

# 3D Simultaneous Localization and Mapping and Navigation Planning for Mobile Robots in Complex Environments

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Autonomous Intelligent Systems



# Some of Our Cognitive Robots

- Equipped with many sensors and DoFs
- Demonstration in complex scenarios



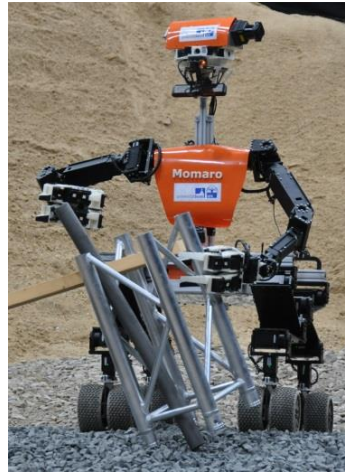
MAV



Soccer robot



Service robot



Exploration robot

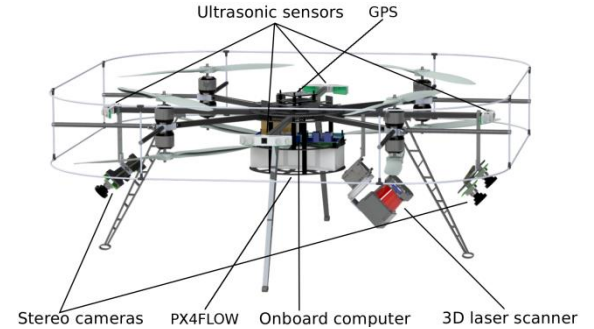
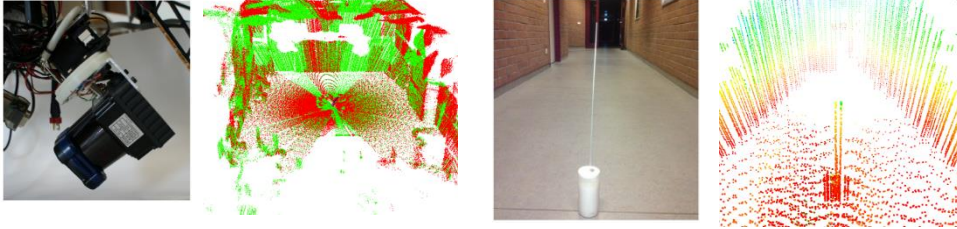


Picking robot

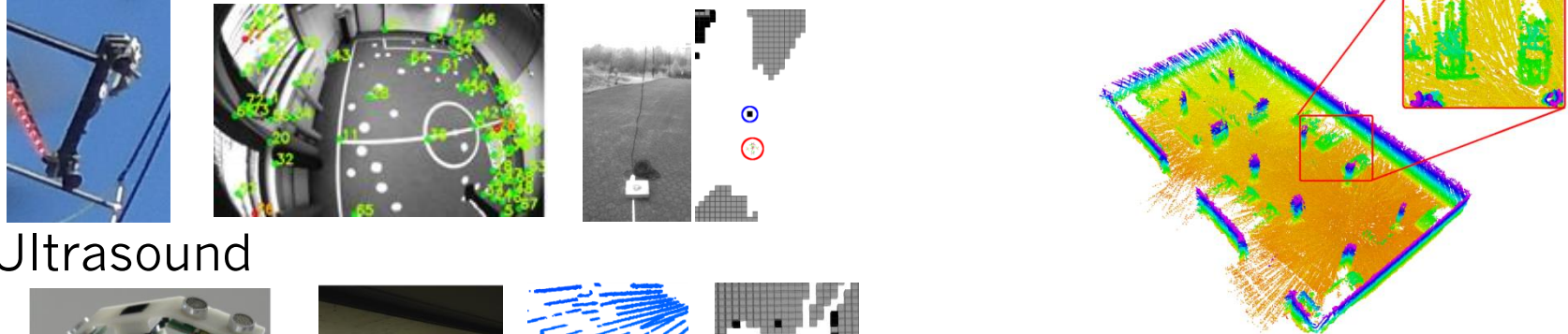
# Autonomous Flight Near Obstacles

- Multimodal obstacle detection

- 3D laser scanner



- Stereo cameras



- Ultrasound

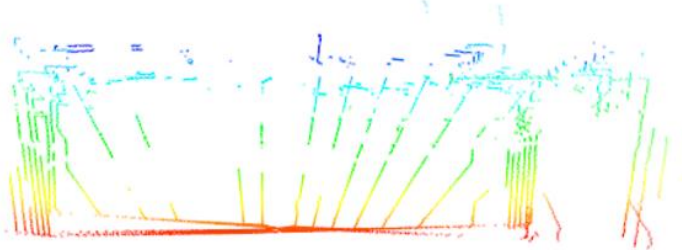


[Droeschel et al.: Journal of Field Robotics, 2015]

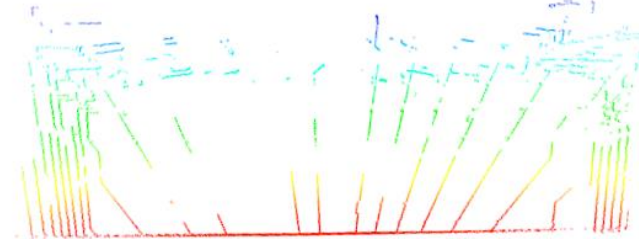
# Egocentric Laser-based 3D Mapping

- Motion compensation

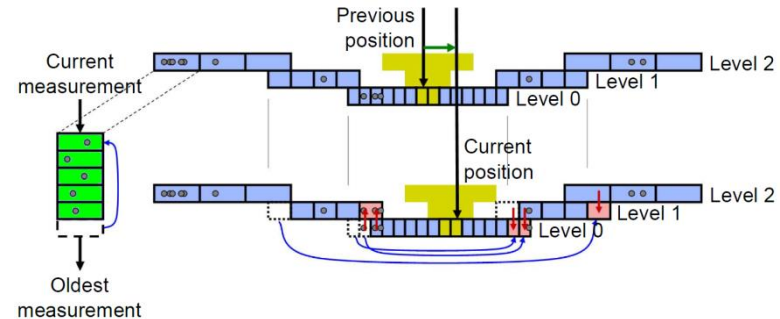
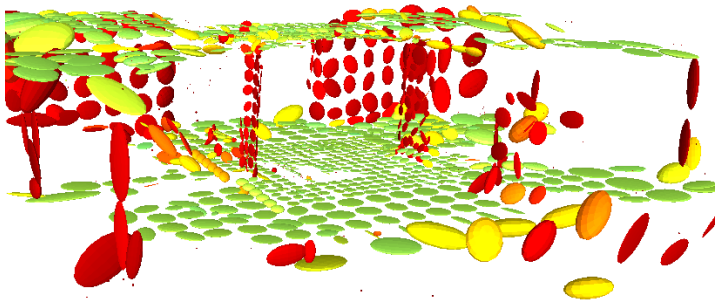
Distorted



Undistorted



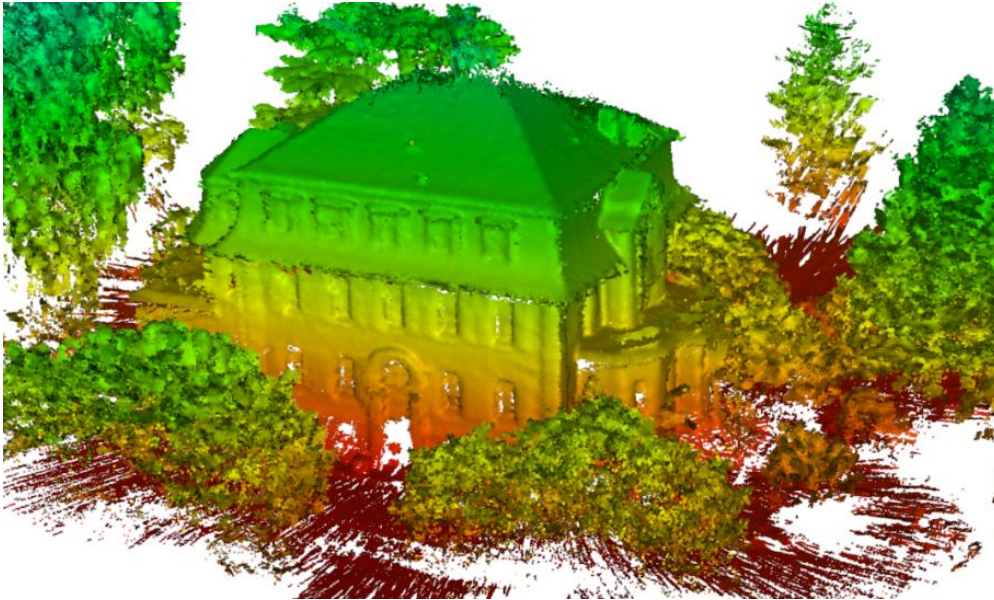
- Local multiresolution surfel maps





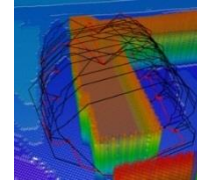
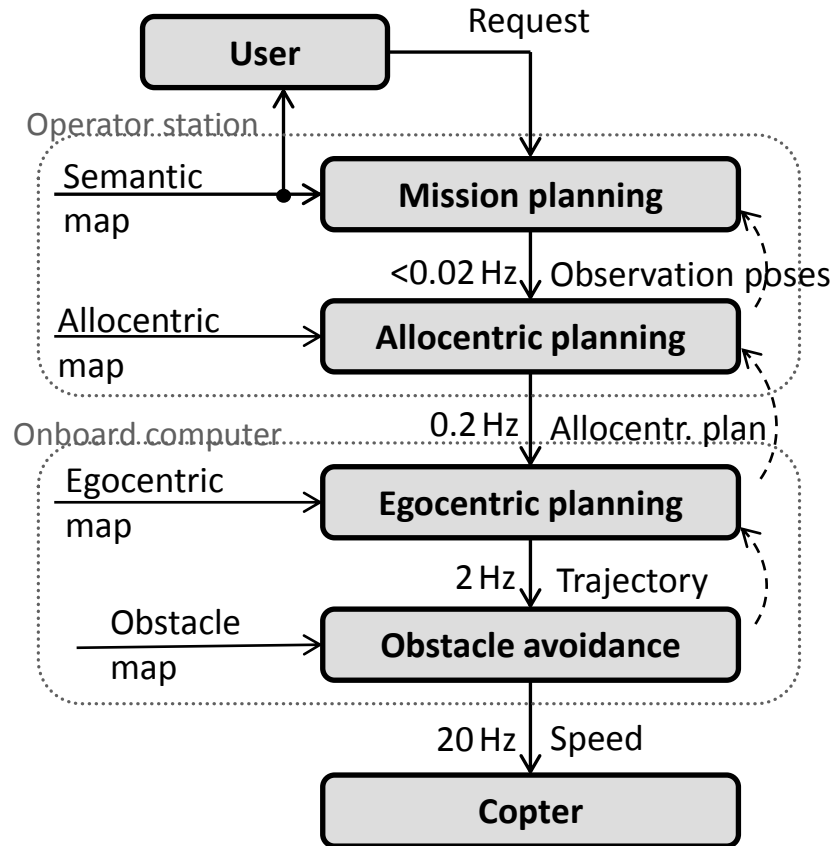
# Allocentric 3D Map

- Registration of egocentric maps
- Global optimization of registration error by GraphSLAM

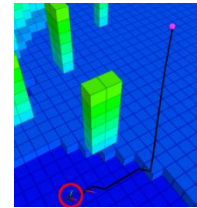


[Droeschel et al. JFR 2016]

# Hierarchical Navigation



**Mission plan**



**Allocentric planning**



**Egocentric planning**

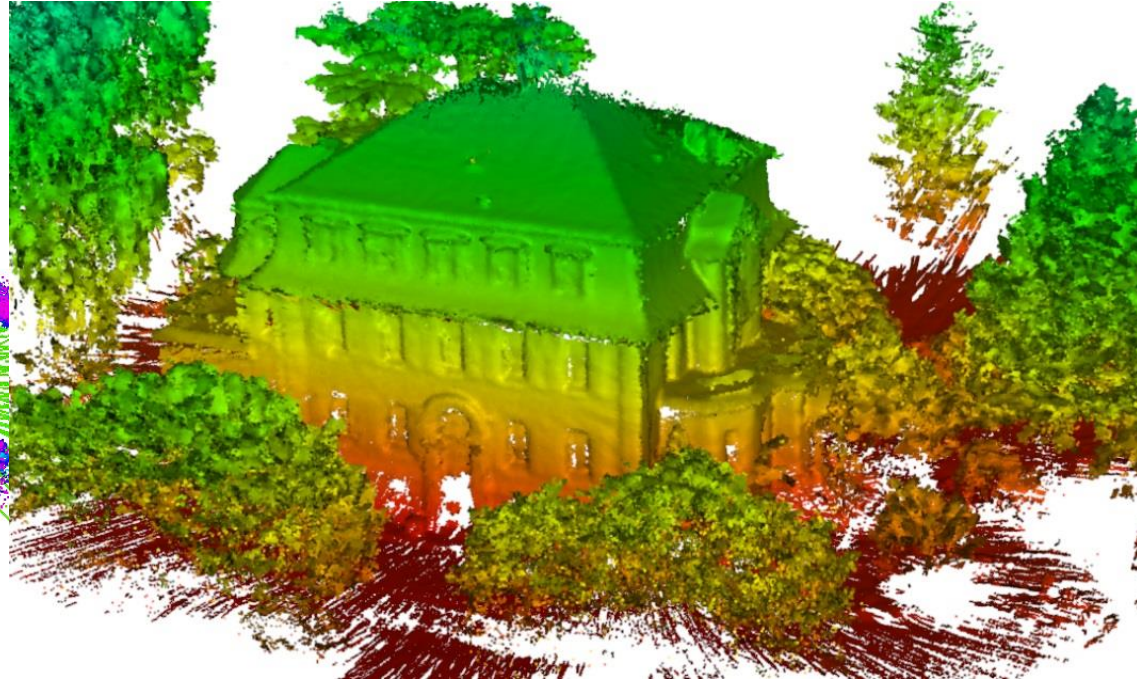
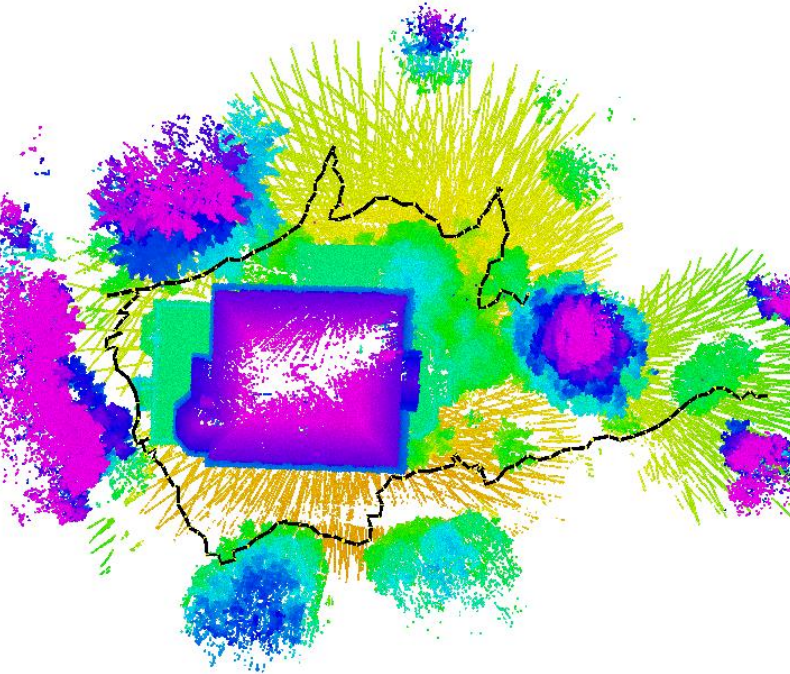


