Autonomous Assistance Functions for Centaur-like Ground Robots and Micro Aerial Vehicles in Disaster Response

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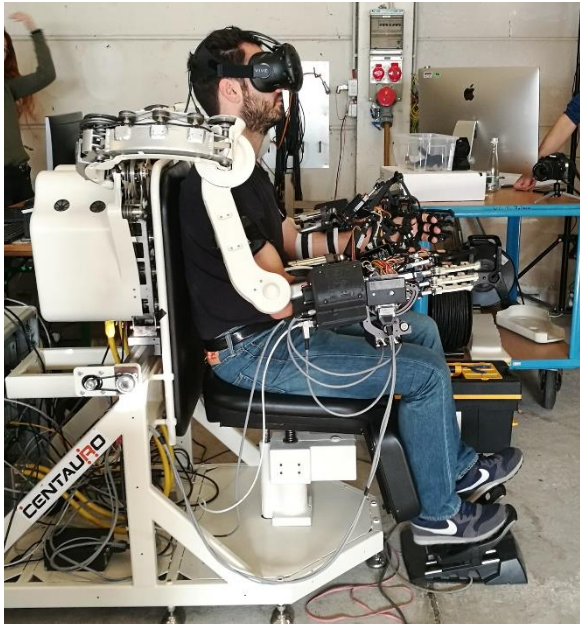
Autonomous Intelligent Systems

Direct Control vs. Autonomous Assistance

- Direct teleoperation offers a high degree of flexibility
- Requires special operator interfaces, good connection, extensive operator training, and induces high cognitive load on the operator
- Not all DoFs can be mapped directly
- => Use autonomous assistance functions on all levels of control!

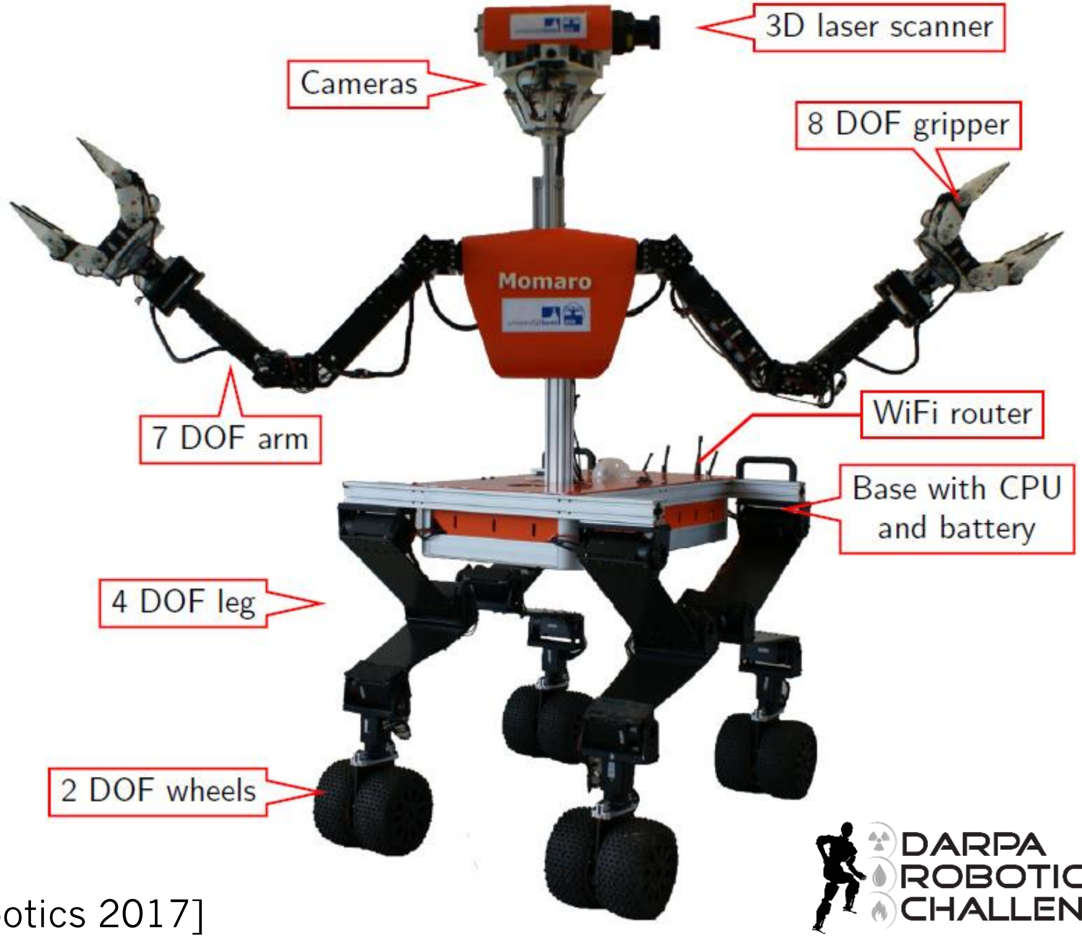


CENTAURO

[Klamt et al., Journal of Field Robotics 2020]

Mobile Manipulation Robot Momaro

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

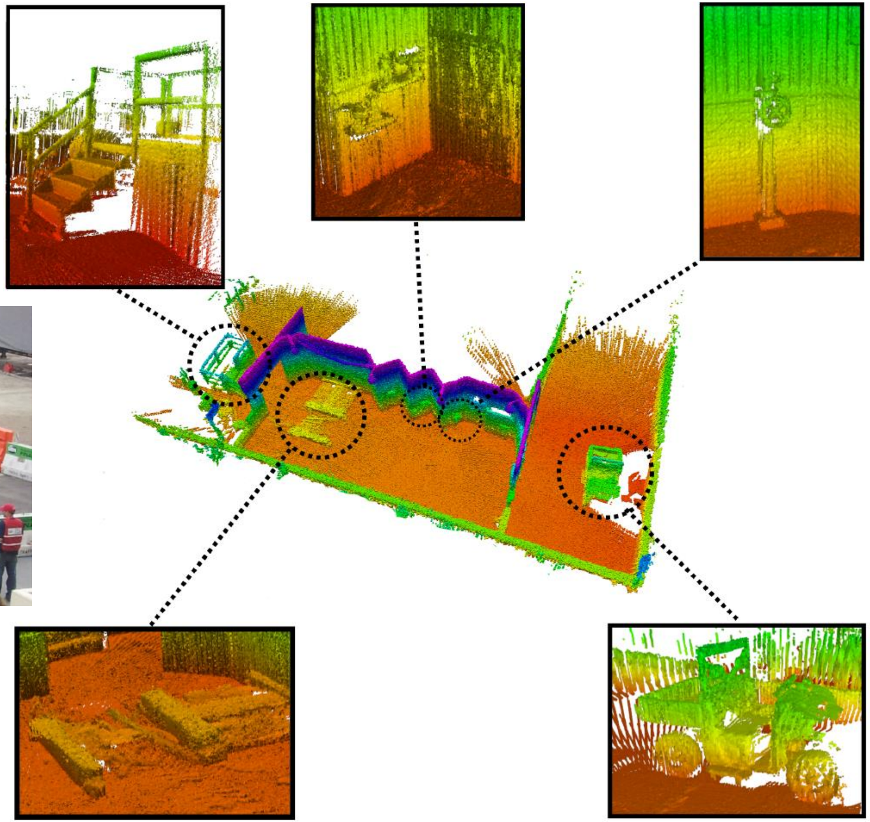


[Schwarz et al. Journal of Field Robotics 2017]

DARPA Robotics Challenge

Allocentric 3D Mapping

- Registration of egocentric maps by graph optimization

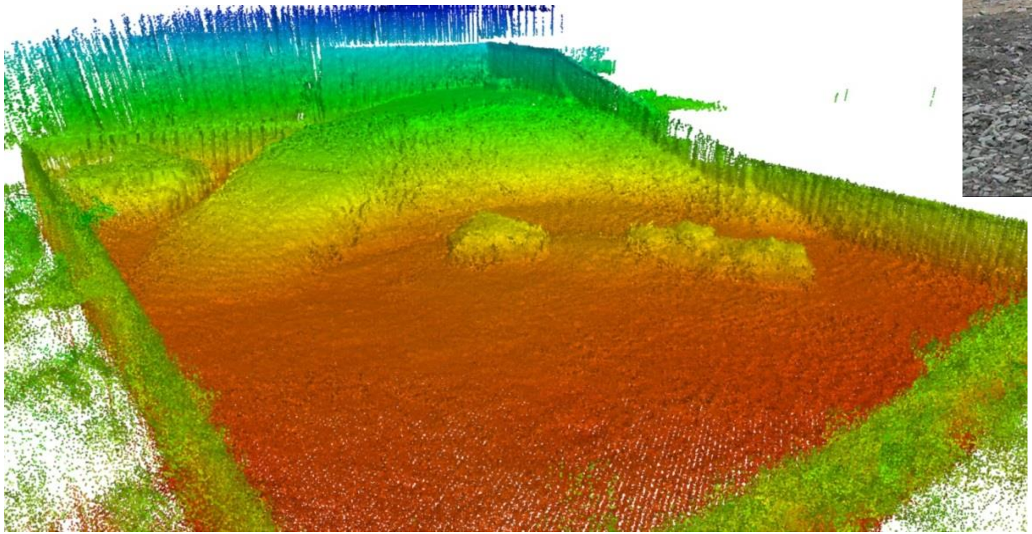


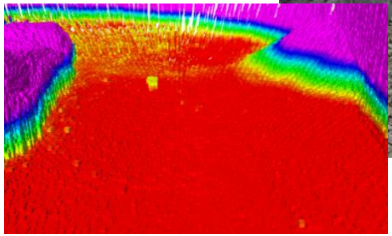
[Droeschel et al., Robotics and Autonomous Systems 2017]

DLR SpaceBot Cup 2015

- Mobile manipulation in rough terrain

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

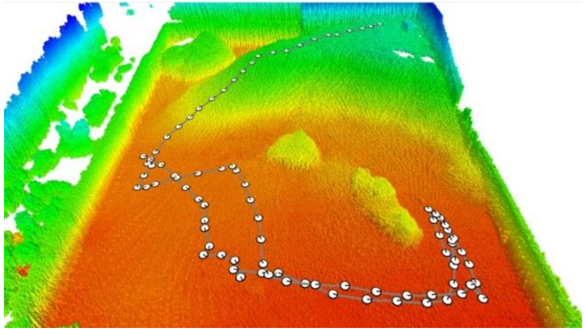




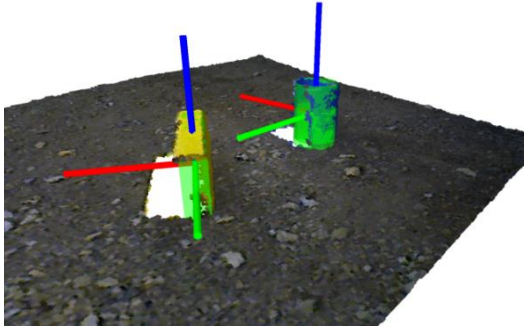

8X

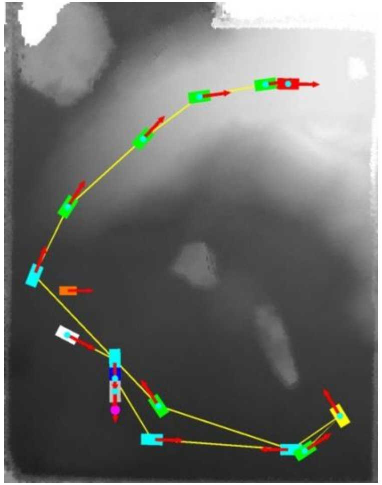
Autonomous Mission Execution

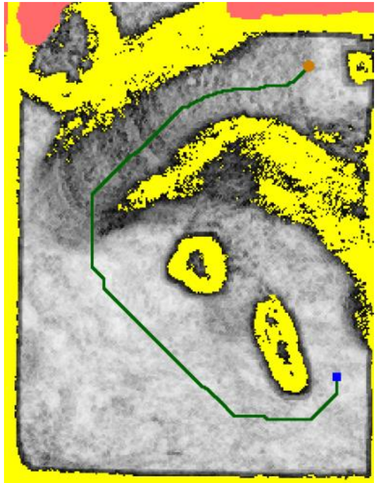
- 3D mapping, localization, mission and navigation planning

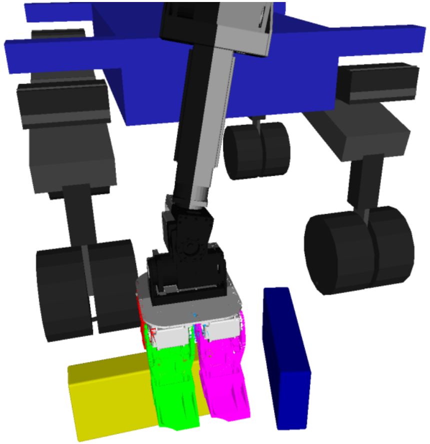


- 3D object perception and grasping





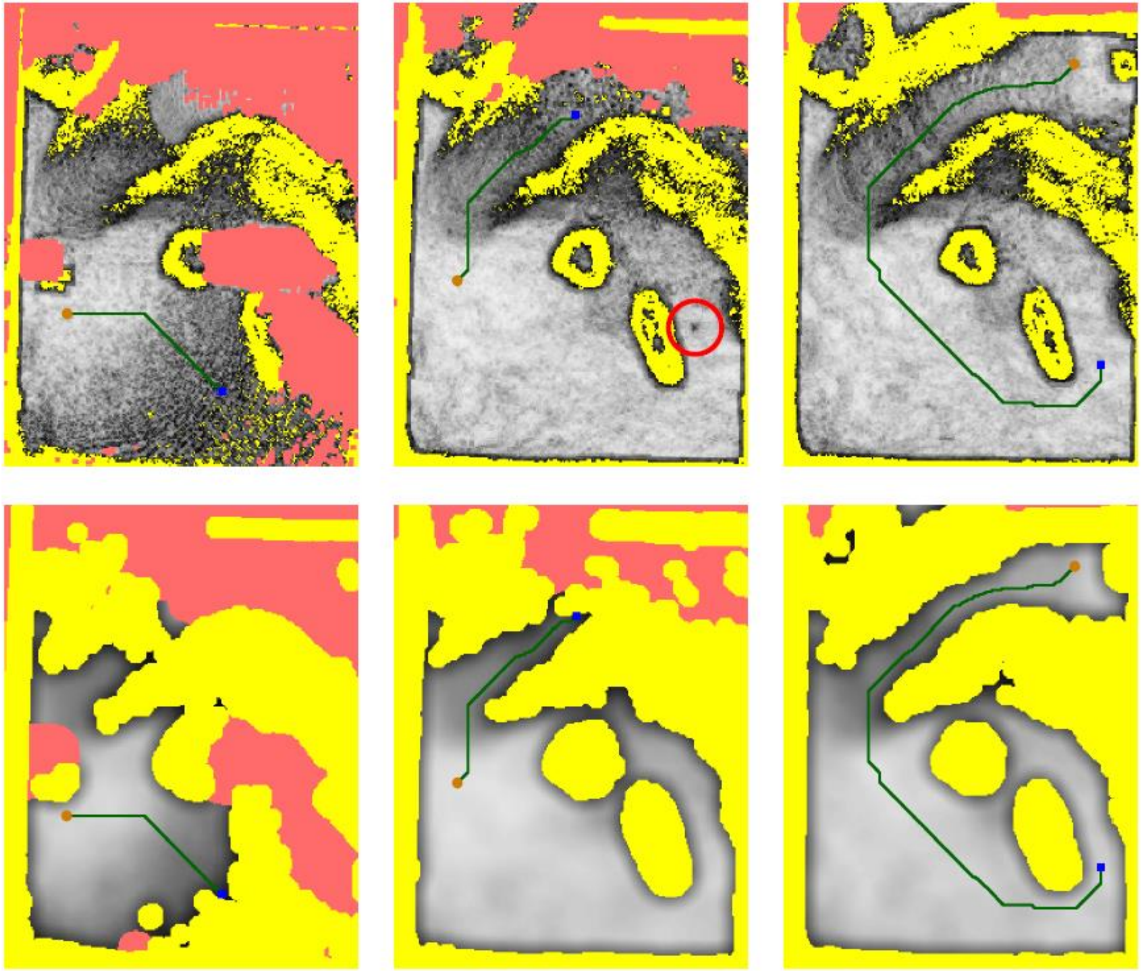




[Schwarz et al. Frontiers 2016]

