Perception, Planning, and Learning for Cognitive Robots

Sven Behnke

University of Bonn
Computer Science Institute VI
Autonomous Intelligent Systems

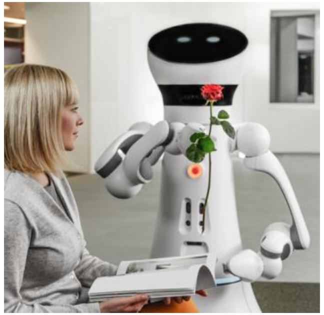
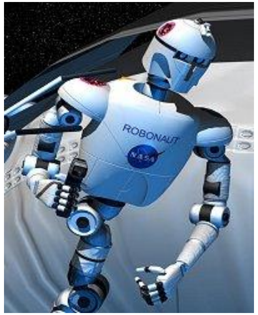
Many New Application Areas for Robots

- Self-driving cars
- Logistics
- Agriculture, mining
- Collaborative production
- Personal assistance
- Space, search & rescue
- Healthcare
- Toys

Need more cognitive abilities!






Some of our Cognitive Robots

- Equipped with numerous sensors and actuators
- Complex demonstration scenarios

Soccer

Domestic service

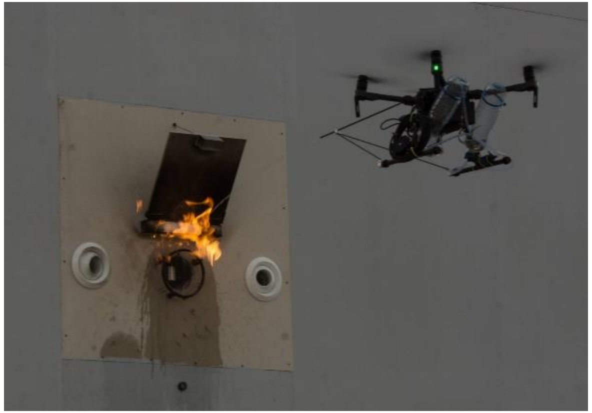
Mobile manipulation

Bin picking

Aerial inspection

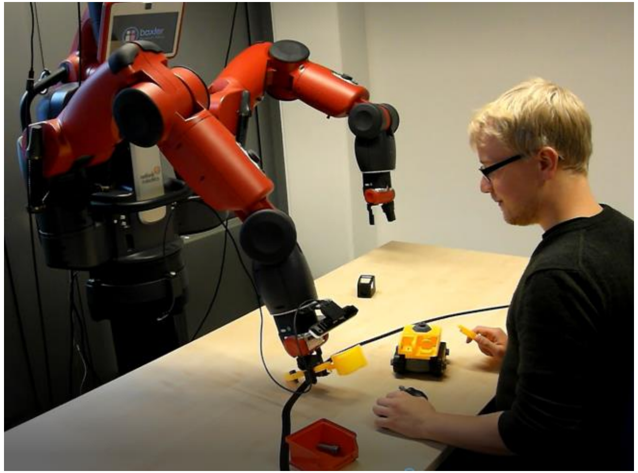
Some more of our Cognitive Robots

- Equipped with numerous sensors and actuators
- Complex demonstration scenarios

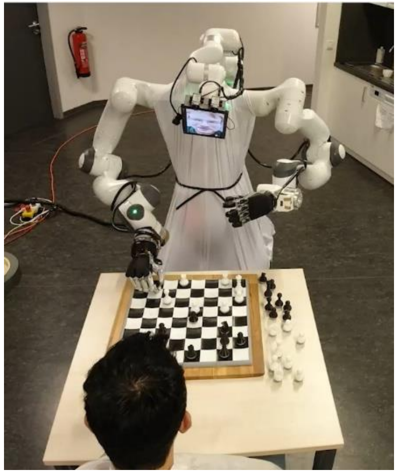


Rescue

Phenotyping



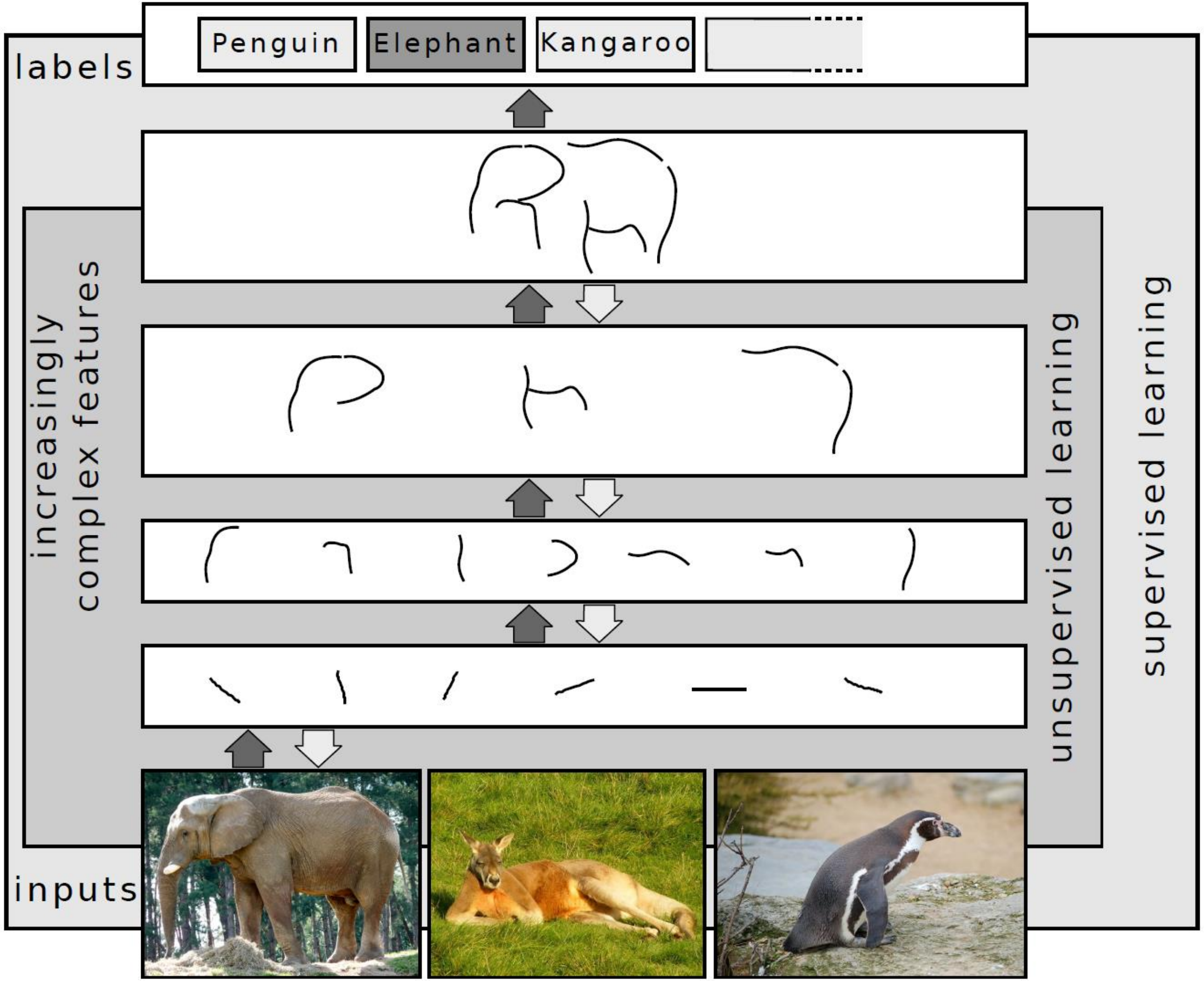
Human-robot collaboration



Telepresence

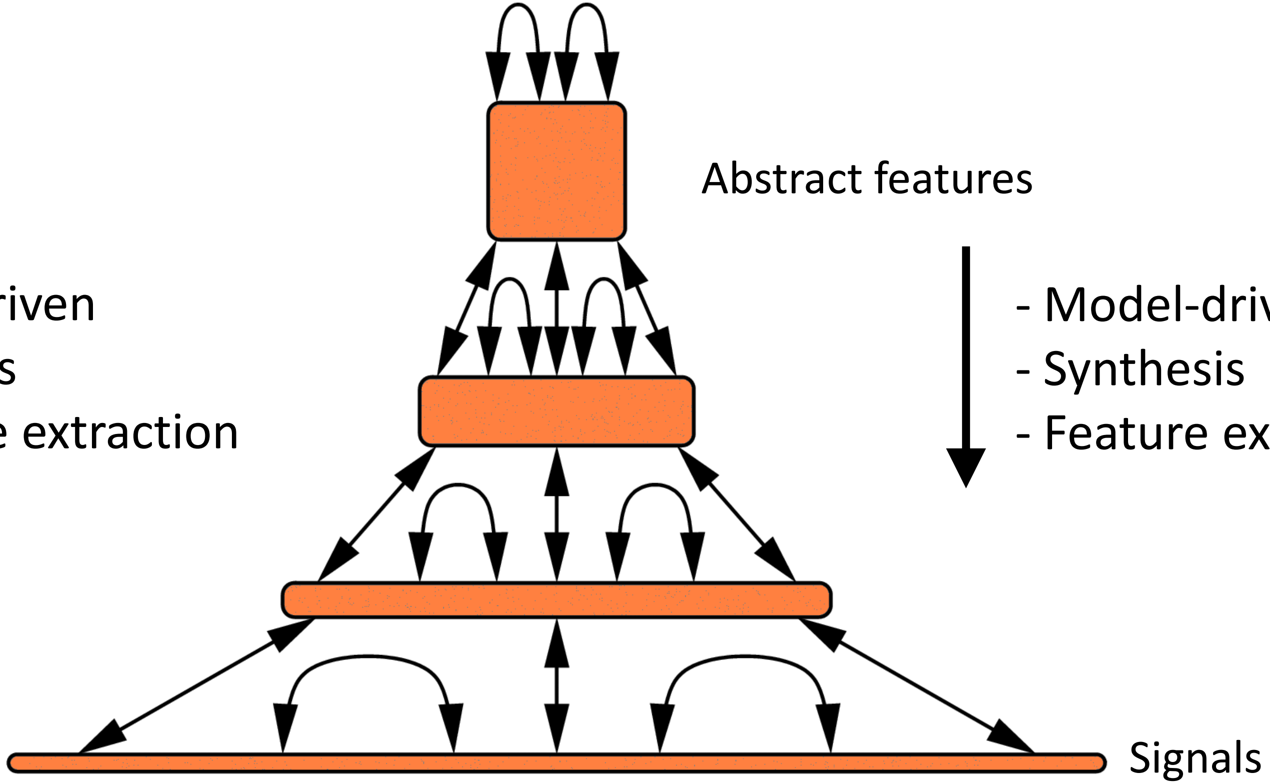
Deep Learning

- Learning layered represen-tations
- Compositionality



[Schulz; Behnke, KI 2012]

Neural Abstraction Pyramid



- Data-driven
- Analysis
- Feature extraction

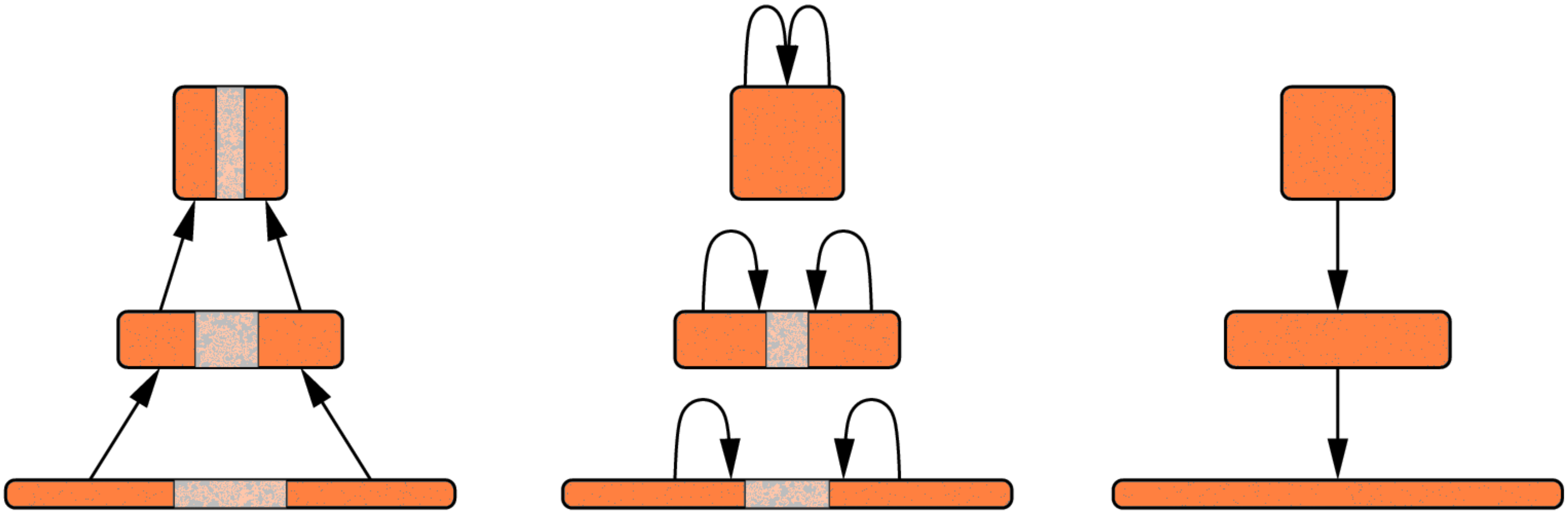
- Model-driven
- Synthesis
- Feature expansion

- Grouping - Competition - Completion

[Behnke, Rojas, IJCNN 1998] [Behnke, LNCS 2766, 2003]

Iterative Image Interpretation

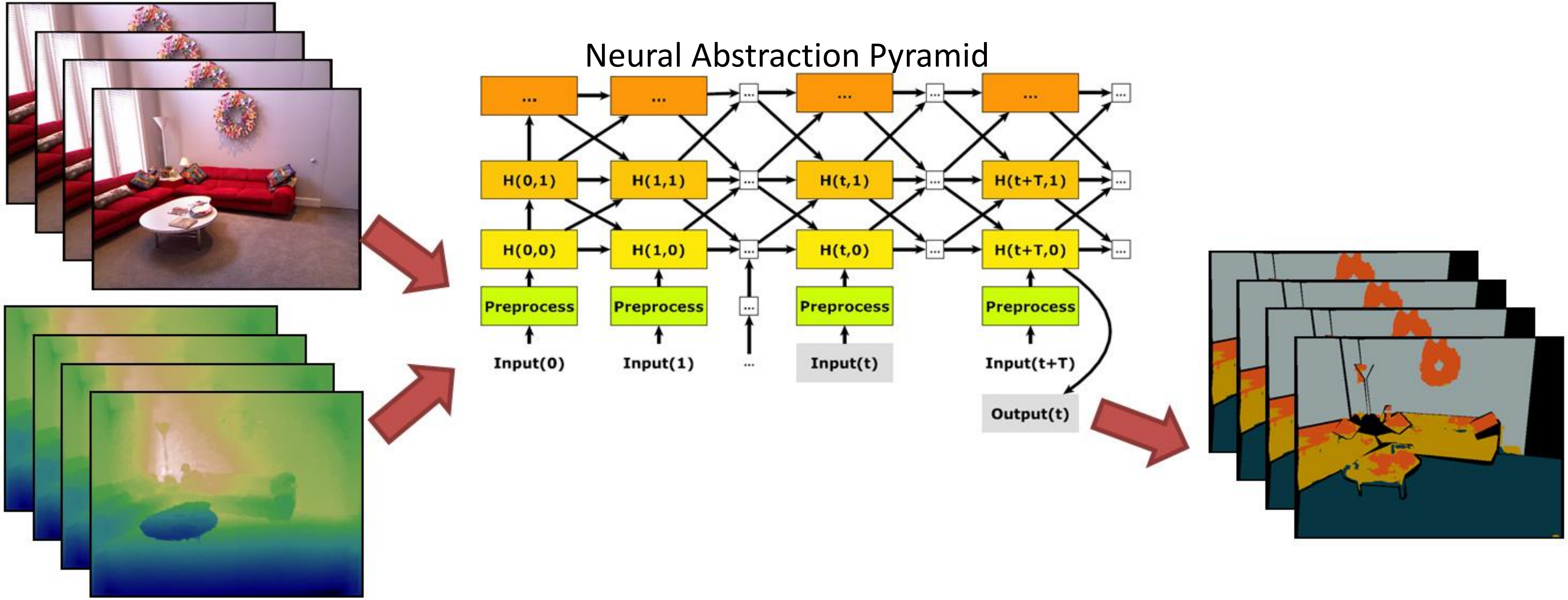
- Interpret most obvious parts first
- Use partial interpretation as context to iteratively resolve local ambiguities



[Behnke, Rojas, IJCNN 1998] [Behnke, LNCS 2766, 2003]

Neural Abstraction Pyramid for Semantic Segmentation of RGB-D Video

- Recursive computation is efficient for temporal integration



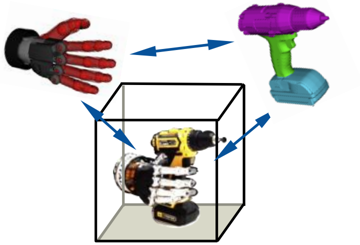
[Pavel, Schulz, Behnke, Neural Networks 2017]

The Data Problem

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

1. **Transfer learning:**
   Pre-training on large related data,
   self-supervised learning

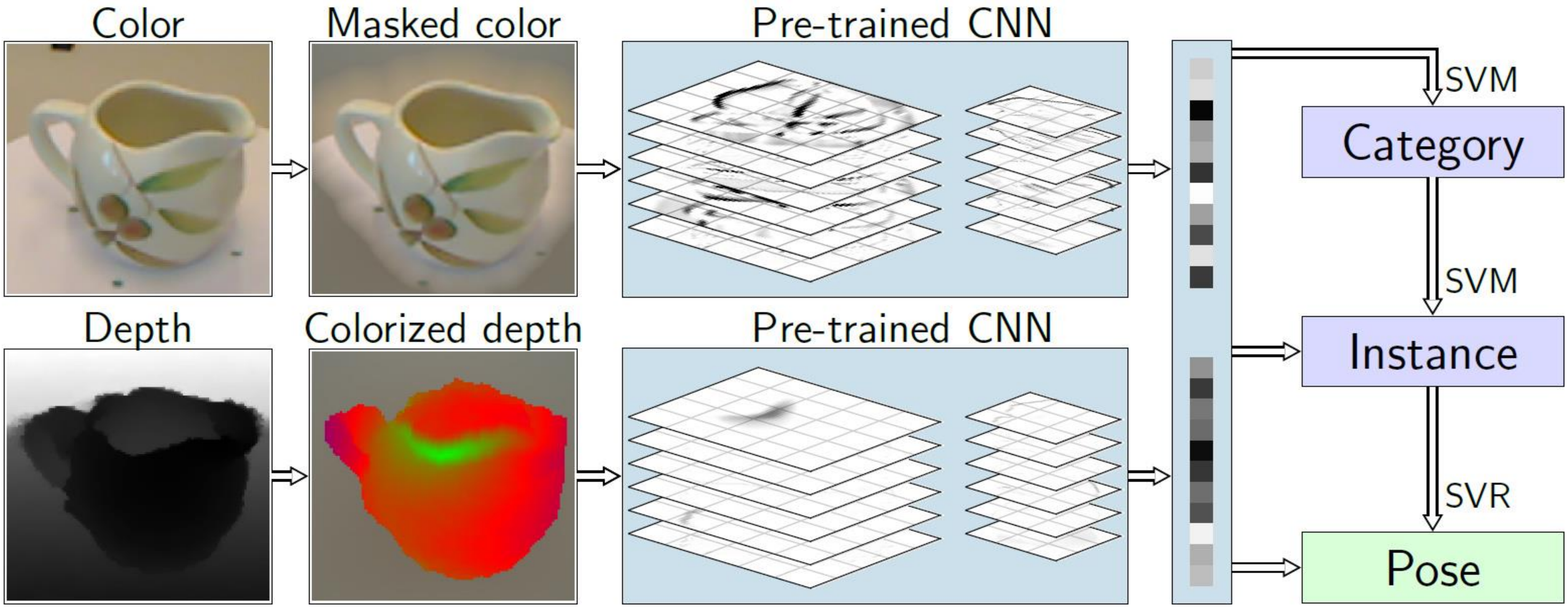
2. **Generating data**:
   Online mesh databases,
   scene synthesis



3. **Inductive biases**:
   3D projective geometry,
   camera motion, canonical frames,
   object relations, compositionality, …

RGB-D Object Recognition and Pose Estimation

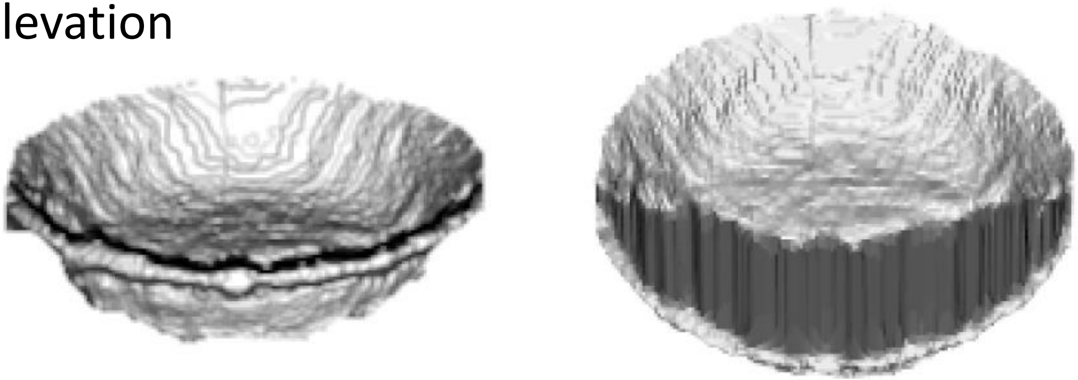
- Transfer learning from large-scale data sets



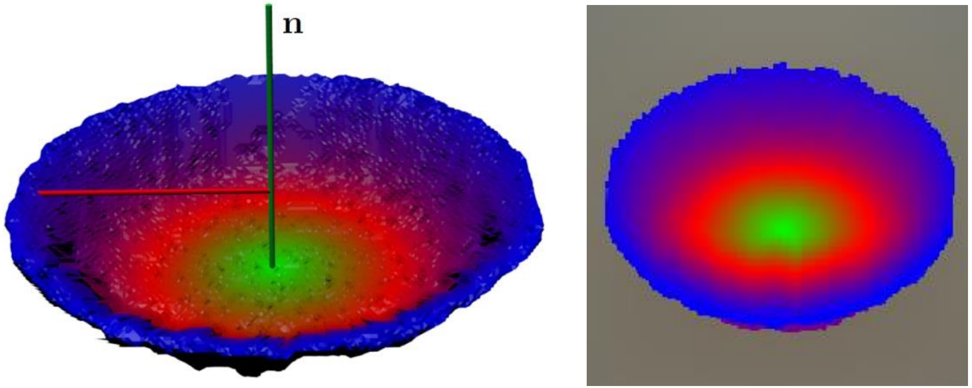
[Schwarz, Schulz, Behnke, ICRA2015]