**Obstacle avoidance**

# Mapping on Demand

Autonomous Flight to Planned View Poses

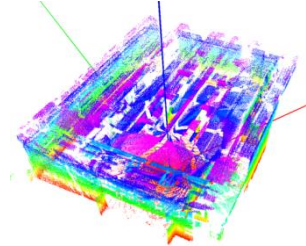
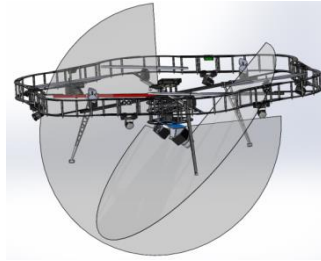
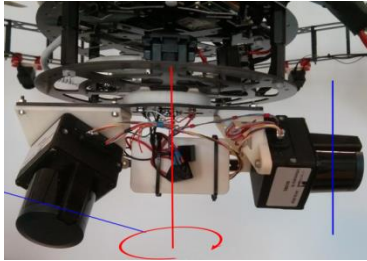
# 3D Simultaneous Localization and Mapping



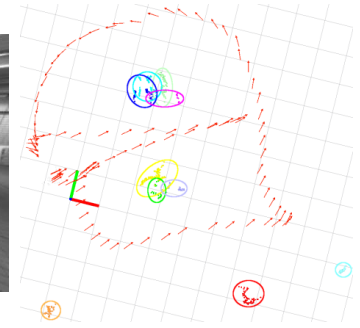
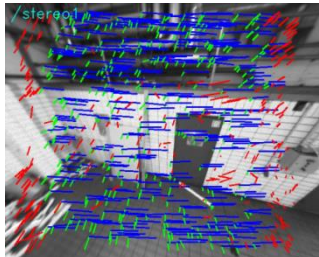
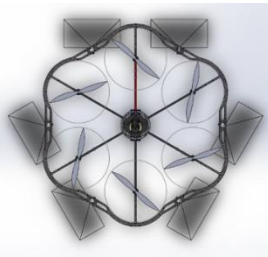
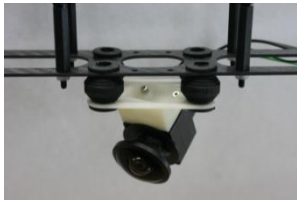


# Autonomous Flight in Warehouses

- Dual 3D laser scanner

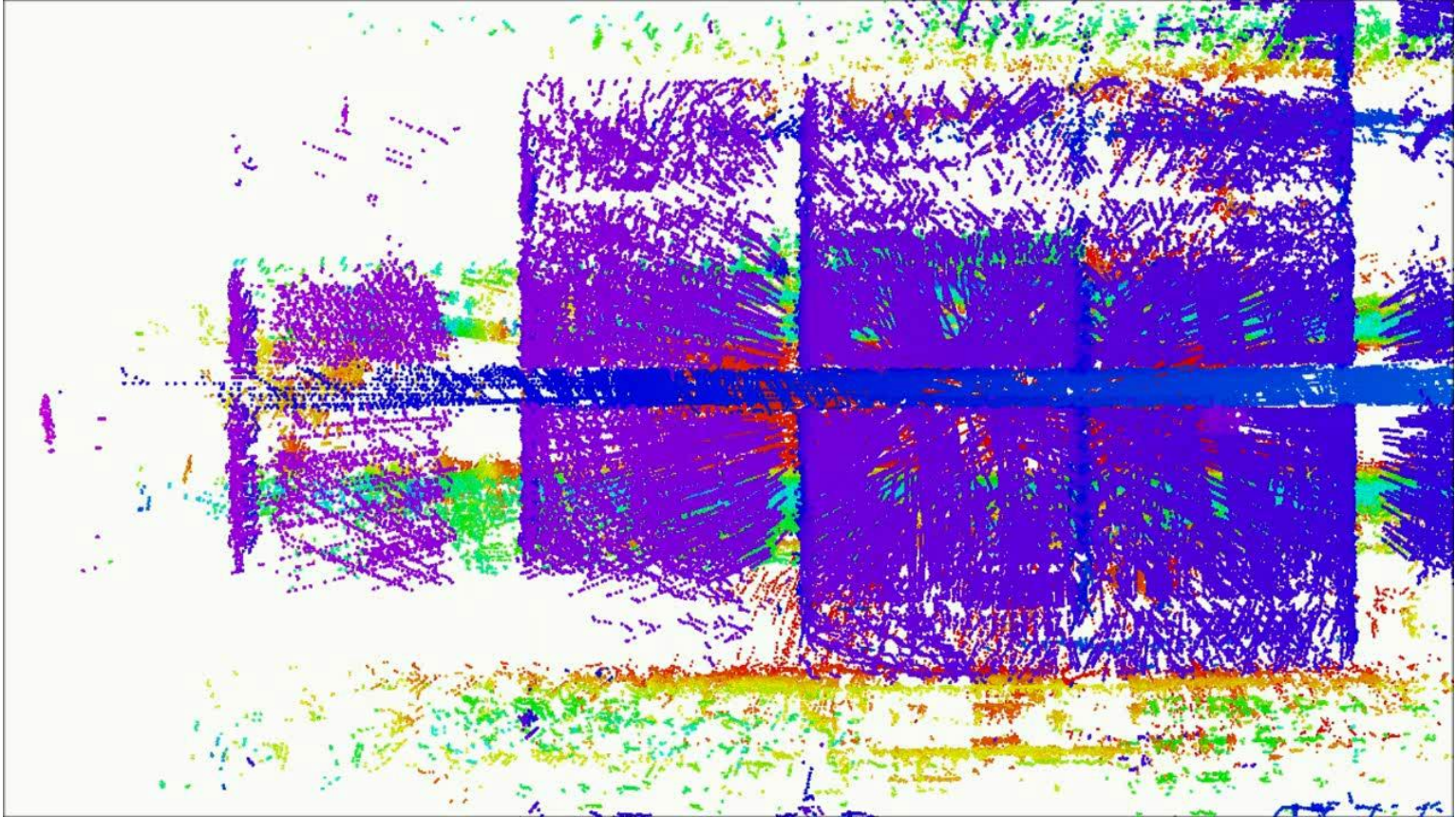


- Omnidirectional cameras



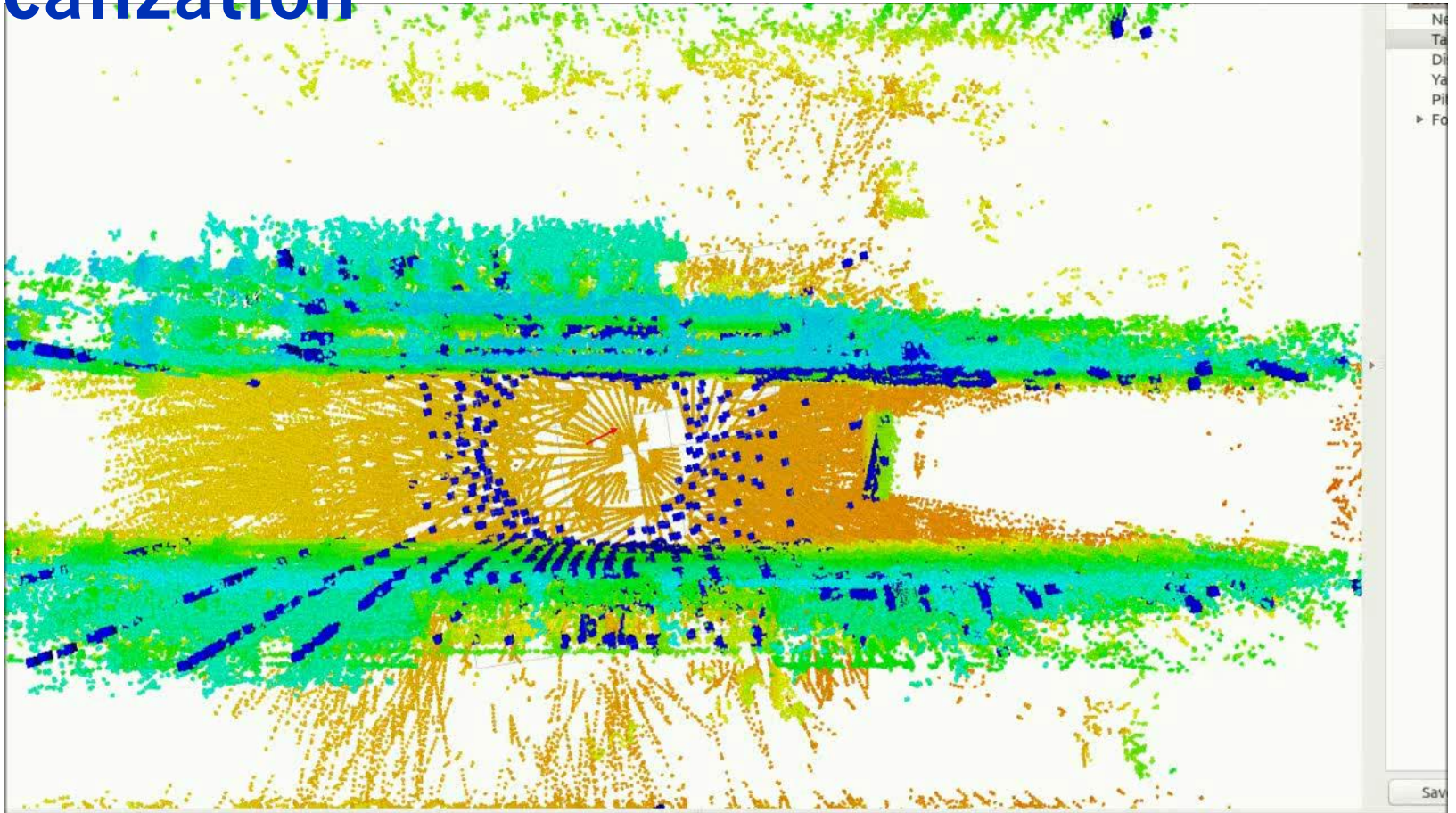
- RFID reader

# 3D Map





# Localization



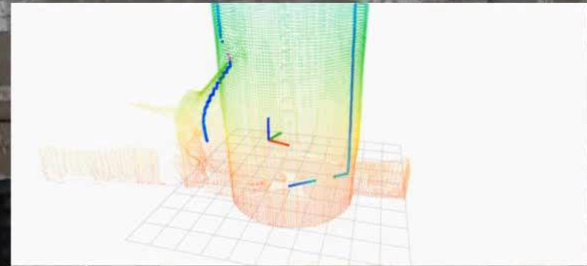
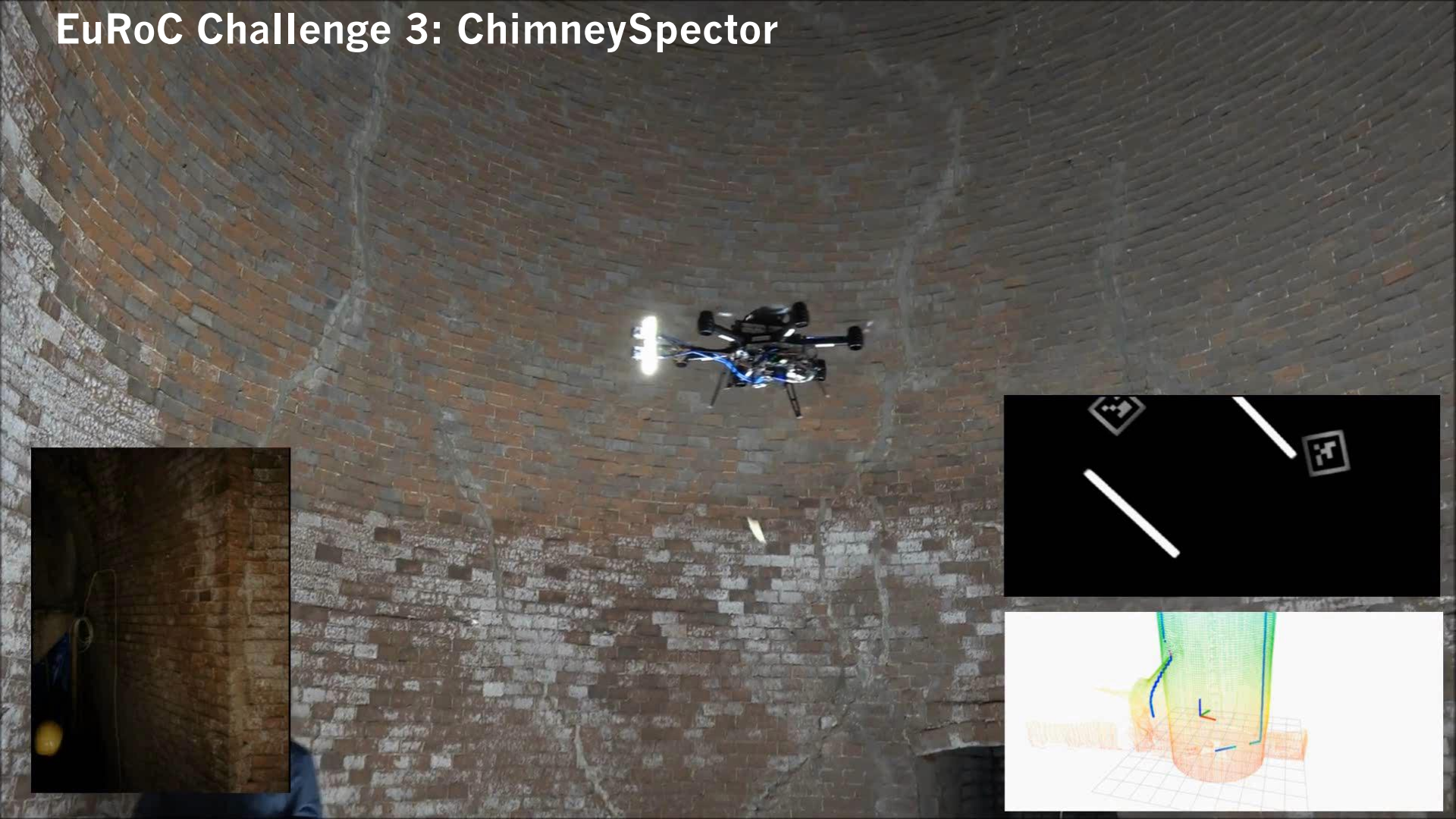