Navigation Planning

- Costs from local height differences
- A* path planning

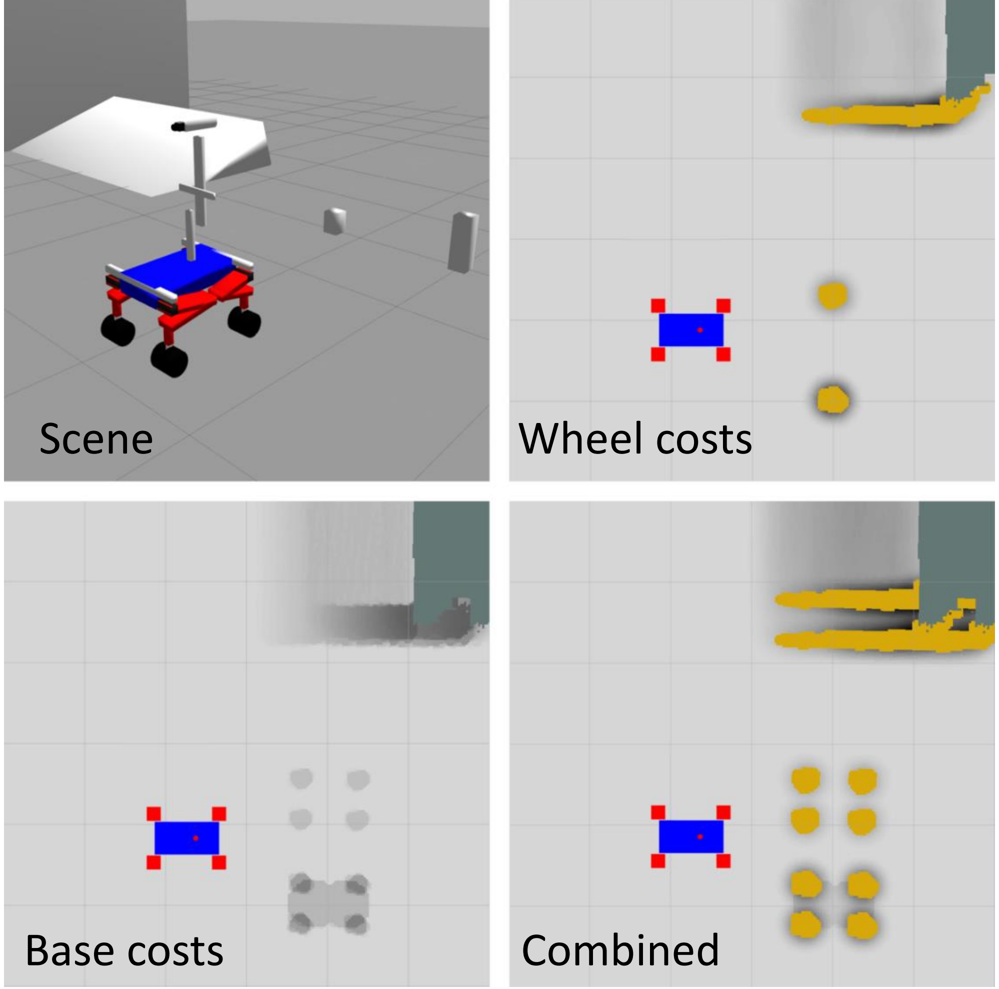


[Schwarz et al., Frontiers in Robotics and AI 2016]

Considering Robot Footprint

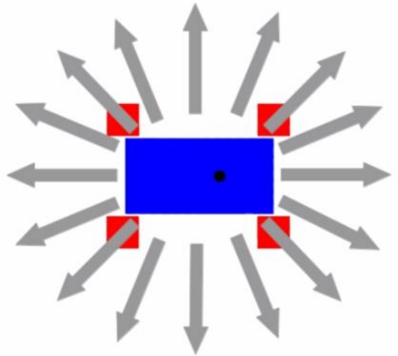
- Costs for individual wheel pairs from height differences
- Base costs
- Non-linear combination yields 3D (x, y, θ) cost map

[Klamt and Behnke, IROS 2017]

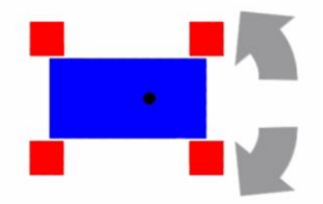


3D Driving Planning (x, y, θ): A*

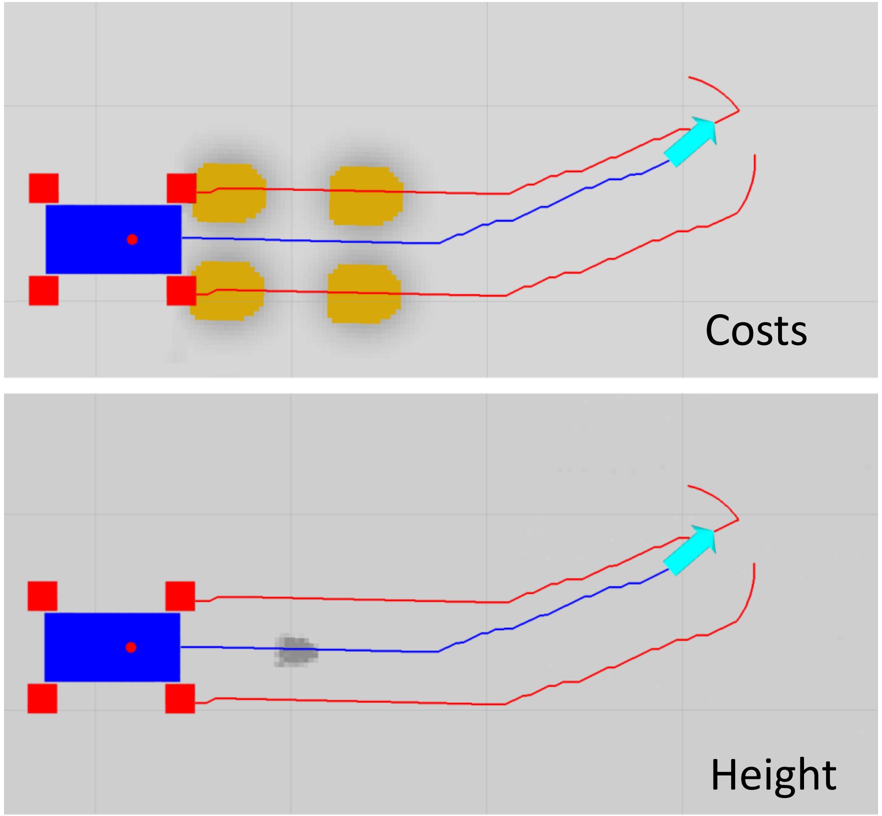
- 16 driving directions



- Orientation changes



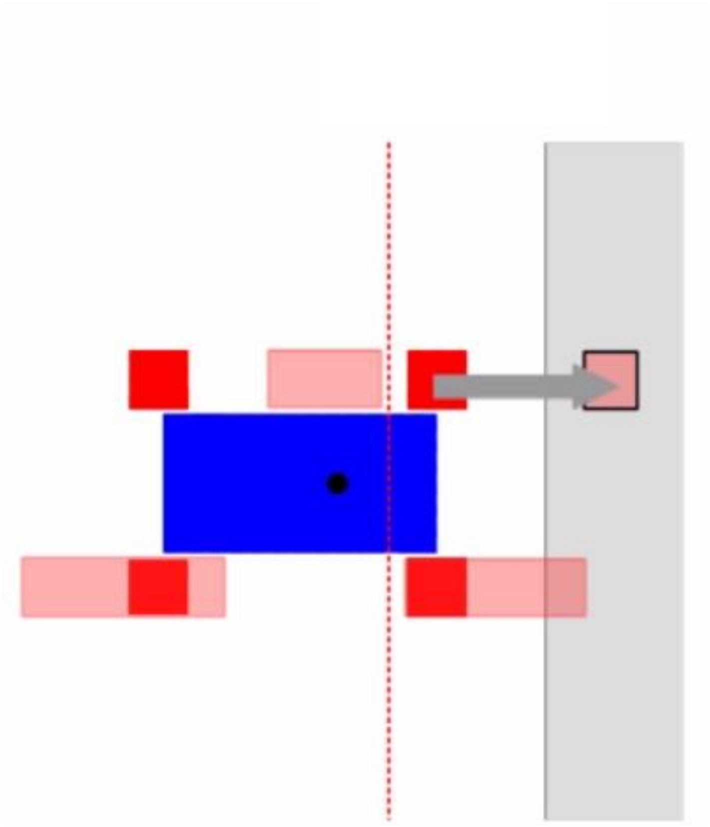
=> Obstacle between wheels



[Klamt and Behnke, IROS 2017]

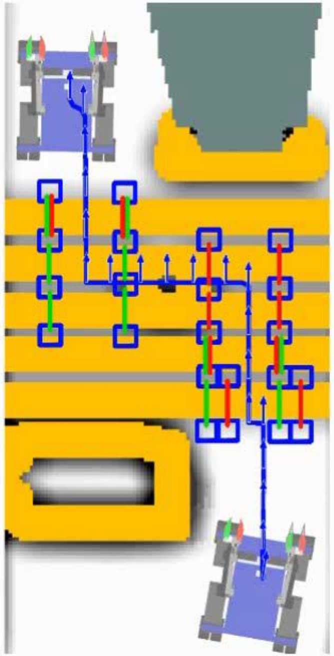
Making Steps

- If non-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 a Challenging Scenario



[Klamt and Behnke: IROS 2017]

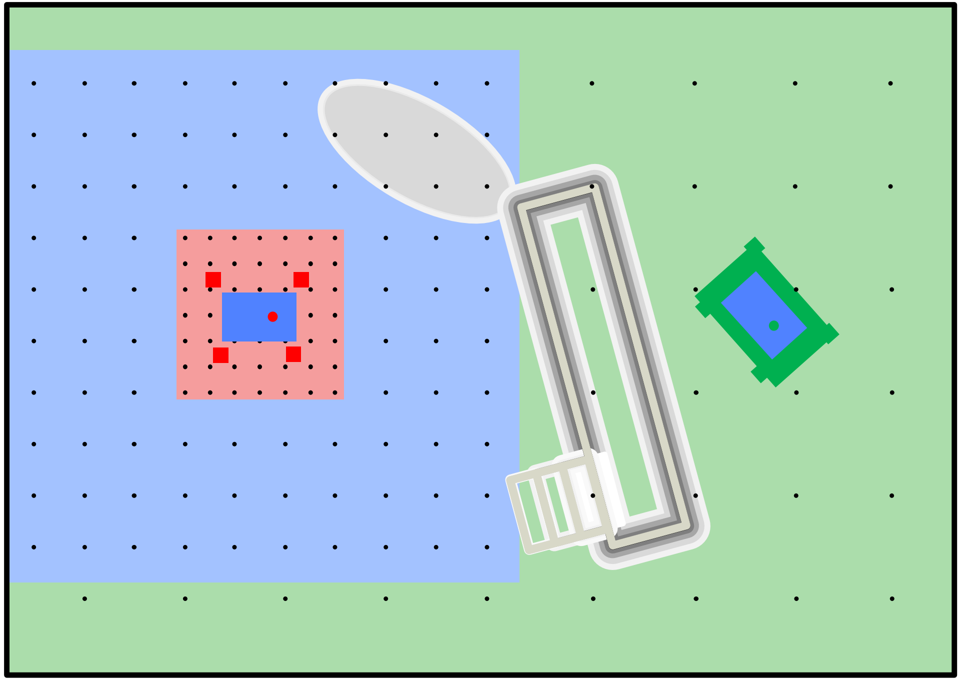
Centauro Robot

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

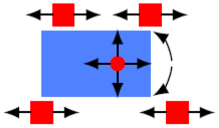
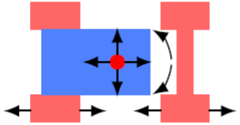
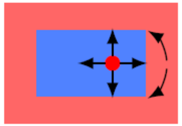
[Tsagarakis et al., IIT 2017]

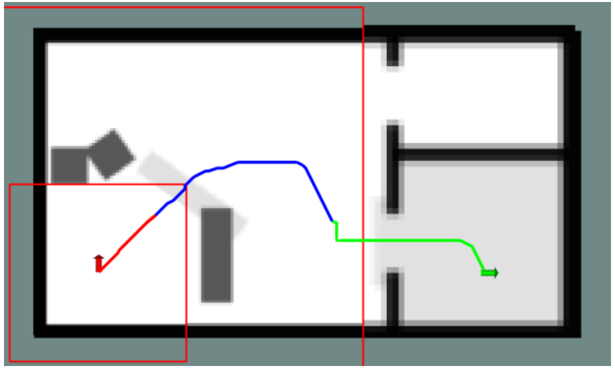
Hybrid Driving-Stepping Locomotion Planning: Abstraction

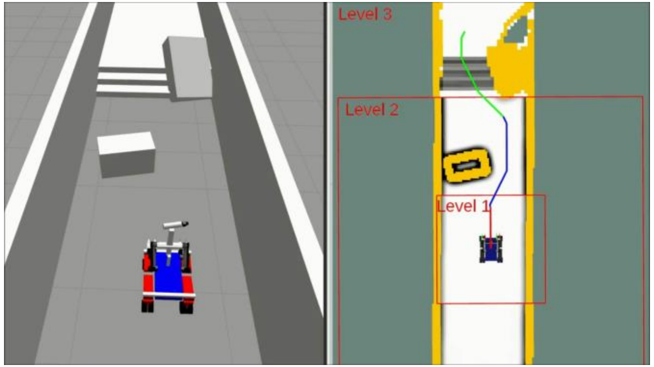
- Planning in the here and now
- Far-away details are abstracted away



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

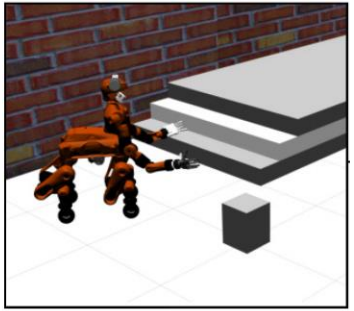




[Klamt and Behnke, IROS 2017, ICRA 2018]

Learning Cost Functions of Abstract Representations

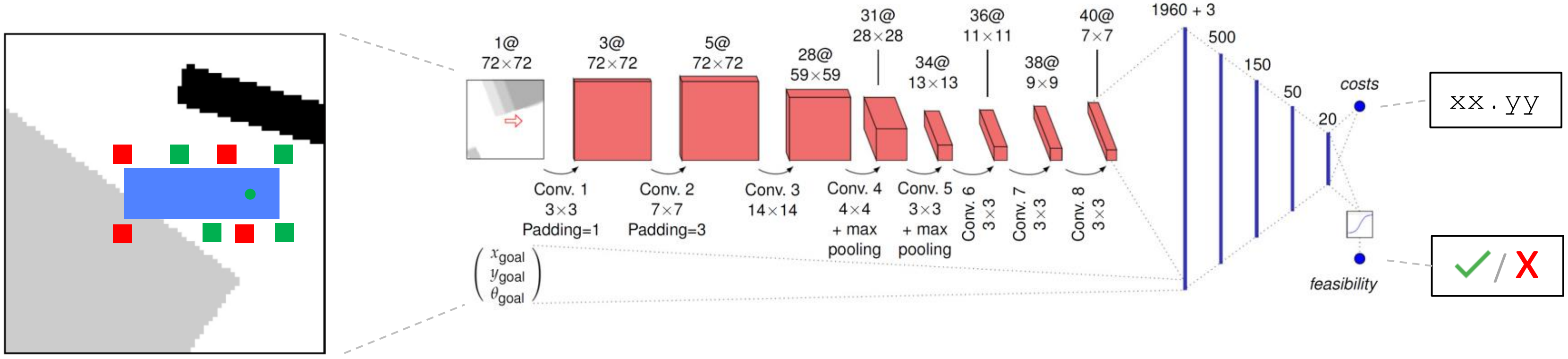
Planning problem



[Klamt and Behnke, ICRA 2019]