Canonical View, Colorization

- Objects viewed from different elevation
- Render canonical view



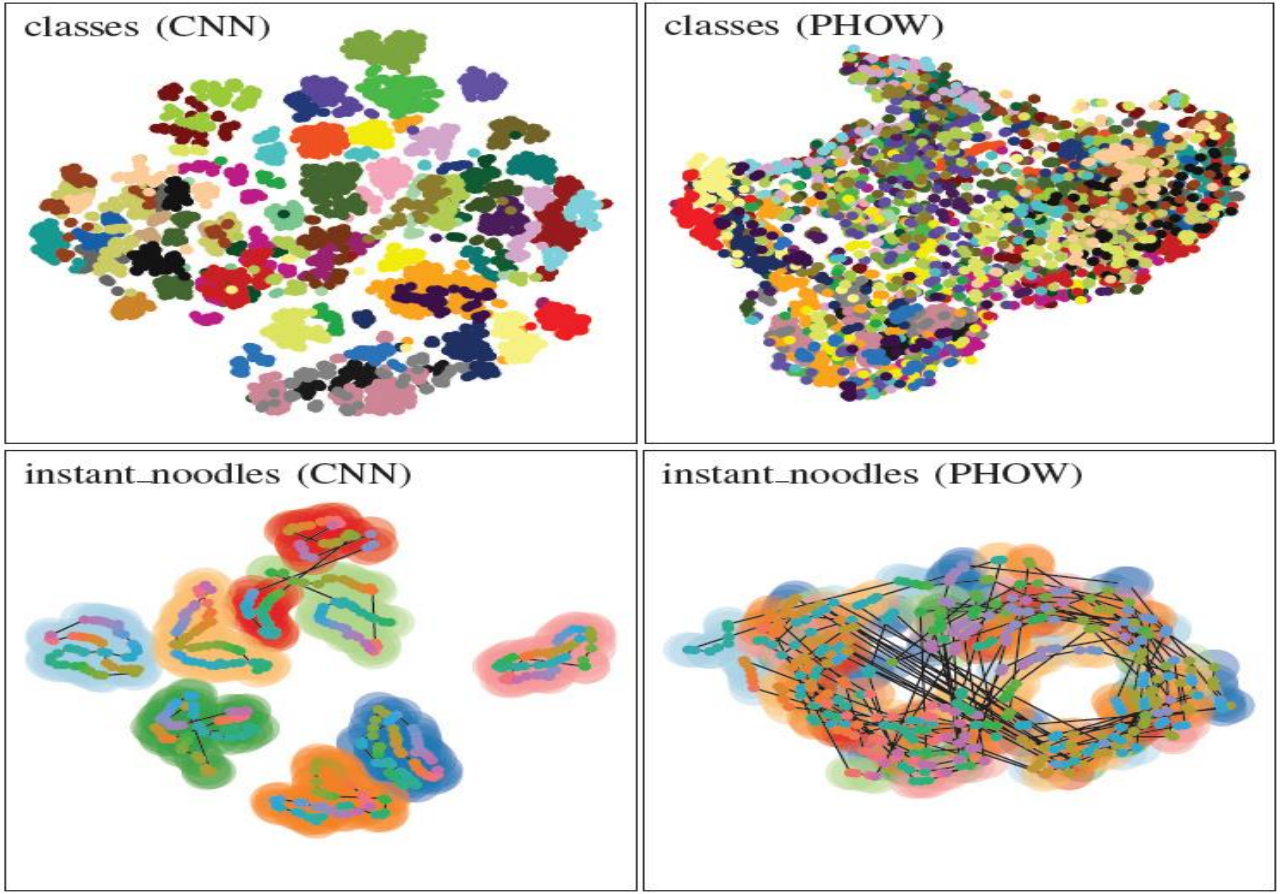
- Colorization based on distance from center vertical



[Schwarz, Schulz, Behnke, ICRA2015]

Pretrained Features Disentangle Data

- t-SNE embedding



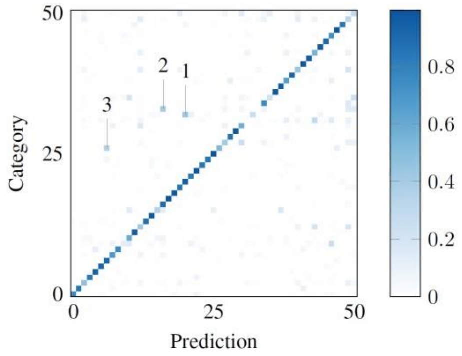
[Schwarz, Schulz, Behnke ICRA2015]

Recognition Accuracy

- Improved both category and instance recognition

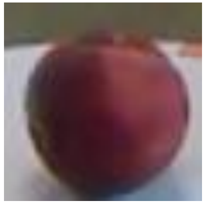
Method	Category Accuracy (%) RGB	Category Accuracy (%) RGB-D	Instance Accuracy (%) RGB	Instance Accuracy (%) RGB-D
Lai *et al.* [1]	74.3 ± 3.3	81.9 ± 2.8	59.3	73.9
Bo *et al.* [2]	82.4 ± 3.1	87.5 ± 2.9	**92.1**	92.8
PHOW[3]	80.2 ± 1.8	—	62.8	—
Ours	$\mathbf{83.1 \pm 2.0}$	88.3 ± 1.5	92.0	**94.1**
Ours	$\mathbf{83.1 \pm 2.0}$	$\mathbf{89.4 \pm 1.3}$	92.0	**94.1**

- Confusion:



1: pitcher / coffe mug

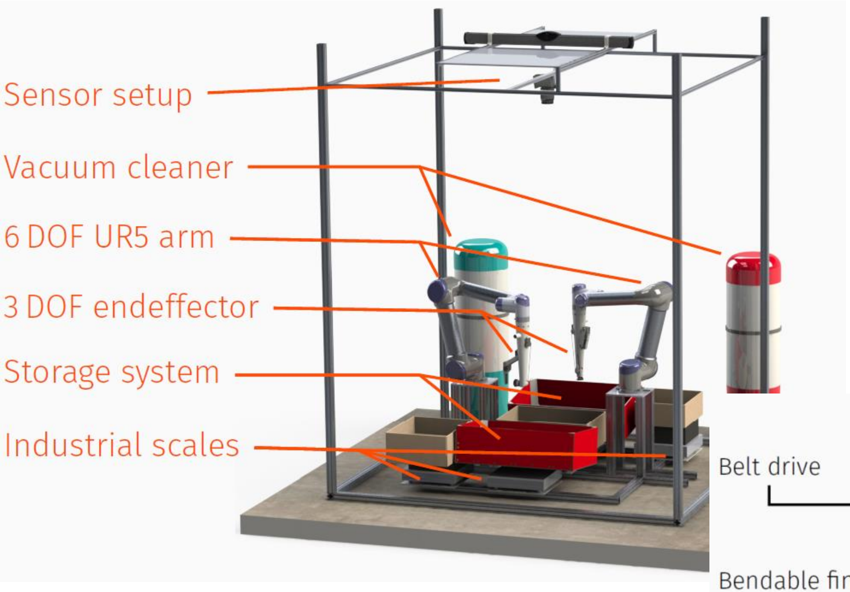

2: peach / sponge

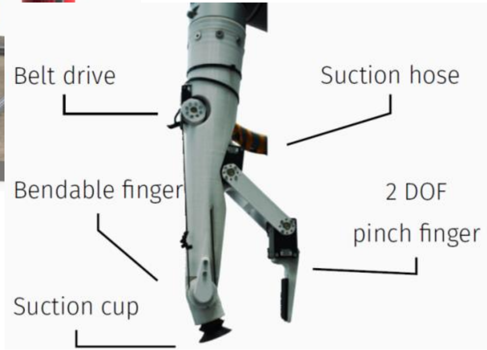



[Schwarz, Schulz, Behnke, ICRA2015]

Amazon Robotics Challenge

- Storing and picking of items
- Dual-arm robotic system





[Schwarz et al. ICRA 2018]

amazon robotics CHALLENGE

[Amazon]

UNIVERSITÄT BONN AIS

Object Capture and Scene Rendering

- Turntable + DLSR camera

- Insertion in complex annotated scenes

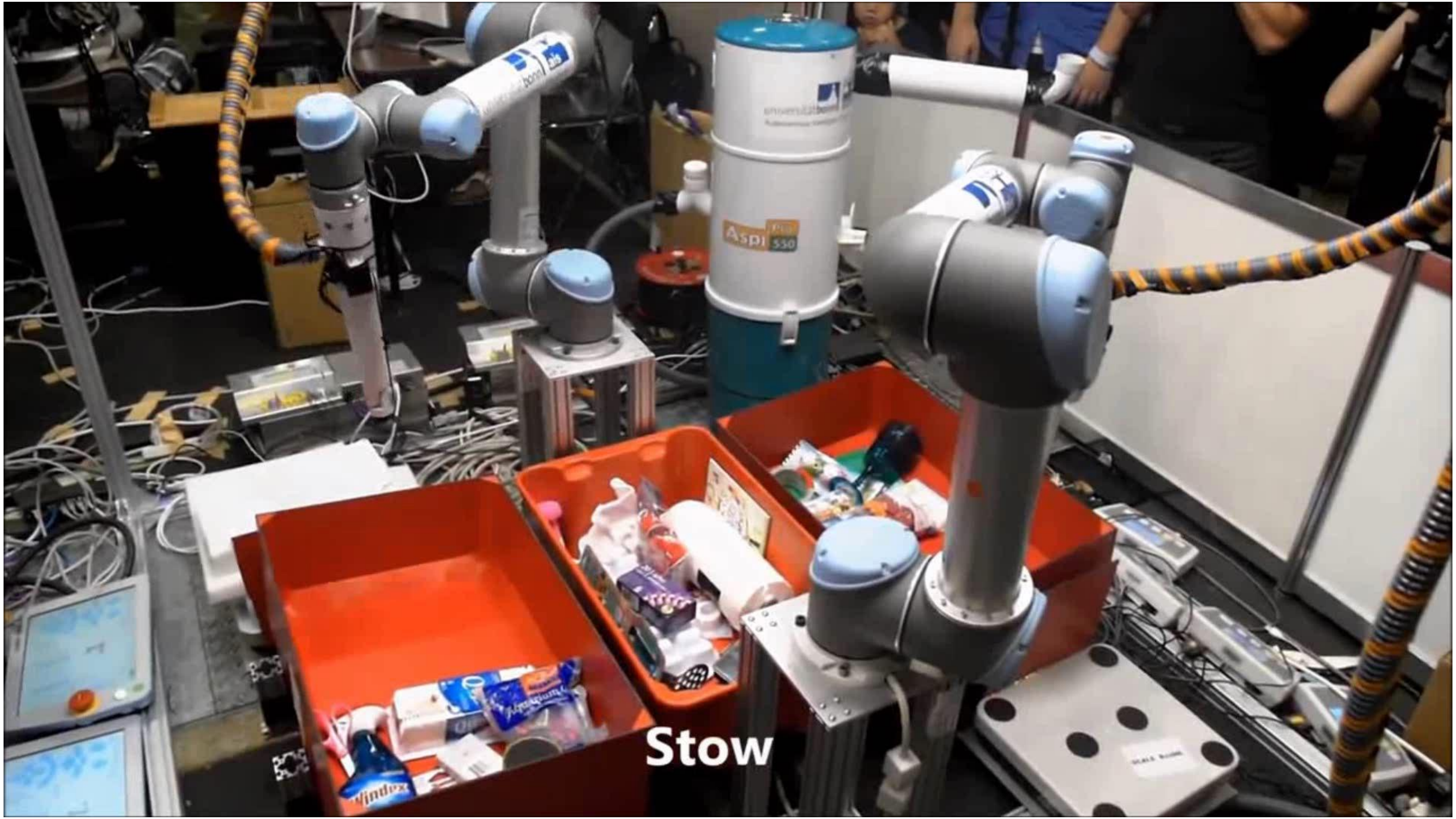
[Schwarz et al. ICRA 2018]

Semantic Segmentation and Grasp Pose Estimation

- Semantic segmentation using RefineNet [Lin et al. CVPR 2017]
- Grasp positions in segment centers

[Schwarz et al. ICRA 2018]

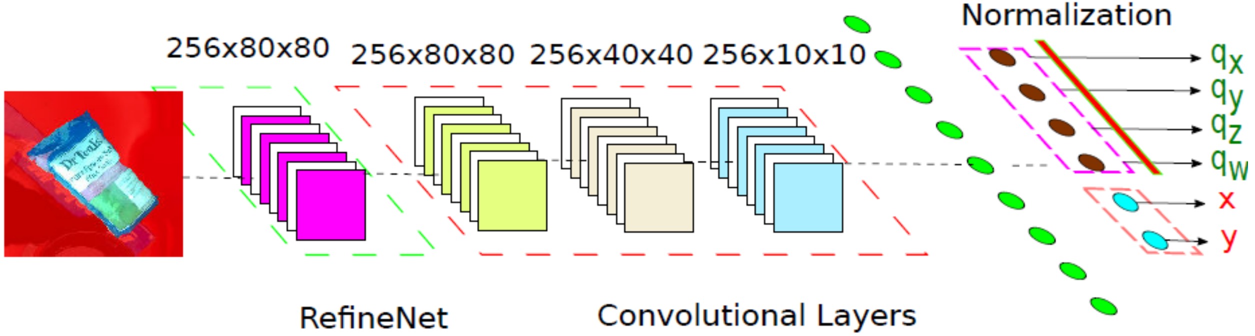
Amazon Robotics Challenge 2017



[Schwarz et al. ICRA 2018]

Object Pose Estimation

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



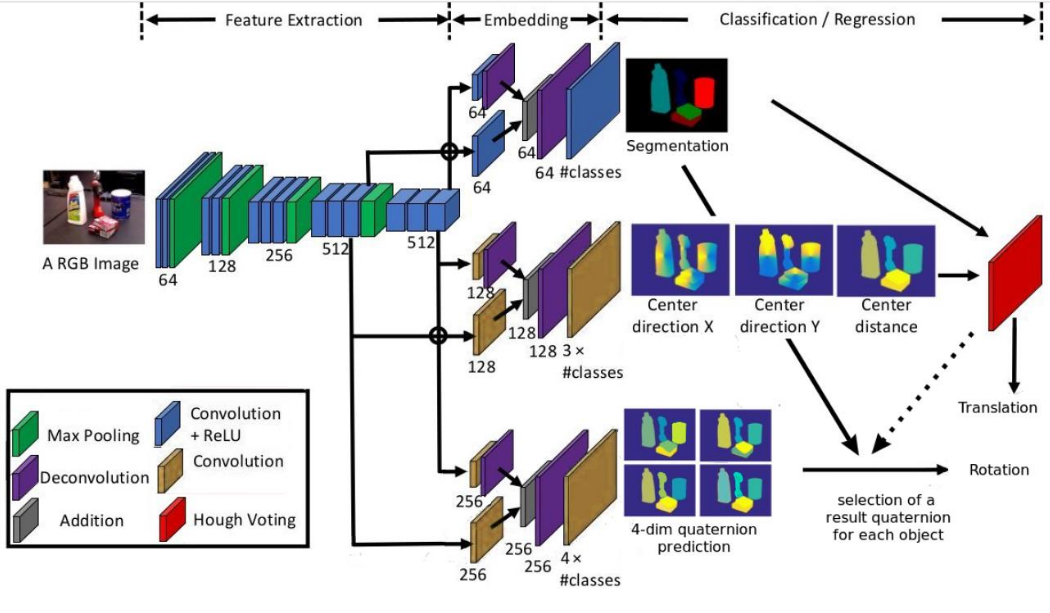
Input

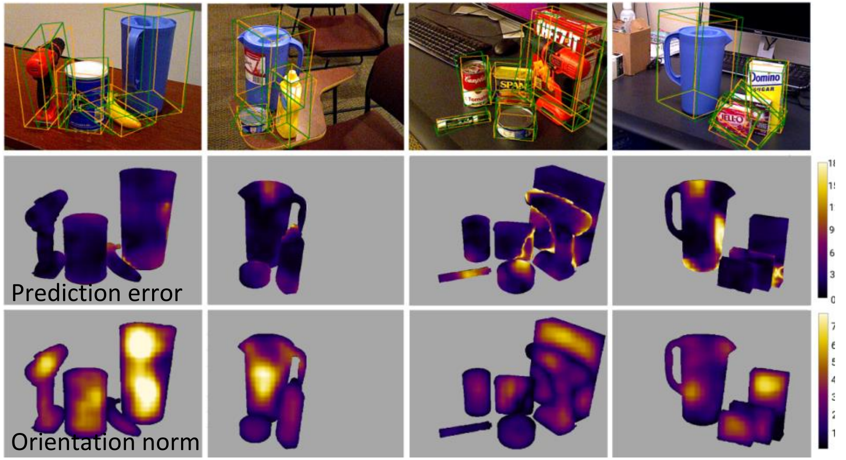
Predicted pose

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

Dense Convolutional 6D Object Pose Estimation

- Extension of PoseCNN [Xiang et al. RSS 2018]
- Dense prediction of object center and orientation, without cutting out

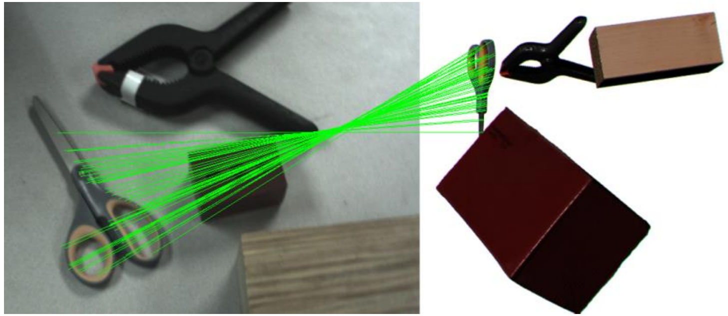




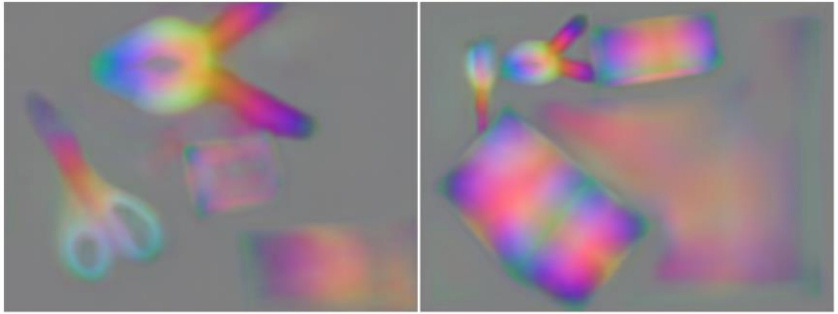
[Capellen et al., VISAPP 2020]

Self-Supervised Surface Descriptor Learning

- Feature descriptor should be constant under different transformations, viewing angles, and environmental effects such as lighting changes
- Descriptor should be unique to facilitate matching across different frames or representations
- Learn dense features using a contrastive loss



Known correspondences



Learned features

[Periyasamy, Schwarz, Behnke Humanoids 2019]

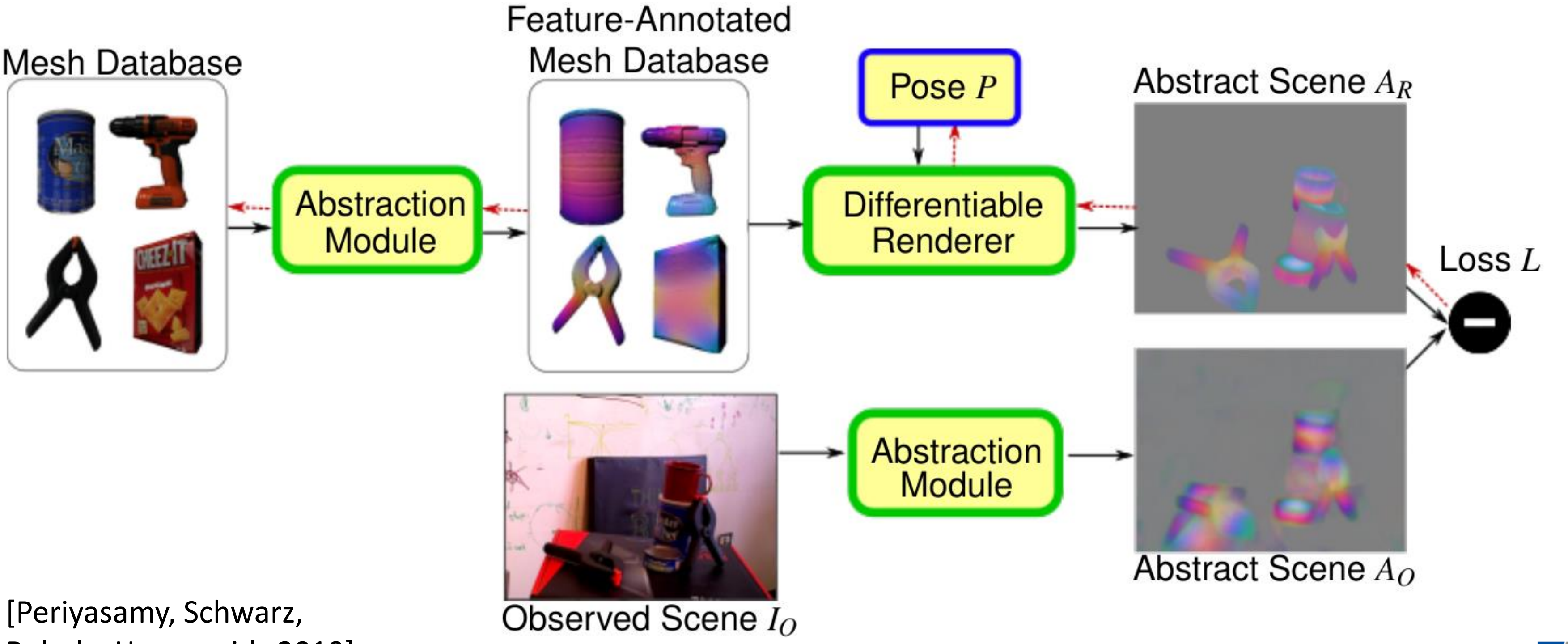
Descriptors as Texture on Object Surfaces

- Learned feature channels used as textures for 3D object models
- Used for 6D object pose estimation

[Periyasamy, Schwarz, Behnke Humanoids 2019]

Abstract Object Registration

- Compare rendered and actual scene in feature space
- Adapt model pose by gradient descent



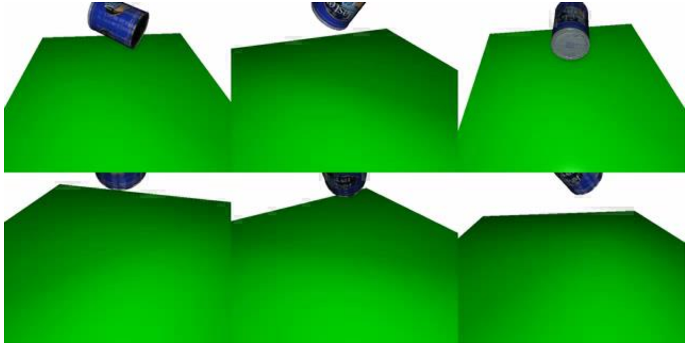
[Periyasamy, Schwarz,
Behnke Humanoids 2019]

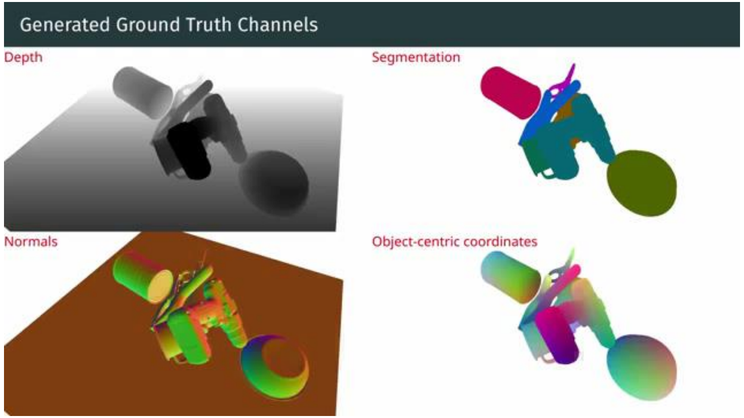
Registration Examples

[Periyasamy, Schwarz, Behnke Humanoids 2019]

Stillleben: Learning from Synthetic Scenes

- Cluttered arrangements from 3D meshes
- Photorealistic scenes with randomized material and lighting including ground truth
- For online learning & render-and-compare
- Semantic segmentation on YCB Video Dataset
  - Close to real-data accuracy
  - Improves segmentation of real data

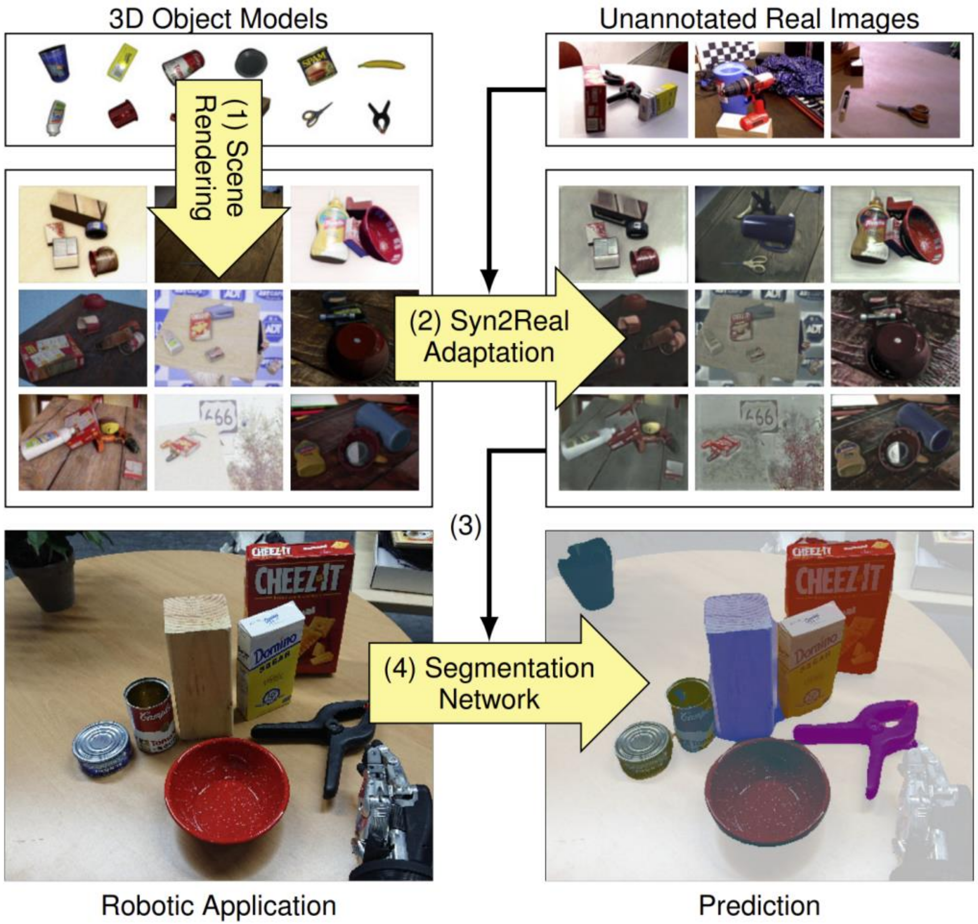




[Schwarz and Behnke, ICRA 2020]