# Autonomous Mission in Warehouse



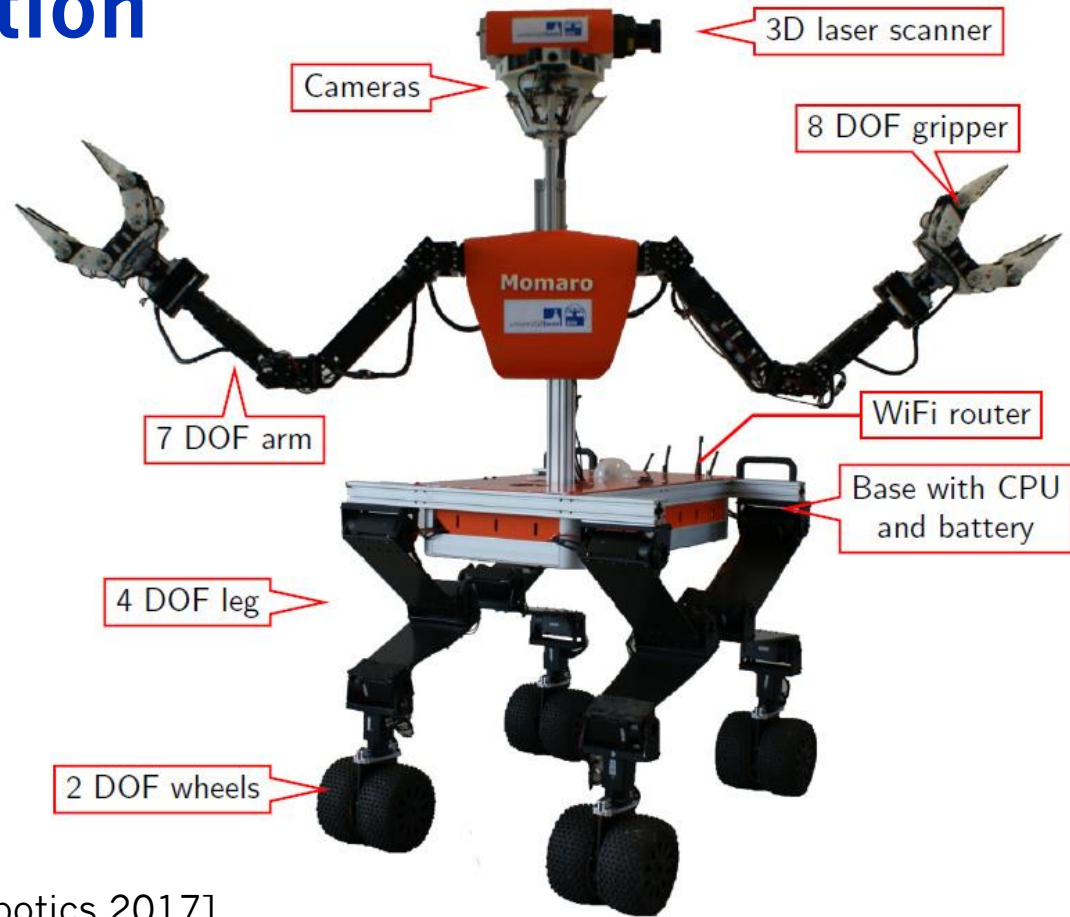


# EuRoC Challenge 3: ChimneySpector



# 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]



# Driving a Vehicle



23:15:03 05/06/2015 UTC

4x

# Egress



23:16:59 05/06/2015 UTC

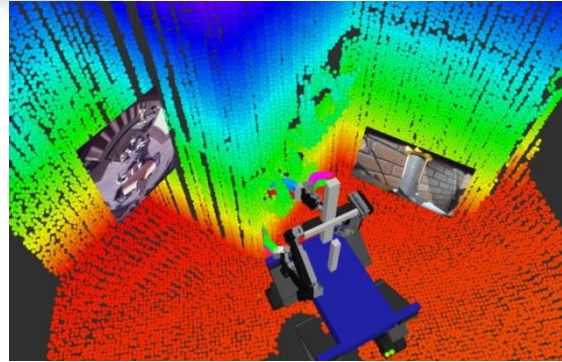
4x



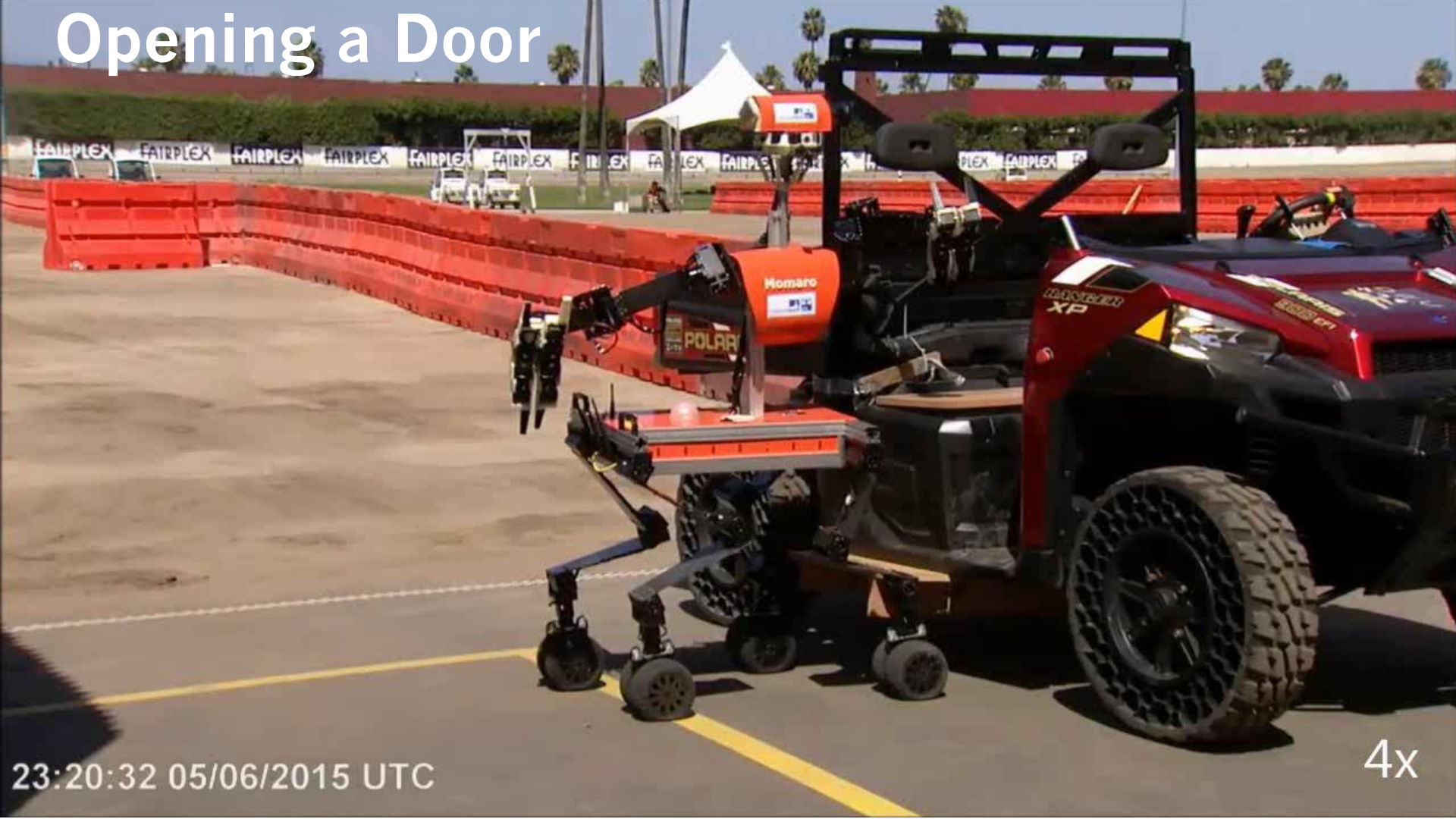
# Manipulation Operator Interface

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

[Rodehuts Kors et al., Humanoids 2015]



# Opening a Door



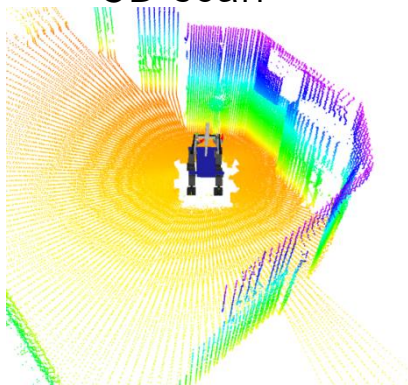
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4x

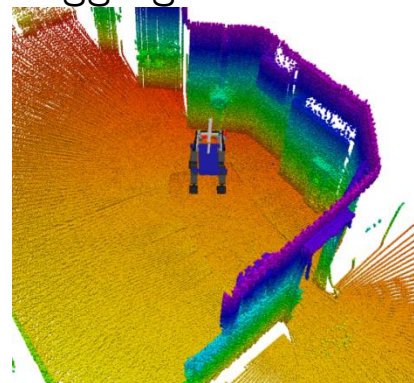
# Local Multiresolution Surfel Map

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

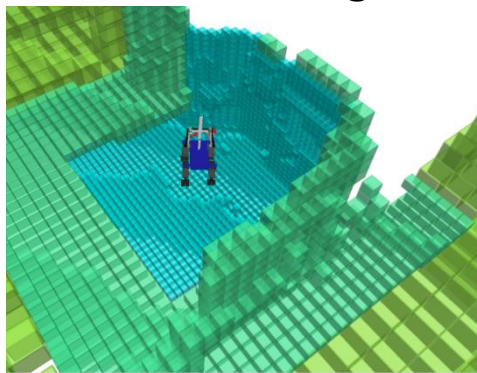
3D scan



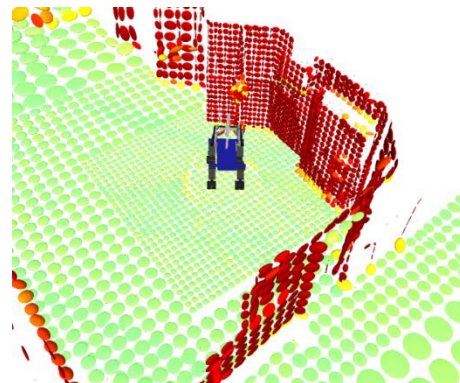
Aggregated scans



Multiresolution grid



Surfels

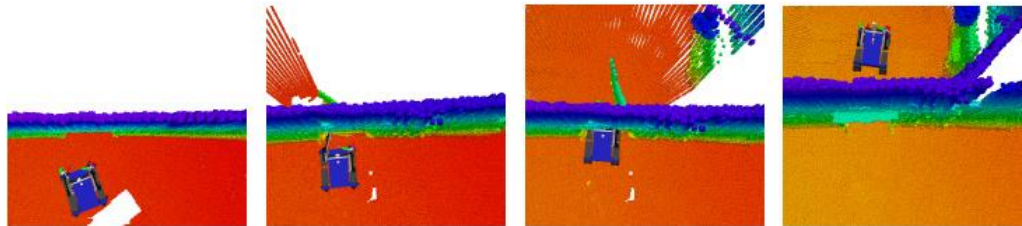
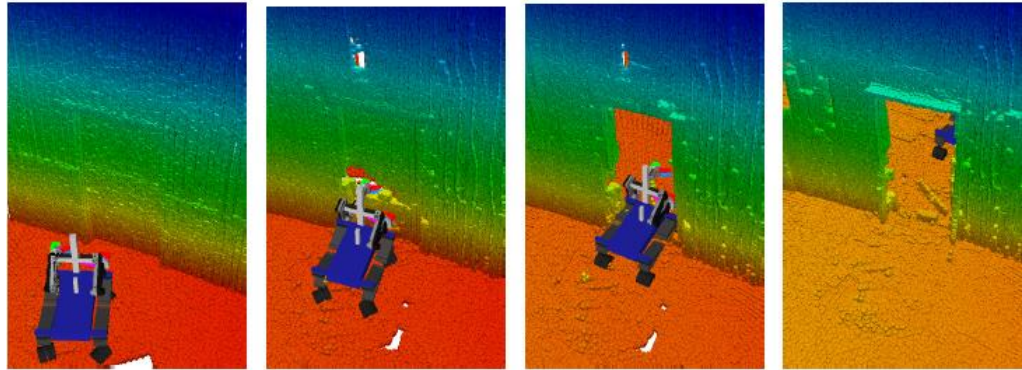


[Droeschel et al., Robotics and Autonomous Systems 2017]



# Filtering Dynamic Objects

- Maintain occupancy in each cell



1 scan (5 s)

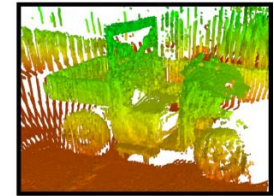
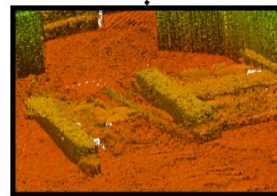
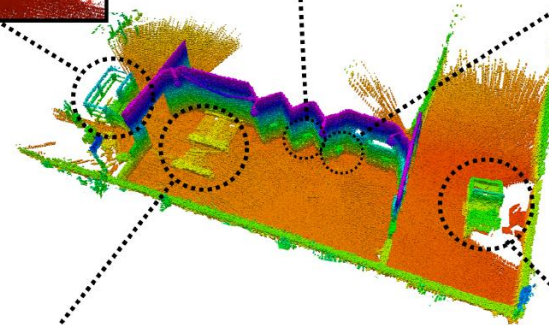
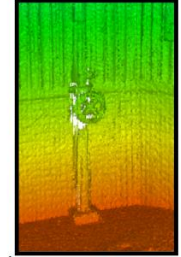
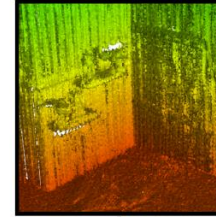
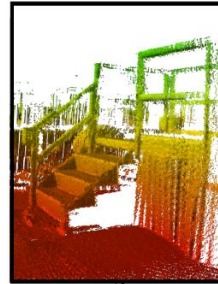
2 scans (10 s)

5 scans (25 s)