Abstraction CNN

- Predict feasibility and costs of local detailed planning



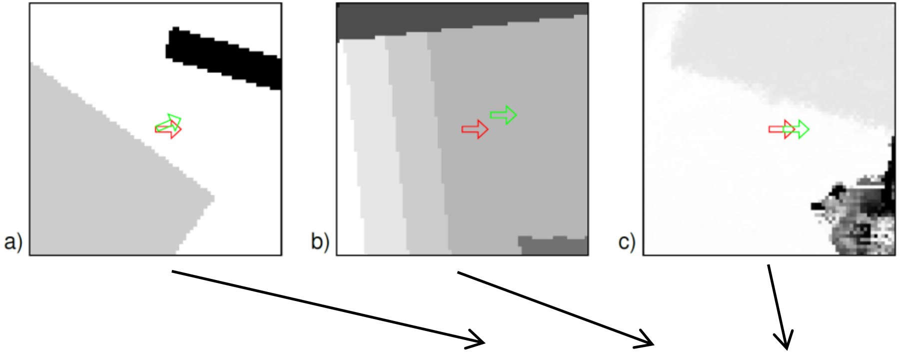
Training data

- generated with random obstacles, walls, staircases
- *costs* and *feasibility* from detailed A*-planner
- ~250.000 tasks

[Klamt and Behnke, ICRA 2019]

Learned Cost Function: Abstraction Quality

- CNN predicts feasibility and costs better than manually tuned geometric heuristics

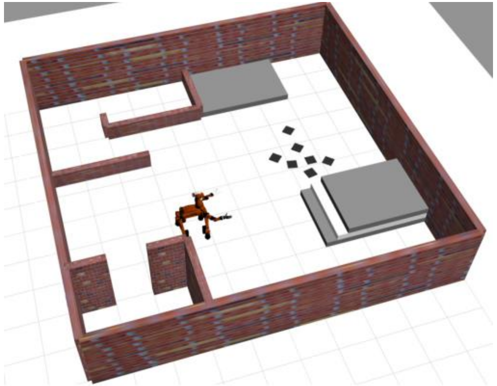


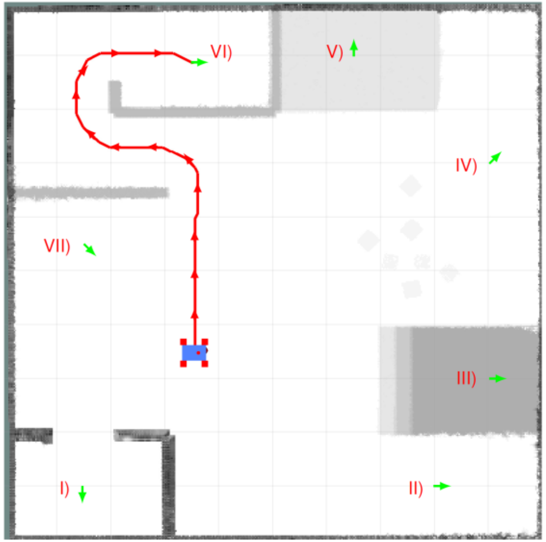
	random	*simulated*	*real*
feasibility correct, man.tuned	79.27%	65.35%	69.77%
Error($\mathcal{C}_{\text{a,man.tuned}}$)	0.057	0.021	0.103
feasibility correct, CNN	95.04%	96.69%	92.62%
Error($\mathcal{C}_{\text{a,CNN}}$)	0.027	0.013	0.081

[Klamt and Behnke, ICRA 2019]

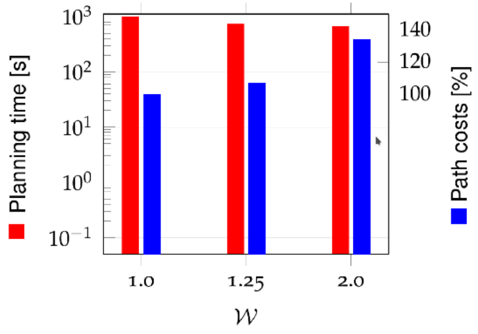
Experiments – Planning Performance

- Learned heuristics accelerates planning, without increasing path costs much

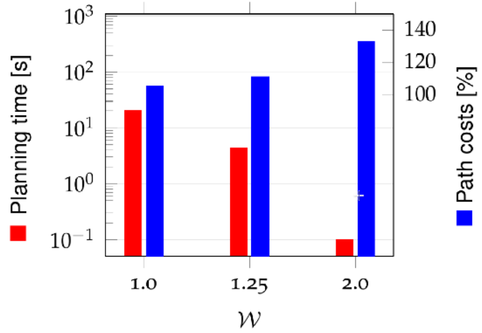




Geometric heuristic



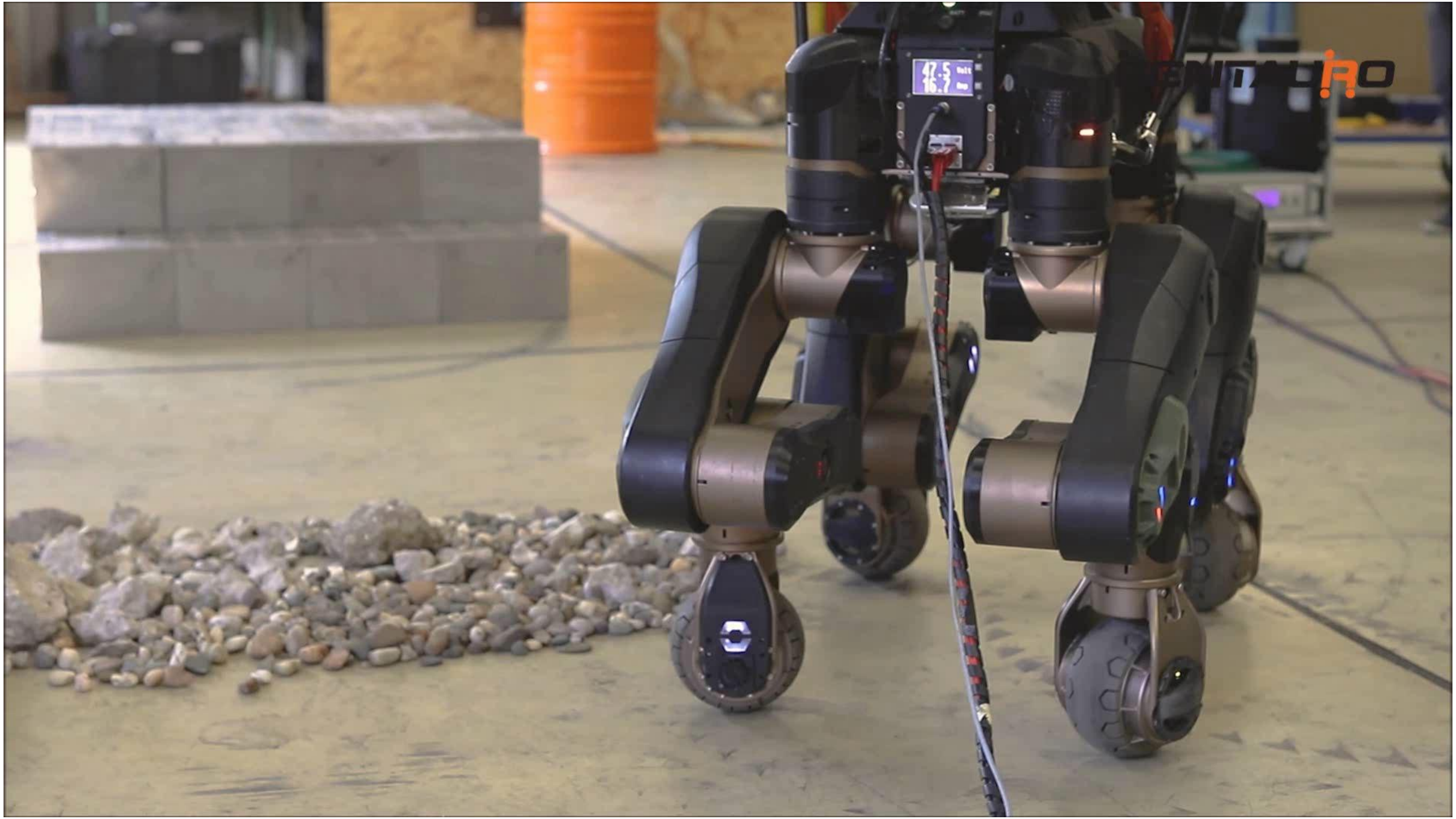
Abstract representation heuristic



Heuristic preprocessing: 239 sec

[Klamt and Behnke, ICRA 2019]

CENTAURO Evaluation @ KHG: Locomotion Tasks



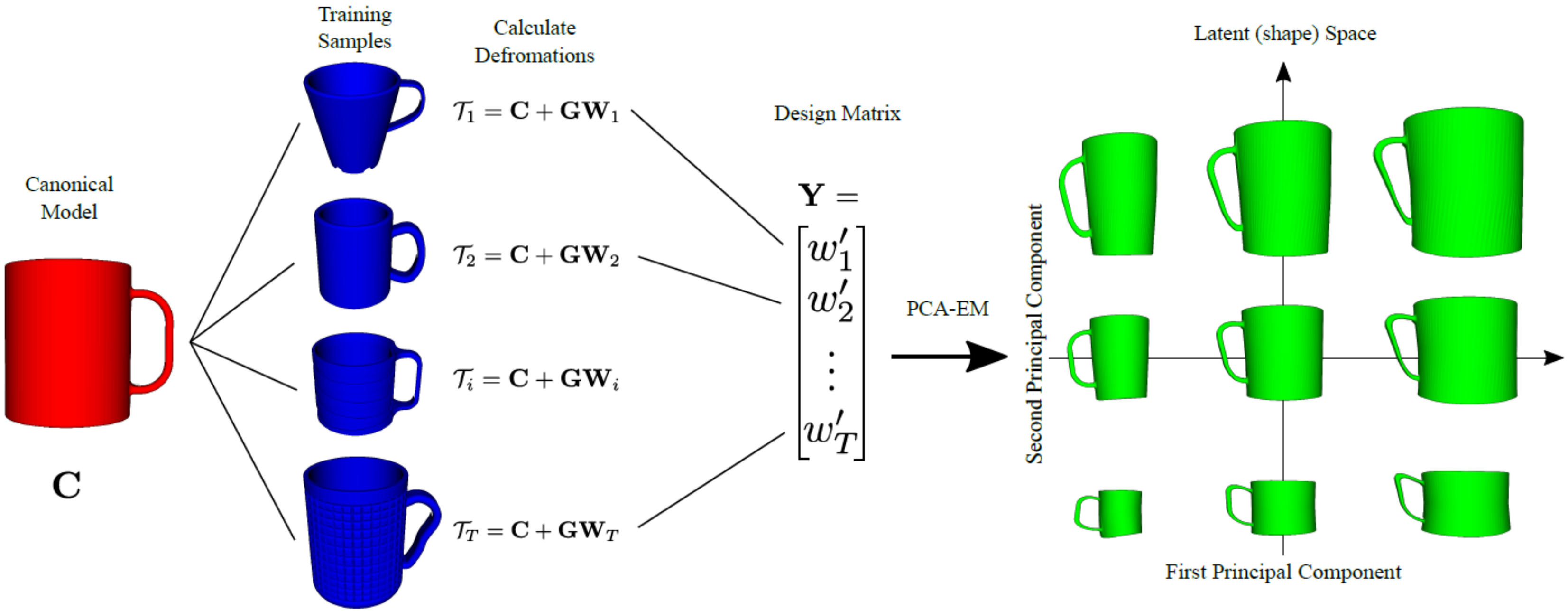
[Klamt et al. RAM 2019]

Transfer of Manipulation Skills

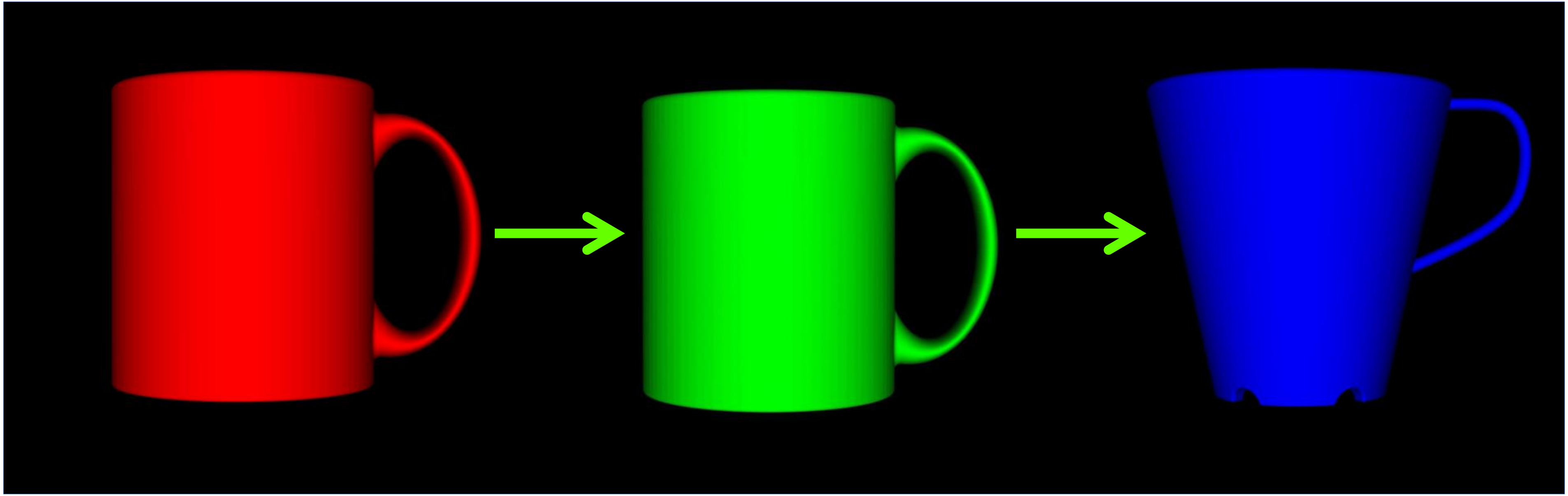
Knowledge
Transfer

Learning a Latent Shape Space

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



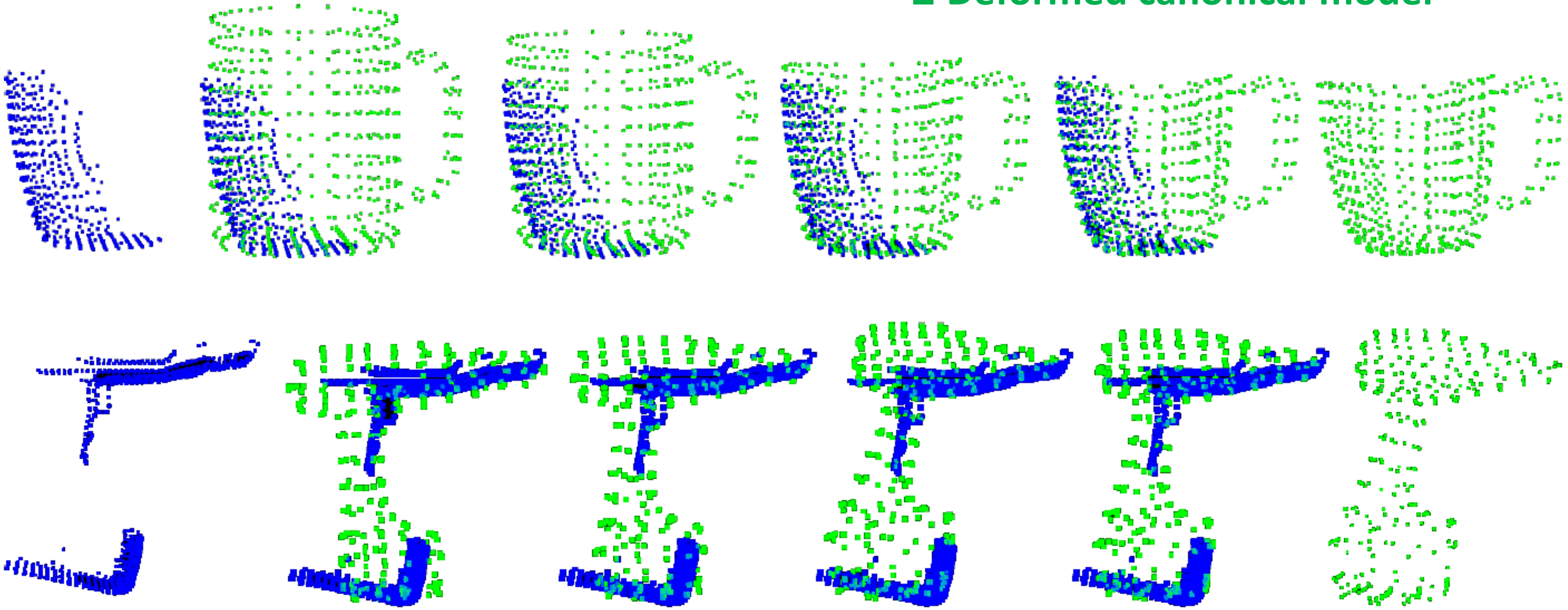
Interpolation in Shape Space



[Rodriguez and Behnke ICRA 2018]