Synthetic-to-Real Domain Adaptation

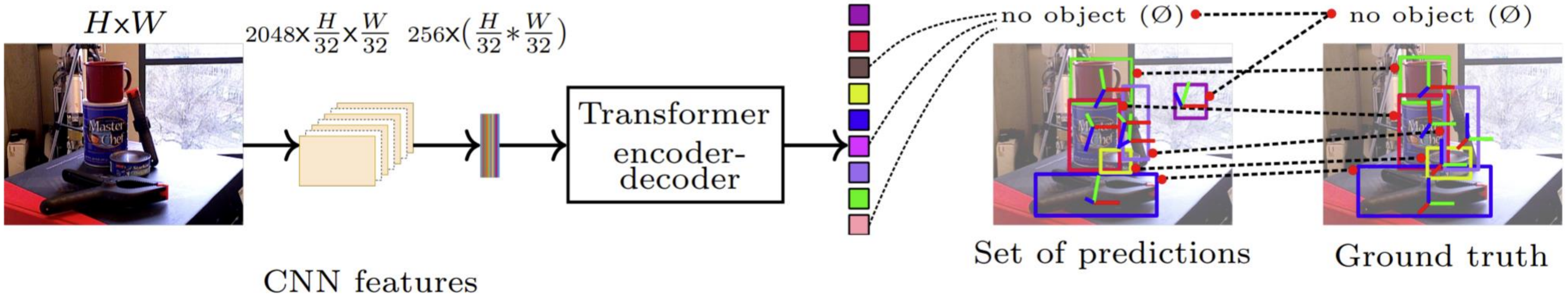
- Generate images from 3D object meshes
- Adapt the synthetic images to the real domain using un-annotated real images (GAN loss)
- Train downstream task using adapted images
- Semantic segmentation results almost as good as trained with real images
- Improved results in combina-tion with real annotations



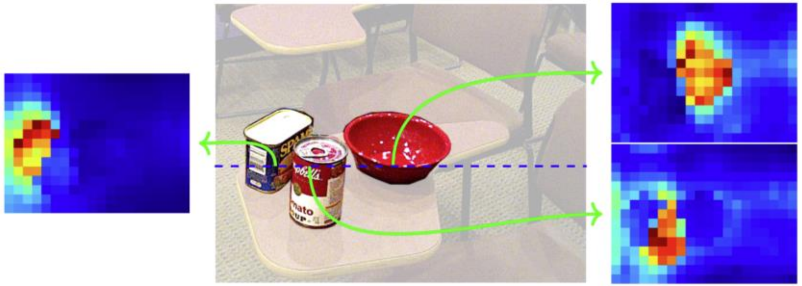
[Imbusch et al. CASE 2022]

T6D-Direct: Transformers for Multi-Object 6D Pose Direct Regression

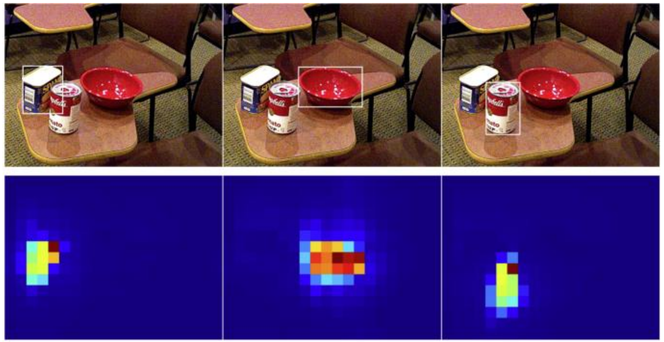
- Extends DETR: End-to-end object detection with transformers [Carion et al. ECCV 2020]
- End-to-end differentiable pipeline for 6D object pose estimation



Encoder self-attention

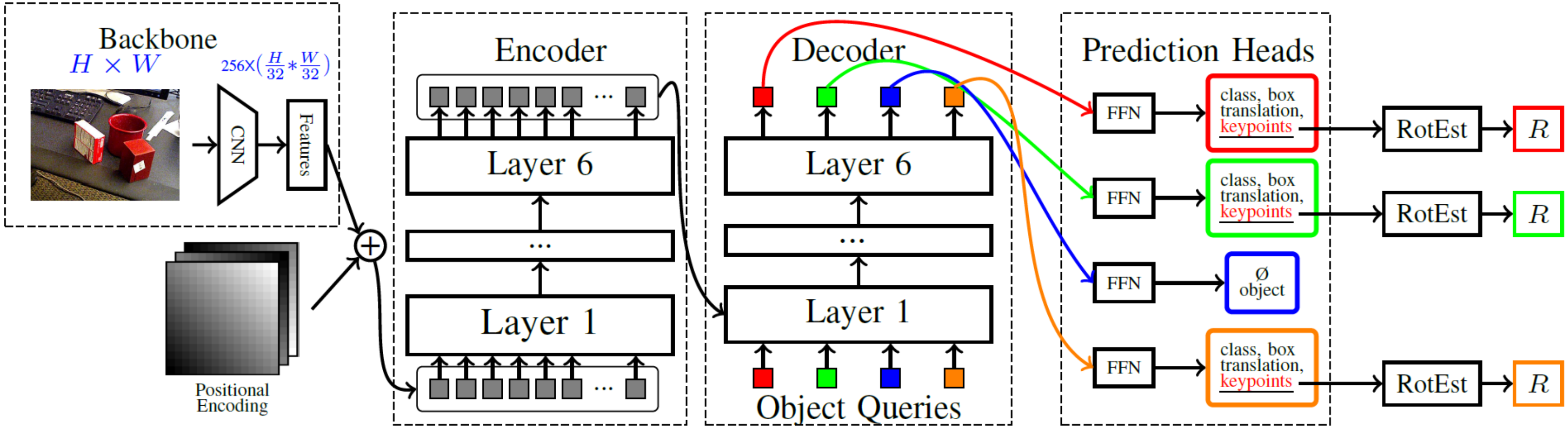


Object detections and decoder attention



[Amini et al. GCPR 2021]

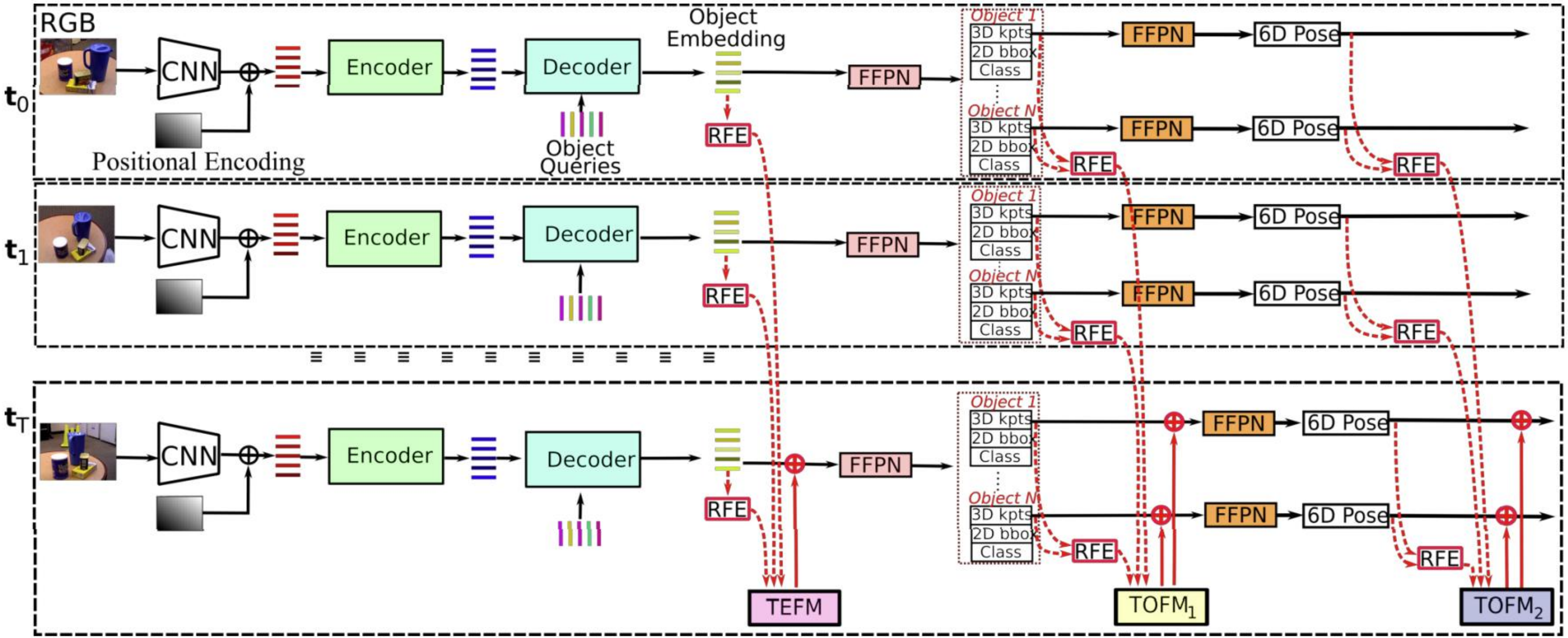
Multi-Object 6D Pose Estimation using Keypoint Regression



[Amini et al. IAS 2022, Best Paper Award]

MOTPose: Attention-based Temporal Fusion for Multi-object 6D Pose Estimation

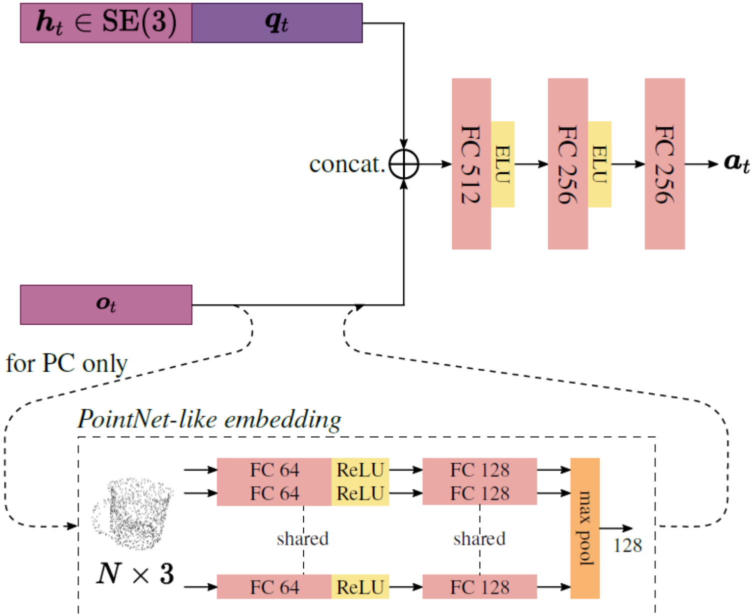
- Transformer-based temporal embedding and object fusion modules

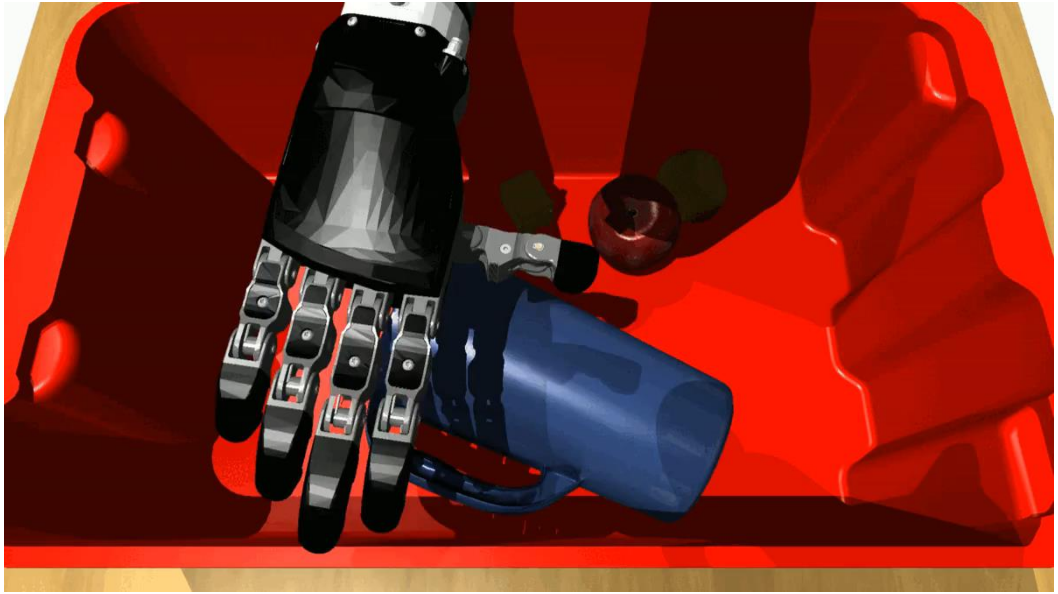


[Periyasamy and Behnke 2023]

Learning Interactive Grasping

- Deep RL-based interactive policy
- Input: object parameters or point cloud + hand pose
- Output: increments of hand DoF:



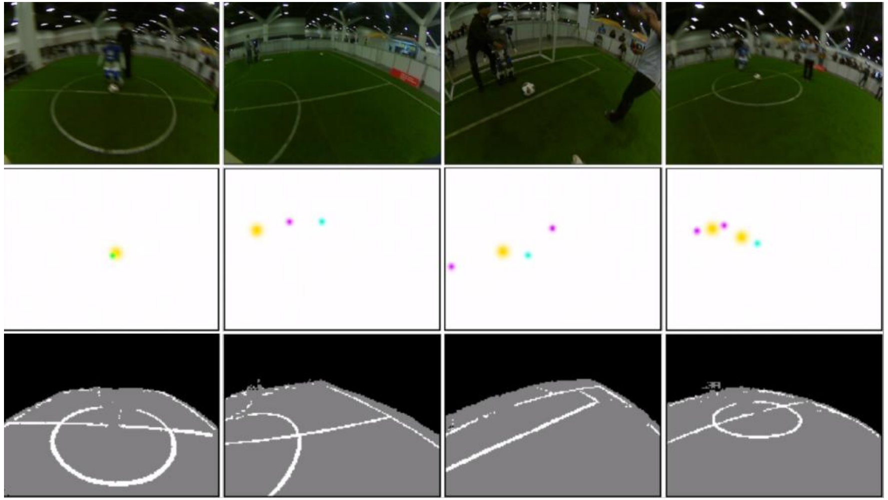


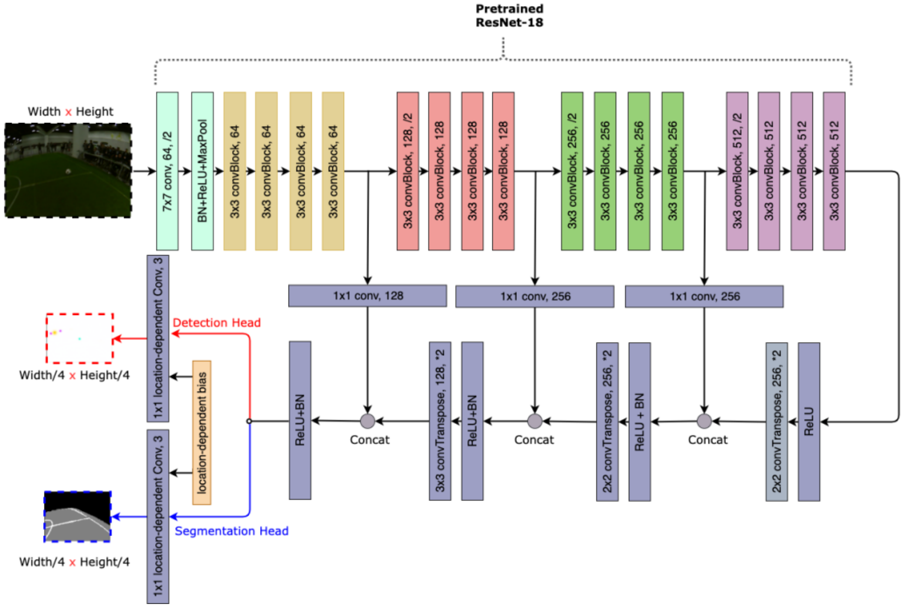
[Mosbach and Behnke, IRC 2022]

Humanoid AdultSize Soccer: RoboCup 2022 in Bangkok

Transfer Learning for Visual Perception

- Encoder-decoder network
- Two outputs
  - Object detection
  - Semantic segmentation
- Location-dependent bias



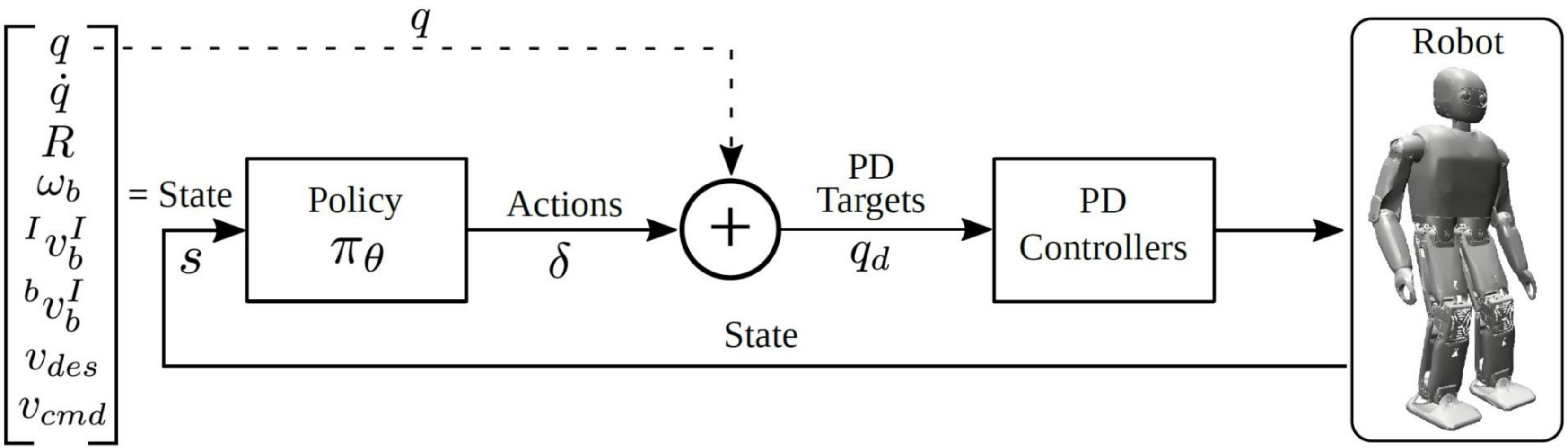


- Detects objects that are hard to recognize for humans
- Robust to lighting changes

[Rodriguez et al. RoboCup 2019]

Learning Omnidirectional Gait from Scratch

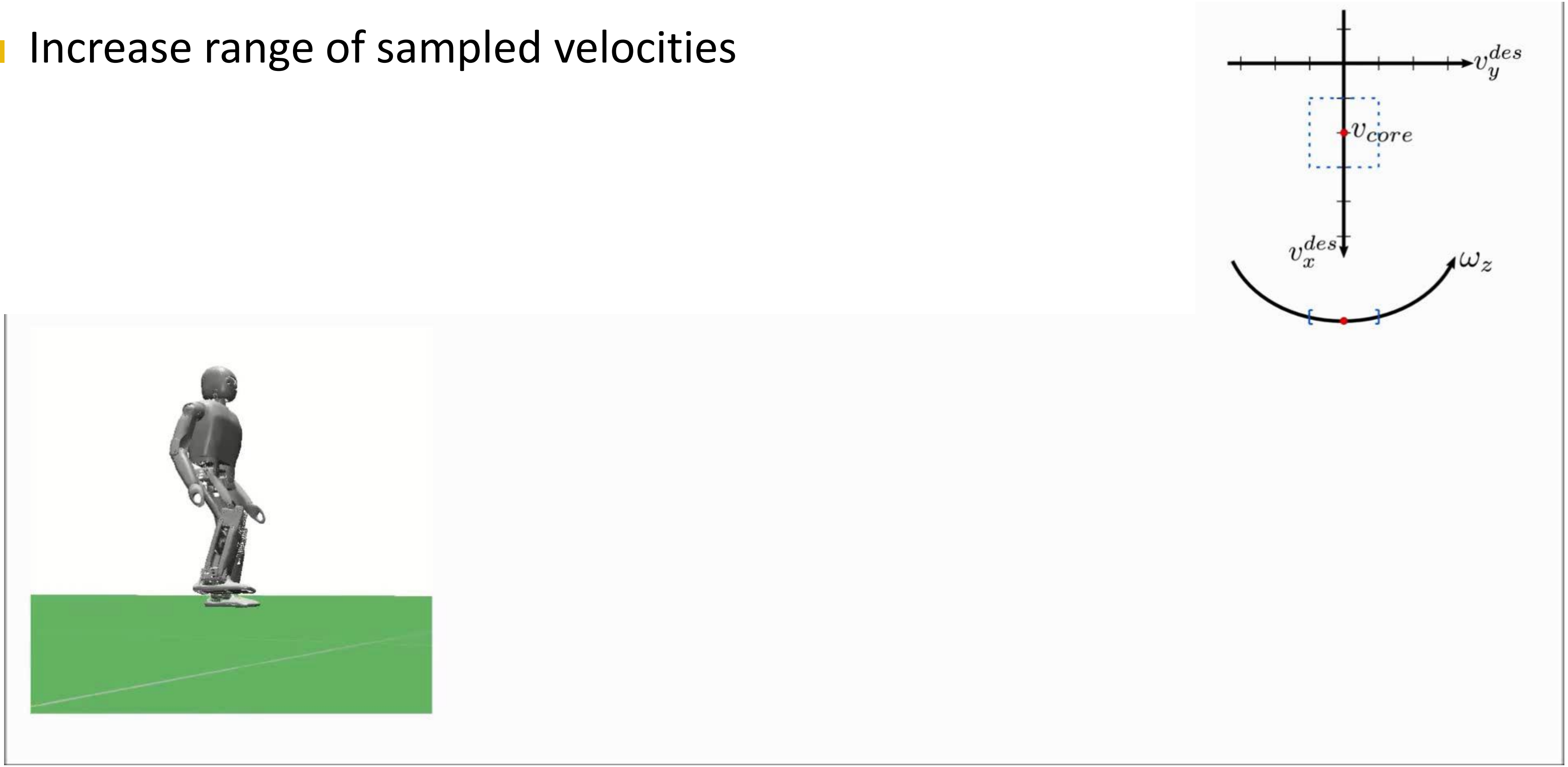
- State includes joint positions and velocities, robot orientation, robot speed
- Actions are increments of joint positions
- Simple reward structure
  - Velocity tracking
  - Pose regularization
  - Not falling



[Rodriguez and Behnke, ICRA 2021]