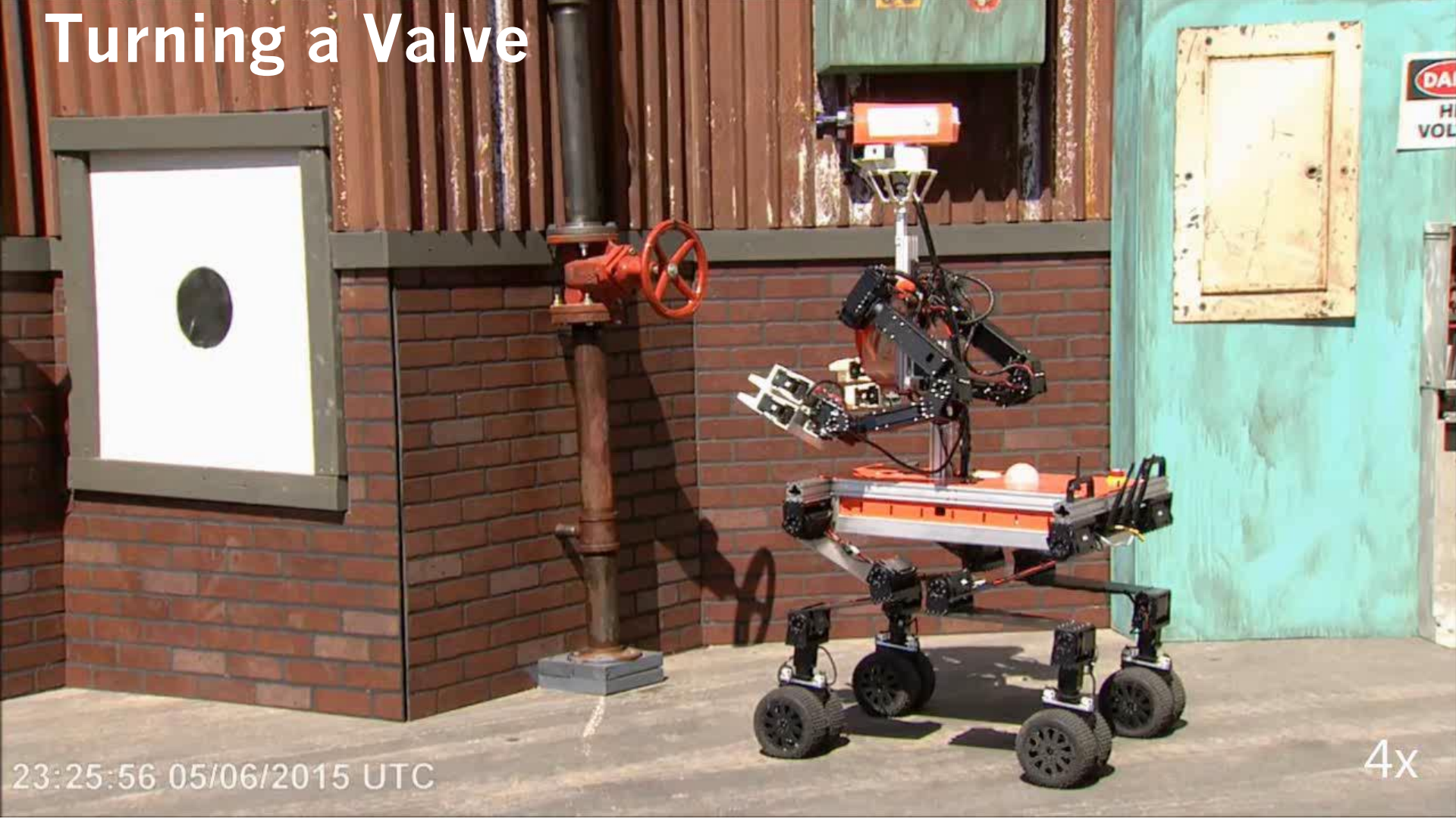
# Allocentric 3D Mapping

- Registration of egocentric maps by graph optimization



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

# Turning a Valve



23:25:56 05/06/2015 UTC

4x



# Operating a Switch



23:28:21 05/06/2015 UTC

4x



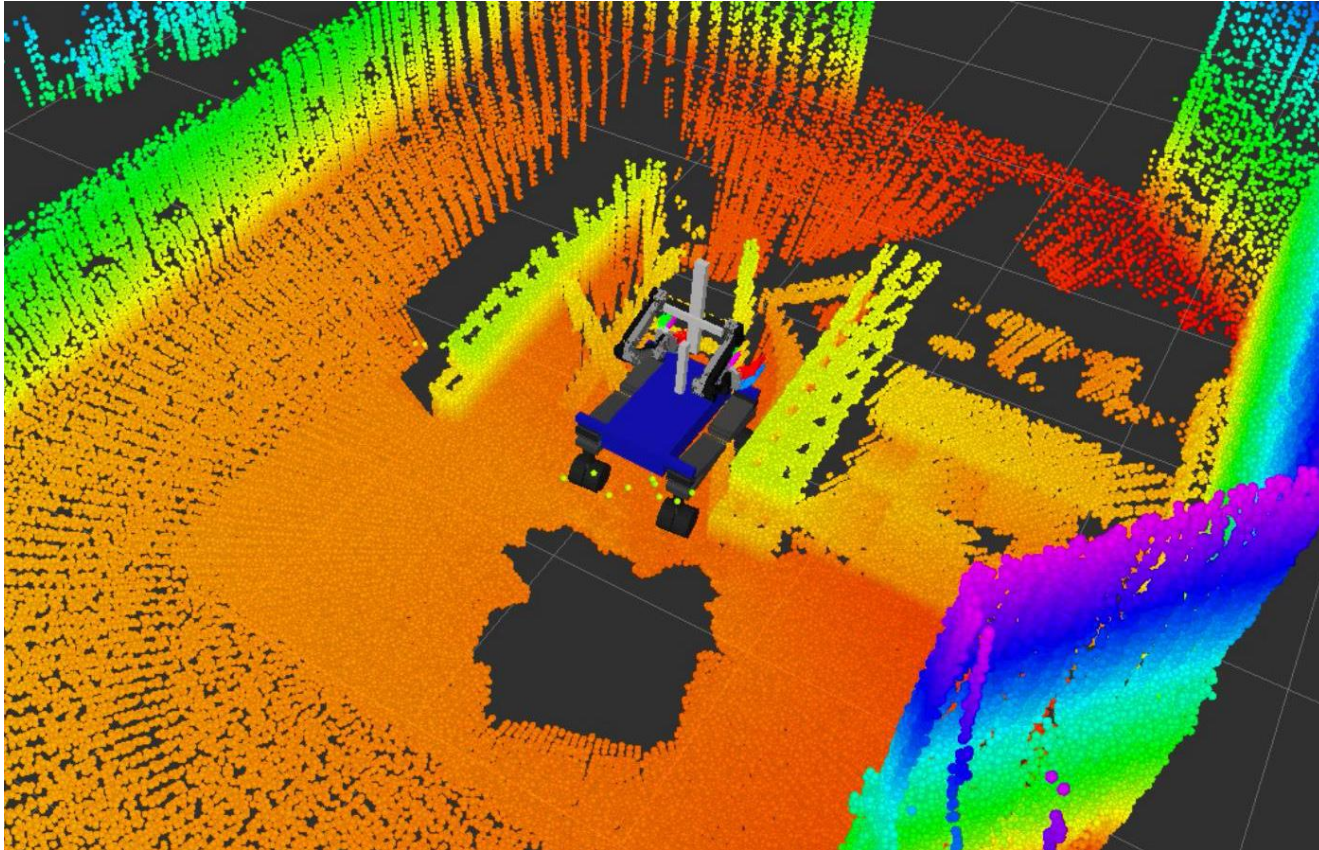
# Plug Task



02:23:20 07/06/2015 UTC

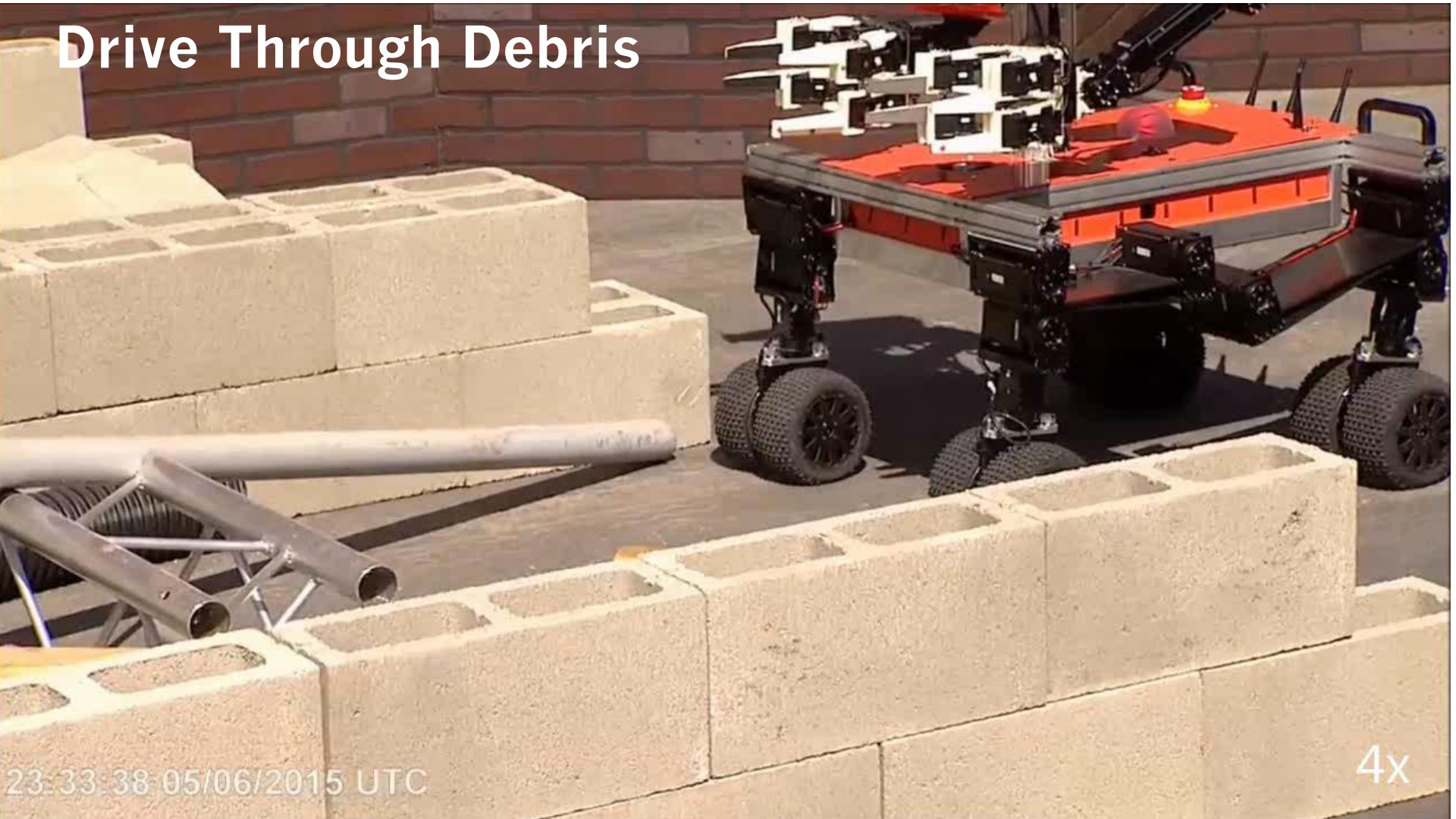
4X

# Debris Tasks





# Drive Through Debris

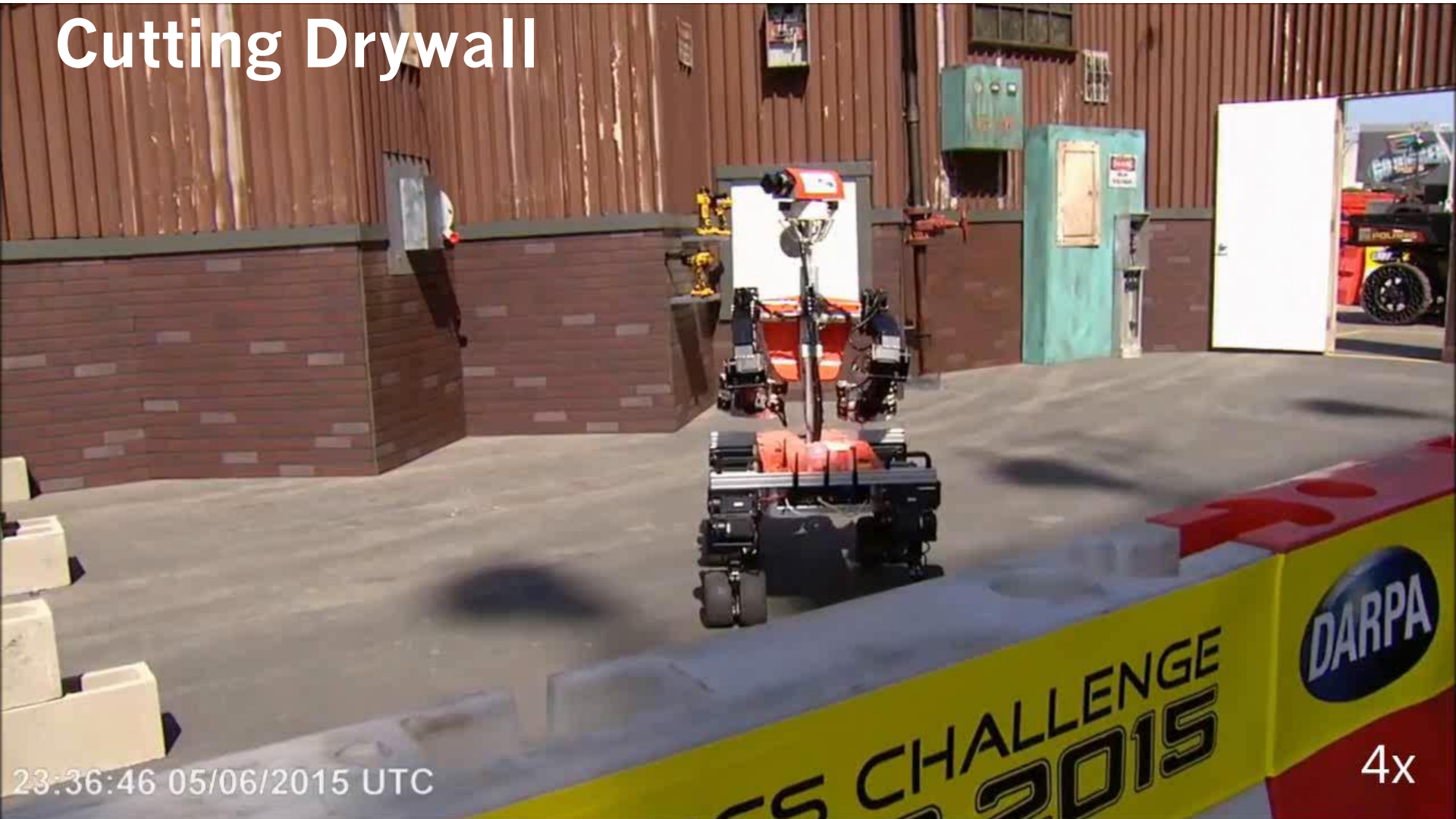


23:33:38 05/06/2015 UTC

4x



# Cutting Drywall



23:36:46 05/06/2015 UTC

CHALLENGE  
2015

DARPA

4x

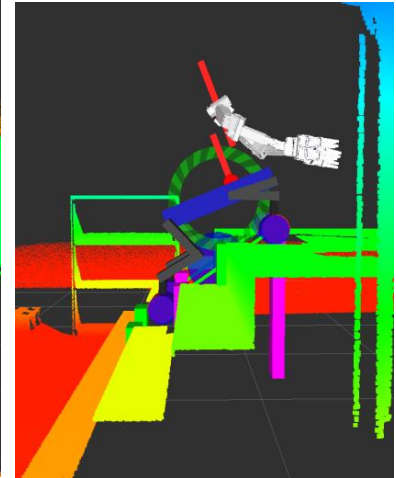
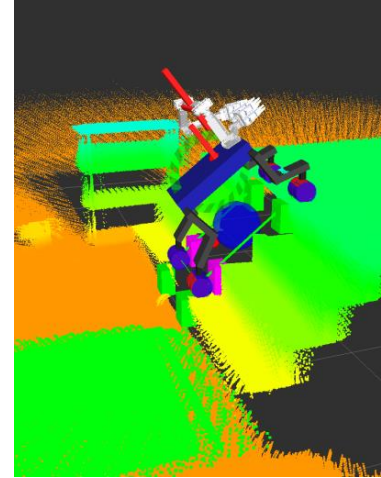
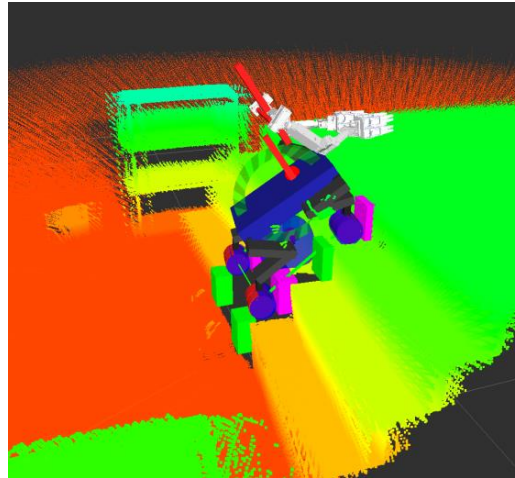
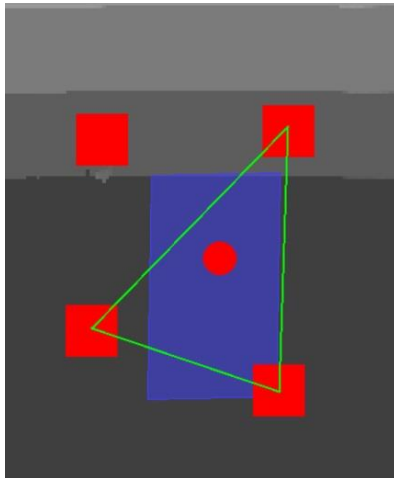
# Team NimbRo Rescue



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

# Stair Climbing

- Determine leg that most urgently needs to step
- Weight shift: sagittal, lateral, driving changes support
- Step to first possible foot hold after height change