Shape-aware Non-rigid Registration

- Partial view of novel instance
- Deformed canonical model

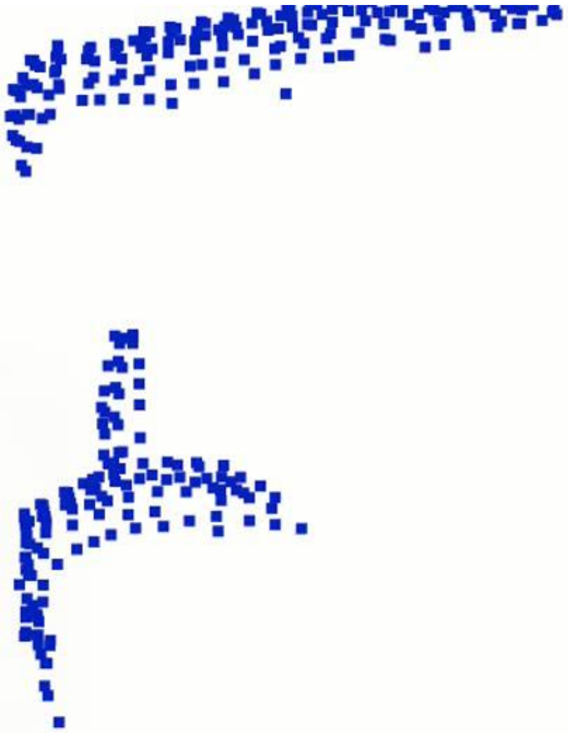


[Rodriguez and Behnke ICRA 2018]

Shape-aware Registration for Grasp Transfer

- Full point cloud

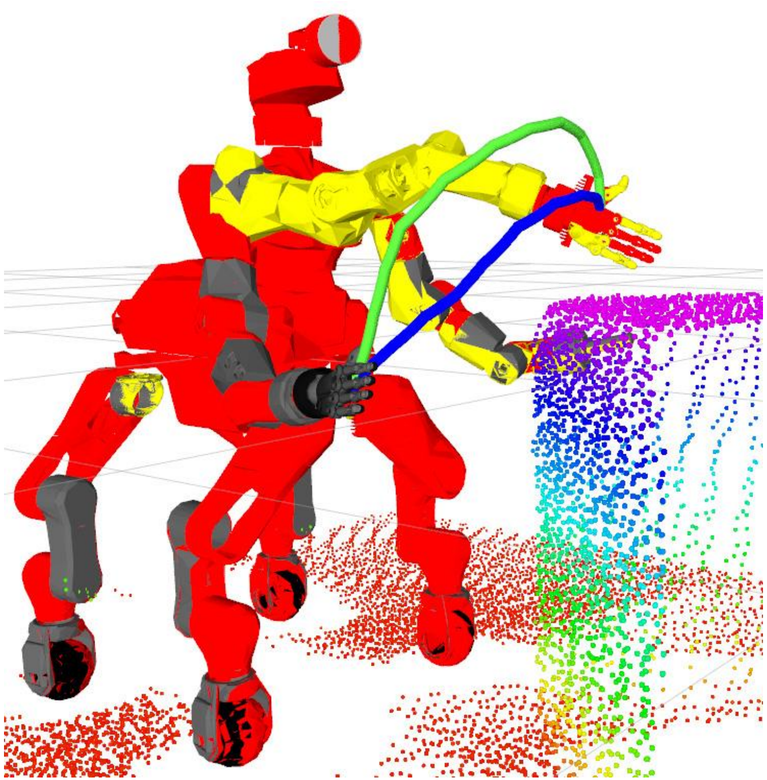
- Partial view



Collision-aware Motion Generation

Constrained Trajectory Optimization:

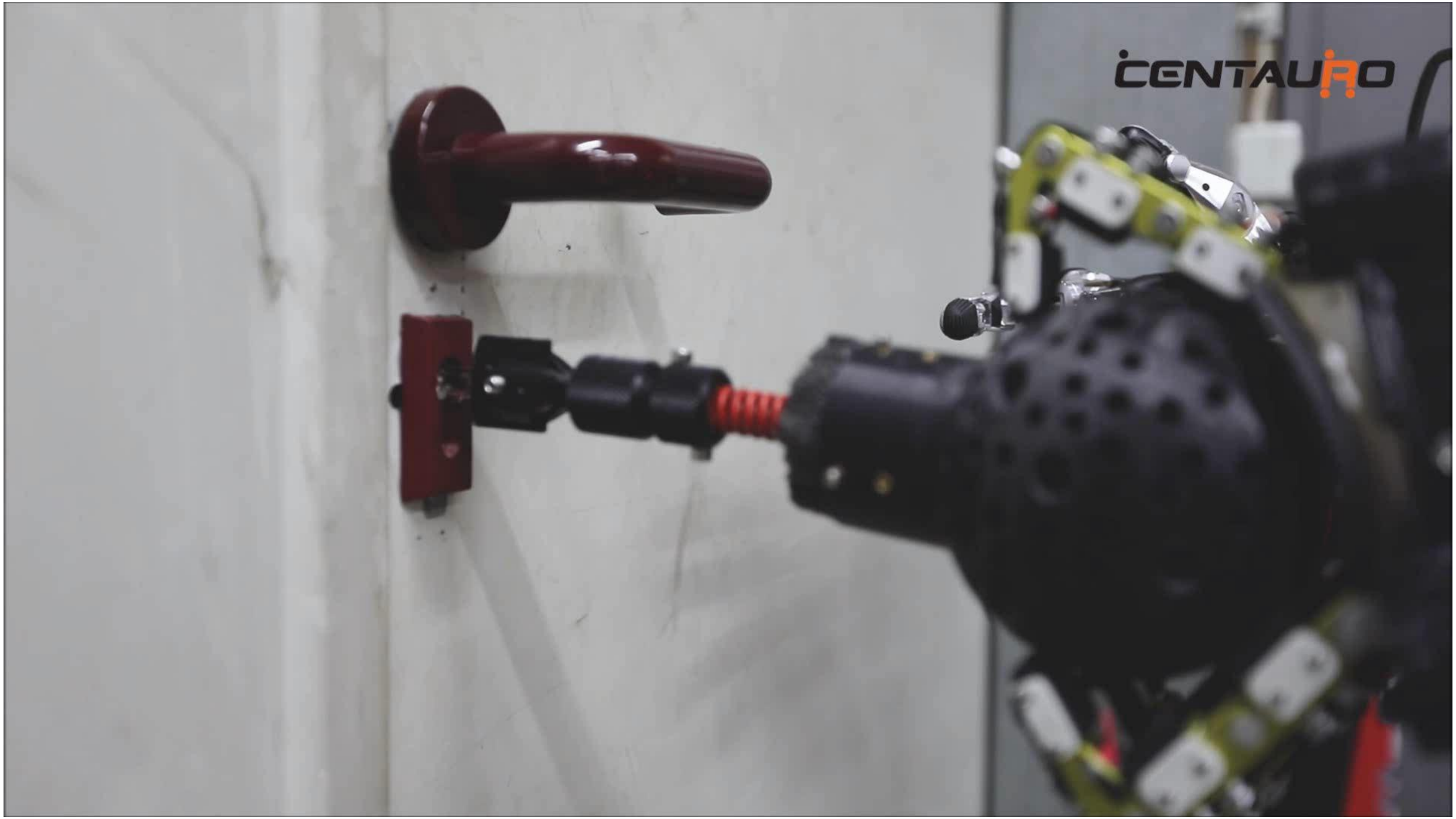
- Collision avoidance
- Joint limits
- Time minimization
- Torque optimization



[Pavlichenko et al., IROS 2017]

Grasping an Unknown Power Drill and Fastening Screws

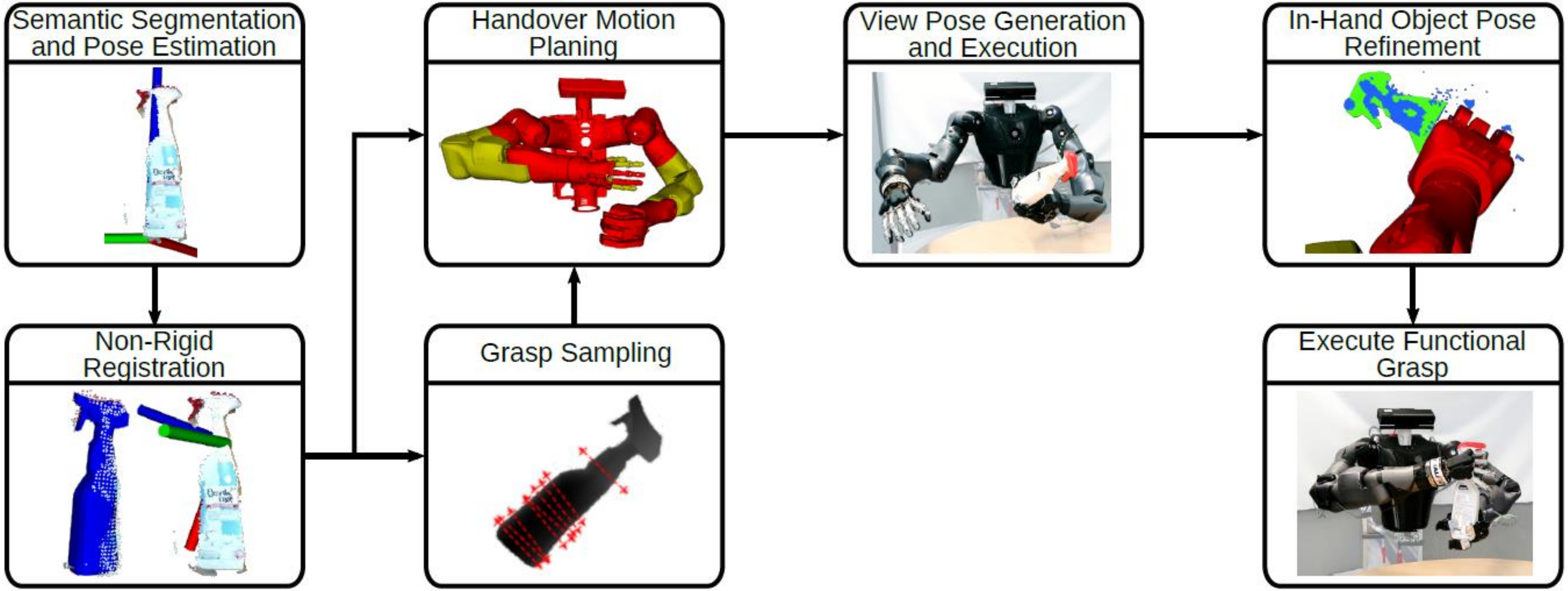
CENTAURO: Complex Manipulation Tasks



[Klamt et al. RAM 2019]

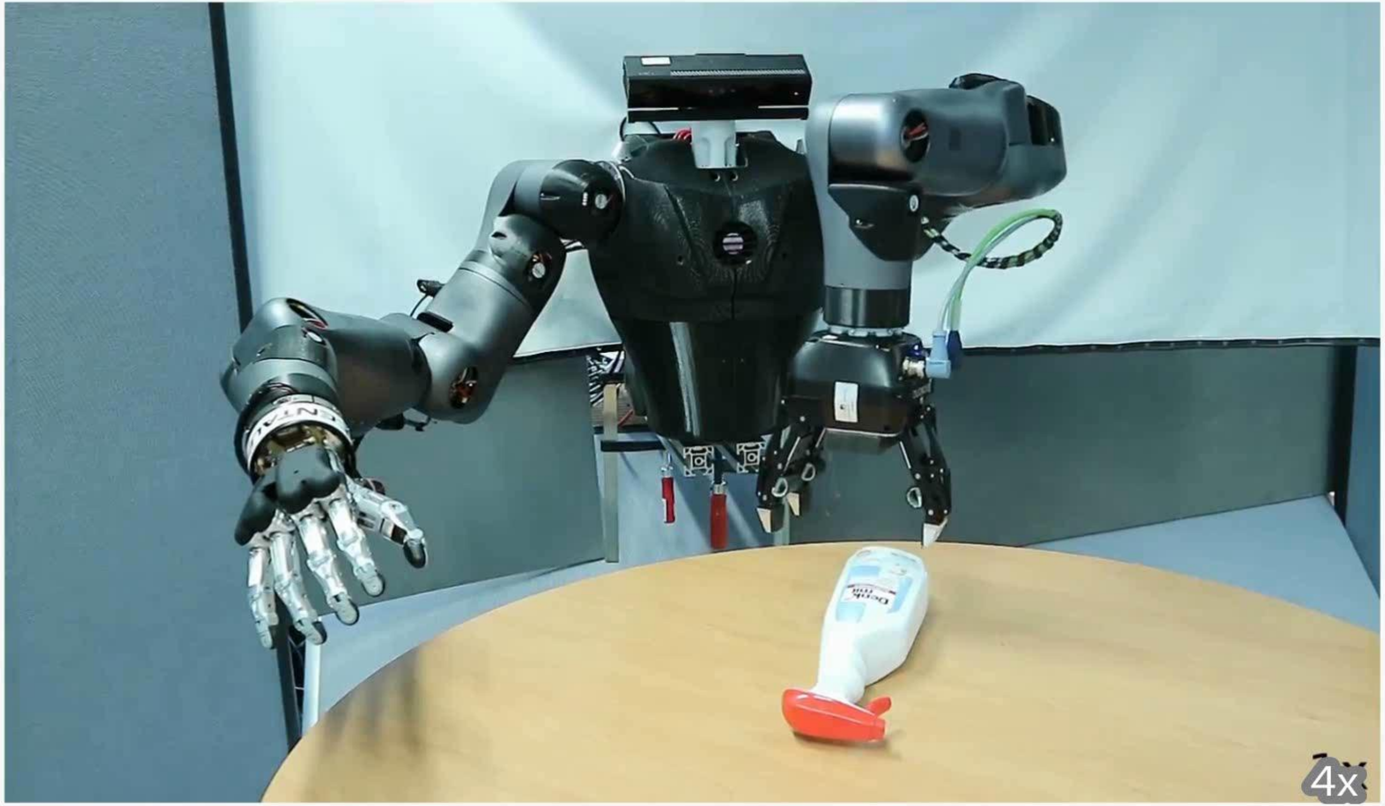
Regrasping for Functional Grasp

- Direct functional grasps not always feasible
- Pick up object with support hand, such that it can be grasped in a functional way



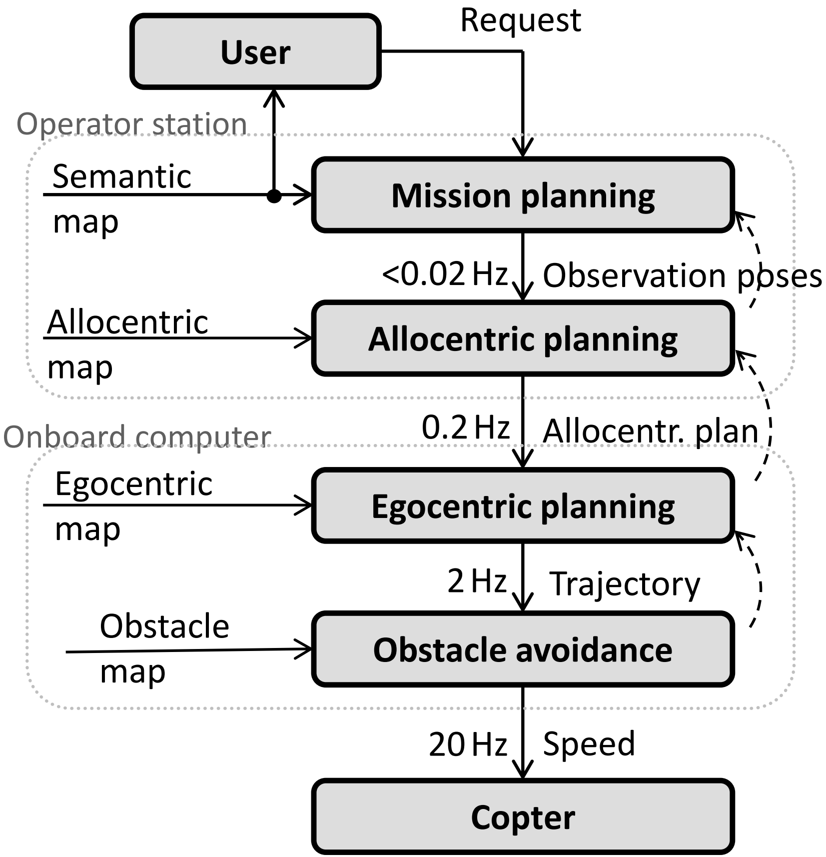
[Pavlichenko et al. Humanoids 2019]