Learning Curriculum

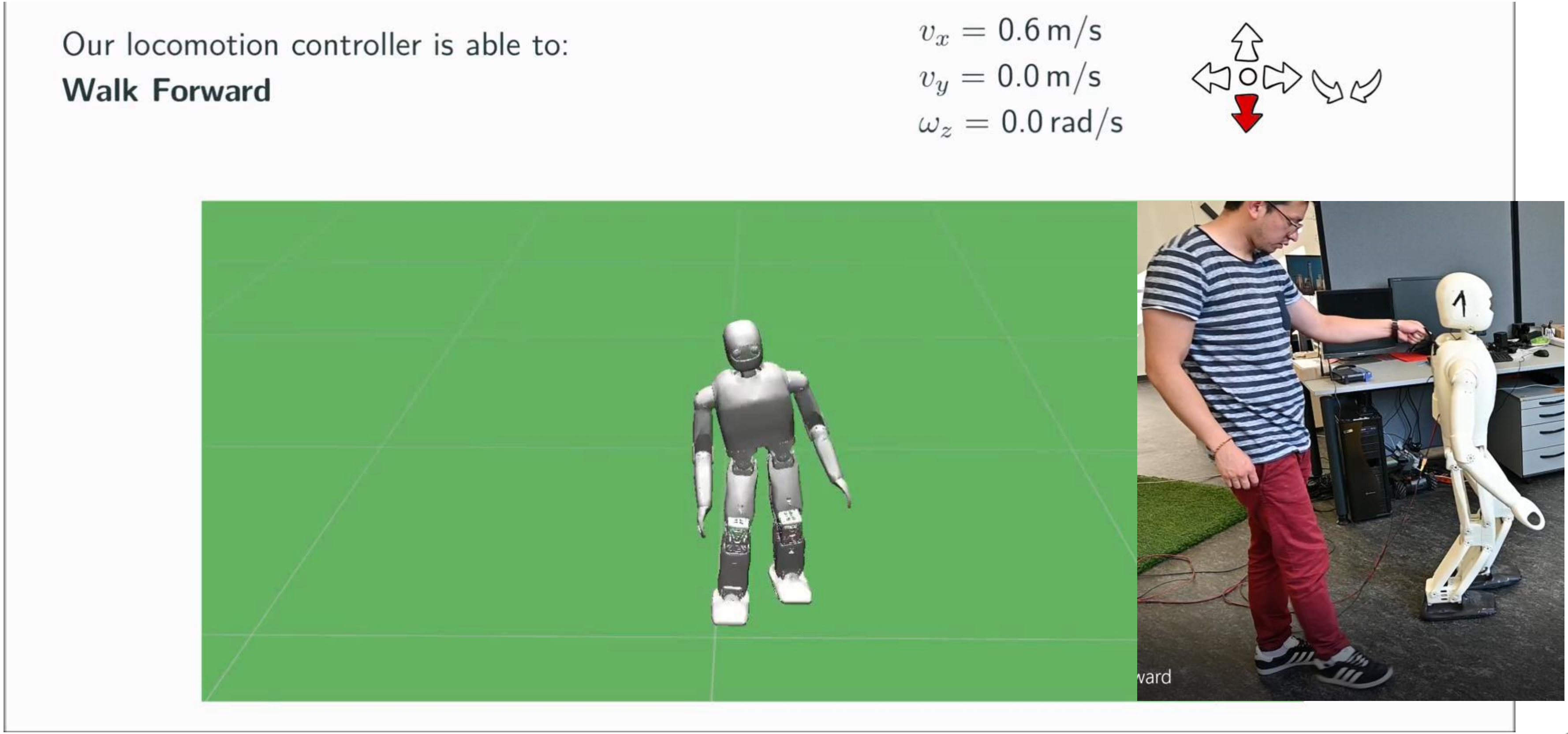
- Start with small velocities
- Increase range of sampled velocities



[Rodriguez and Behnke, ICRA 2021]

Learned Omnidirectional Gait

- Target velocity can be changed continuously

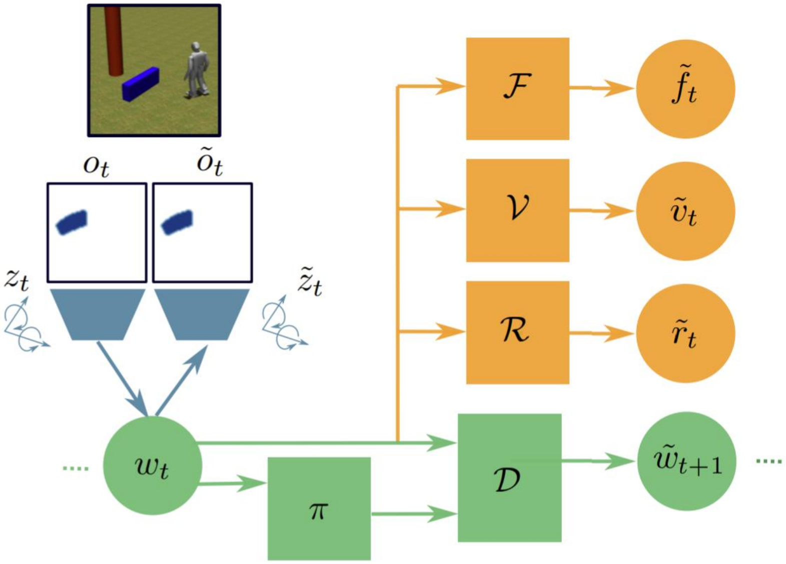


[Rodriguez and Behnke, ICRA 2021]

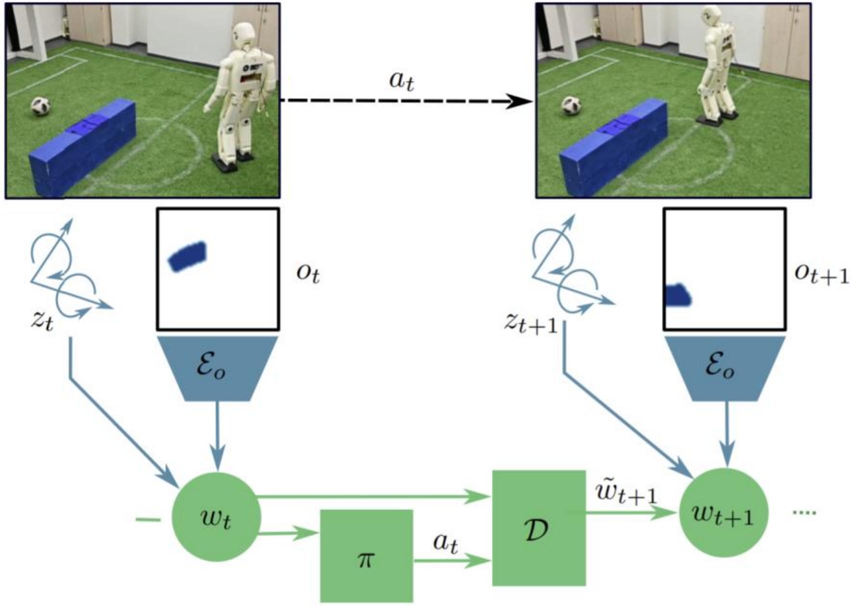
Learning Mapless Humanoid Navigation

- Visual (RGB images) and nonvisual observations to learn a control policy and an environment dynamics model
- Anticipate terminal states of success and failure

Training



Inference

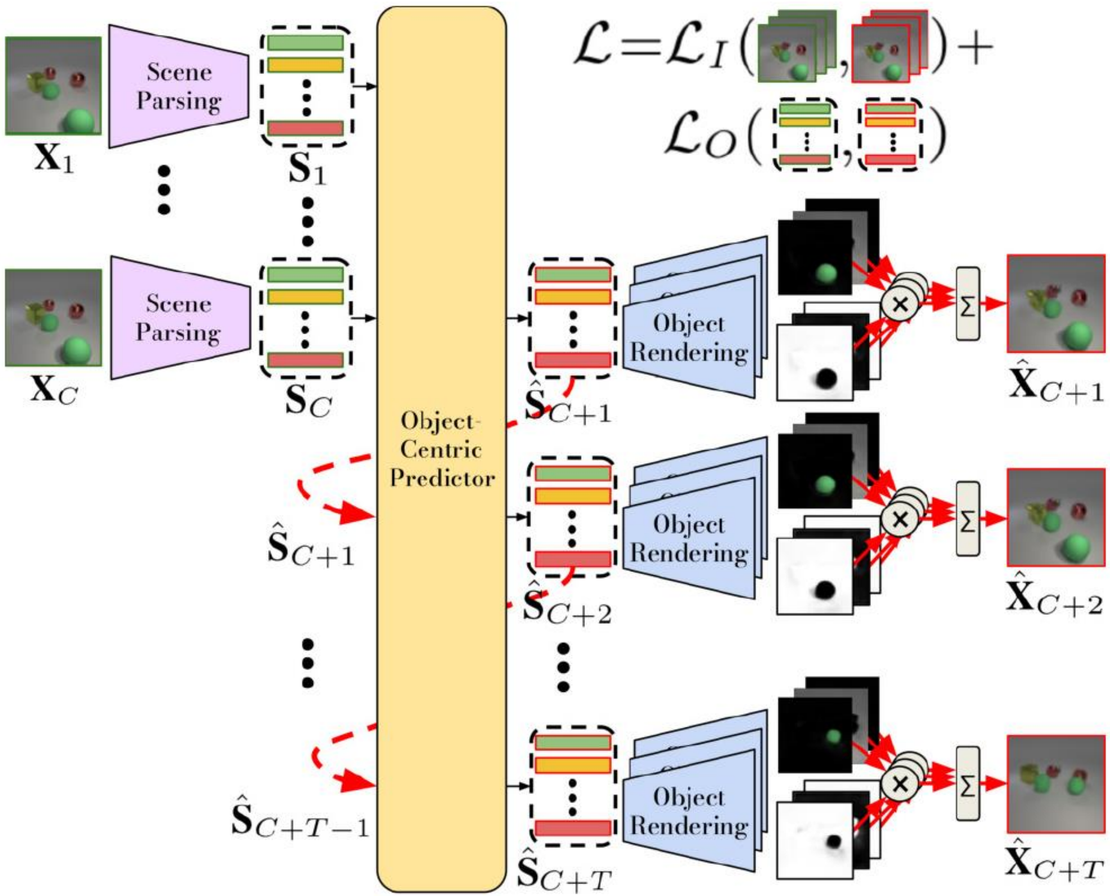


[Brandenburger et al. IROS 2021]

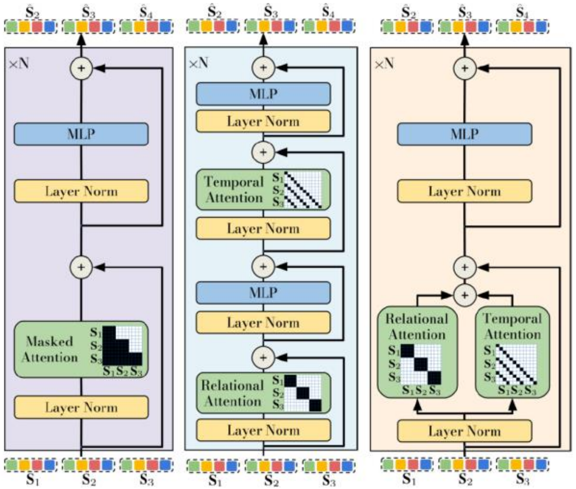
Learning Mapless Humanoid Navigation

[Brandenburger et al. IROS 2021]

Object-centric Video Prediction Decoupling Dynamics and Interaction

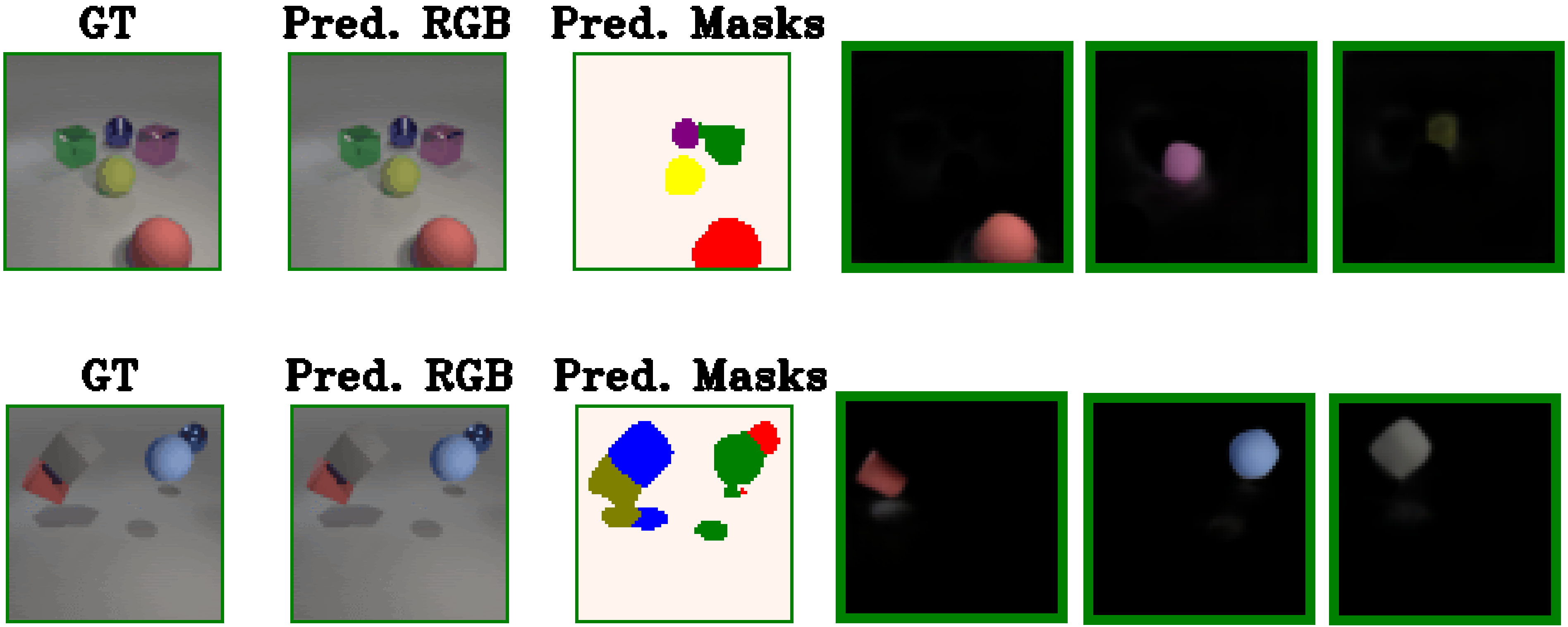


- Scene parsing into object slots
- Video synthesis from objects and masks
- Predictor decouples temporal and relational attention



[Villar-Corrales et al. arXiv:2302.11850]

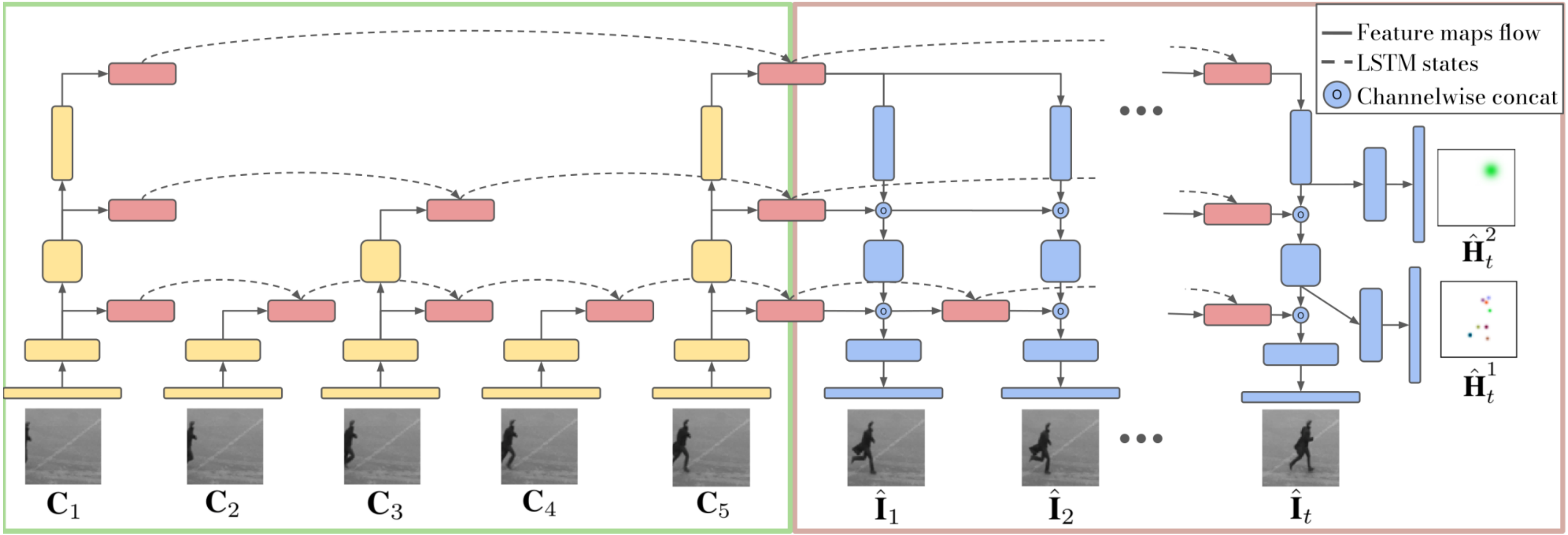
Object-centric Video Prediction Decoupling Dynamics and Interaction



[Villar-Corrales et al. arXiv:2302.11850]

MSPred: Video Prediction at Multiple Spatio-Temporal Scales

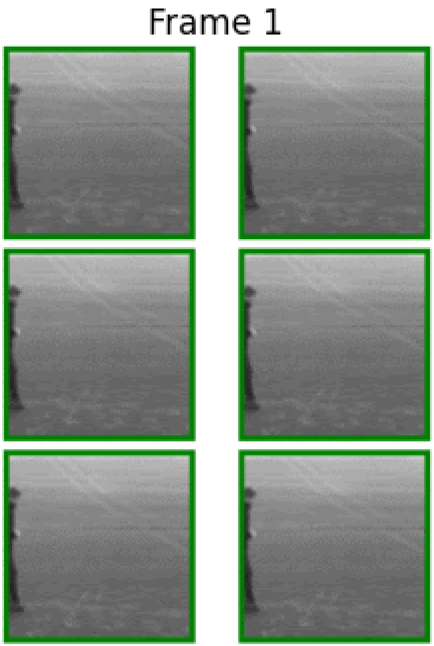
- Coarser, more abstract predictions for longer time horizons in higher layers
- Predict image itself, human pose joint keypoints, and human body position

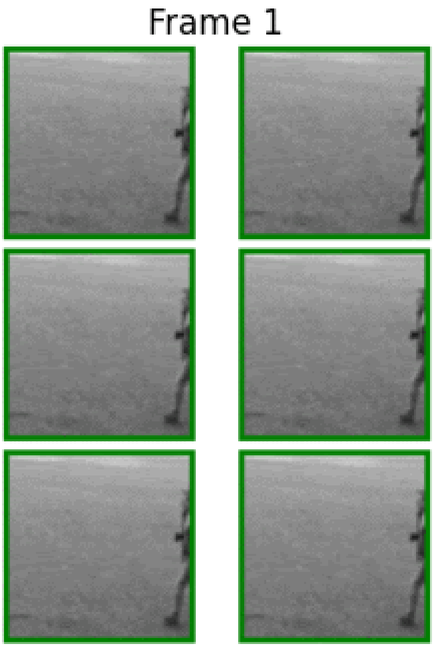


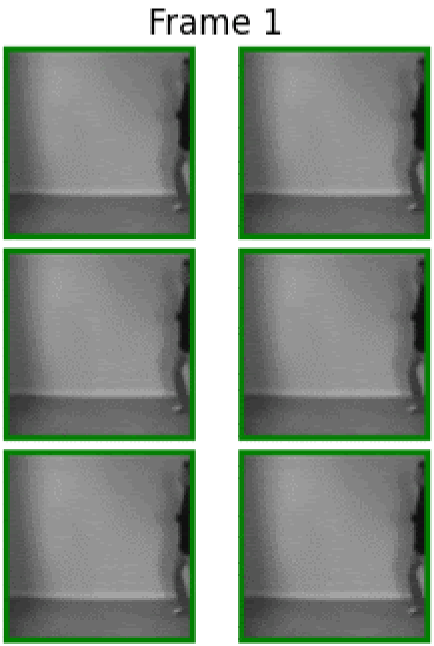
[Villar-Corrales et al., BMVC 2022]

MSPred: Video Prediction at Multiple Spatio-Temporal Scales

- Coarser, more abstract predictions for longer time horizons in higher layers
- Predict image itself, human pose joint keypoints, and human body position



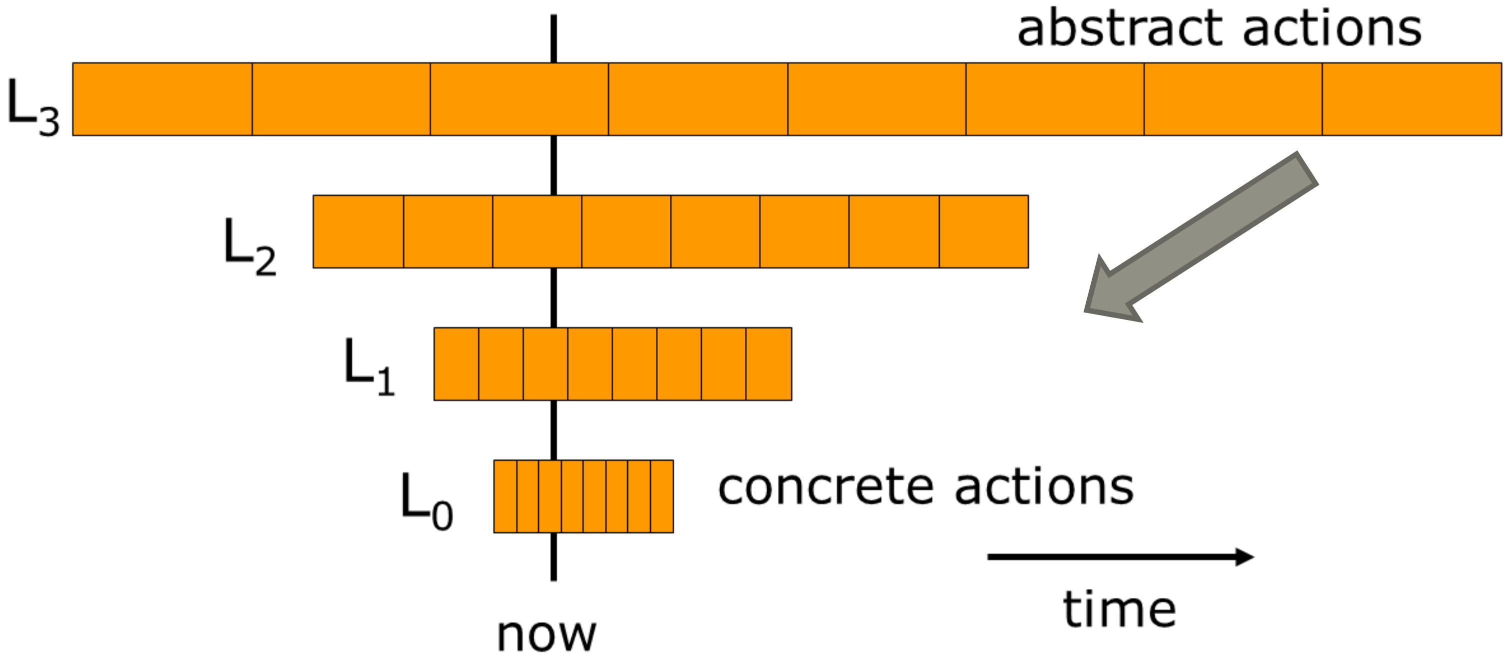




[Villar-Corrales et al., BMVC 2022]

Hierarchical Planning in the Now

- Use predicted state on different layers of abstraction for planning
- Coarse-to-fine planning makes actions more concrete as they come closer to execution
- Plan consists of few steps on each layer



Centauro Robot

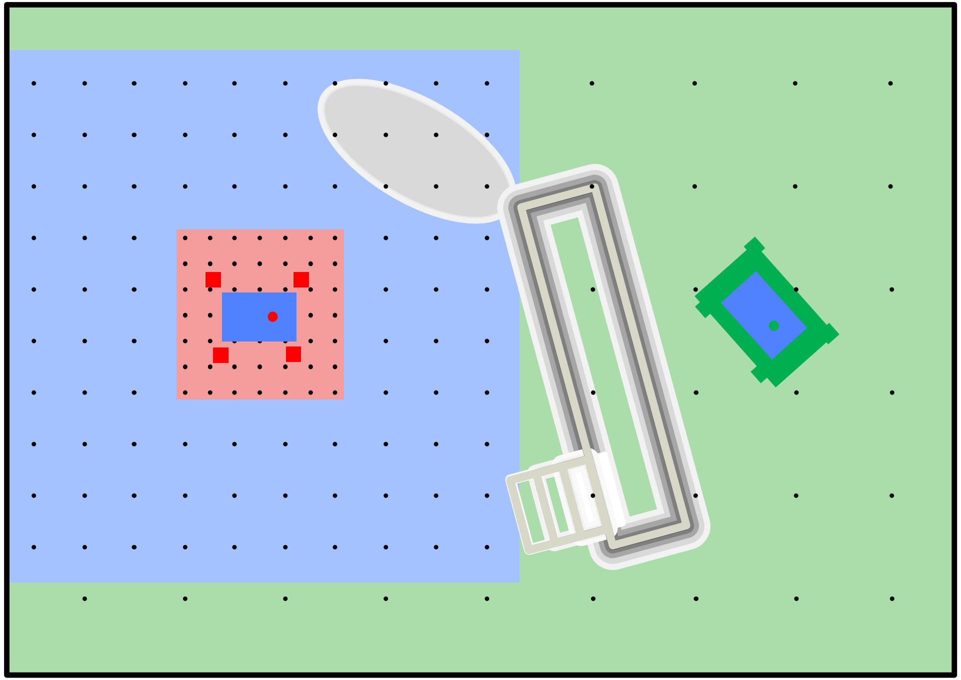
CENTAURO

- 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

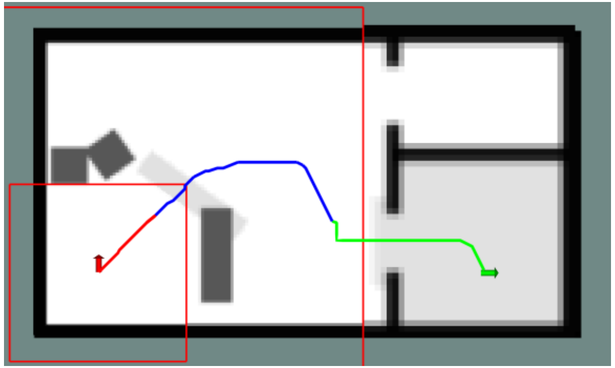
- Planning in the here and now
- Far-away details are abstracted away