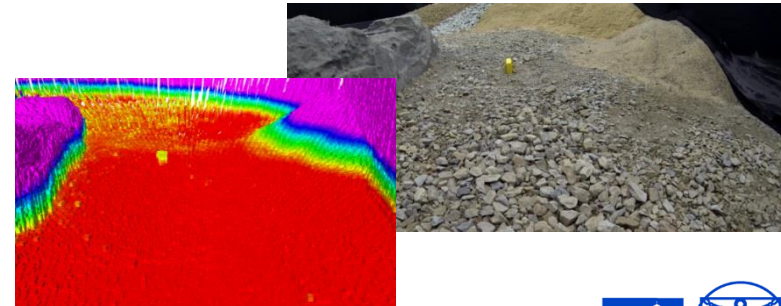
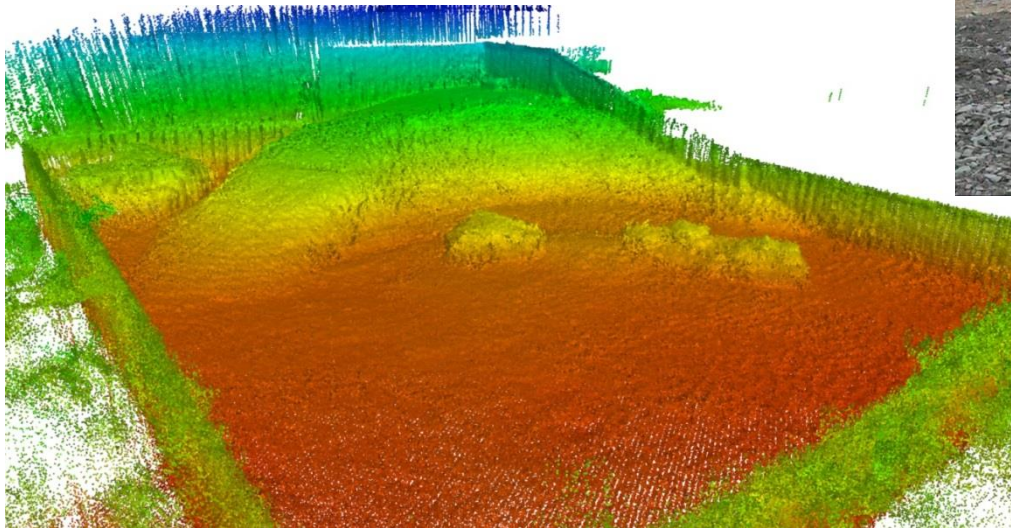
# Stair Crawling



# DLR SpaceBot Cup 2015

- Mobile manipulation in rough terrain

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





# DLR SpaceBot Camp 2015

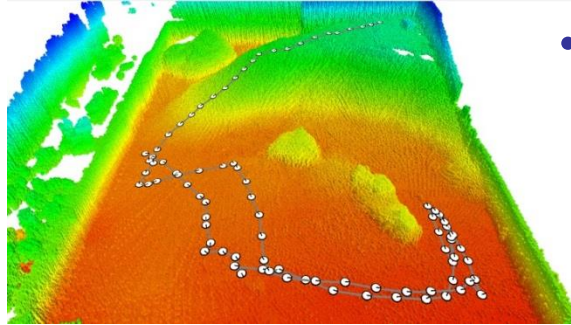


8X

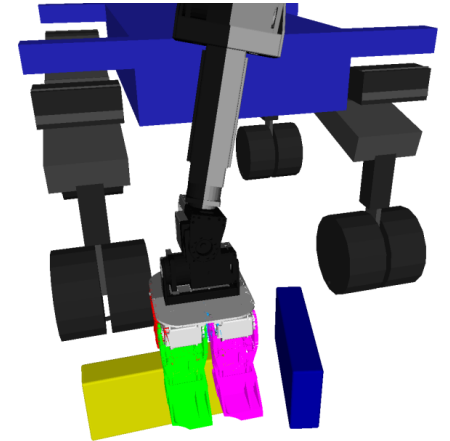
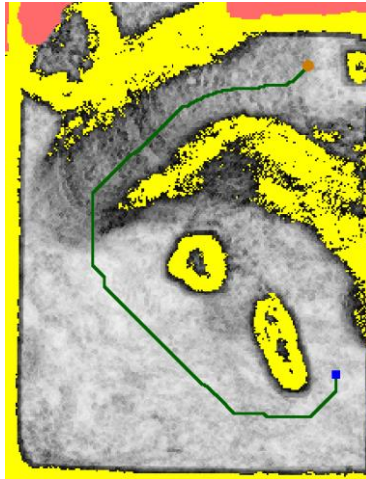
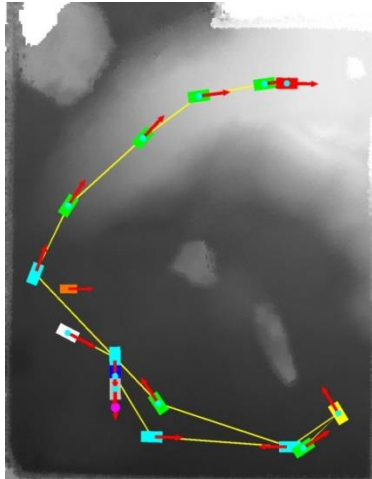
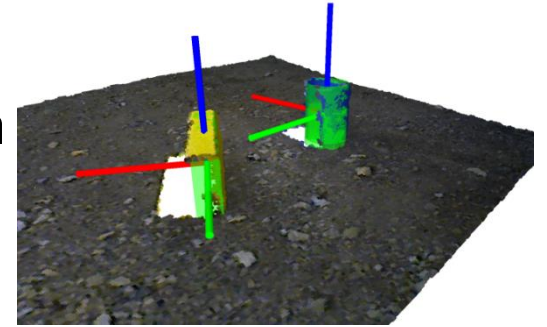


# Autonomous Mission Execution

- 3D mapping, localization, mission and navigation planning



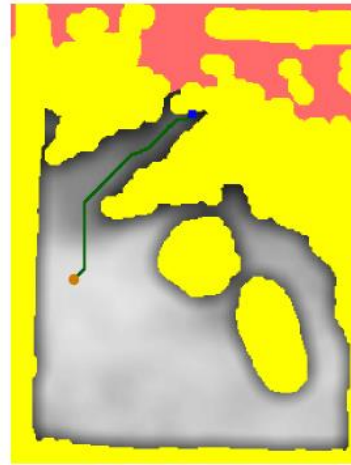
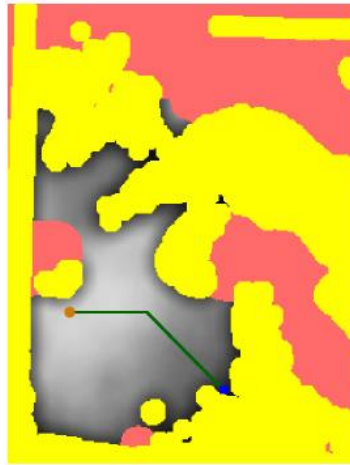
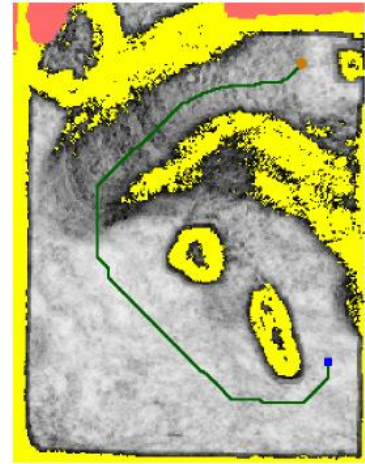
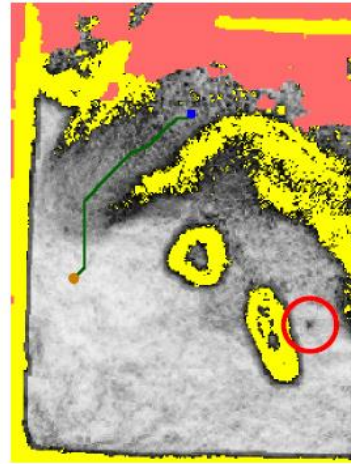
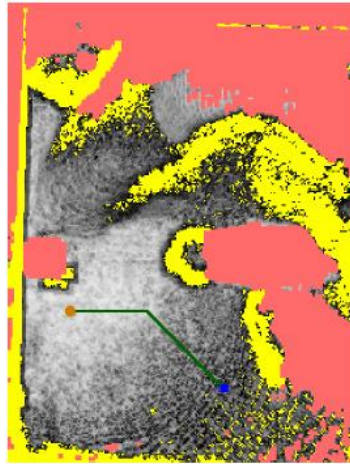
- 3D object perception and grasping



[Schwarz et al. Frontiers 2016]

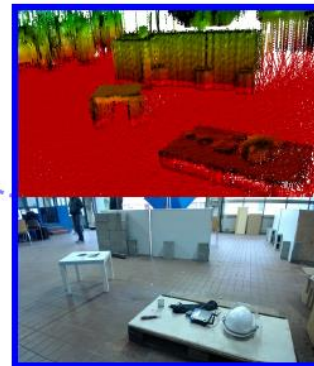
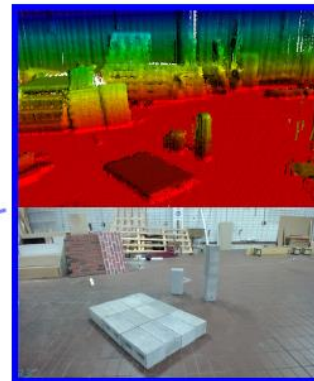
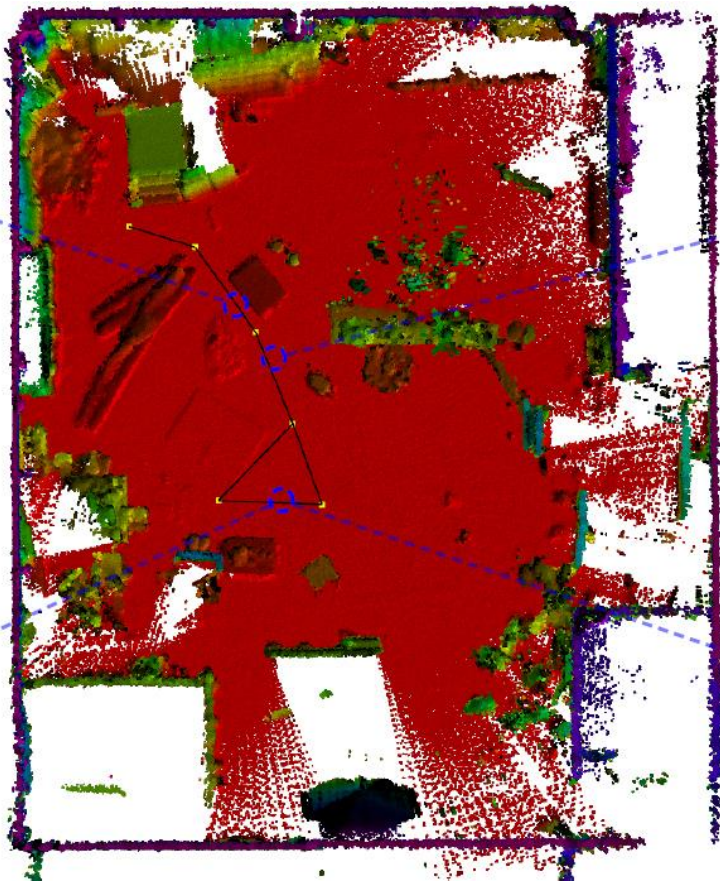
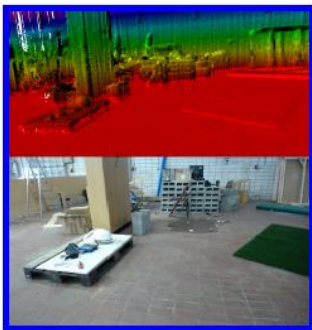
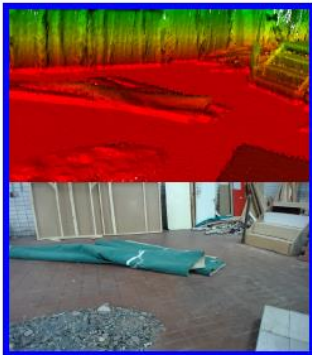
# Navigation Planning

- Costs from local height differences
- A\* path planning



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

# 3D Map

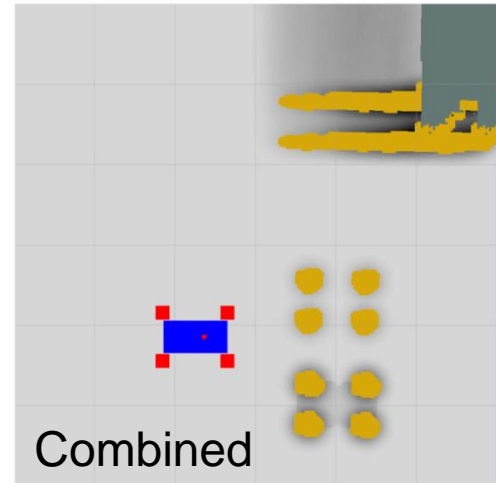
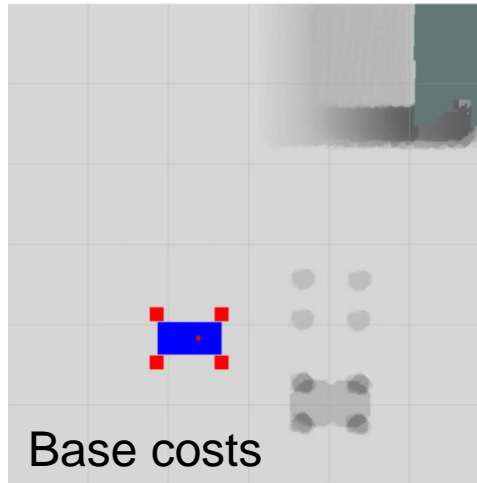
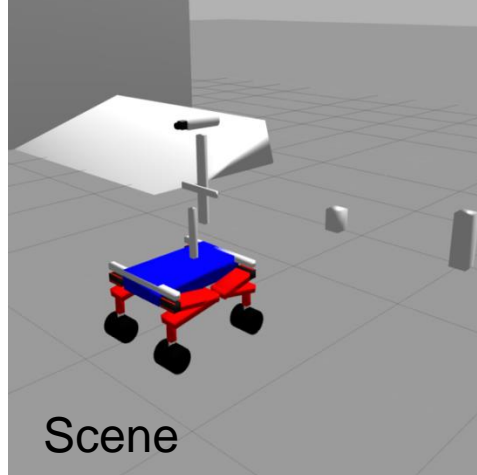




# Considering Robot Footprint

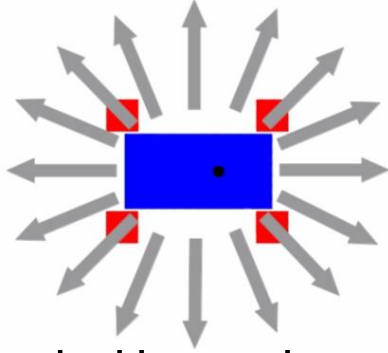
- Costs for individual wheel pairs from height differences
- Base costs
- Non-linear combination yields 3D  $(x, y, \theta)$  cost map

[Klamt and Behnke, IROS 2017]