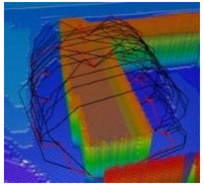
Regrasping Experiments



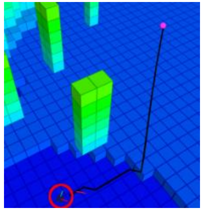
[Pavlichenko et al. Humanoids 2019]

Micro Aerial Vehicles: Hierarchical Navigation

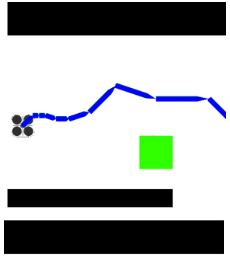




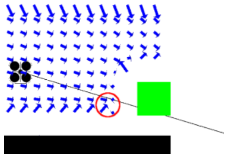
Mission plan



Allocentric planning

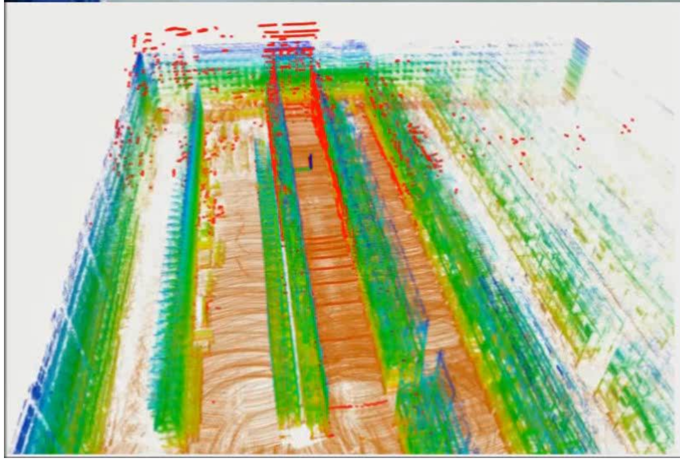


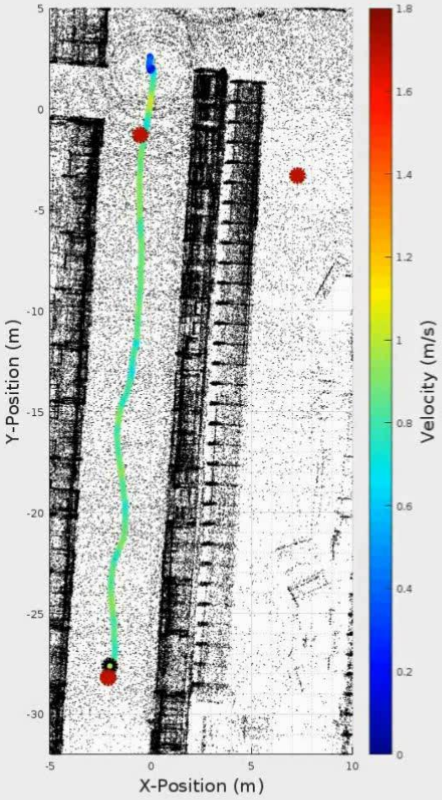
Egocentric planning



Obstacle avoidance

InventAIRy: Autonomous Navigation in a Warehouse

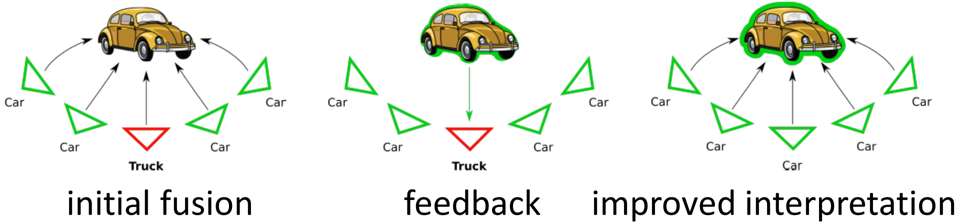


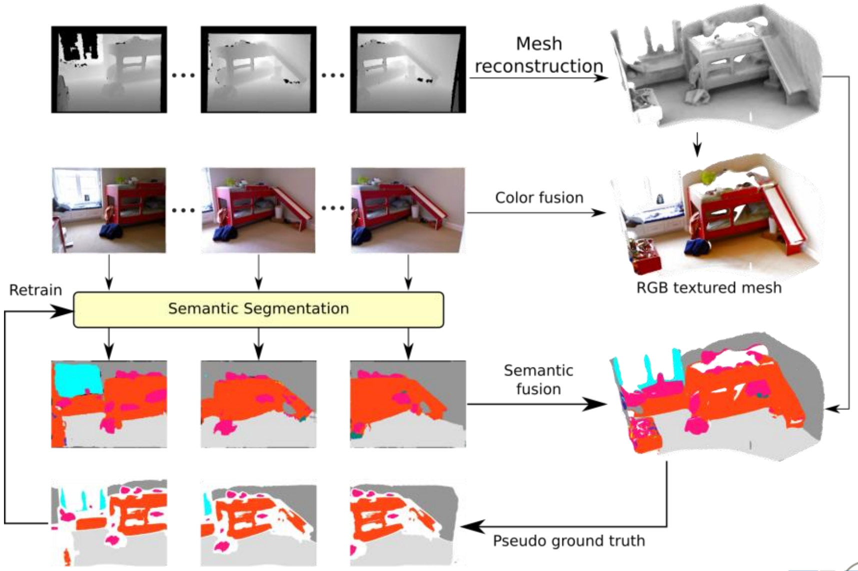


InventAIRy: Detected Tags in Shelf

Label Propagation for 3D Semantic Mapping

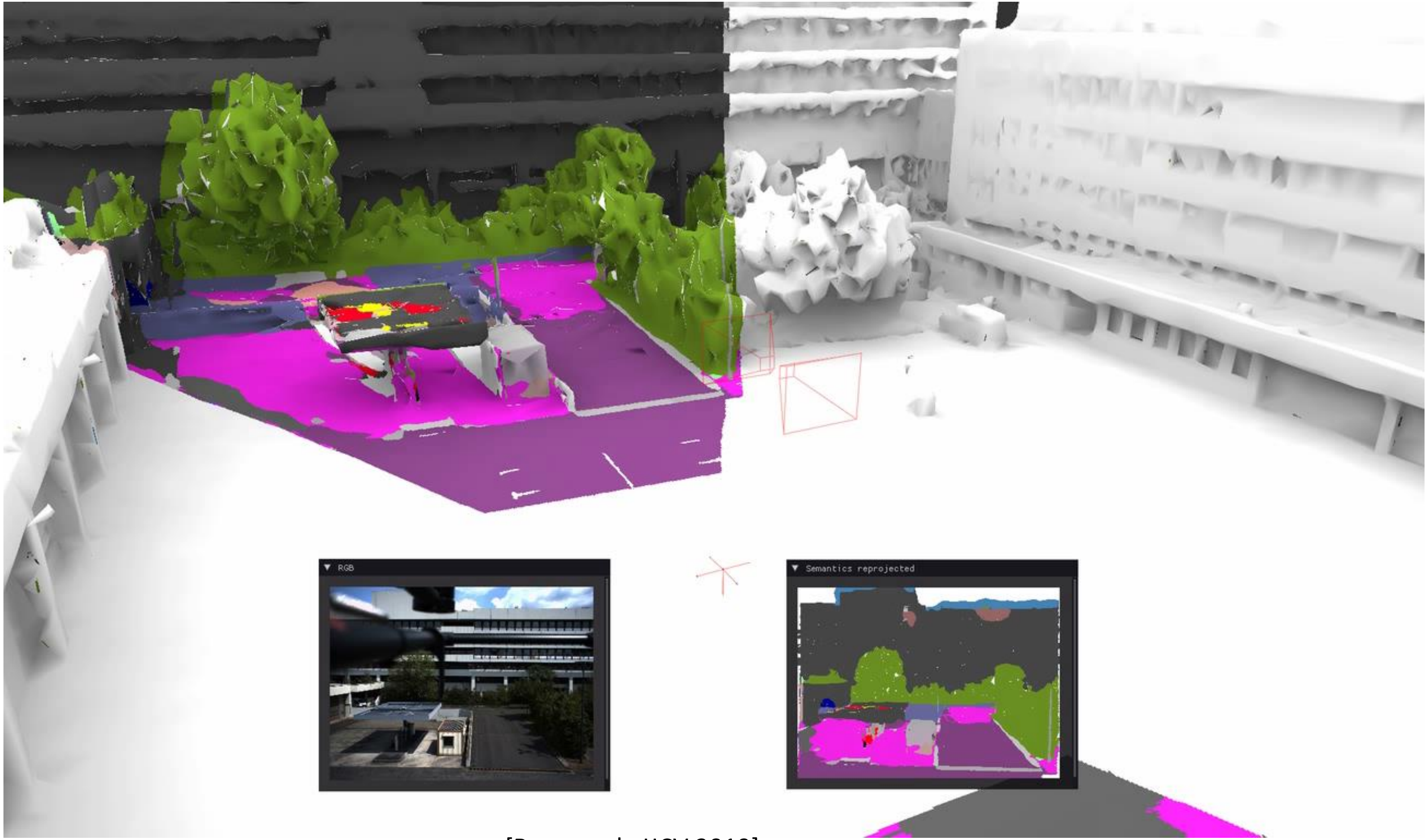
- Image-based semantic categorization, trained with Mapillary data set
- 3D fusion in semantic texture
- Backprojection of labels to other views





[Rosu et al., IJCV 2019]

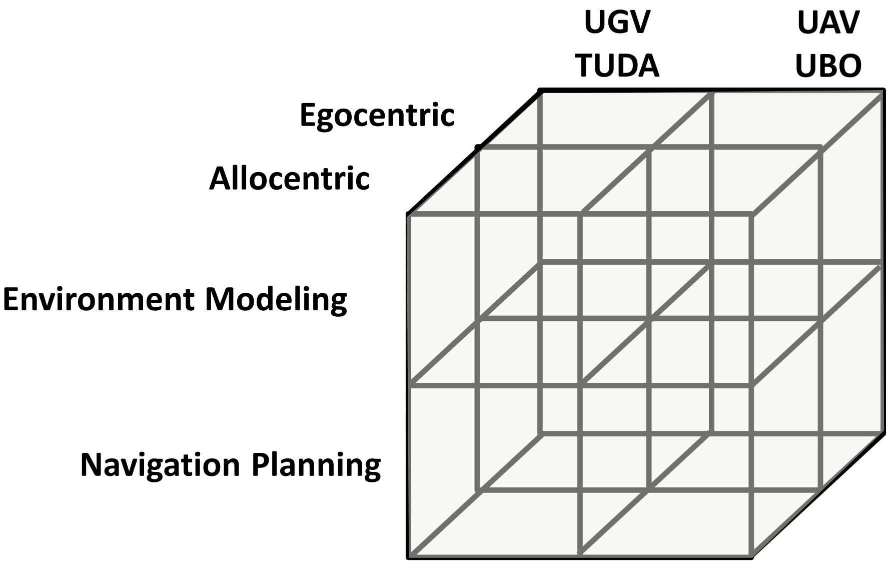
3D Semantic Mapping



[Rosu et al., IJCV 2019]

German Rescue Robotics Center (DRZ): Autonomus Assistance Functions

- Development of autonomous assistance functions for ground and flying robots
- Initially egocentric, later allocentric: Environment modeling and navigation planning
- Integration with operator interfaces



UAV Demonstrators

Initial demonstrator

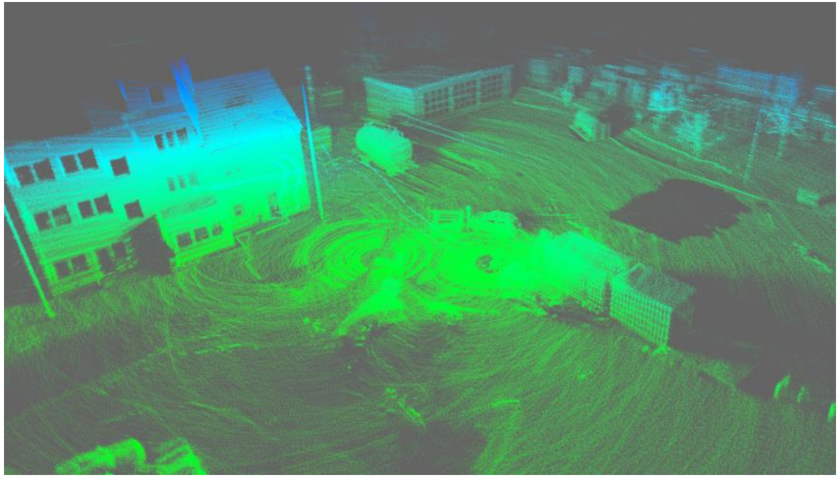
- Basis: DJI Matrice 600 Pro
- Sensors: Velodyne VLP 16, FLIR Boson, 2x FLIR BlackFly S
- Tiltable sensor head

Current demonstrator

- Basis: DJI Matrice 210 v2
- Sensors: Ouster OS-0, FLIR AGX, 2× Intel RealSense D455
- IP43 water resistance

Supporting Fire Fighters (A-DRZ)

- Added thermal camera
- Flight at Brandhaus Dortmund



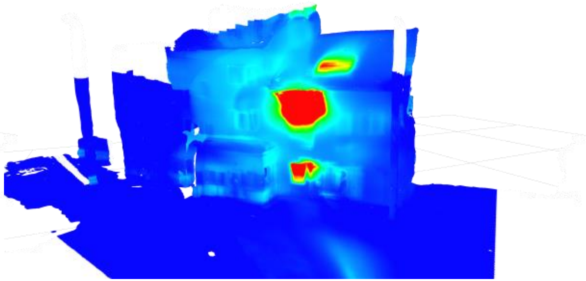
[Rosu et al. SSRR 2019]

Mesh-based 3D Modeling + Textures

- Model 3D geometry with mesh
- Appearance and temperature as high-resolution texture