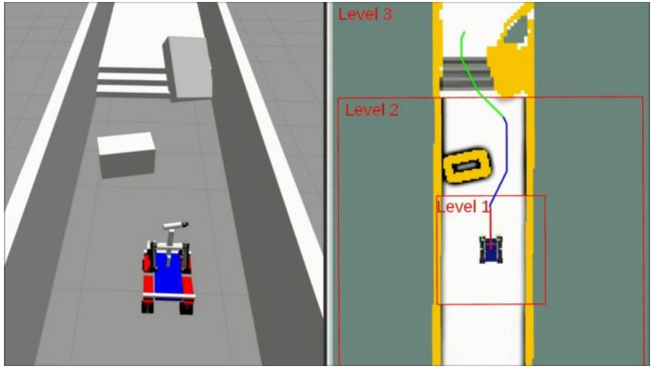


[Klamt and Behnke, IROS 2017, ICRA 2018]

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

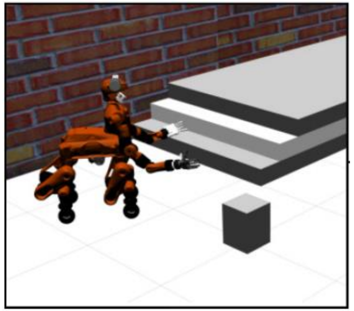




[Klamt and Behnke, IROS 2017, ICRA 2018]

Learning Cost Functions of Abstract Representations

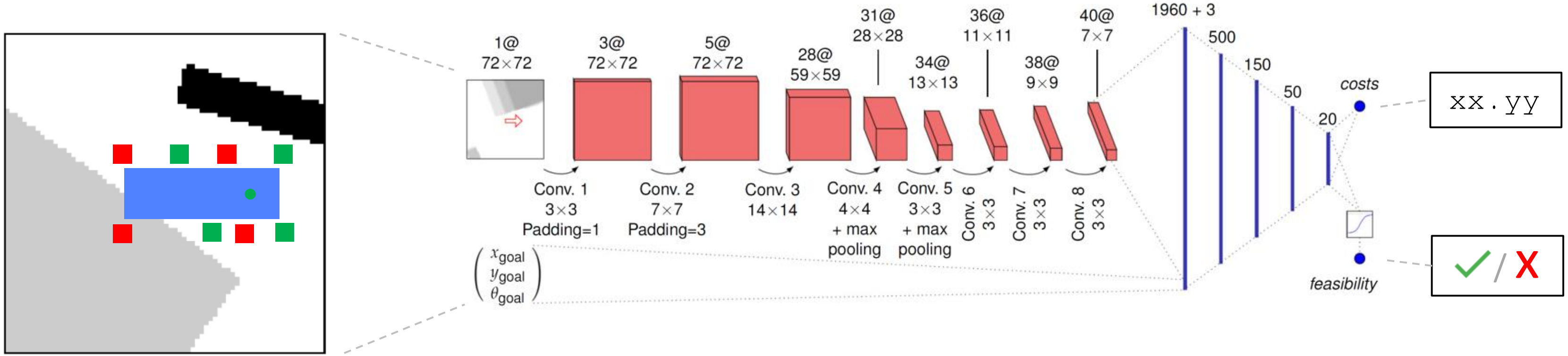
Planning problem



[Klamt and Behnke, ICRA 2019]

Abstraction CNN

- Predict feasibility and costs of local detailed planning



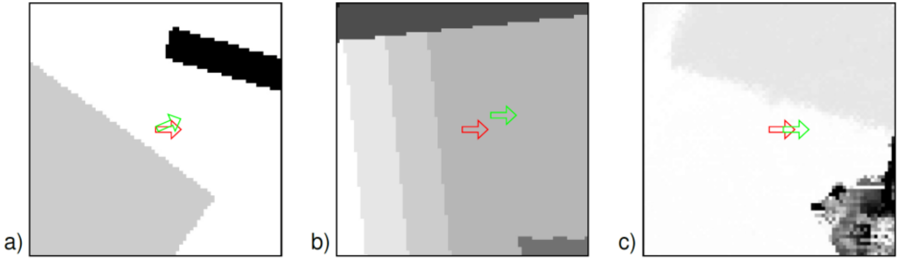
Training data

- 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

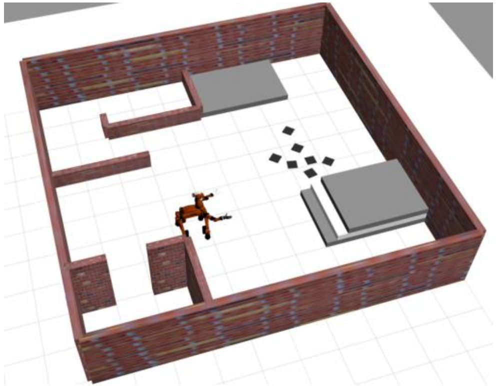


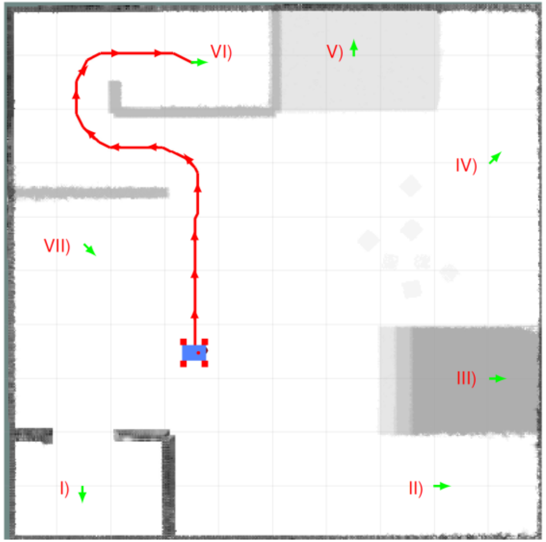
	random	*simulated*	*real*
feasibility correct, man.tuned	79.27%	65.35%	69.77%
Error($\mathcal{C}_{a,\mathrm{man.tuned}}$)	0.057	0.021	0.103
feasibility correct, CNN	95.04%	96.69%	92.62%
Error($\mathcal{C}_{a,\mathrm{CNN}}$)	0.027	0.013	0.081

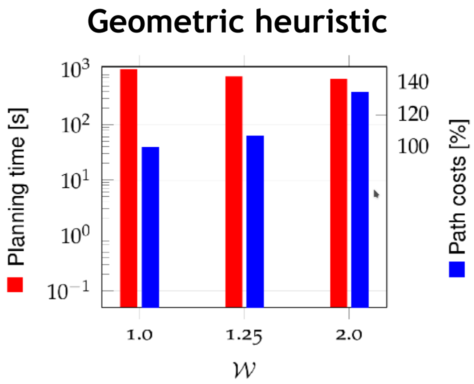
[Klamt and Behnke, ICRA 2019]

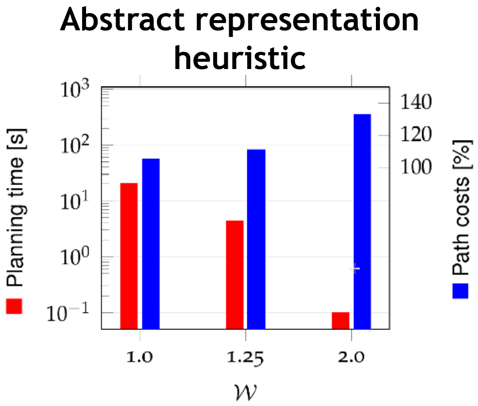
Experiments – Planning Performance

- Learned heuristics accelerates planning, without increasing path costs much





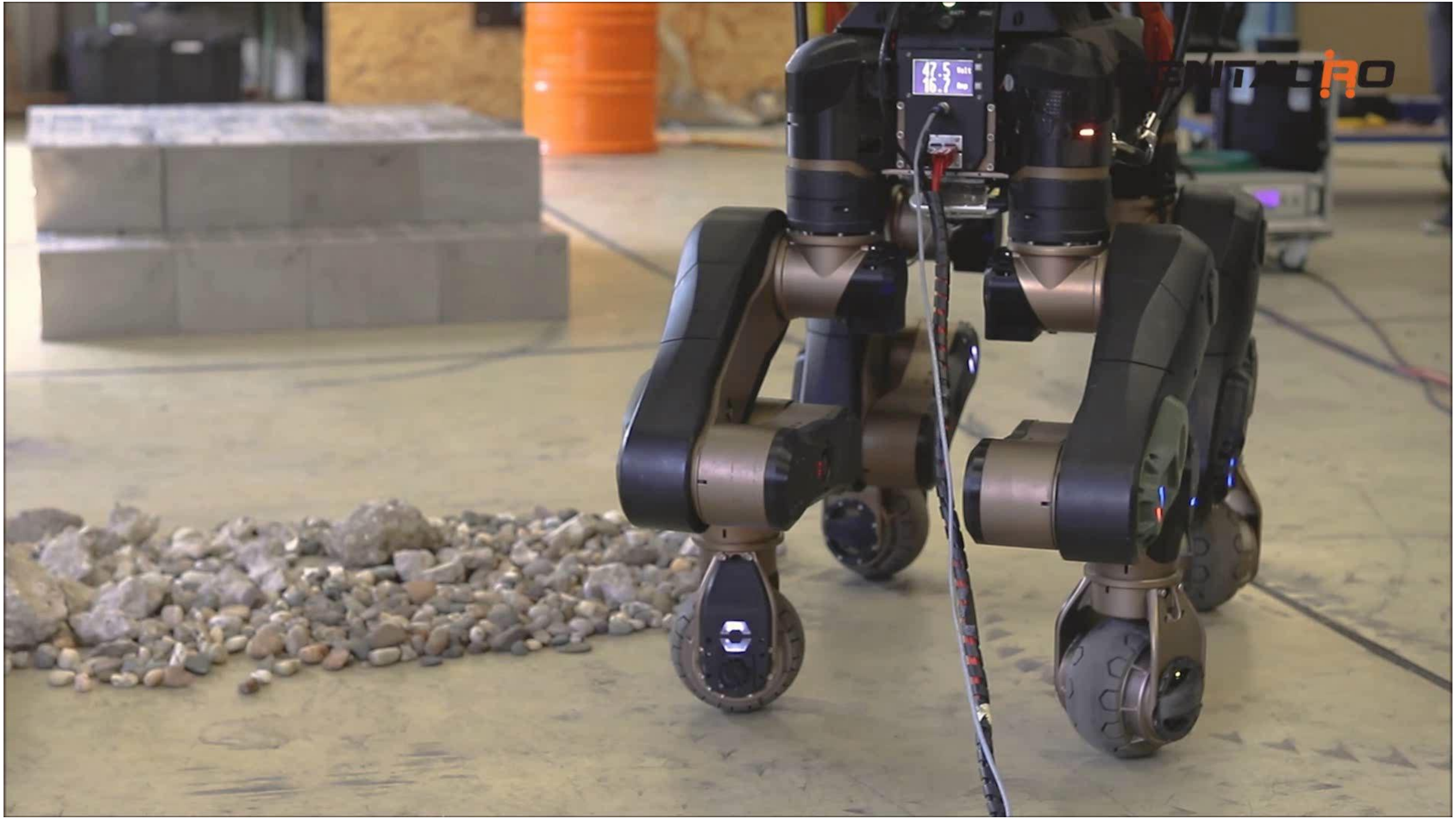




Heuristic preprocessing: 239 sec

[Klamt and Behnke, ICRA 2019]

CENTAURO Evaluation @ KHG: Locomotion Tasks



[Klamt et al. RAM 2019]

UNIVERSITÄT BONN AIS

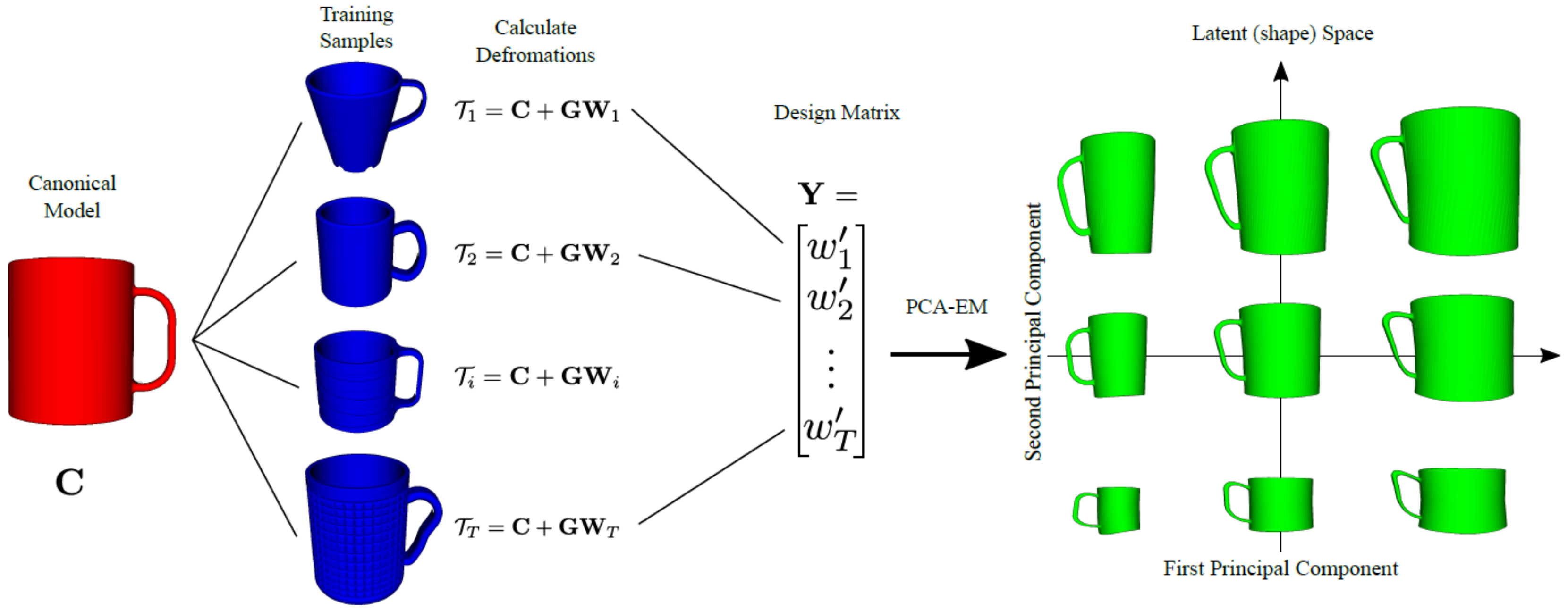
Transfer of Manipulation Skills

Knowledge Transfer

[Rodriguez and Behnke ICRA 2018]

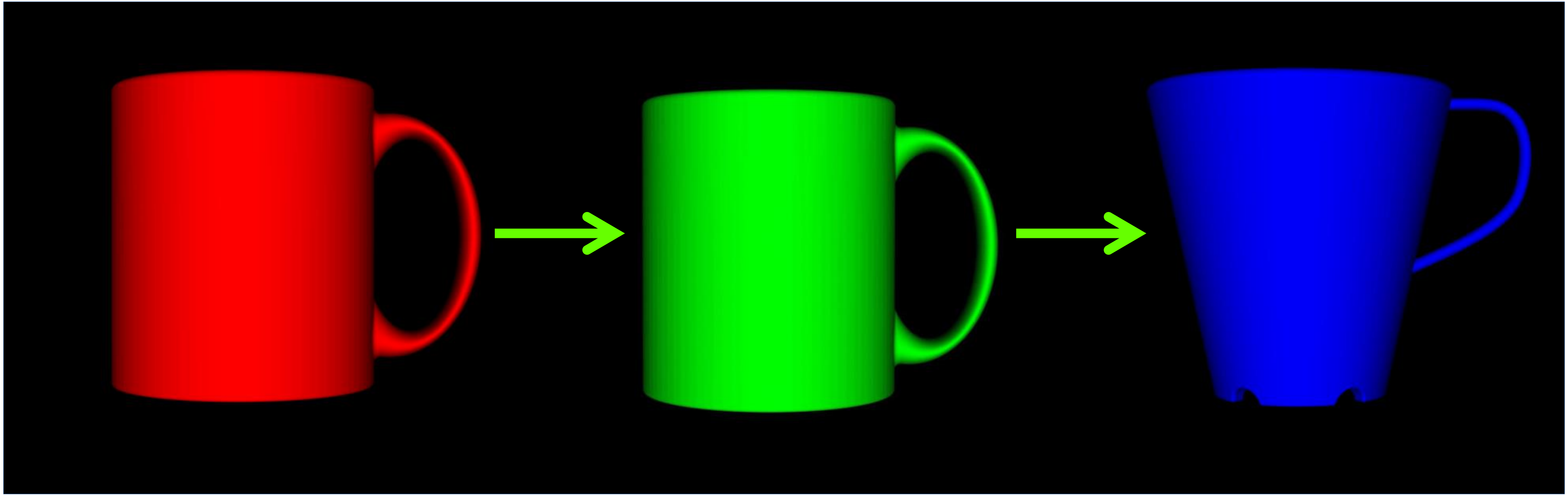
Learning a Latent Shape Space

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



[Rodriguez and Behnke ICRA 2018]

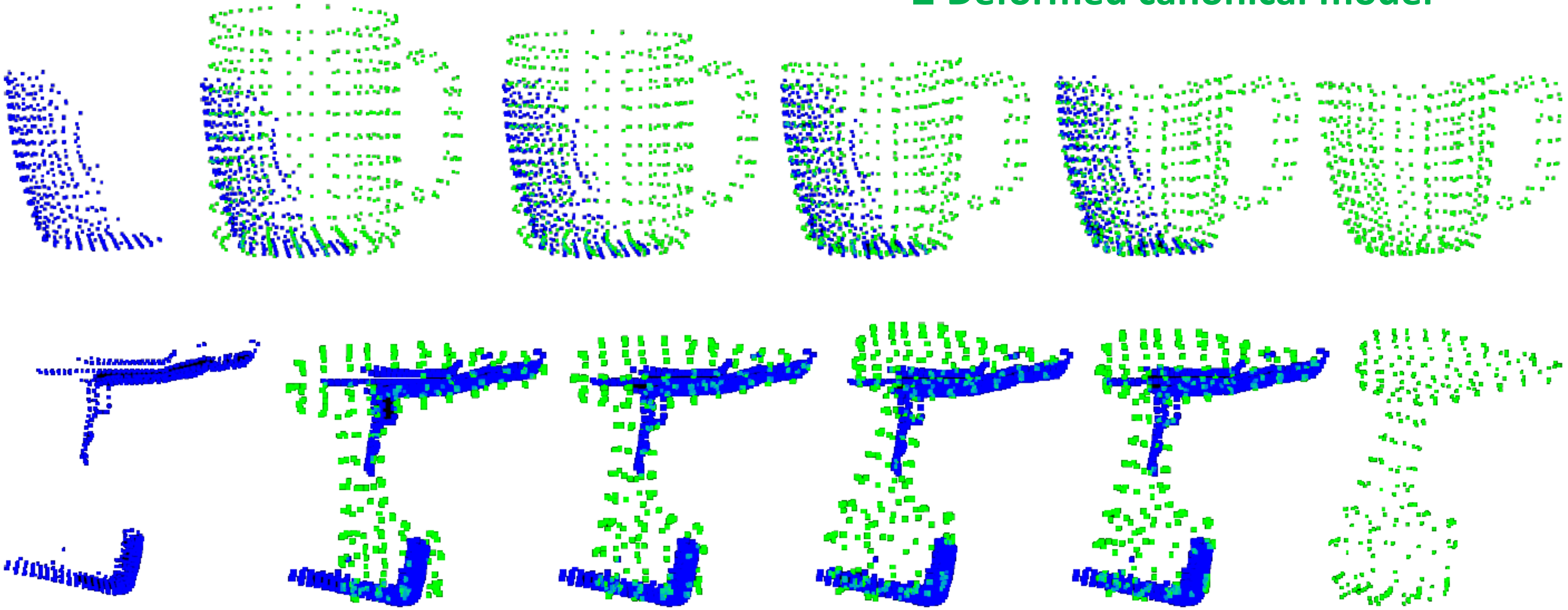
Interpolation in Shape Space



[Rodriguez and Behnke ICRA 2018]

Shape-aware Non-rigid Registration

- Partial view of novel instance
- Deformed canonical model

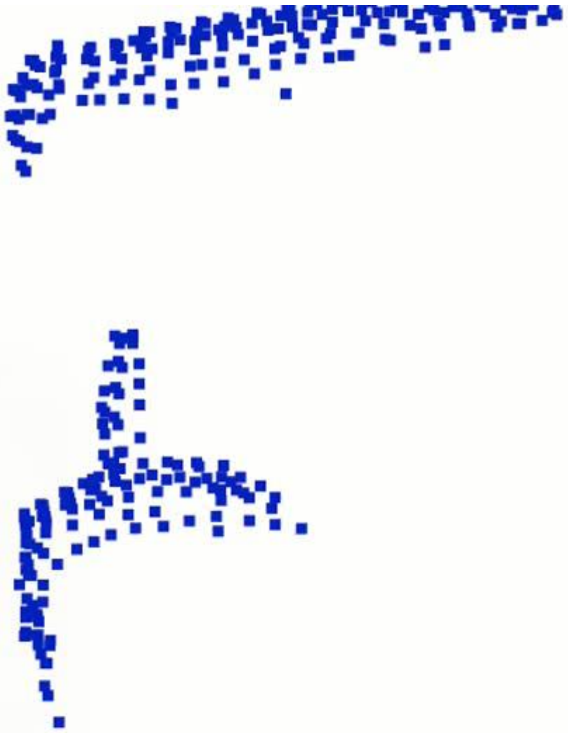


[Rodriguez and Behnke ICRA 2018]

Shape-aware Registration for Grasp Transfer

- Full point cloud

- Partial view

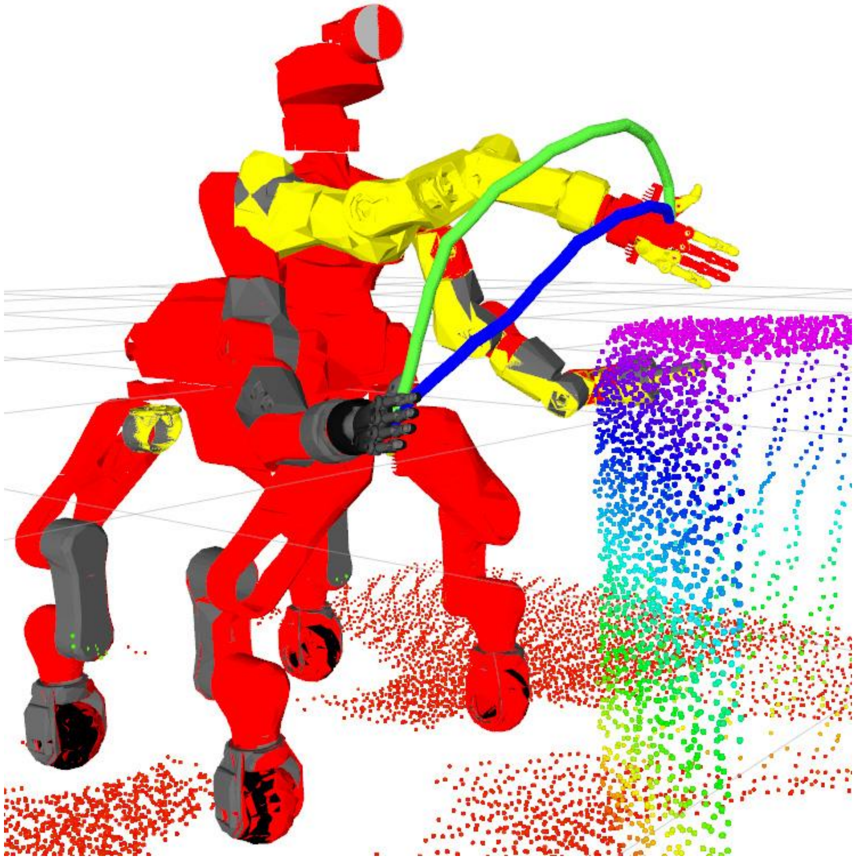


[Rodriguez and Behnke ICRA 2018]