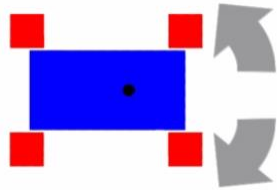


# 3D Driving Planning ( $x, y, \theta$ ): $A^*$

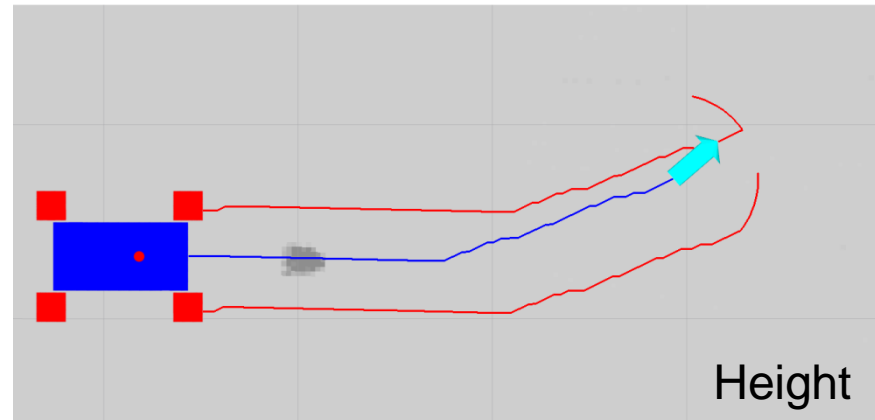
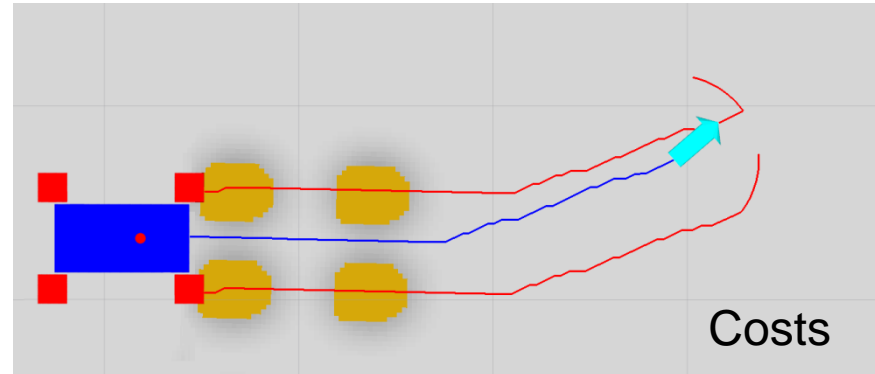
- 16 driving directions



- Orientation changes



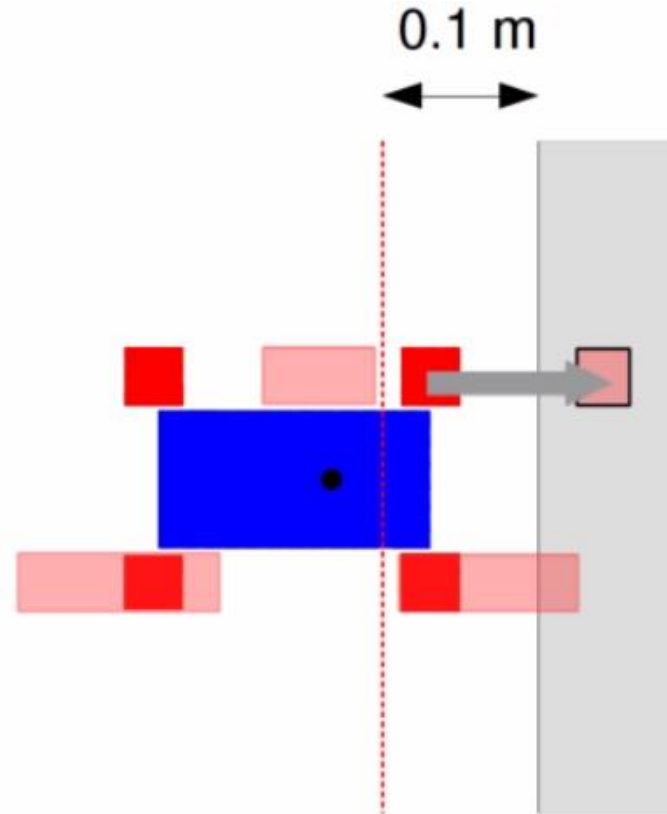
**=> Obstacle  
between wheels**



[Klamt and Behnke, IROS 2017]

# Making Steps

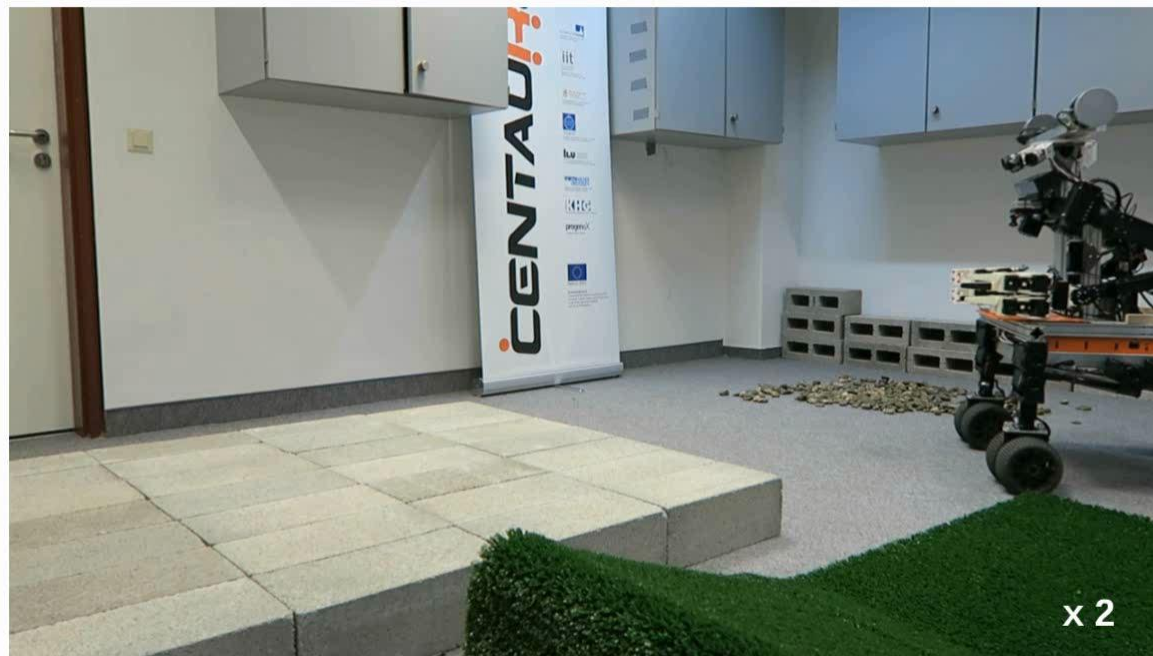
- If not drivable obstacle in front of a wheel
- Step landing must be drivable
- Support leg positions must be drivable



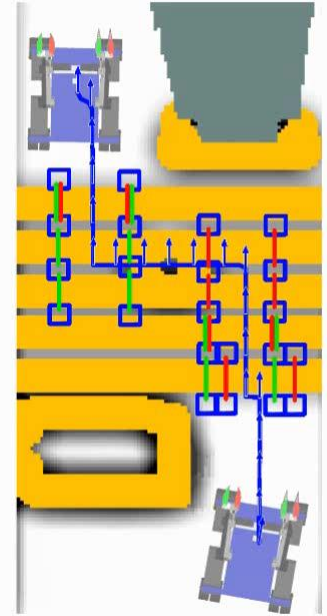
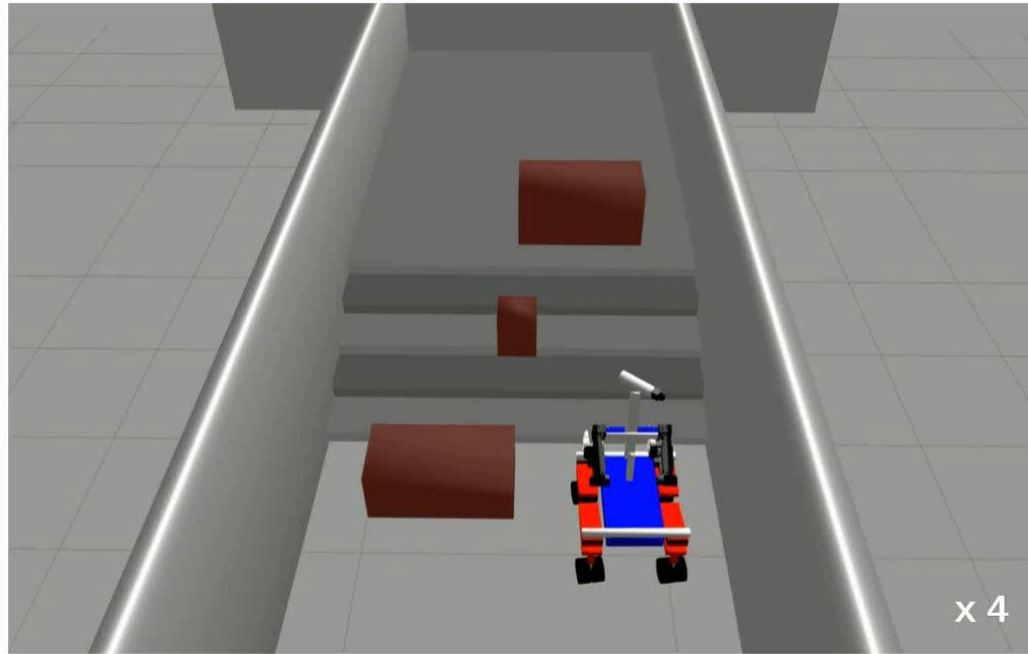
[Klamt and Behnke: IROS 2017]



## Expanding Abstract Steps to Detailed Motion Sequences



# Planning for Challenging Scenarios



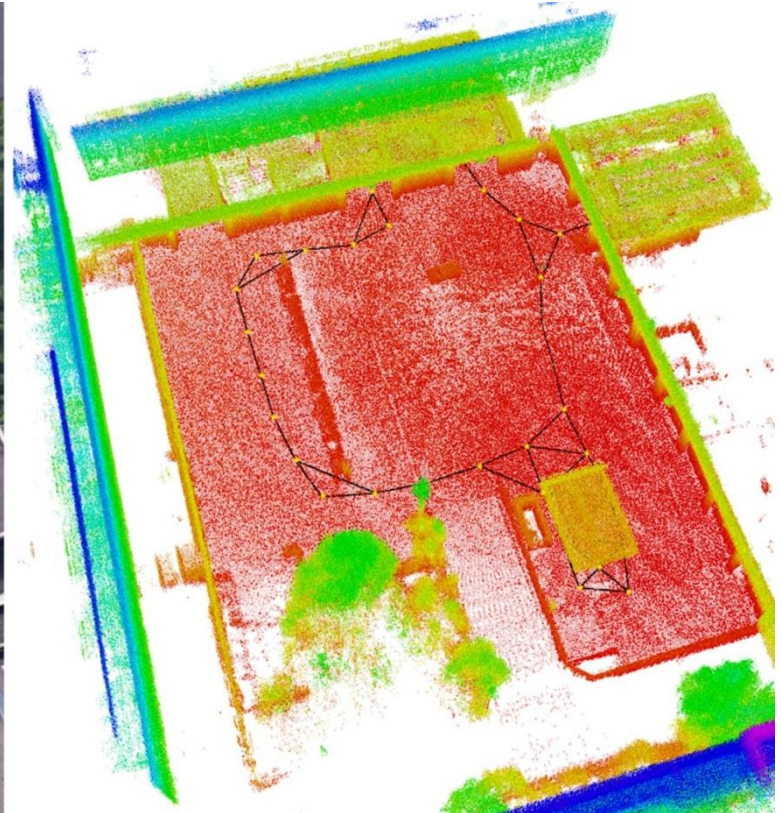
# New Sensor Head

- 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  $210 \times 103^\circ$ )
- Kinect V2 RGB-D camera on pan-tilt unit

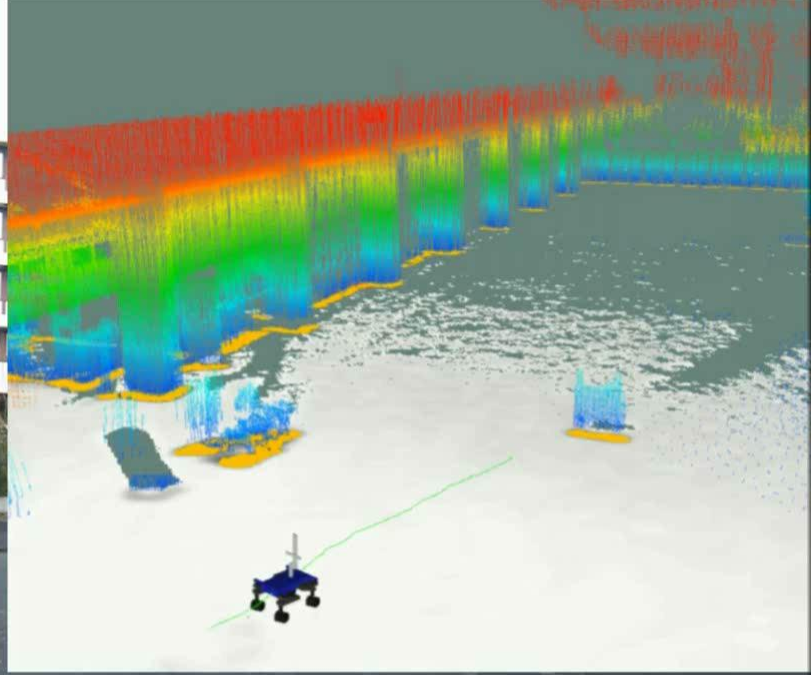




# 3D Map of Indoor+Outdoor Scene



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



Navigation in allocentric laser map (colored points)