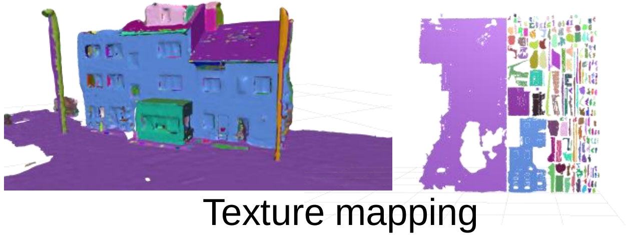
Mesh geometry

RGB texture



Thermal texture

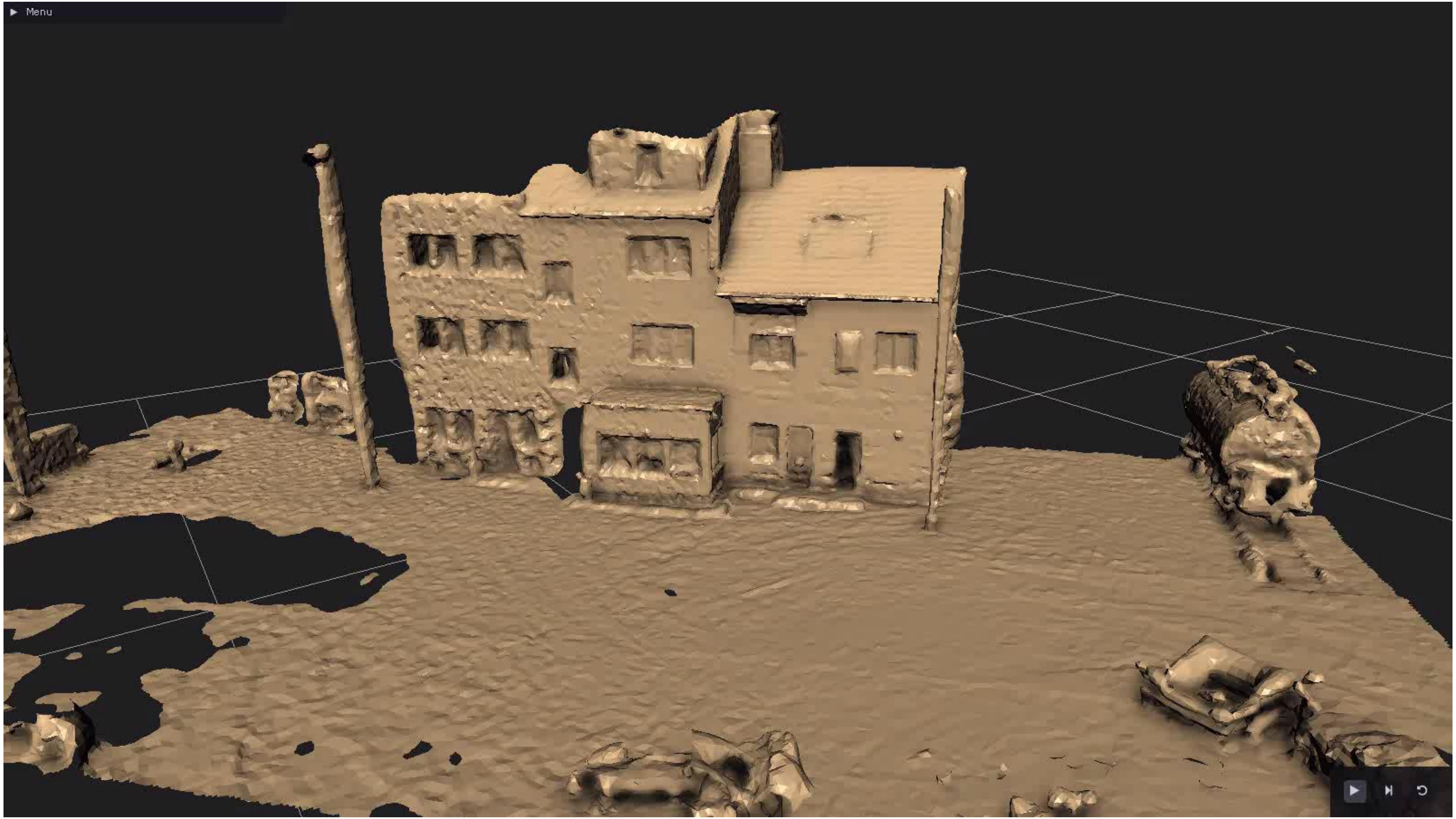
- Mapping from 3D mesh to 2D texture



Texture mapping

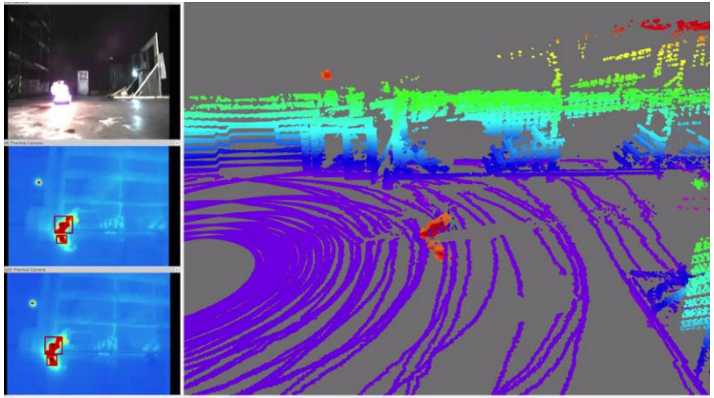
[Rosu et al. SSRR 2019]

Modeling the Brandhaus Dortmund

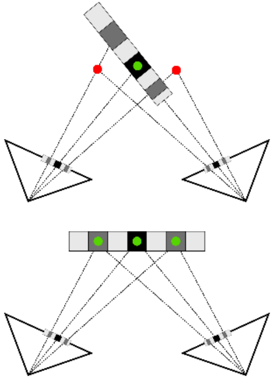


[Rosu et al. SSRR 2019]

Depth Estimation from Stereo Thermal Images



Depth estimation of fire from thermal stereo, Minimax-Viking fire house



Triangulation errors caused by incorrect data association

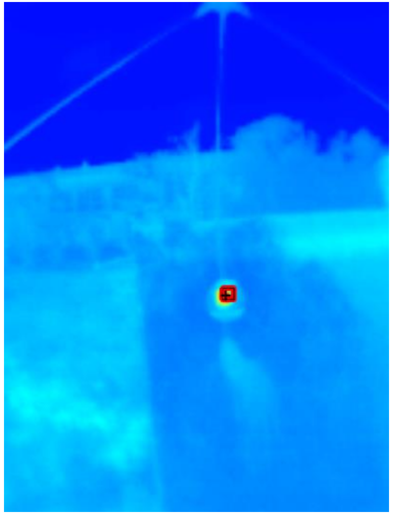
Correct 3D reconstruction

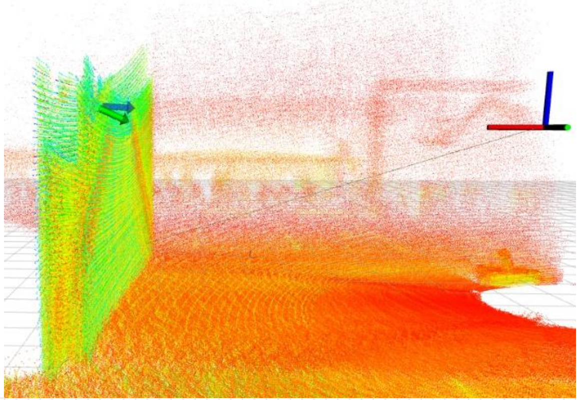
- Problem: Flames are transparent to LiDAR and brightness and illumination changes in images lead to false association
- Gradient-based similarity measure sgf combines orientation and magnitude of normalized gradient field
- Correct 3D location of fire sources with sgf and stereo thermal imagery

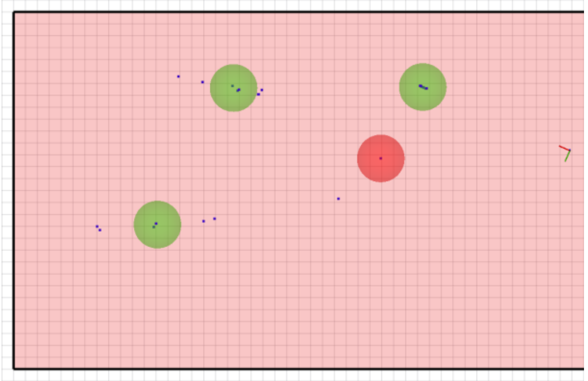
[Quenzel et al. ICRA 2020]

Multi-hypothesis Tracking of Fire Detections

- Aggregation of egocentric fire detections to filtered allocentric fire hypotheses
- Integration of 2D detections (direction vector) by ray-casting and of 3D detections

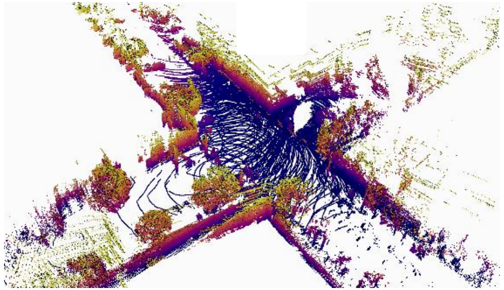




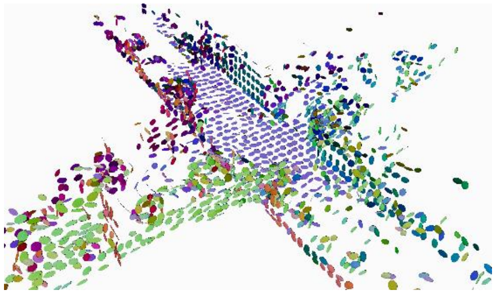


[Quenzel et al. ICUAS 2021]

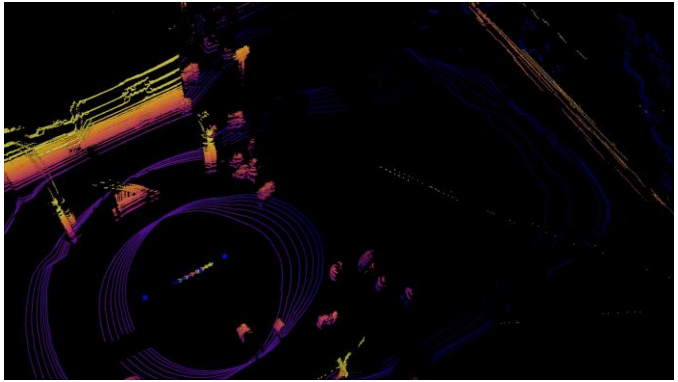
Real-time LiDAR Odometry with Continuous-time Trajectory Optimization



Point cloud



Multiresolution surfel map



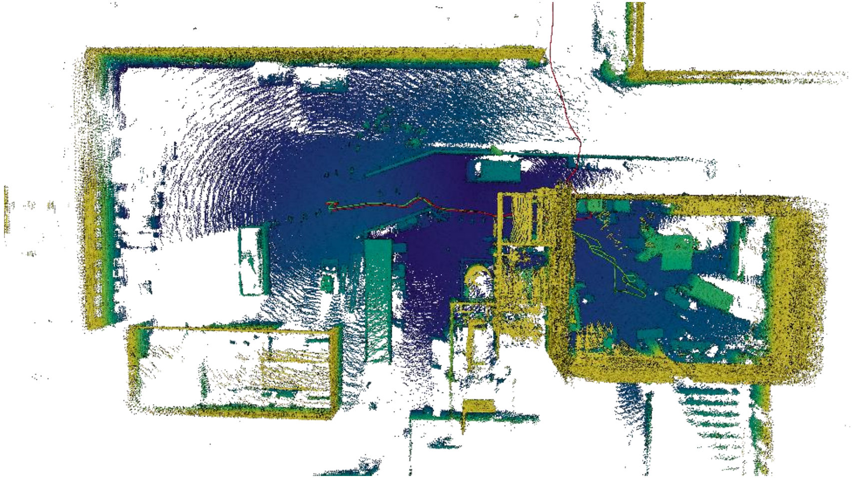
Time-continuous spline

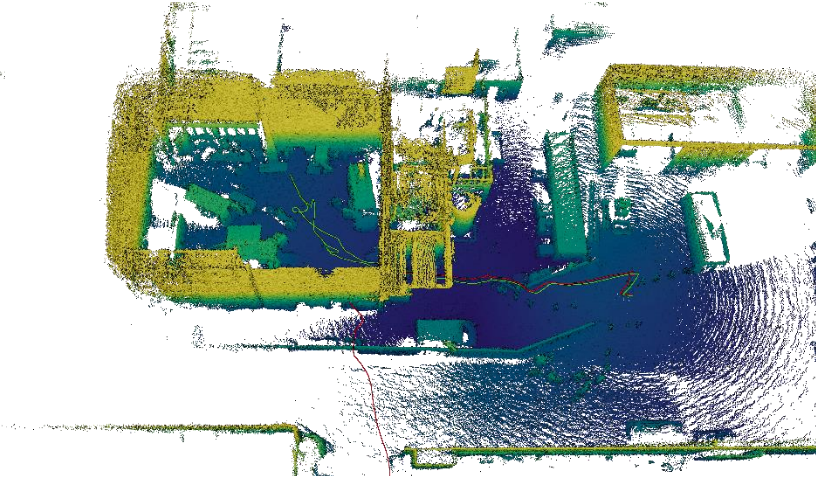
- Simultaneous registration of multiple multiresolution survey maps using Gaussian mixture models and temporally continuous B-spline
- Accelerated by sparse voxel grids and adaptive choice of resolution

[Quenzel and Behnke, IROS 2021]

LiDAR Odometry

Minimax-Viking fire house



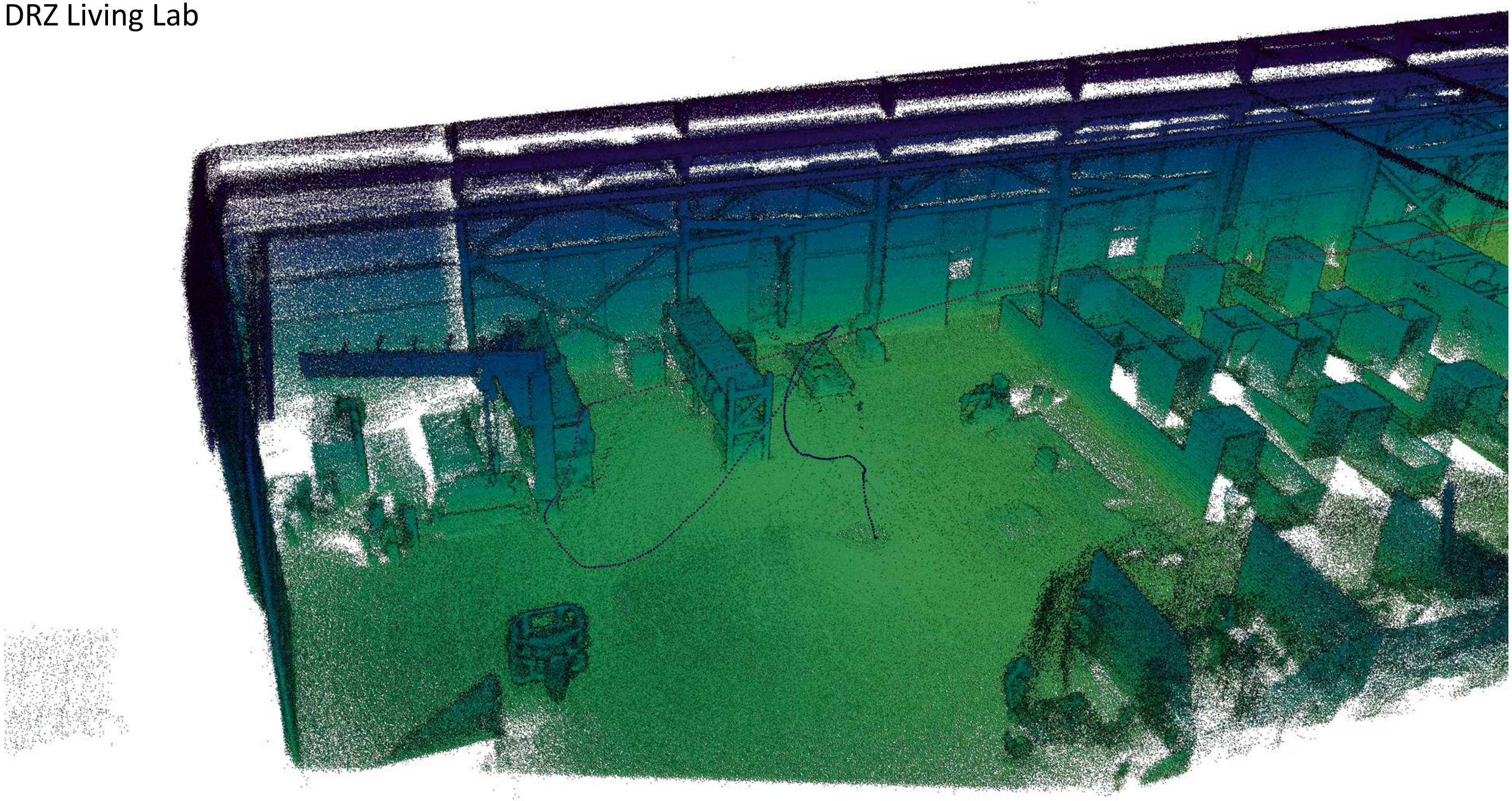


- Sliding window keyframe approach for drift reduction
- Scan fusion and moving the local map on the surfel level

[Quenzel and Behnke, IROS 2021]