Collision-aware Motion Generation

Constrained Trajectory Optimization:

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

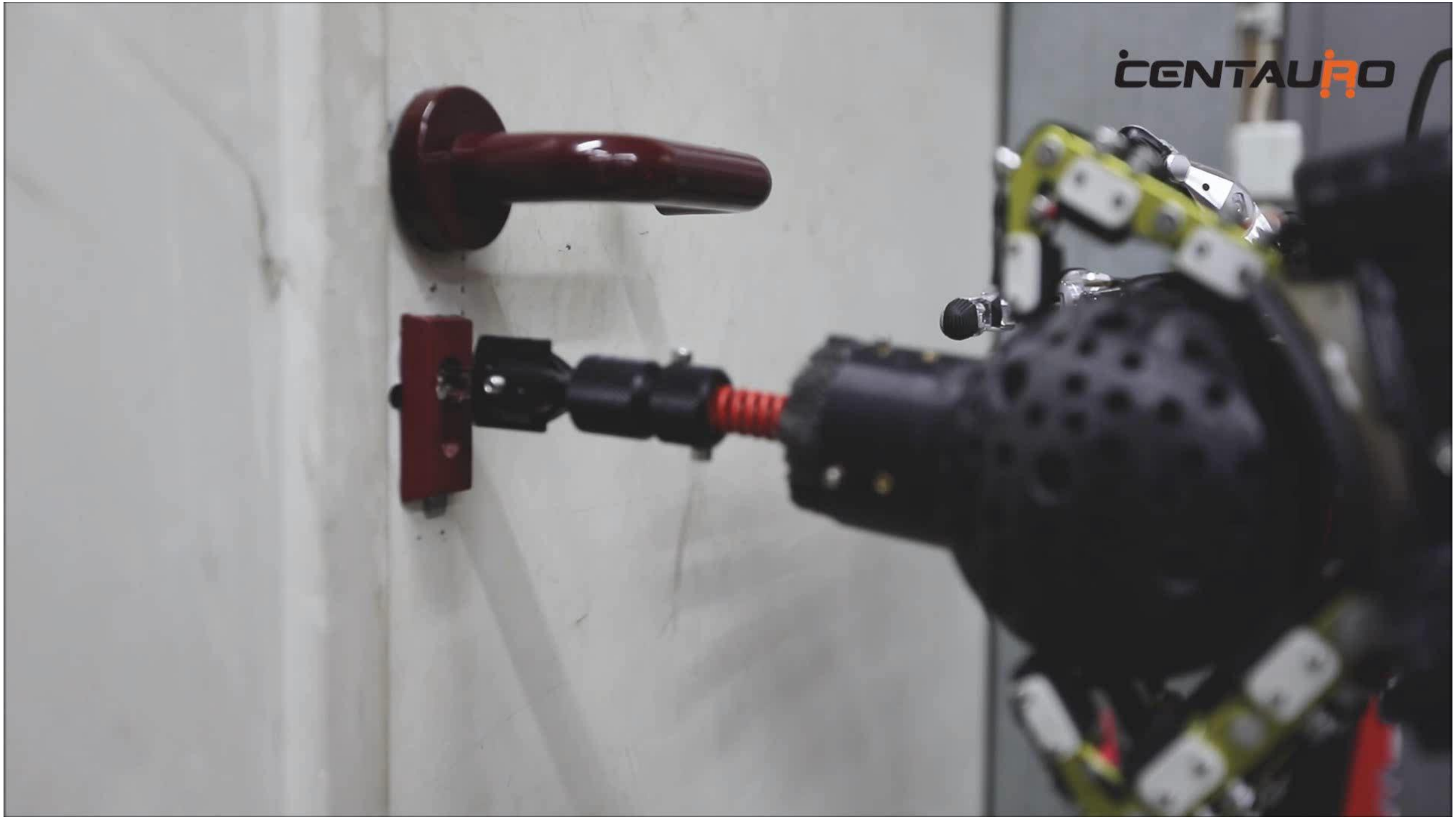


[Pavlichenko et al., IROS 2017]

Grasping an Unknown Power Drill and Fastening Screws

[Rodriguez and Behnke ICRA 2018]

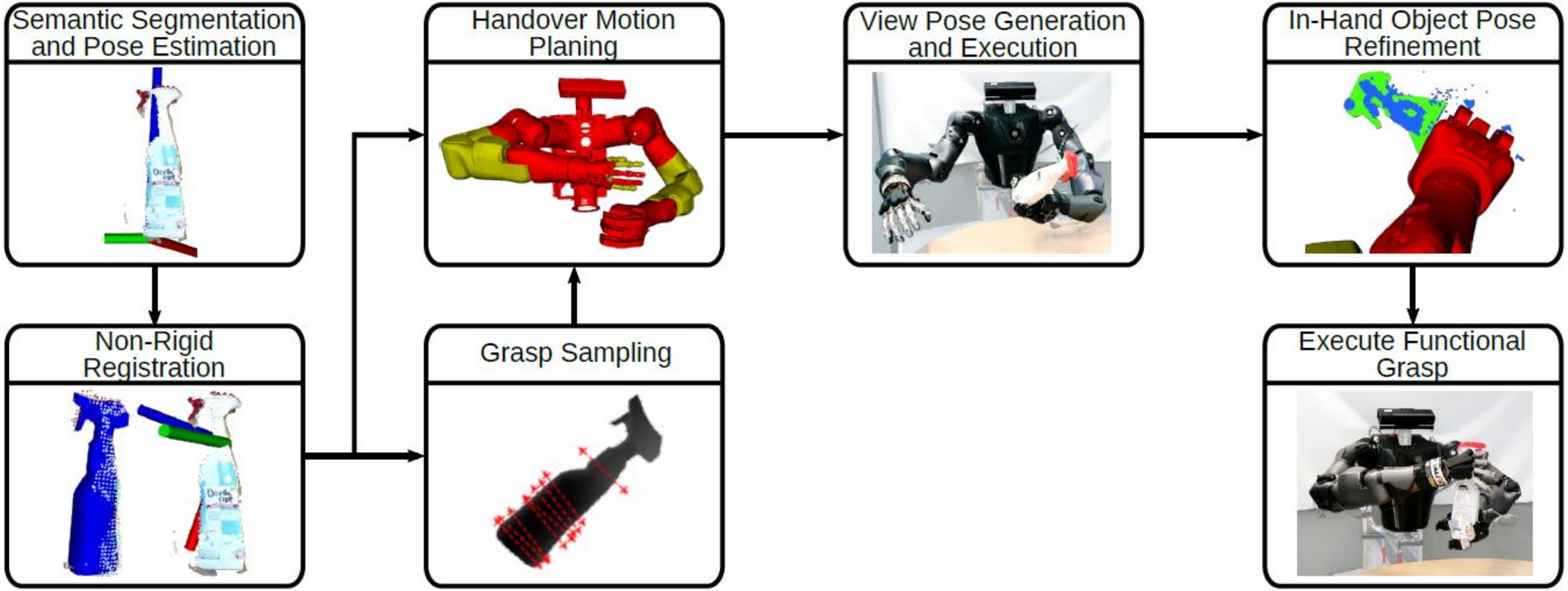
CENTAURO: Complex Manipulation Tasks



[Klamt et al. RAM 2019]

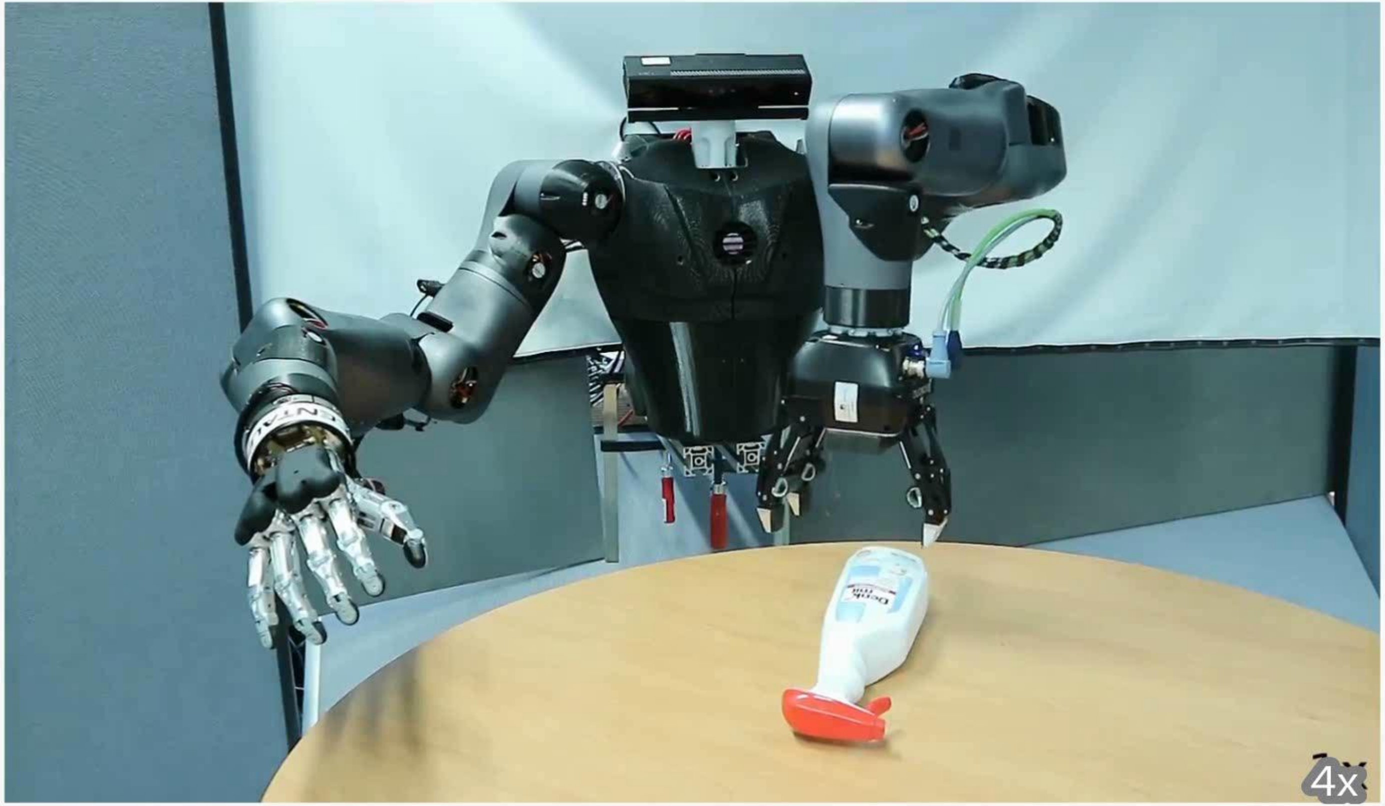
Regrasping for Functional Grasp

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



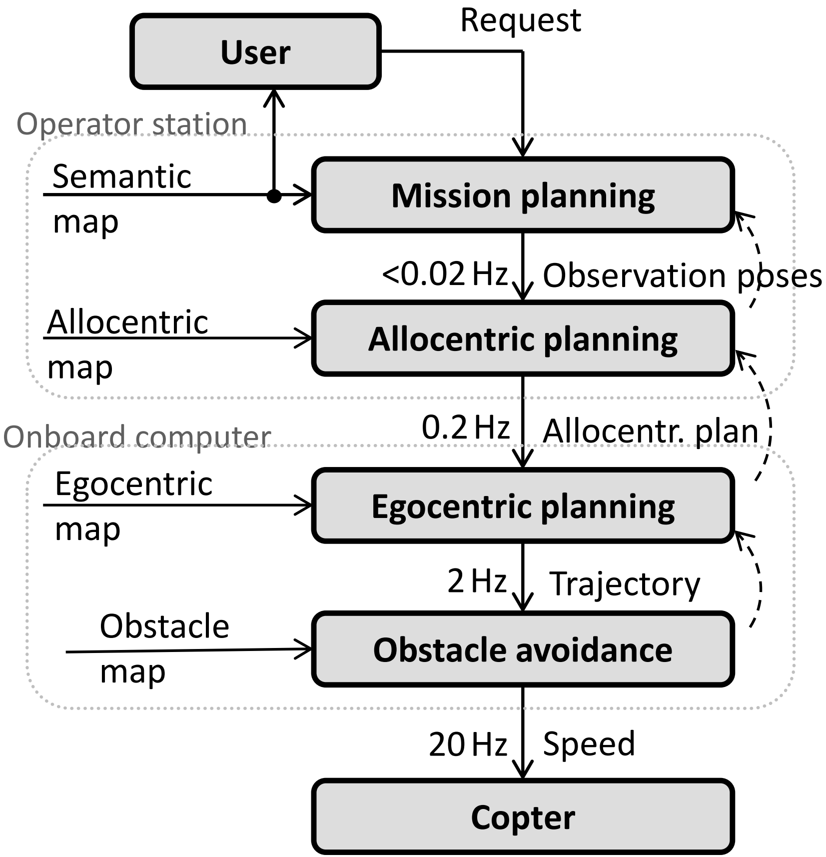
[Pavlichenko et al. Humanoids 2019]

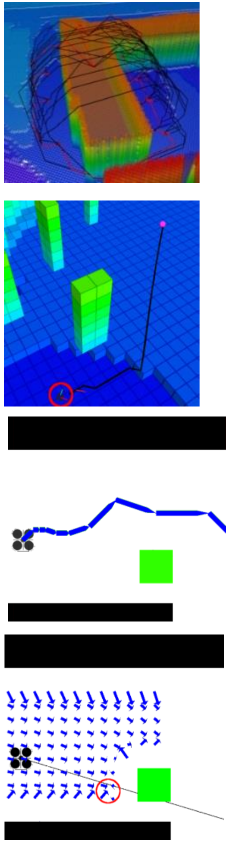
Regrasping Experiments



[Pavlichenko et al. Humanoids 2019]

Micro Aerial Vehicles: Hierarchical Navigation





Mission plan

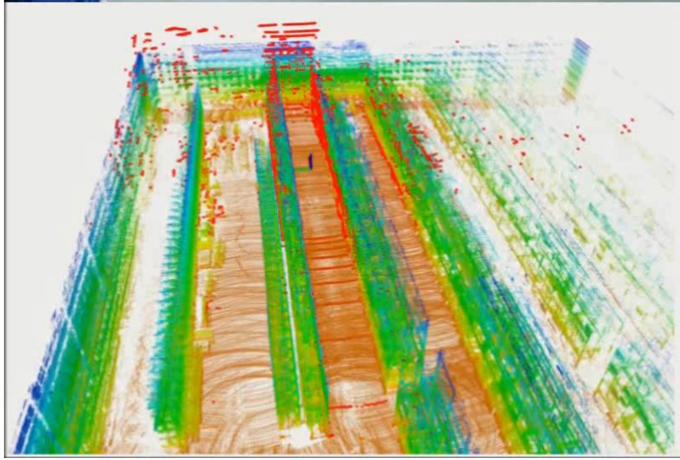
Allocentric planning

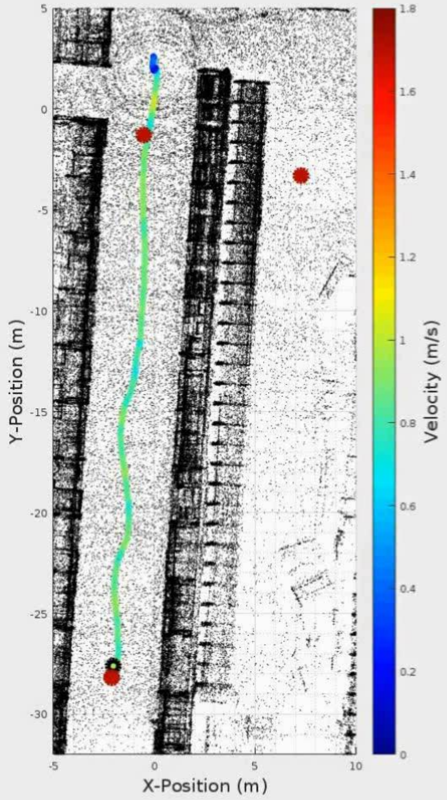
Egocentric planning

Obstacle avoidance

[Droeschel et al. JFR 2016]

InventAIRy: Autonomous Navigation in a Warehouse





[Beul et al. RA-L 2018]

InventAIRy: Detected Tags in Shelf

[Beul et al. RA-L 2018]

German Rescue Robotics Center

DRZ
DEUTSCHES RETTUNGSROBOTIK ZENTRUM

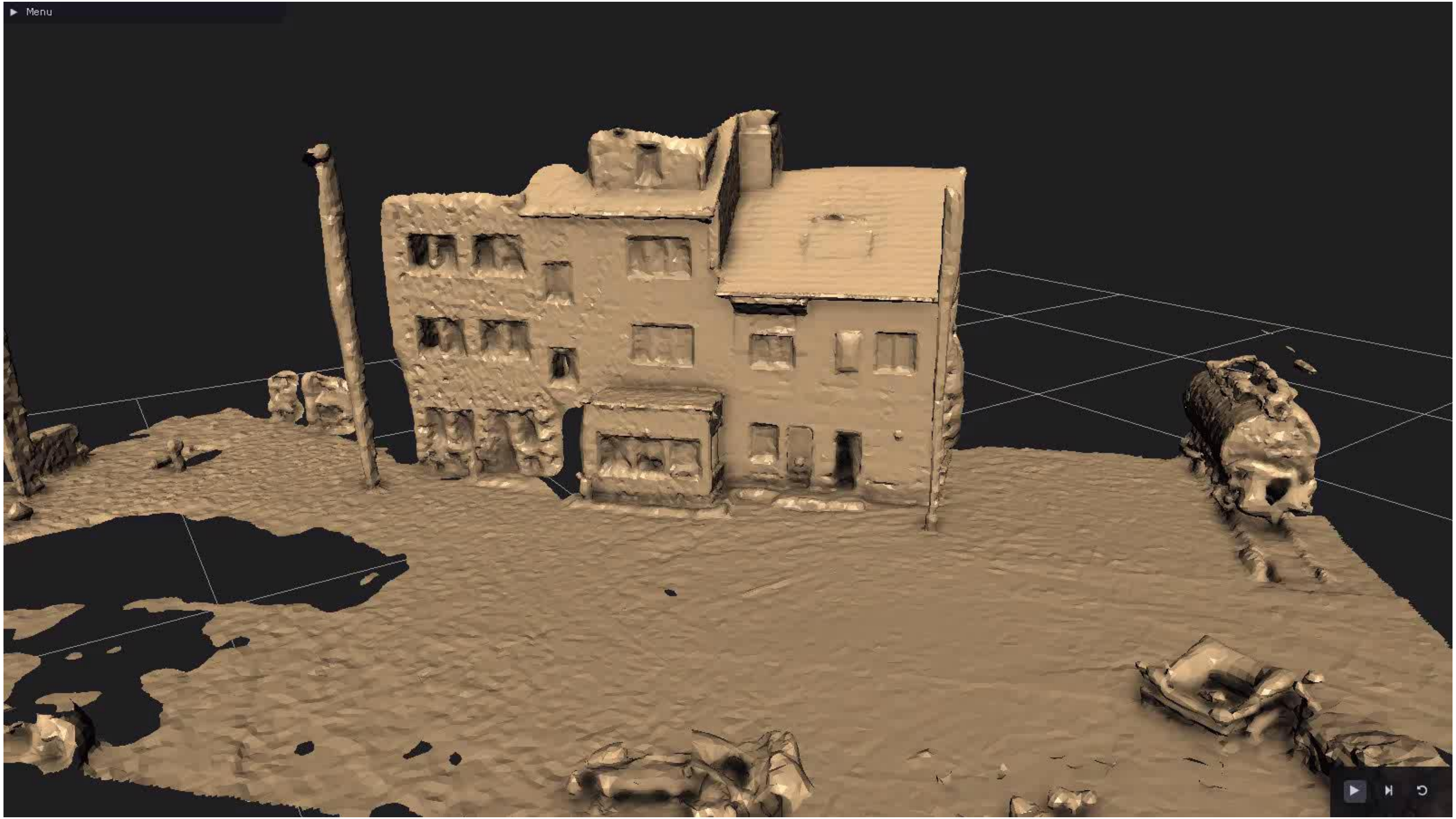
Initial demonstrator

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

Current demonstrator

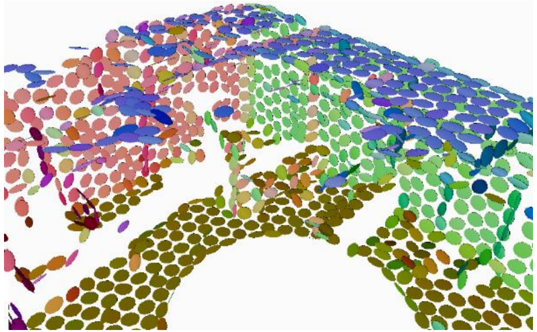
- Basis: DJI Matrice 210 v2
- Sensors: Ouster OS-0, FLIR AGX, 2× Intel RealSense D455
- IP43 water resistance

Modeling the Brandhaus Dortmund

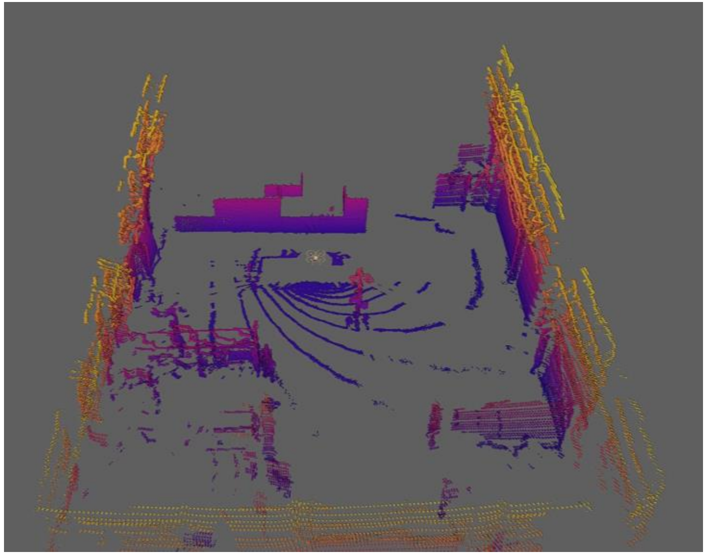


[Rosu et al. SSRR 2019]

Real-time LiDAR Odometry with Continuous-time Trajectory Optimization



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

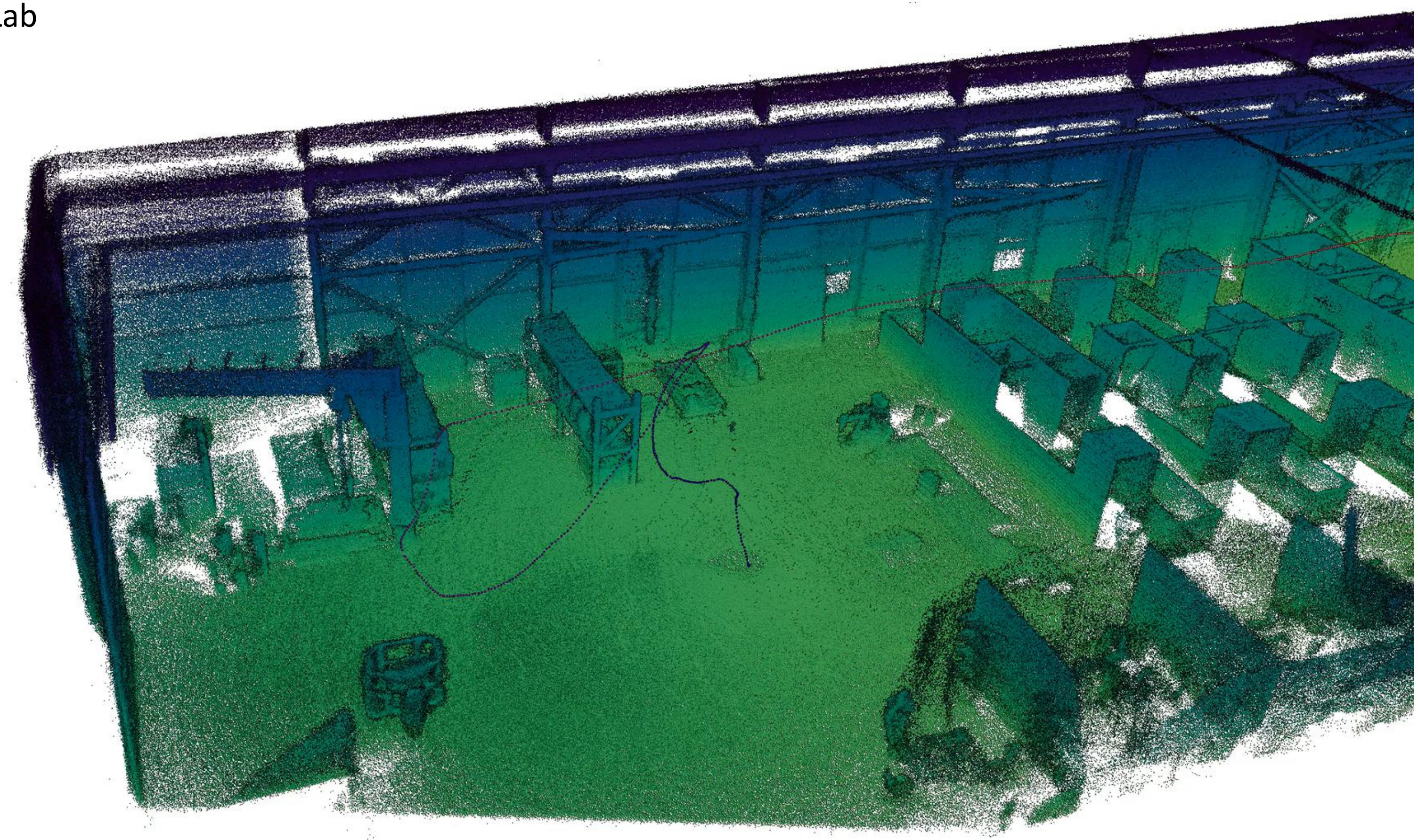


- Real-time onboard processing 16-20 Hz
- Open-Source
  https://github.com/AIS-Bonn/lidar_mars_registration