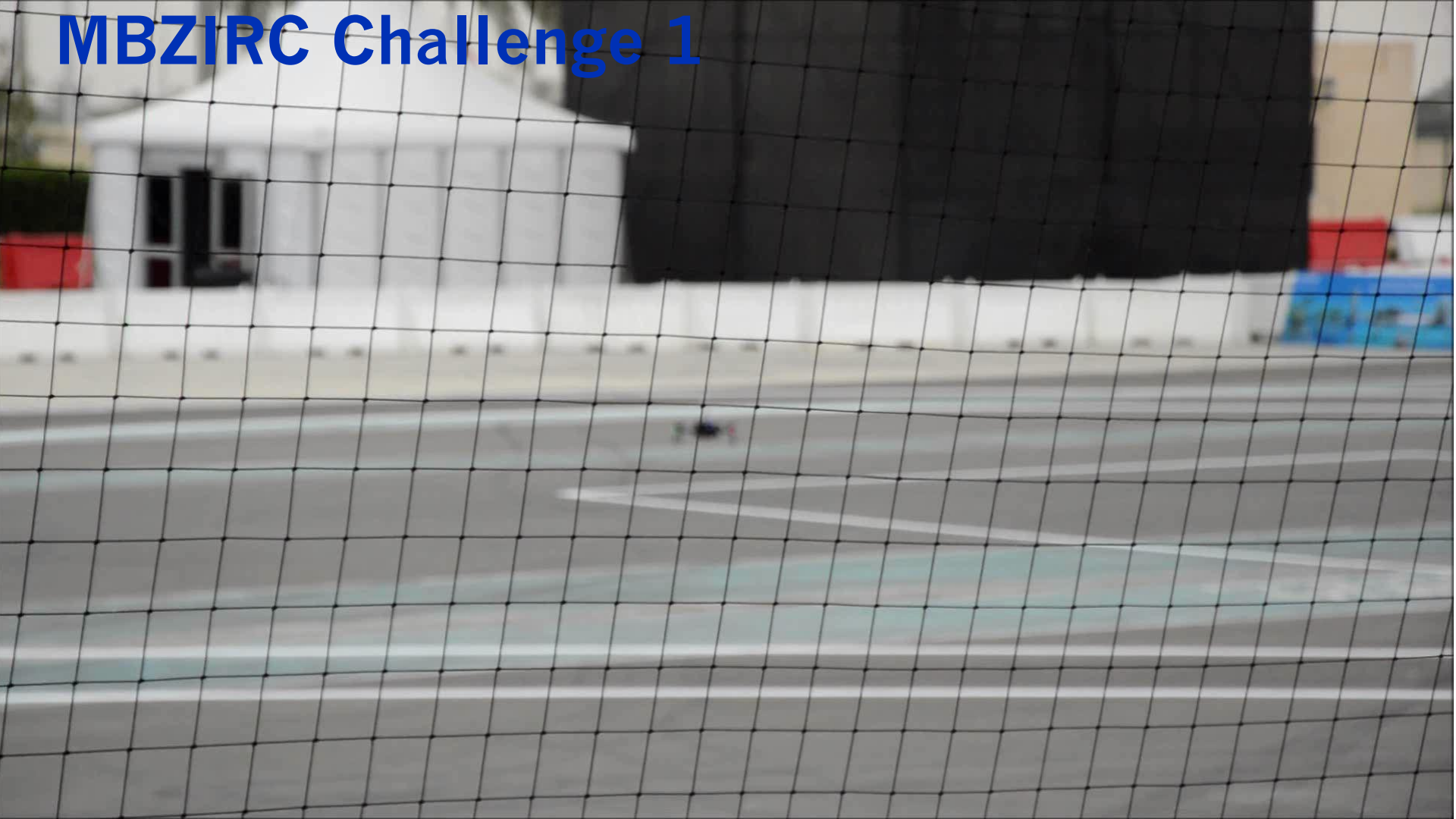
# MBZIRC Challenge 2



2x

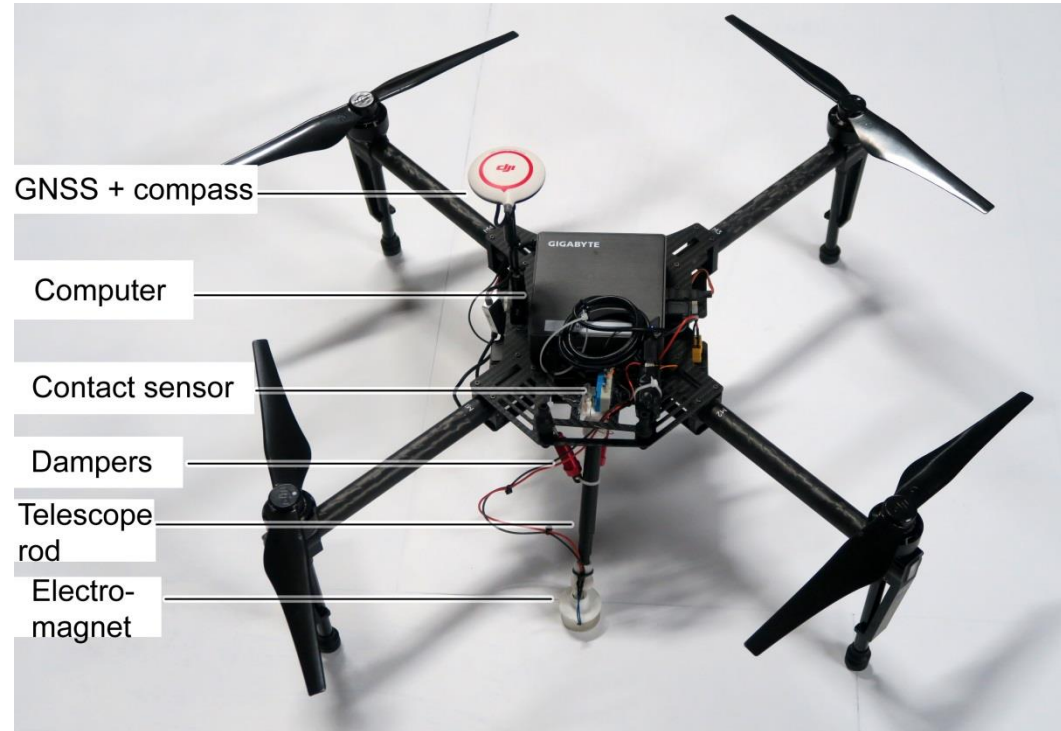


# MBZIRC Challenge 1



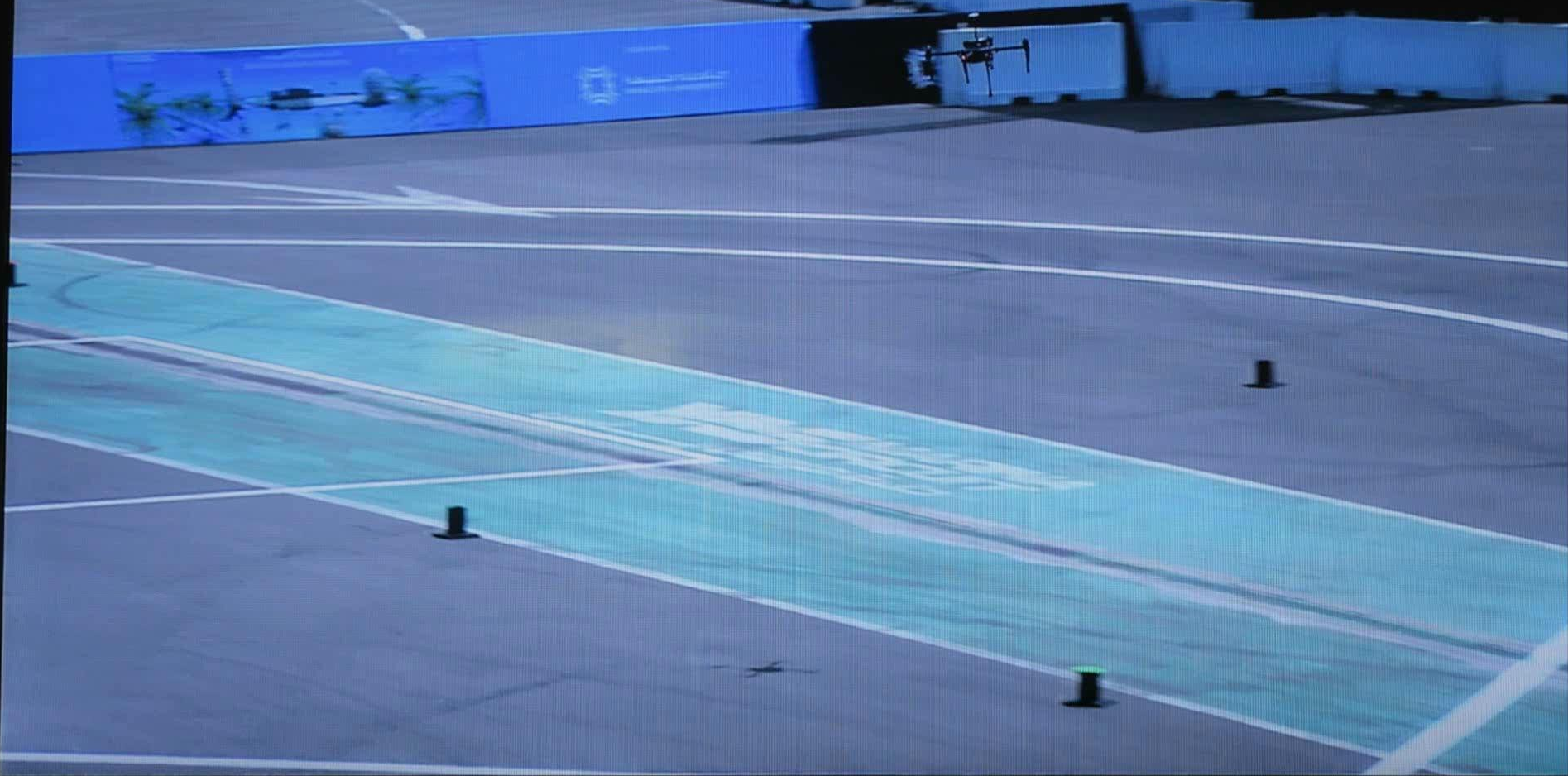
# Picking Copter DJI Matrice 100

- Wide-angle downward looking color camera
- Electromagnetic gripper
- Laser-distance sensor to ground
- Dual-core PC



7:13

# MBZIRC Challenge 3





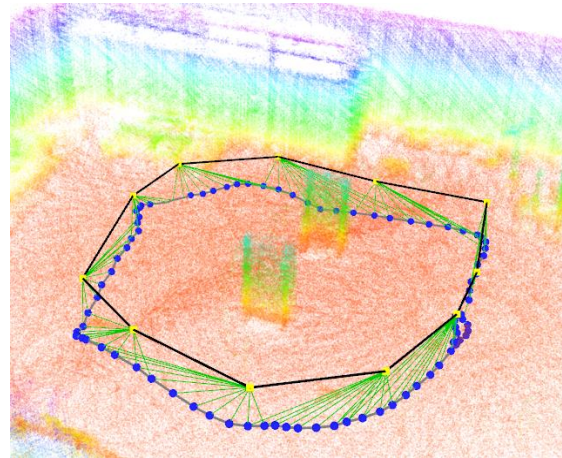
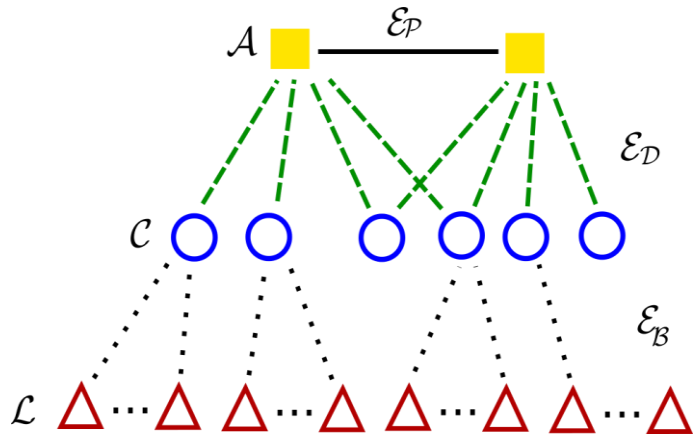
# MBZIRC Team NimbRo



Sven Behnke: 3D SLAM and Navigation in Complex Environments

# Hierarchical Map Refinement

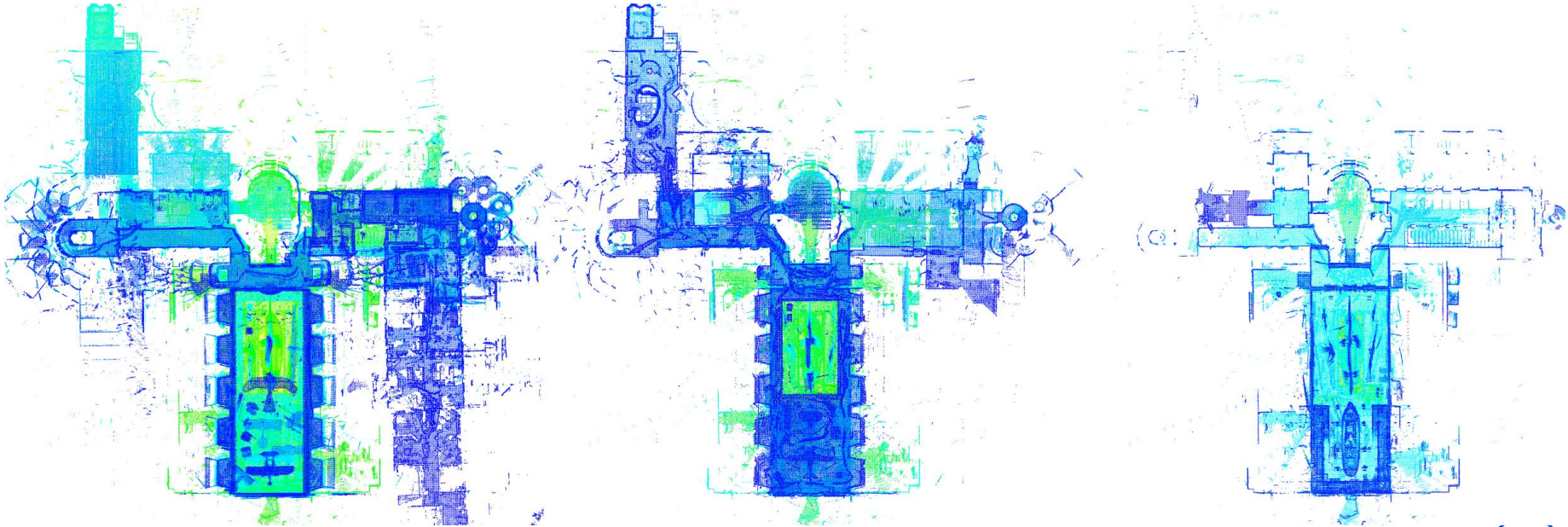
- Hierarchical graph structure: Allocentric map, local multiresolution maps, 3D scan, scan line
- Refinement of local maps by realigning 3D scans





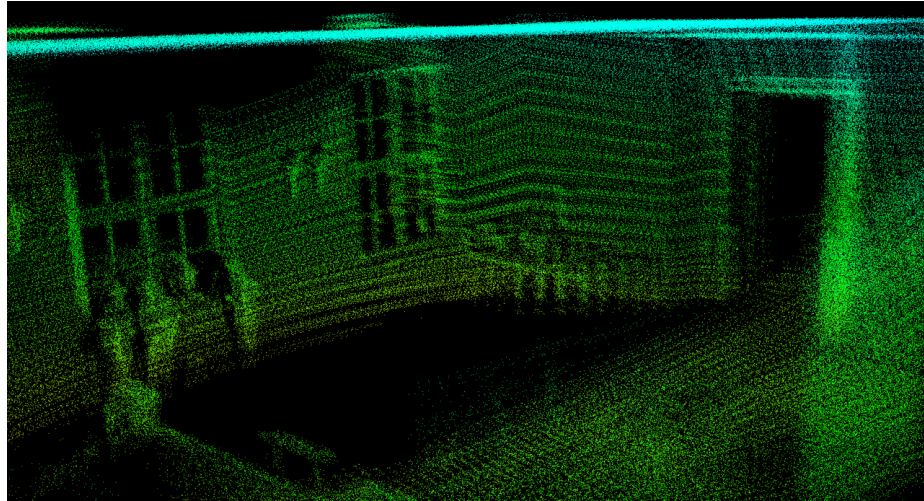
# Experiment: Deutsches Museum

- 3D LIDAR backpack by Google Cartographer team
- IMU, two Velodyne VLP-16, 1200s, ~1500m, 3 levels