3D LiDAR Mapping

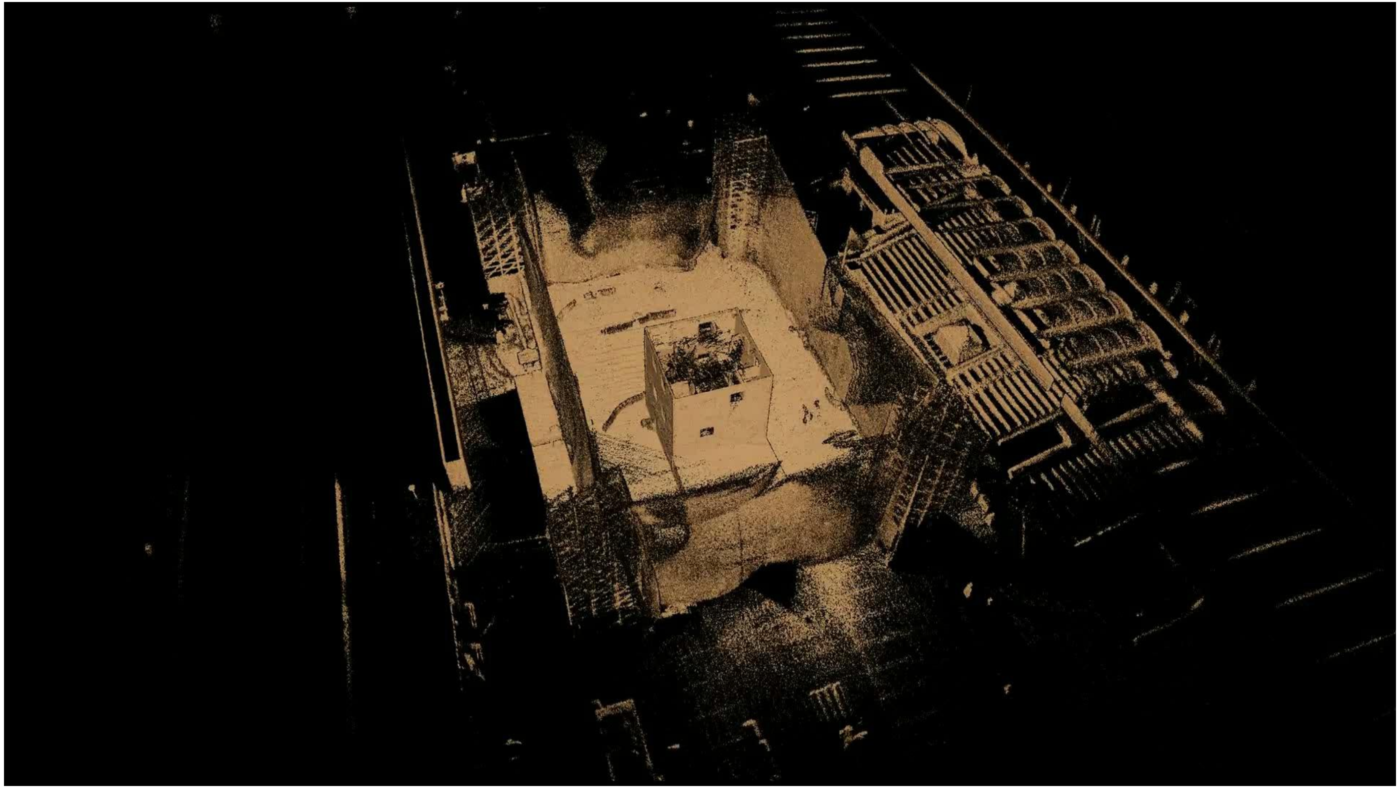
DRZ Living Lab



3D LiDAR Mapping

- Local mapping with position prior
- GPS offset correction for improved localization
- Dedicated outdoor and indoor maps with seamless localization switching

MBZIRC 2020



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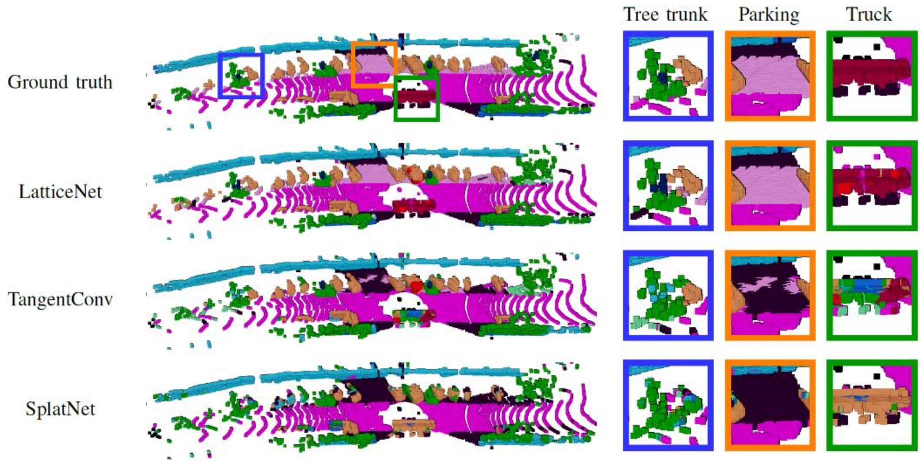
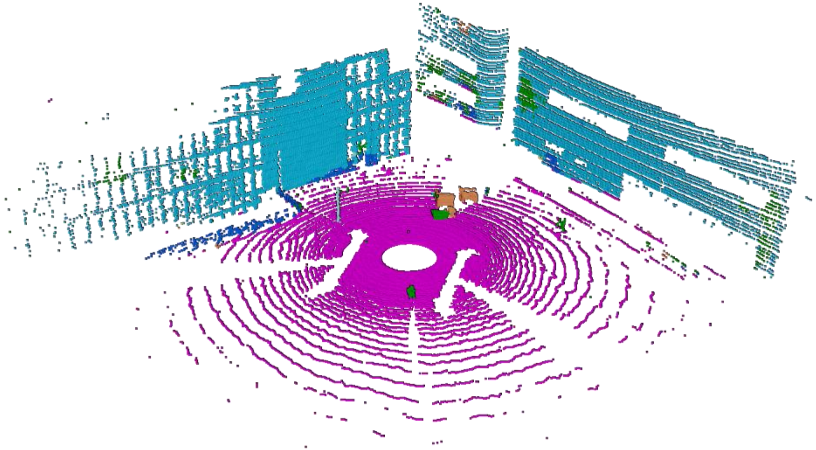
Semantic Perception: LiDAR Segmentation



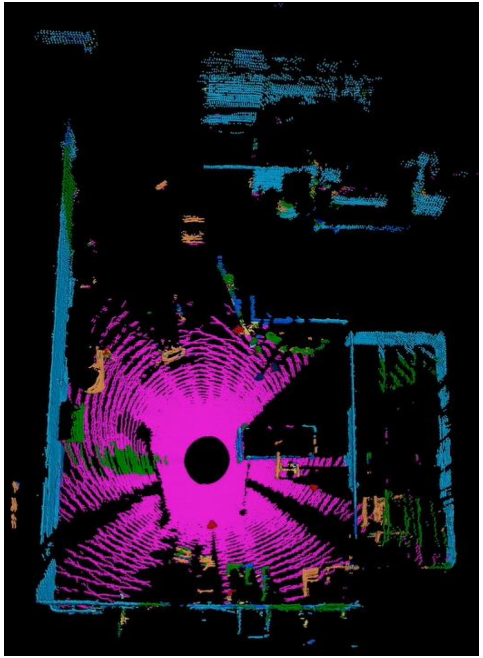


- LatticeNet segmentation of 3D point clouds based on sparse permutohedral grid
- Hierarchical information aggregation through U-Net architecture
- LatticeNet is real-time capable and achieves excellent results in benchmarks

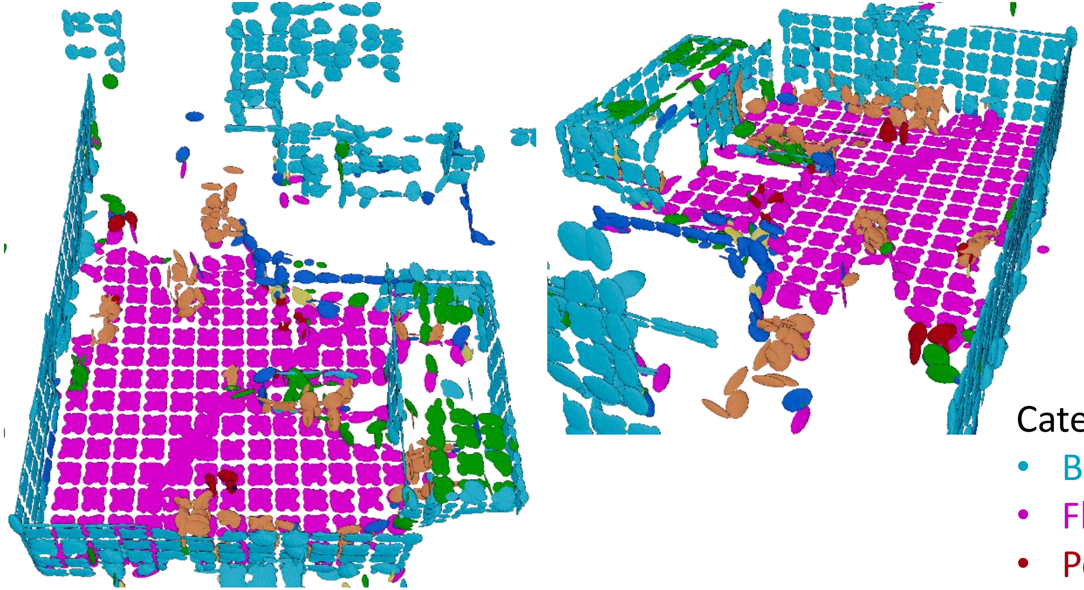
[Rosu et al., RSS 2020]

Semantic Fusion: 3D LiDAR Mapping

Minimax-Viking fire house



Segmented point cloud



Semantic multiresolution surfel map

Categories:

- Building
- Floor
- Persons
- Vehicles
- Fence
- Vegetation

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Semantic Perception: Camera-based Segmentation + Detection

RGB image

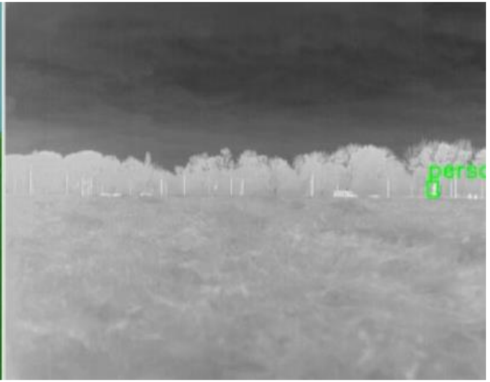
Semantic segmentation with overlaid detections at the DRZ integration sprint in Bad Oldesloe, Germany

- Pixel-wise semantic segmentation and object detection with Google Edge TPU
- Detection of e.g. buildings, vegetation etc. (DeepLab v3 CNN with MobileNet v3 Backbone)

Semantic Perception: Detection of Persons and Vehicles

RGB image

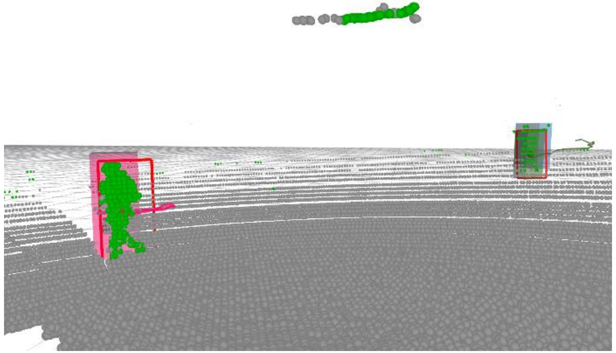
Semantic segmentation



Person detection in thermal images

- Detection of persons and vehicles in color and thermal images (SSD with MobileNet v3 backbone)
- Runs on board computer with approx. 5 images per second

Multi-hypothesis Tracker for Dynamic Objects



- Multi-hypothesis tracker for combining detected objects from image and LiDAR
- Segmentation of LiDAR scan into foreground and background with subsequent grouping of foreground segments of adjacent scan lines and person detection
- 2D image detections + depth camera to derive a 3D detection hypothesis
- Movement of individual instances can be predicted

[Razlaw et al., ICRA 2019]

Semantic Perception: Synthesis of Training Data

- Identification of relevant object categories with DRZ partners IFR, FwDo and DFKI
- Review of available data sets
- Generation of synthetic training data with physics-based renderer EasyPBR

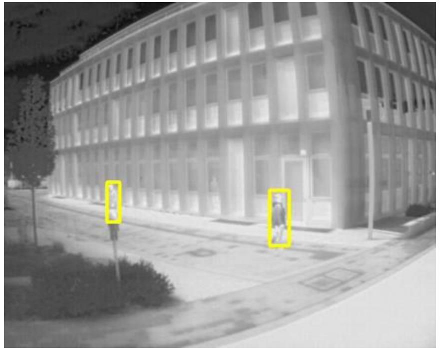
[Rosu and Behnke, GRAPP 2021]

Onboard Multimodal Semantic Fusion

- ECMR 2021 main conference, Thursday, 16:30, Oral Session 5: Semantic Perception

Real-Time Multi-Modal Semantic Fusion on Unmanned Aerial Vehicles

Simon Bultmann*, Jan Quenzel*, and Sven Behnke



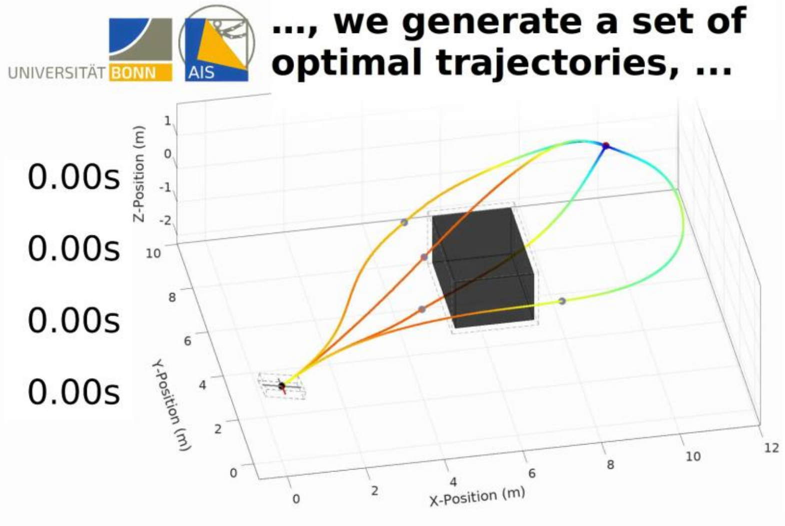
Onboard Multimodal Semantic Fusion

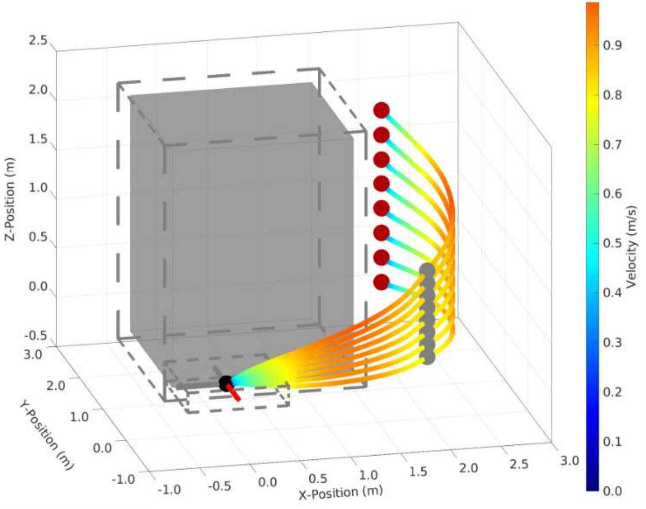
- ECMR 2021 main conference, Thursday, 16:30, Oral Session 5: Semantic Perception

[Bultmann*, Quenzel* and Behnke, ECMR 2021] *equal contribution

Optimal Obstacle Avoidance Trajectories

- Fast avoidance of immediately perceived obstacles (persons, birds, copters, ...)
- Modeling of dynamic obstacles with assumption of constant speed



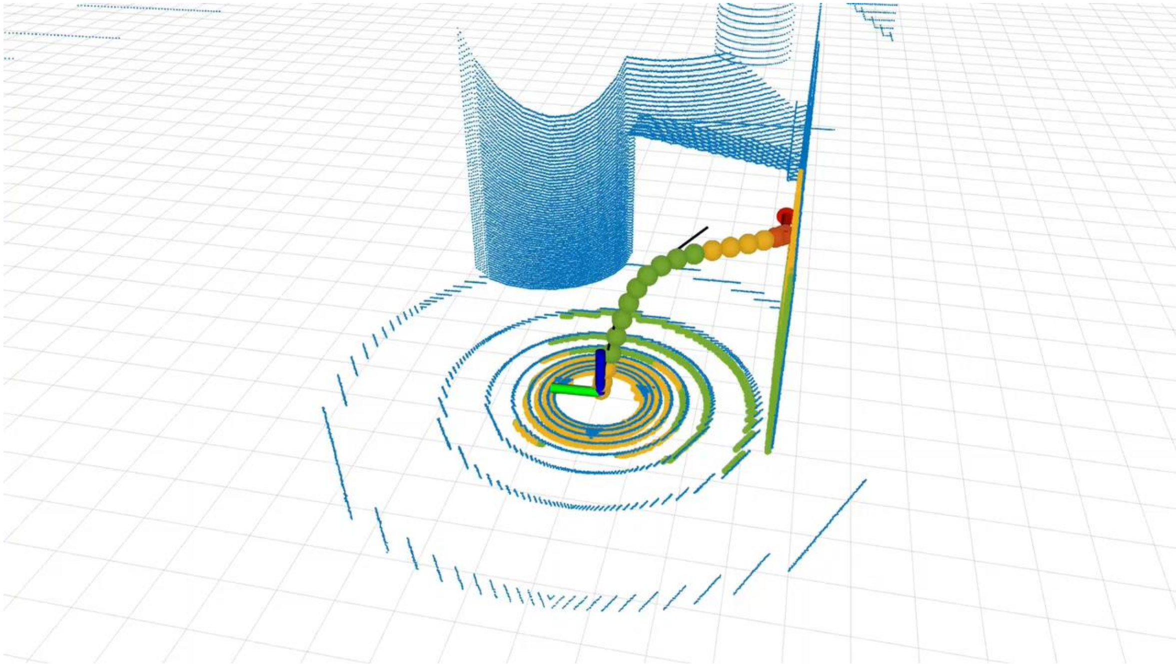


Optimale Ausweichtrajektorien um statische Hindernisse

[Beul and Behnke, IROS 2019]