[Quenzel and Behnke, IROS 2021]

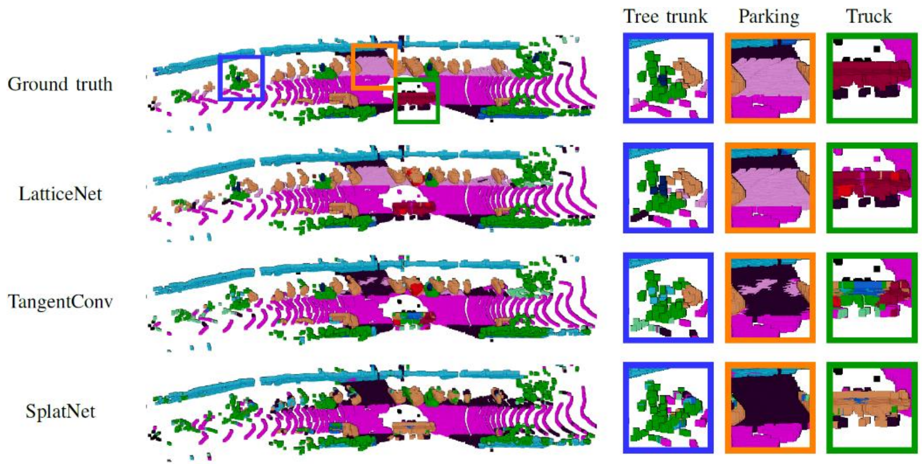
3D LiDAR Mapping

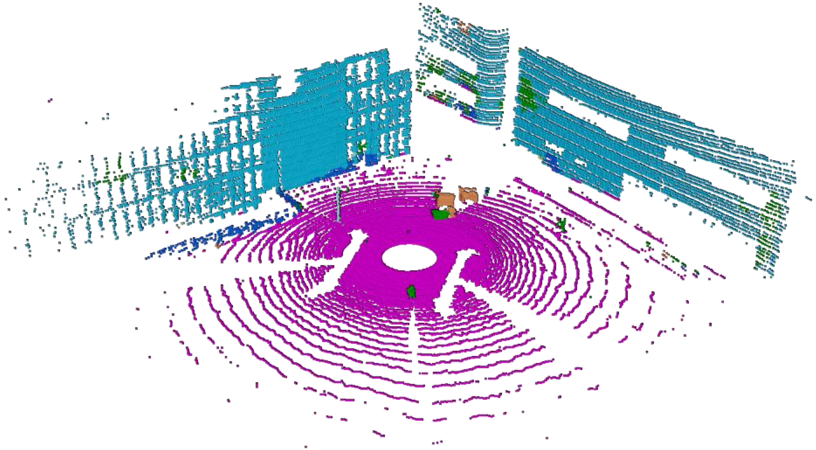
DRZ Living Lab



[Quenzel and Behnke, IROS 2021]

Semantic Perception: LiDAR Segmentation



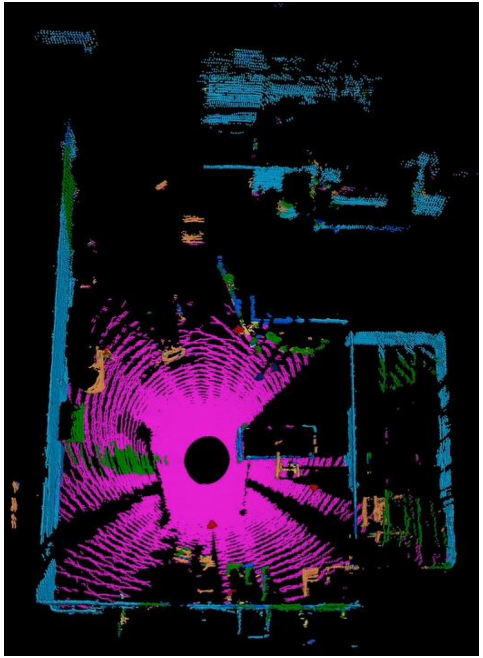


- LatticeNet segmentation of 3D point clouds based on sparse permutohedral grid
- Hierarchical information aggregation through U-Net architecture
- LatticeNet is real-time capable and achieves excellent results in benchmarks

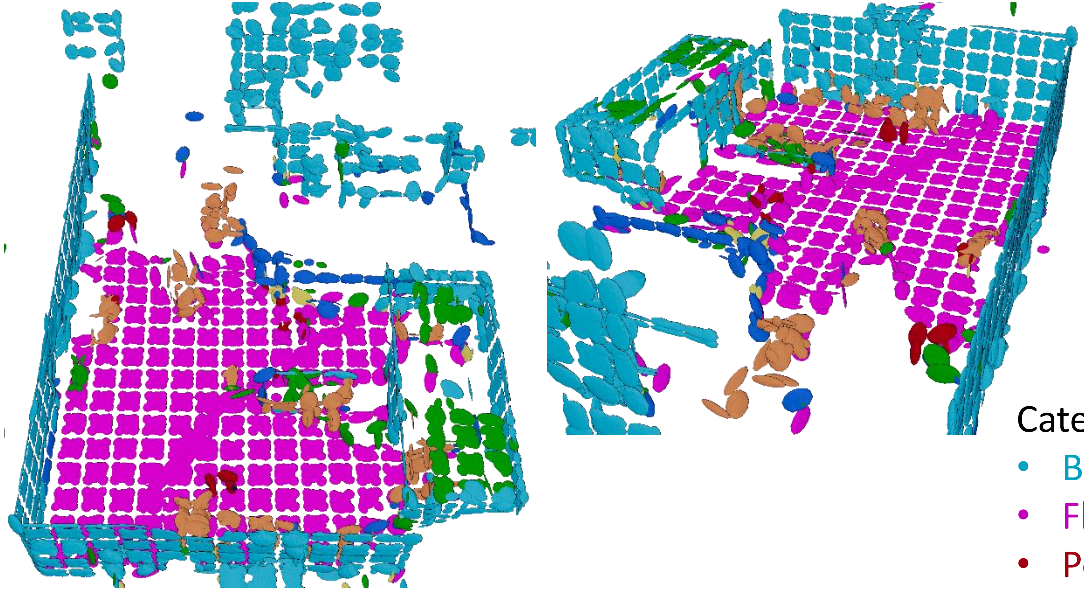
[Rosu et al., RSS 2020]

Semantic Fusion: 3D LiDAR Mapping

Minimax-Viking fire house



Segmented point cloud

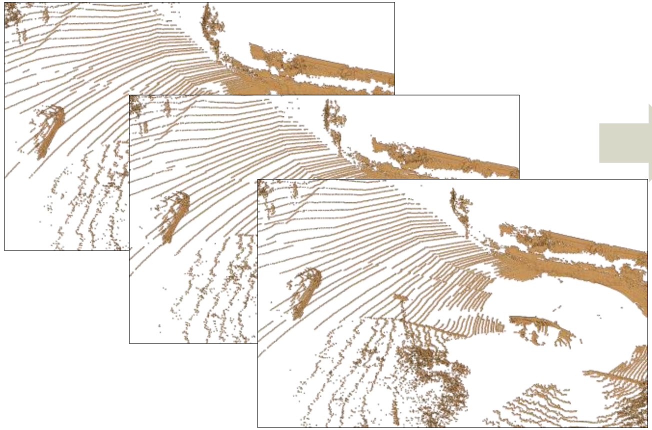


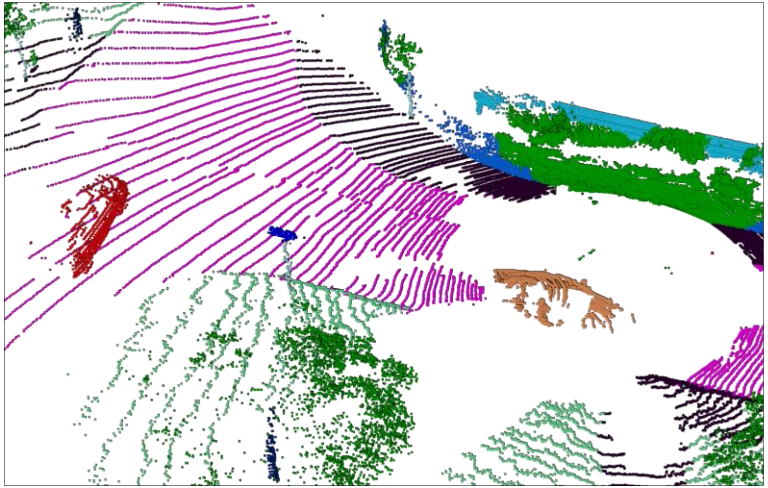
Semantic multiresolution surfel map

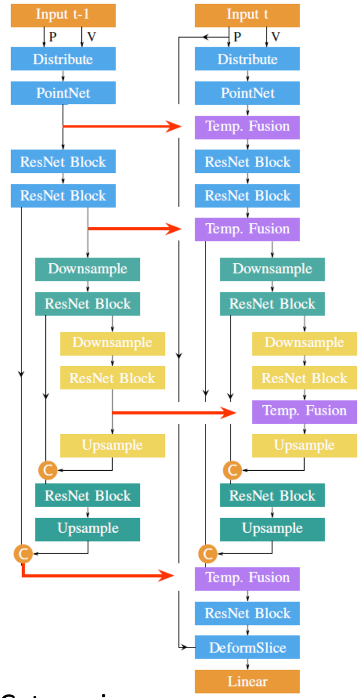
Categories:
- Building
- Floor
- Persons
- Vehicles
- Fence
- Vegetation

Semantic Fusion: Temporal LatticeNet

- Semantic segmentation of sequences of 3D point clouds
- Integration of recurrent connections
- Trained on three scans of SemanticKITTI
- Distinguishing moving from parking vehicles





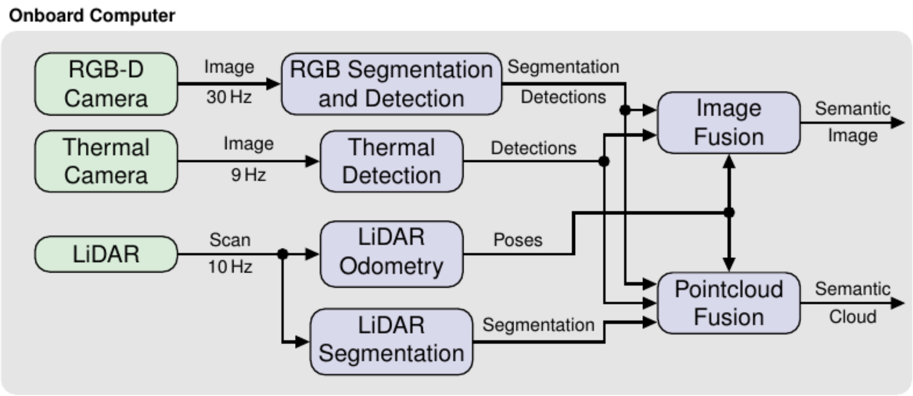


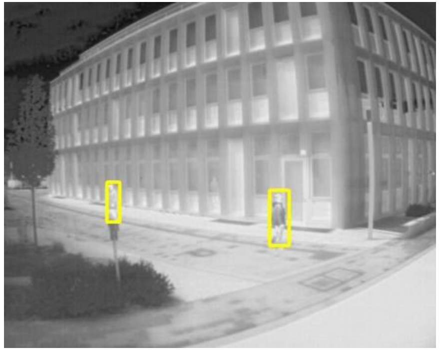
Categories:
- Street
- Moving Vehicle
- Parking Vehicle
- Vegetation

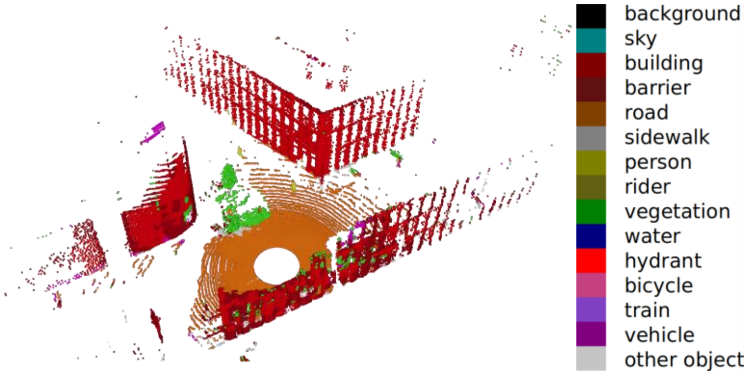
[Rosu et al. Autonomous Robots 2021]

Onboard Multimodal Semantic Fusion

- Real-time semantic segmentation and object detection (≈9Hz) with EdgeTPU / iGPU
  - SalsaNext for LiDAR
  - DeepLabv3 for RGB images
  - SSD MobileDet for Thermal/RGB
- Late-fusion for
  - Point cloud
  - Image segmentation



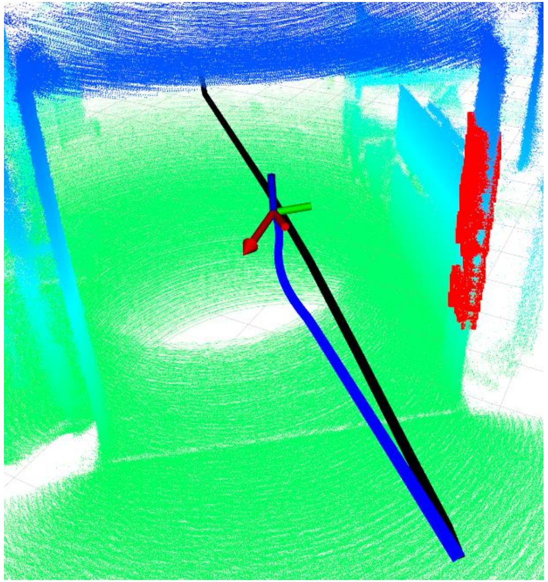


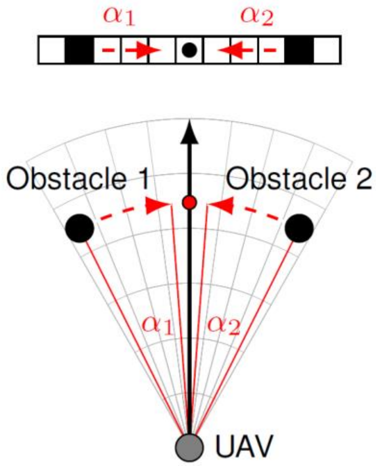


[Bultmann et al. ECMR 2021, RAS 2022]

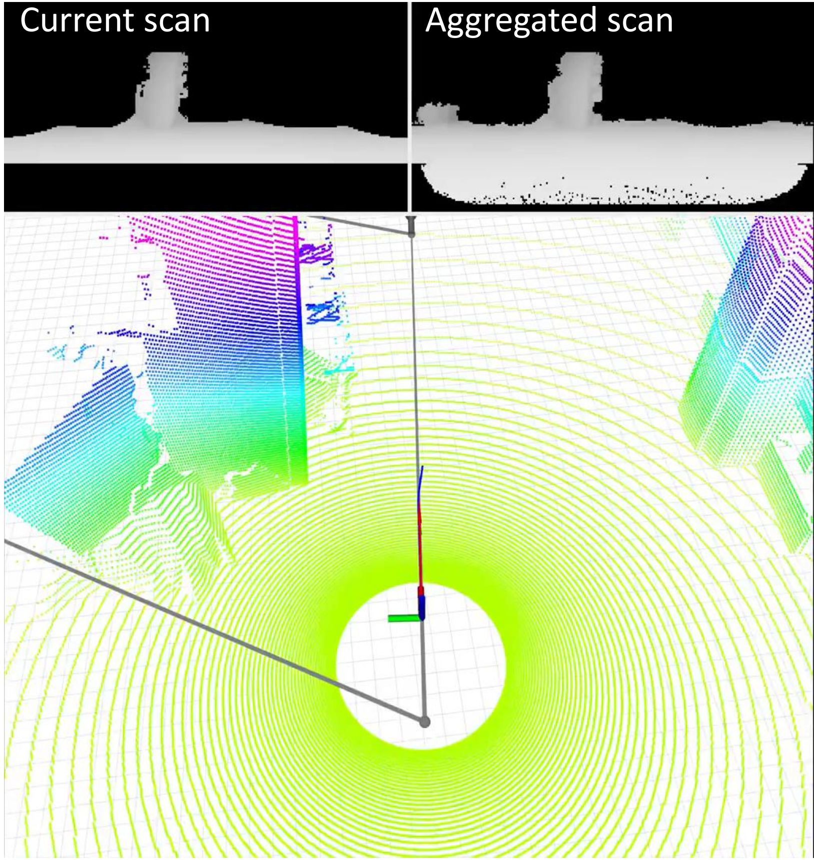
Predictive Angular Potential Field-based Obstacle Avoidance

- Aggregate LiDAR scans in range image
- Adjust direction using angular potential field
- Predict trajectory and range image
- Scale velocity based on time-to-contact





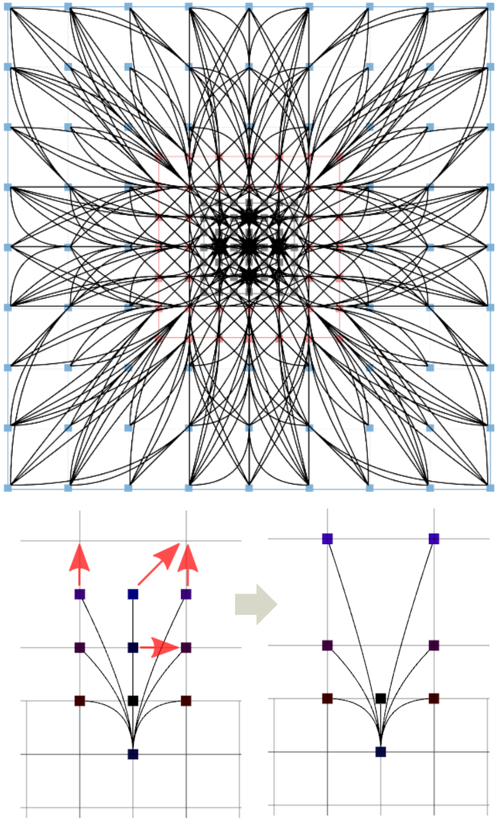
Angular Potential Field

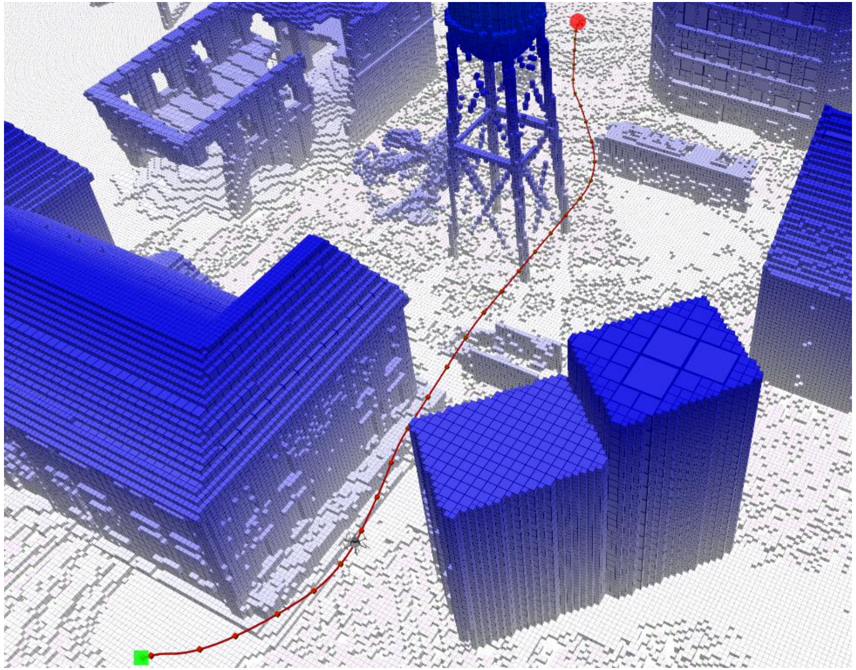


[Schleich and Behnke, IROS 2022]

Dynamic 3D Navigation Planning

- Positions and velocities in sparse local multiresolution grid
- Adaptation of movement primitives to grid
- Optimization of flight time and control costs
- 1 Hz replanning

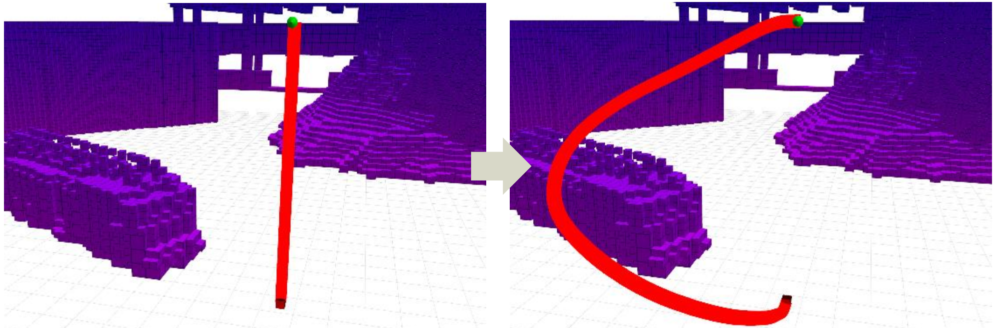




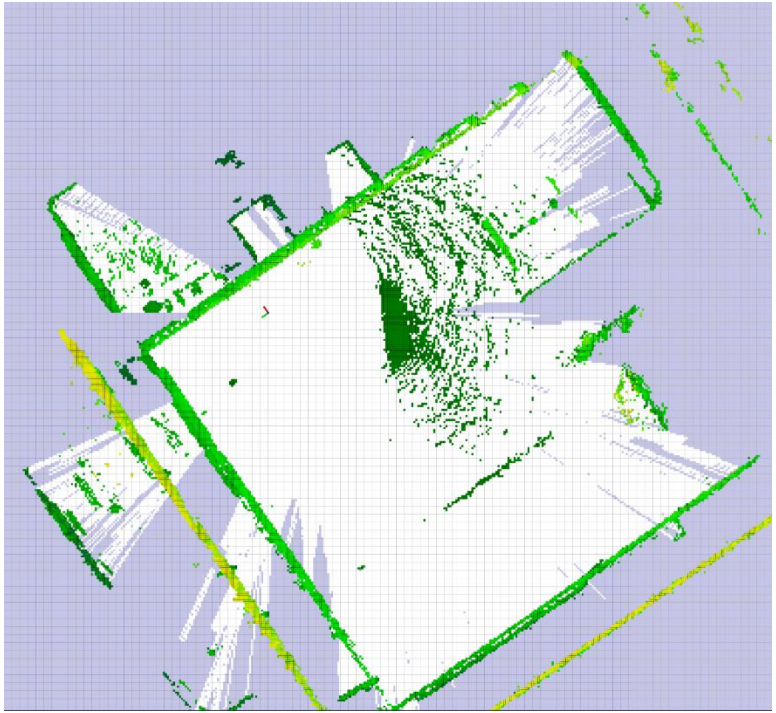
[Schleich and Behnke, ICRA 2021]