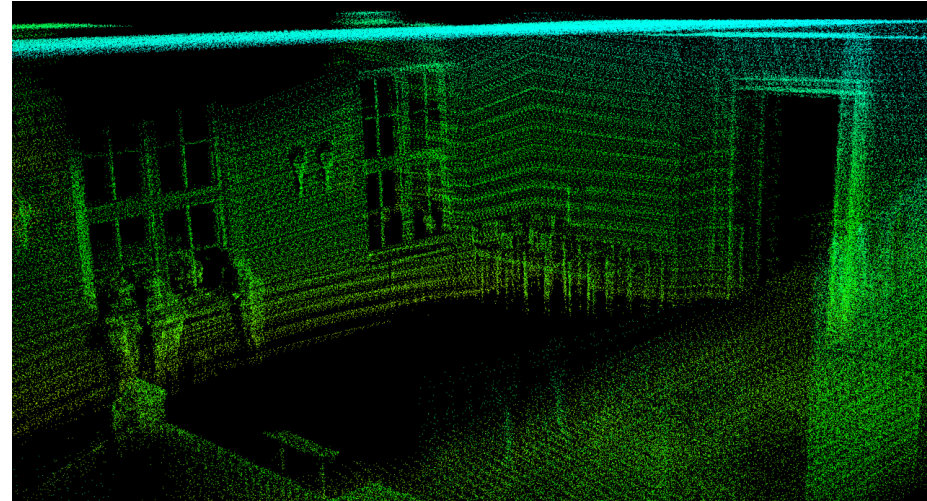




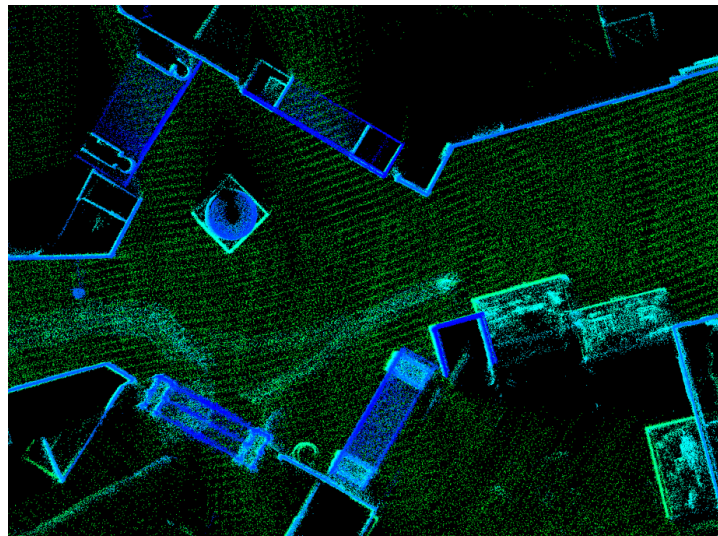
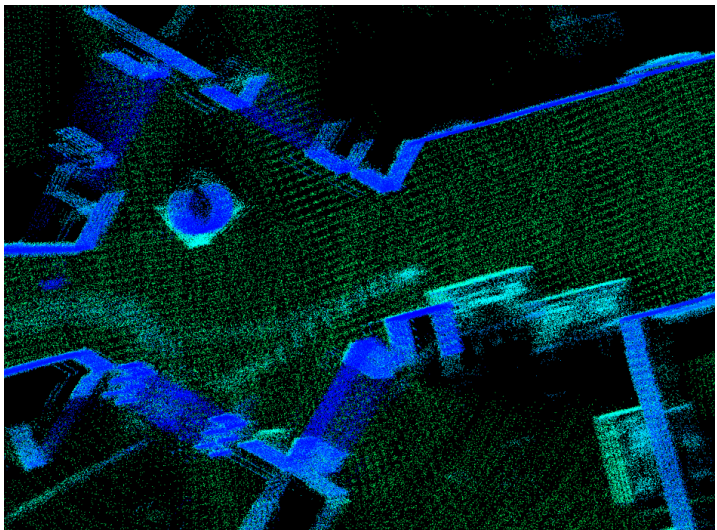
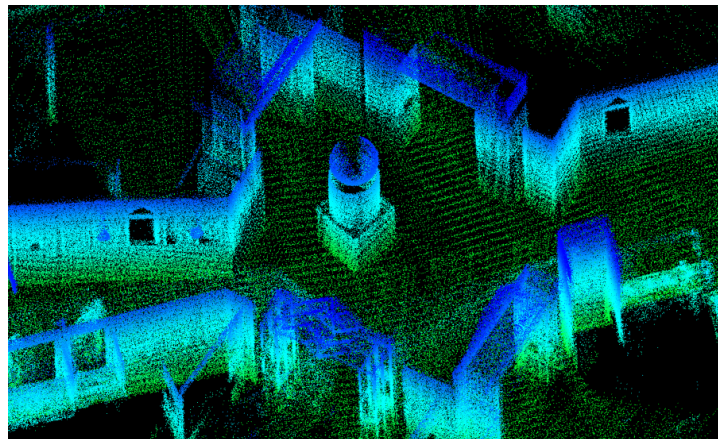
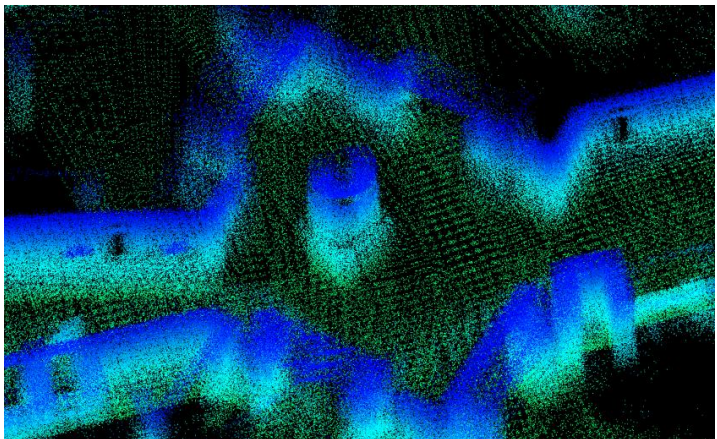
# Experiment: Deutsches Museum



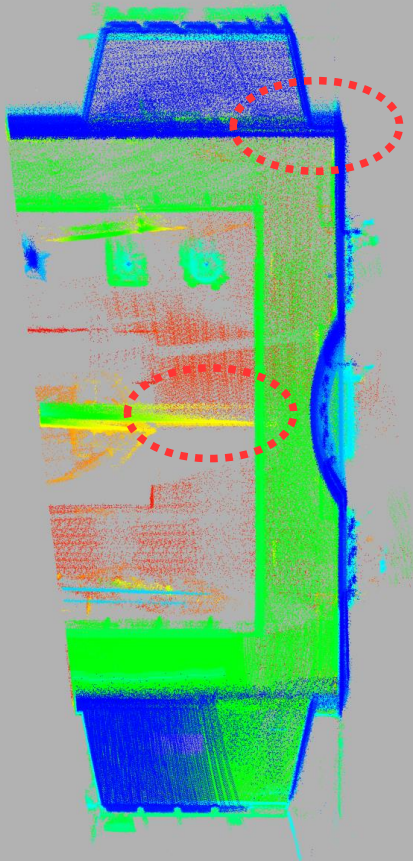
*Without refinement*



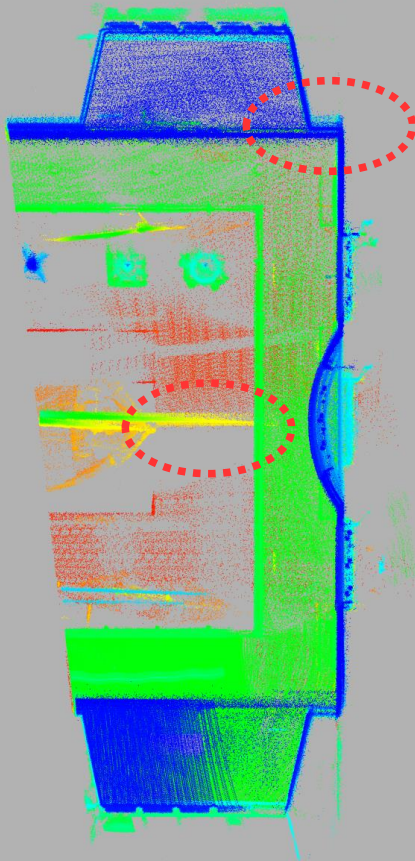
*With refinement*



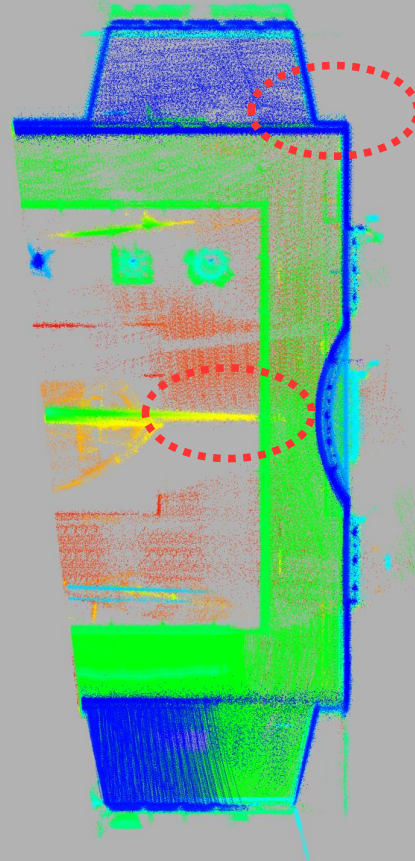




*Cartographer*



*Nuechter et al.*

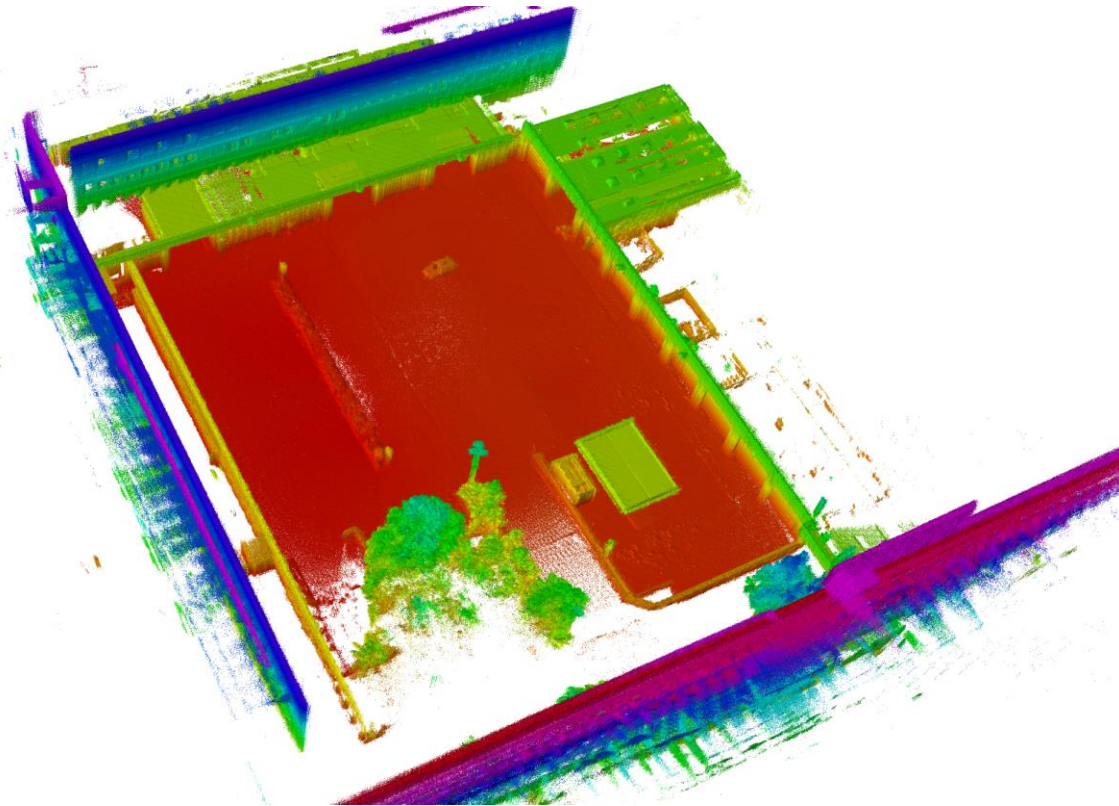


*Ours*

[Nüchter et. al. Improving Google's Cartographer 3D Mapping by Continuous Time SLAM]



# Bonn Courtyard

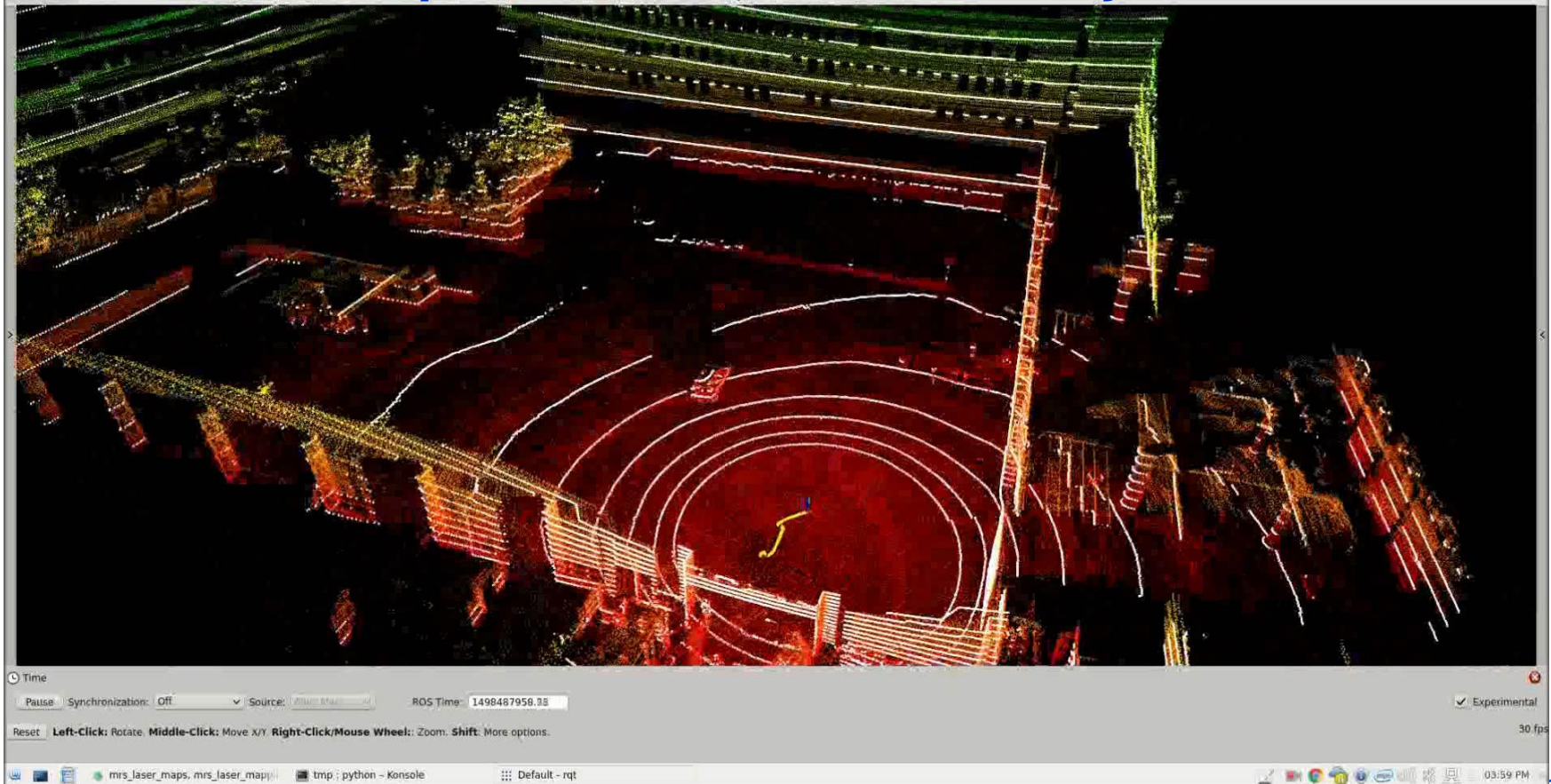


# DJI Matrice 600 with Velodyne Puck





# Copter SLAM in Bonn Courtyard





# Conclusions

- 3D perception necessary for navigation in complex environments
- Progress in sensors, computing
- Efficient SLAM methods
- Hierarchical navigation
- Challenges:
  - Dynamic scenes
  - Semantics

# Questions?