Hose using a Storz Wrench

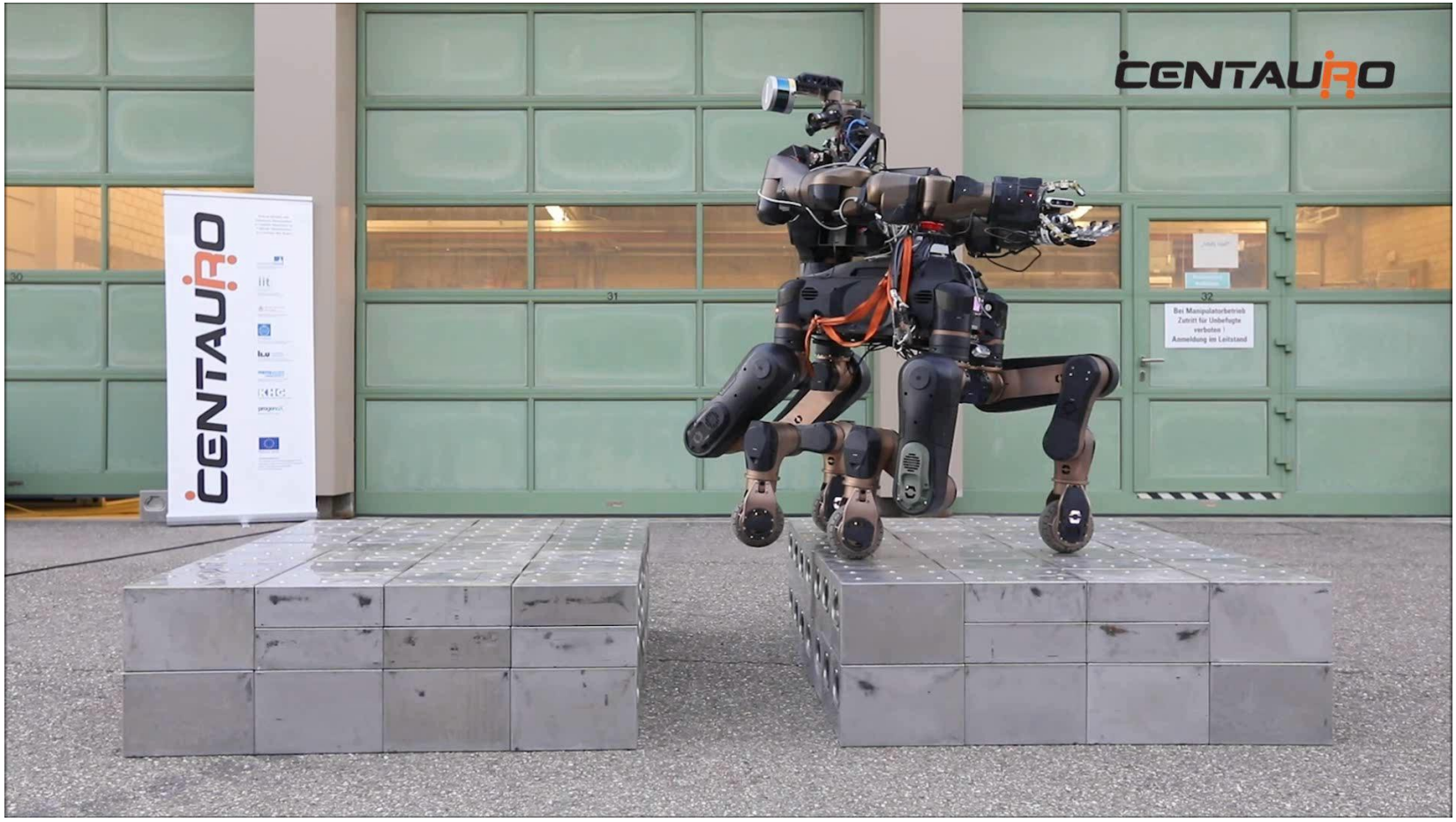


Step Field with Debris

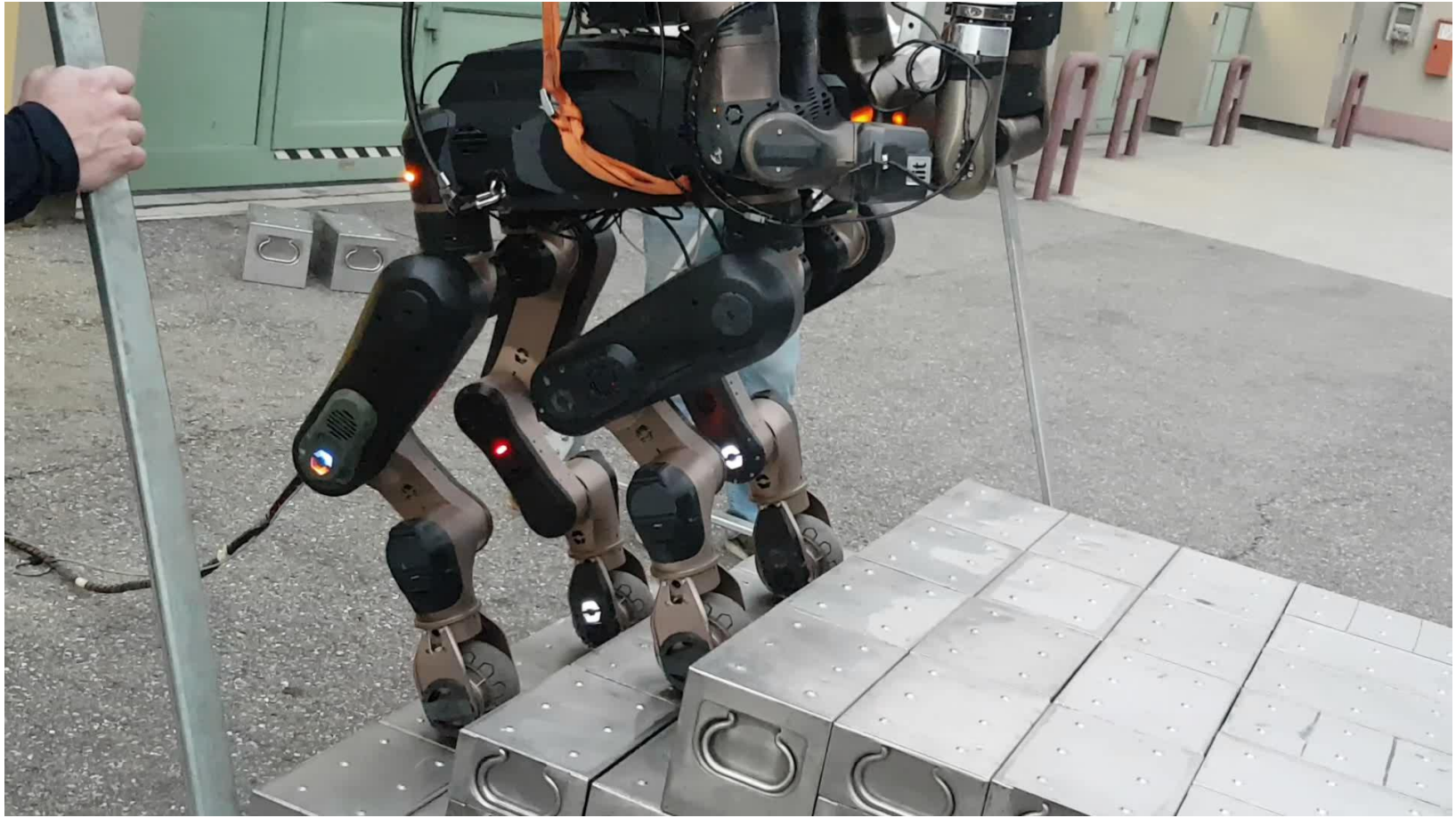


Autonomous Navigation

Climbing over a Gap



Stair Climbing



CENTAURO Team

Conclusions

- Capable robot for disaster-response scenarios
- Immersive teleoperation by exoskeleton and HMD
- Flexible third-person teleoperation interfaces
- 3D mapping and semantic terrain perception
- Efficient hybrid navigation planning
- Semantic perception of manipulation work space
- Grasping skill transfer to unknown instances
- Tool use, bimanual manipulation
- Demonstrated multiple challenging locomotion and manipulation tasks
- Further work needed to
  - Reduce costs, complexity
  - Increase robustness, speed, level of autonomy