LiDAR-based Obstacle Avoidance

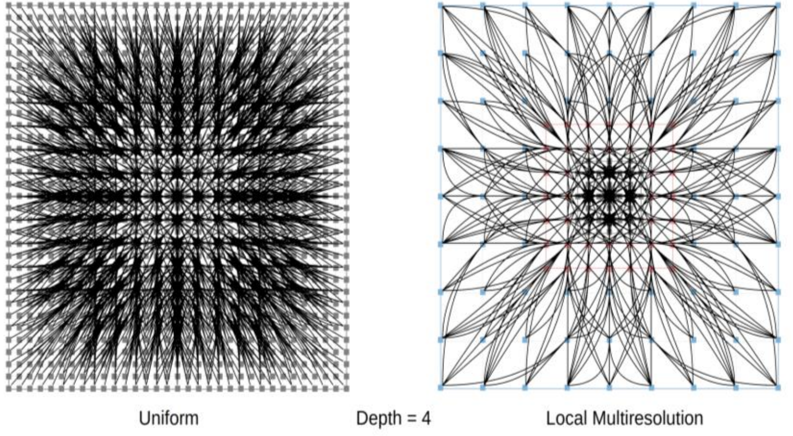
- Fast analytical collision check with 3D point cloud
- Planning of alternative trajectories if original trajectory causes collision
- Selection and execution of a collision-free alternative trajectory
- Evaluation during a training course of the fire departments of the district Viersen for forest fire fighting

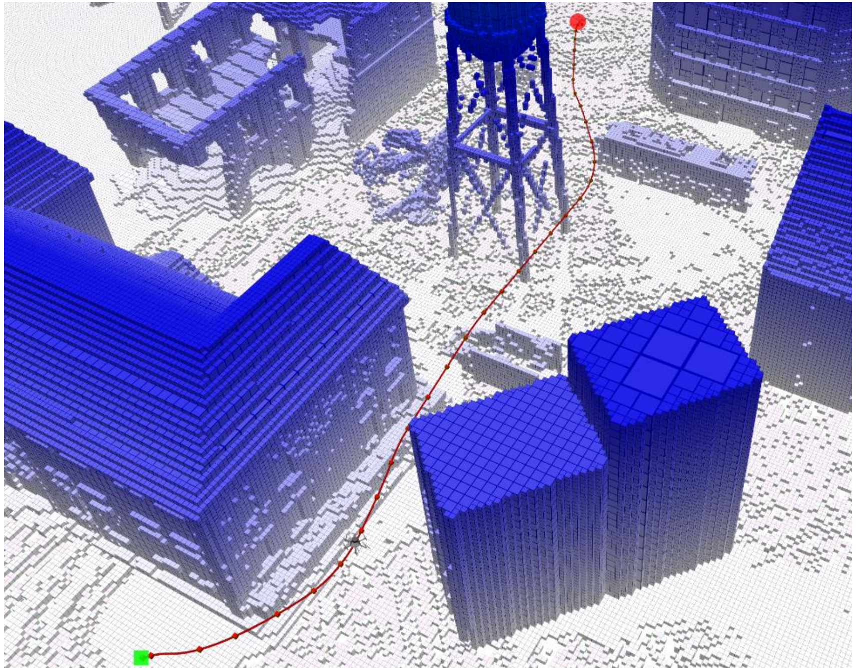


[Beul and Behnke, SSRR 2020]

Dynamic 3D Navigation Planning

- Positions and velocities in sparse local multiresolution grid



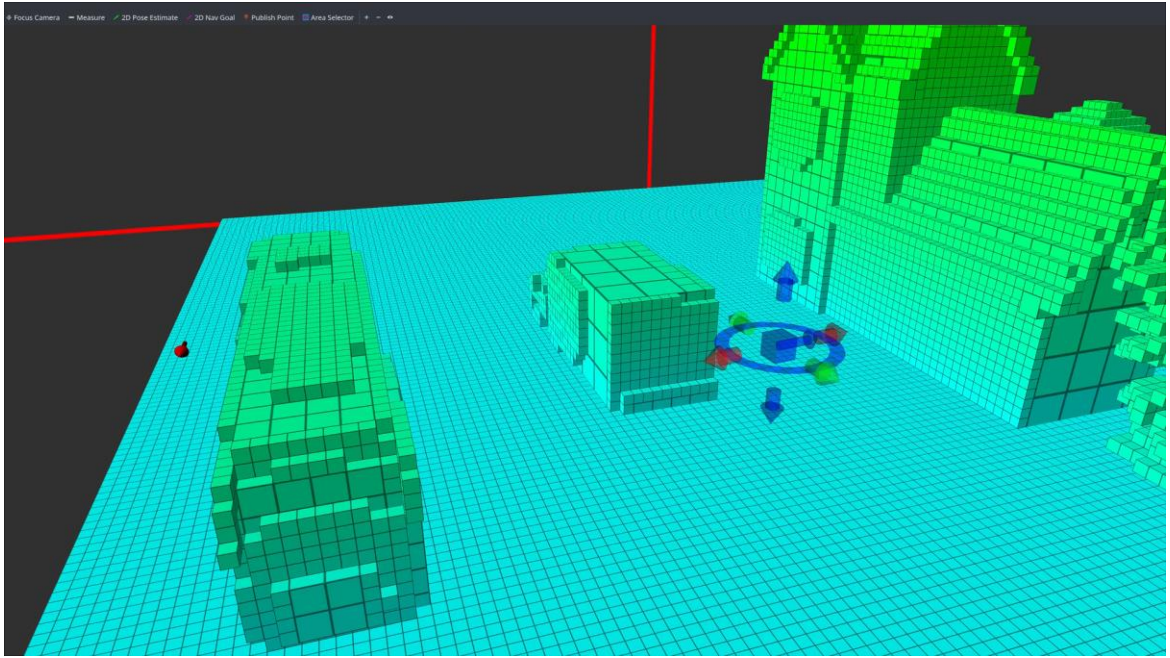


- Optimization of flight time and control costs
- Evaluation during a CBRNE scenario on integration meeting with GNSS
- Evaluation during several autonomous flights without GNSS

[Schleich and Behnke, ICRA 2021]

Interaktive Dynamic 3D Navigation Planning

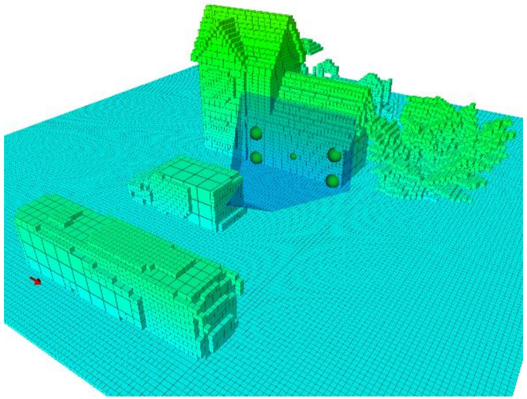
- User interface to set goal poses or observation targets



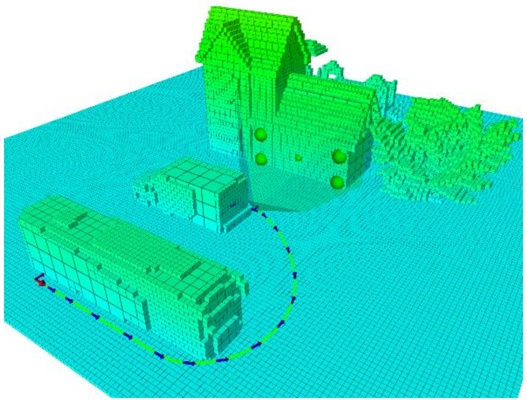
[Schleich and Behnke, ICRA 2021]

Observation Pose Planning

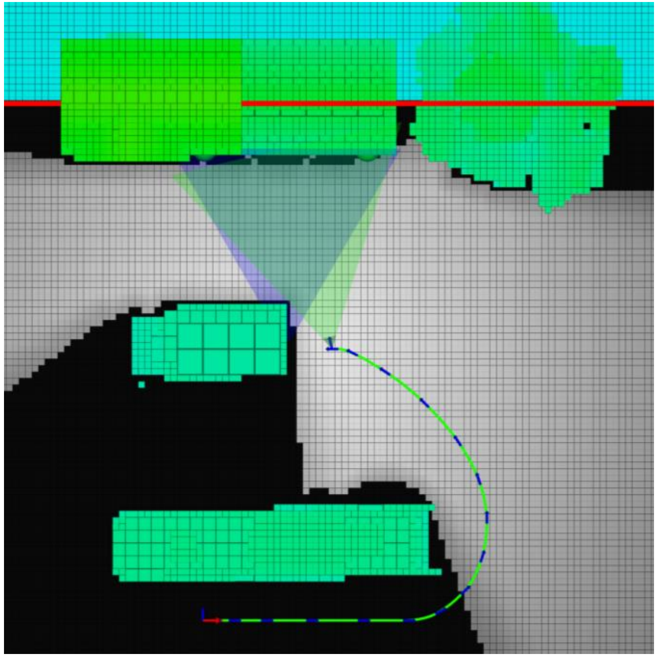
- Planning of observation poses with line of sight to the target object despite occlusions
- Target objects are defined by position, line of sight and distance
- Optimization of observation poses with regard to visibility quality and accessibility



Initial observation pose

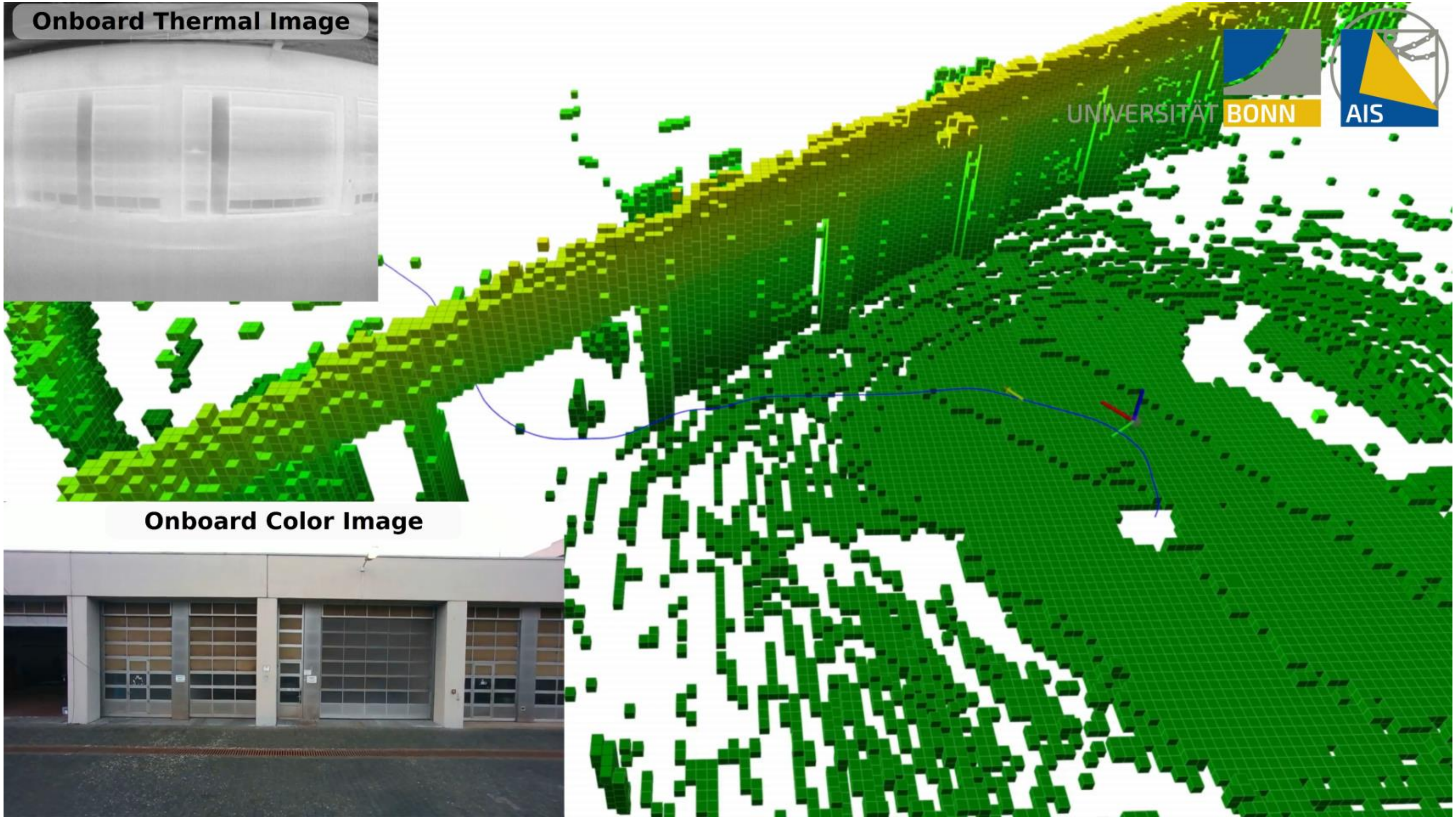


Optimized path



Top-down view

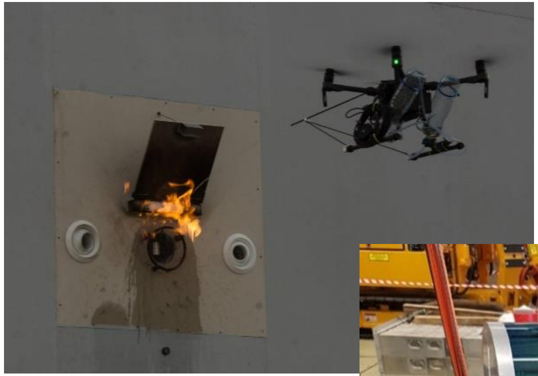
Fully Autonomous Flight without GNSS for Disaster Examination

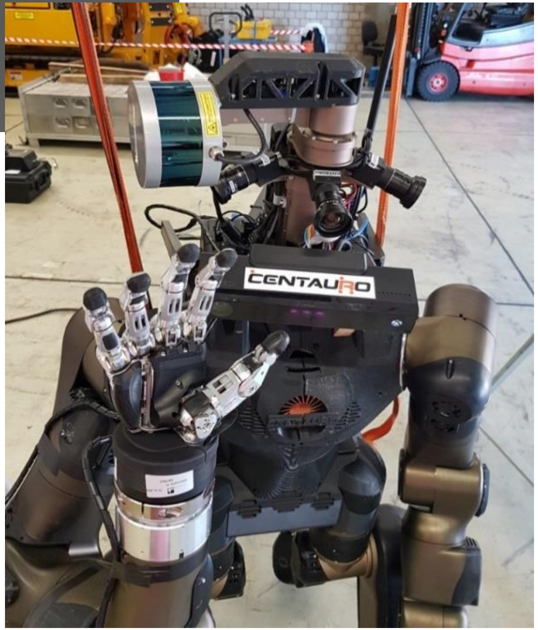


[Schleich et al., ICUAS 2021]

Conclusions

- Developed capable robotic systems for disaster-response
  - Centaur-like ground robots
  - Micro aerial vehicles
- Challenges include
  - 4D semantic perception
  - High-dimensional motion planning
- Promising approaches
  - Prior knowledge (inductive bias)
  - Shared experience (fleet learning)
  - Shared autonomy (human-robot)





Challenges are HUGE, see flooding in Erftstadt July 2021

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