Planning with Visibility Constraints

- Extra costs for flight through unmapped volumes
- Consideration of sensor frustum:
  - Coupling of vertical and horizontal motion
  - Preferred forward flight with limited rotational speed



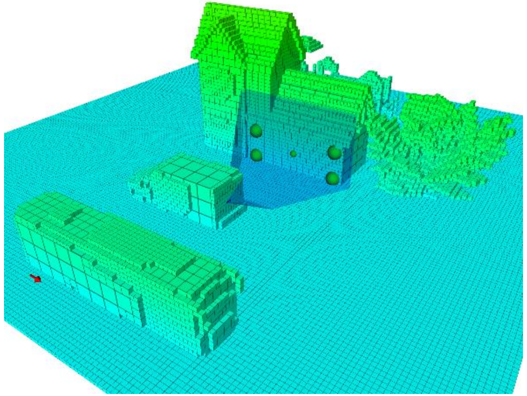
Initial trajectory　　Optimized trajectory

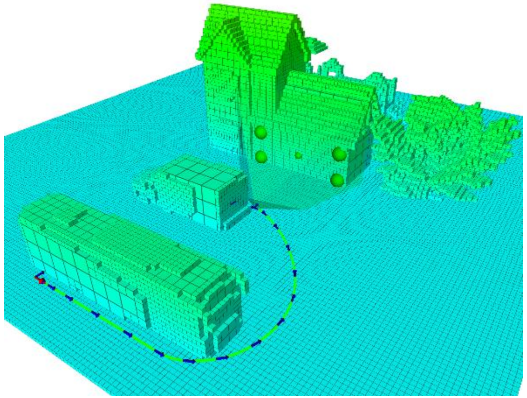


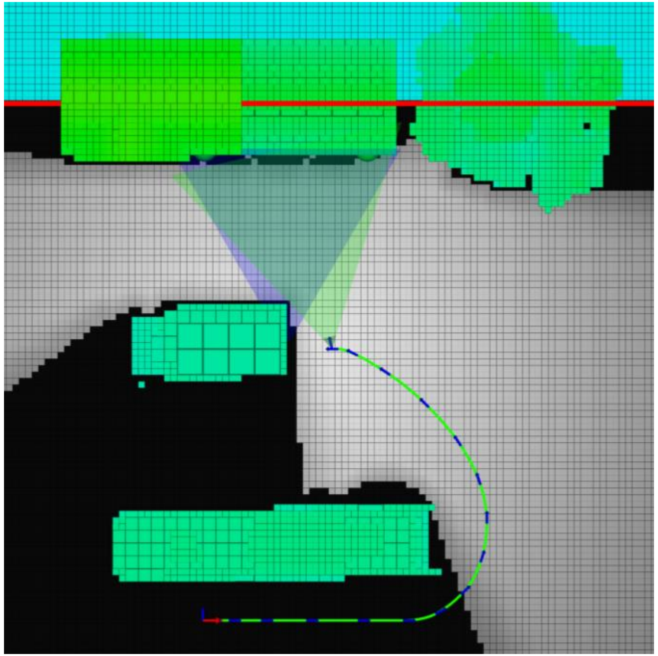
Obstacle map

Observation Pose Planning

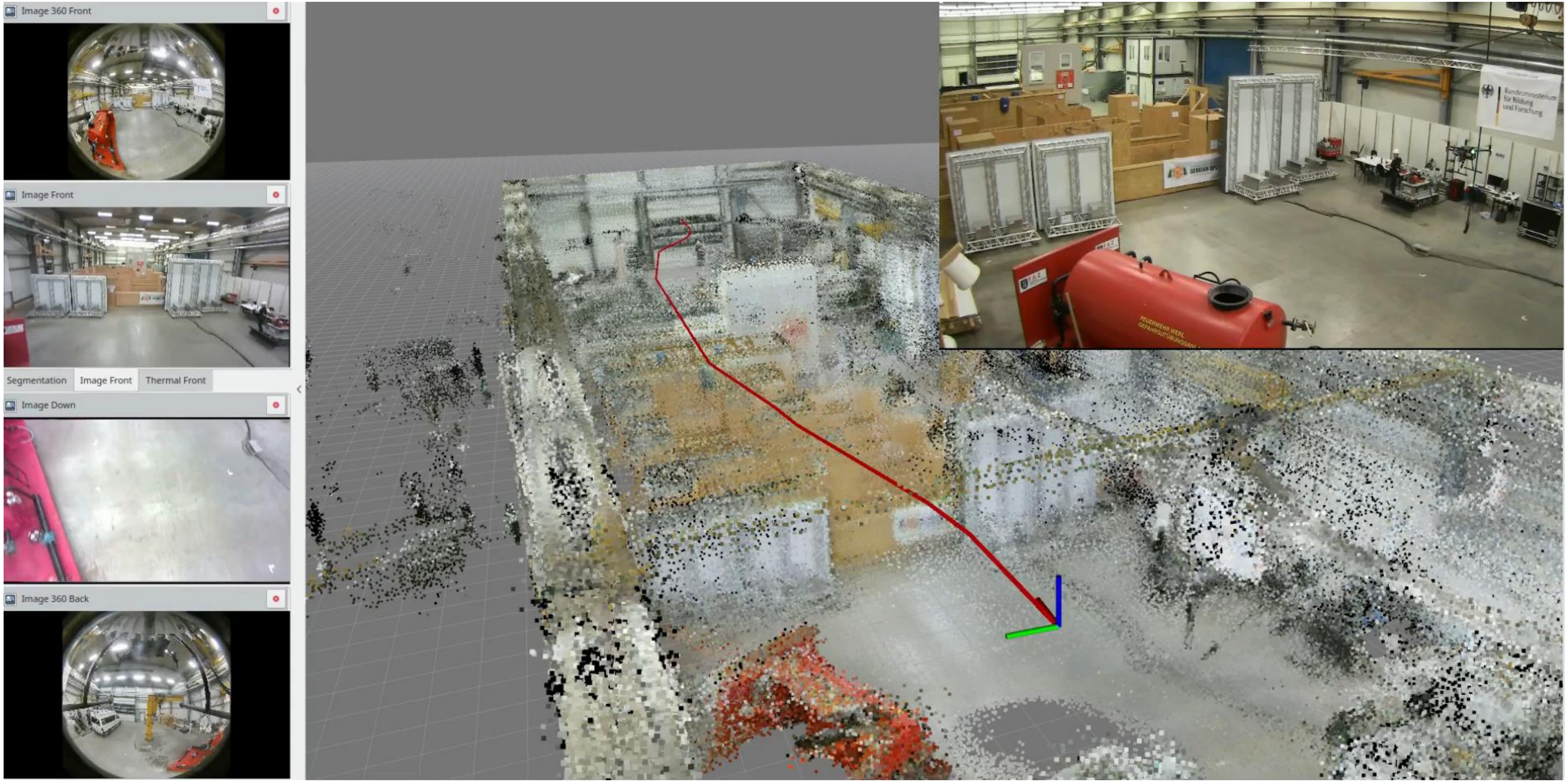
- Planning of observation poses with line of sight to the target object despite occlusions
- Target objects are defined by position, line of sight and distance
- Optimization of observation poses with regard to visibility quality and accessibility


Initial observation pose


Optimized path


Top-down view

Autonomous Flight without GNSS



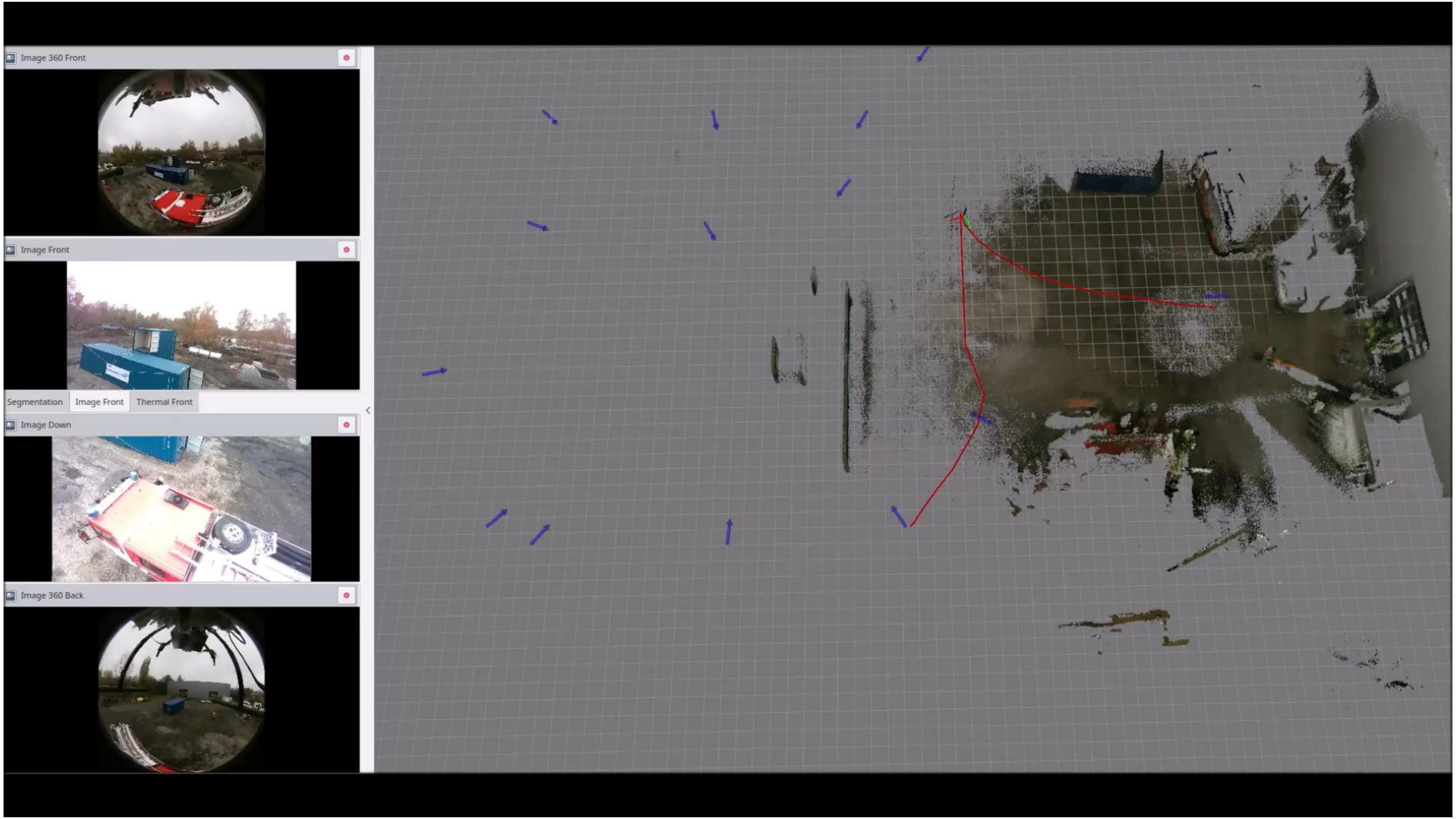
DRZ Dortmund

Exploration

- Definition of target area w.r.t. satellite images or maps
- Simple exploration patterns (spirals, meanders, …)
- Collision check
- TSP to determine segment sequence
- Continuous replanning

Campus Poppelsdorf

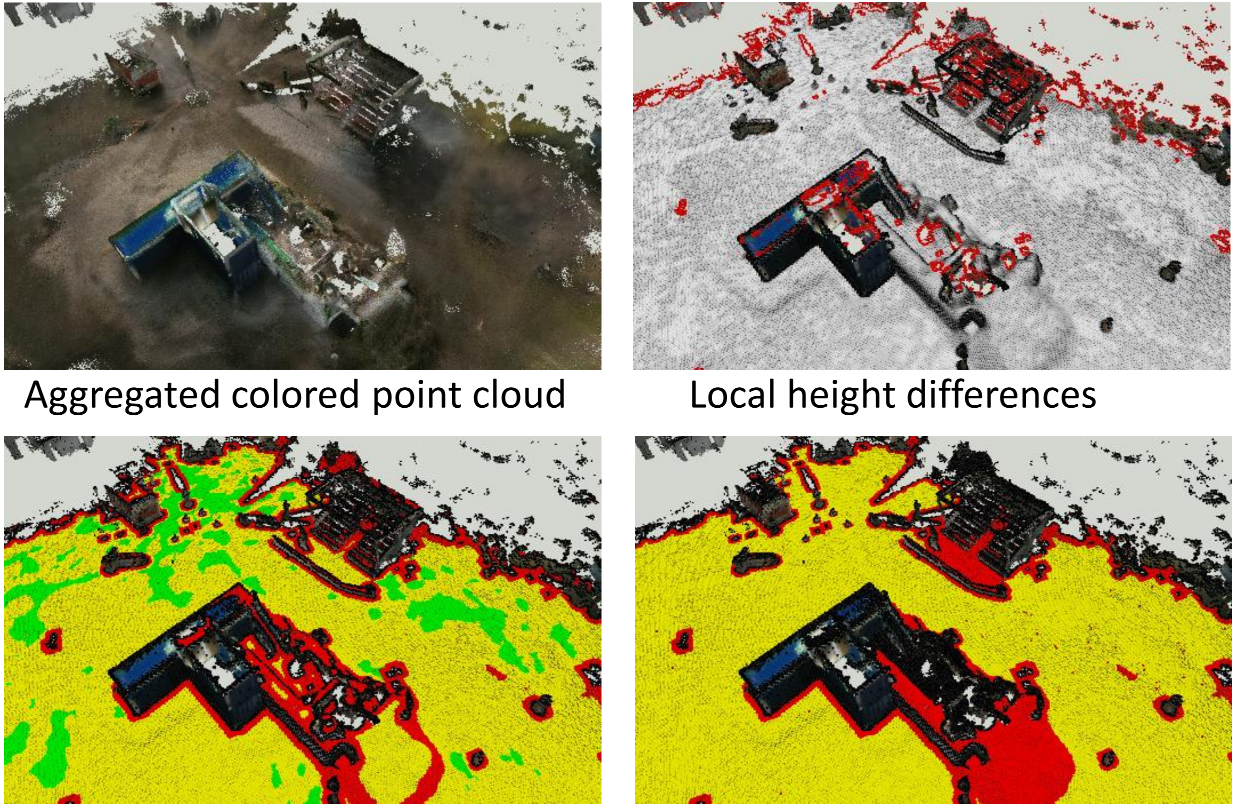
Autonomous Exploration



DRZ Dortmund

Terrain Classification for Traversability

- Based on voxel-filtered aggregated point cloud
- Terrain classification based on local height differences in the robot ground robot footprints
- Categories: drivable, walkable, unpassable
- Reachability analysis



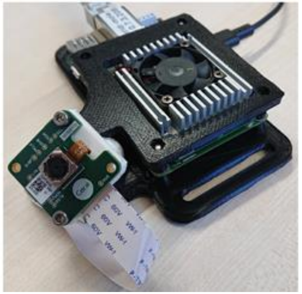
Aggregated colored point cloud | Local height differences

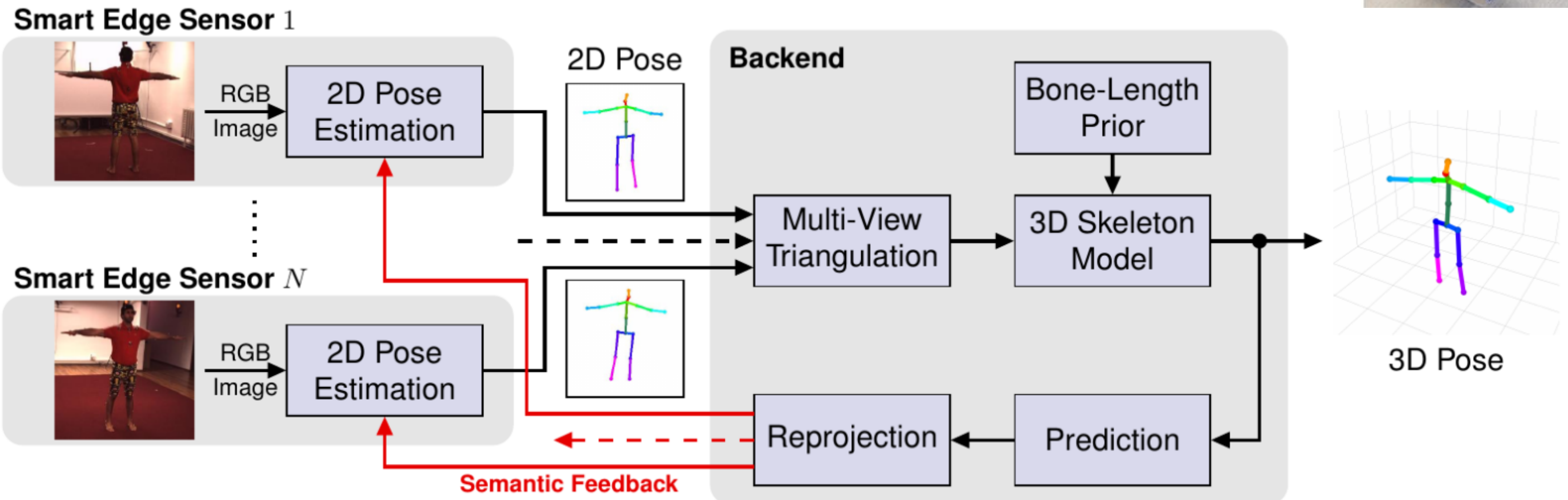
Terrain category | Reachability

[Schleich et al., ICUAS 2021]

Real-Time Multi-View 3D Human Pose Estimation using Semantic Feedback to Smart Edge Sensors

- Triangulation and skeleton model to recover 3D pose
- Semantic feedback channel for bidirectional communication between backend and sensors

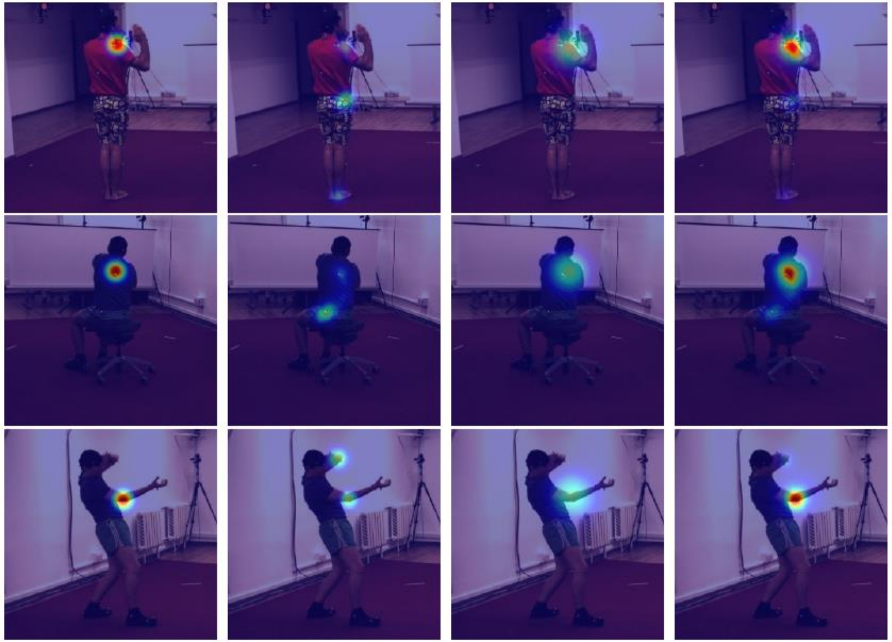




[Bultmann and Behnke, RSS 2021]

Real-Time Multi-View 3D Human Pose Estimation using Semantic Feedback to Smart Edge Sensors

- Feedback heatmap is rendered from feedback skeleton and fused with detection on sensors
- Feedback heatmap helps to recover from incorrect or imprecise 2D joint detections
- Examples:
  - Occluded left wrist (rows 1 and 2)
  - Confusion of left and right elbow (row 3)

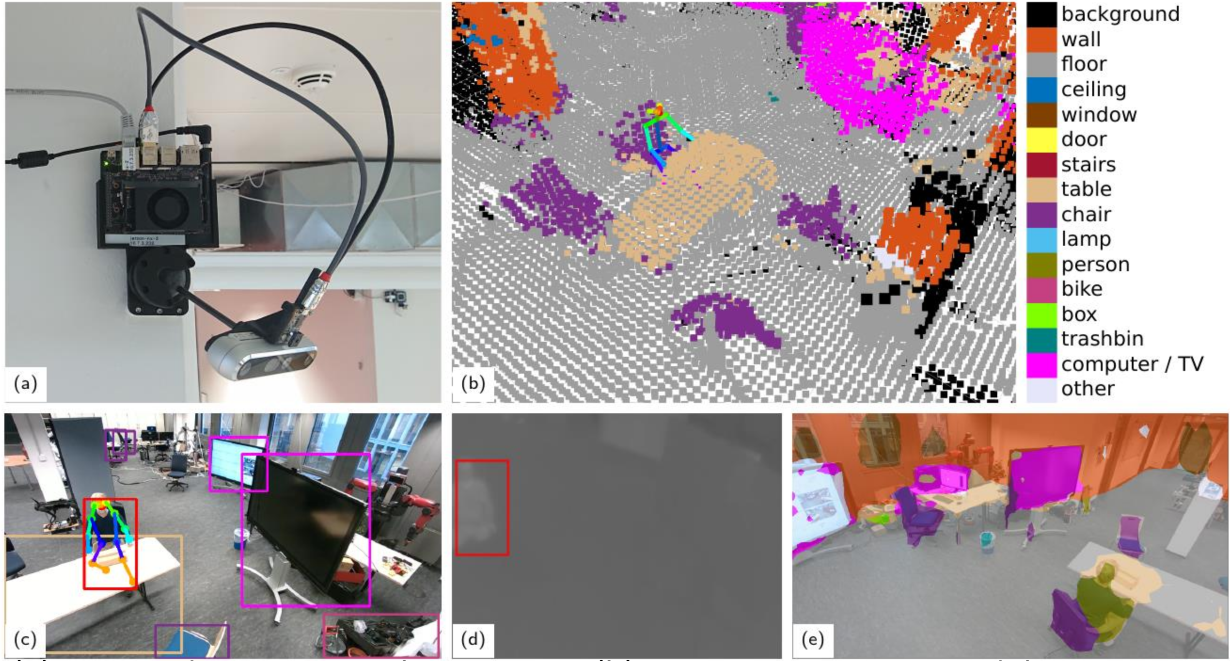


(a) ground-truth (b) detected (c) feedback (d) fused

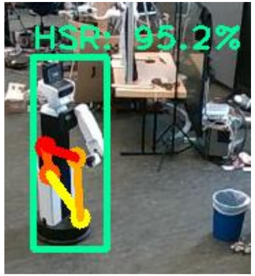
[Bultmann and Behnke, RSS 2021]

Semantic Perception with Smart Edge Sensor Network

- Object detection and semantic segmentation of RGB images
- Person detection in IR images
- Semantic labelling of RGB-D point clouds
- Pose estimation for mobile robot and objects



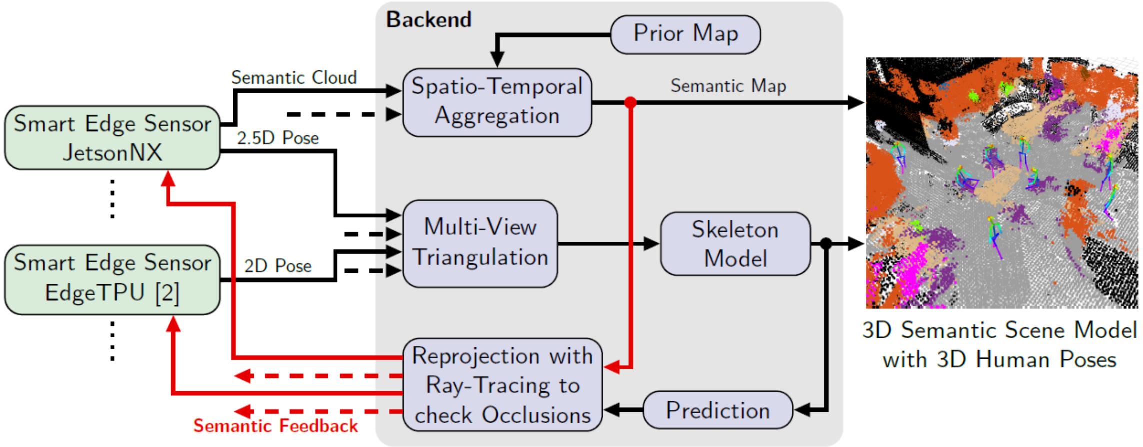
(a) Smart Edge Sensor with Jetson NX (b) 3D semantic scene model, (c) RGB and (d) thermal detections, (e) semantic segmentation

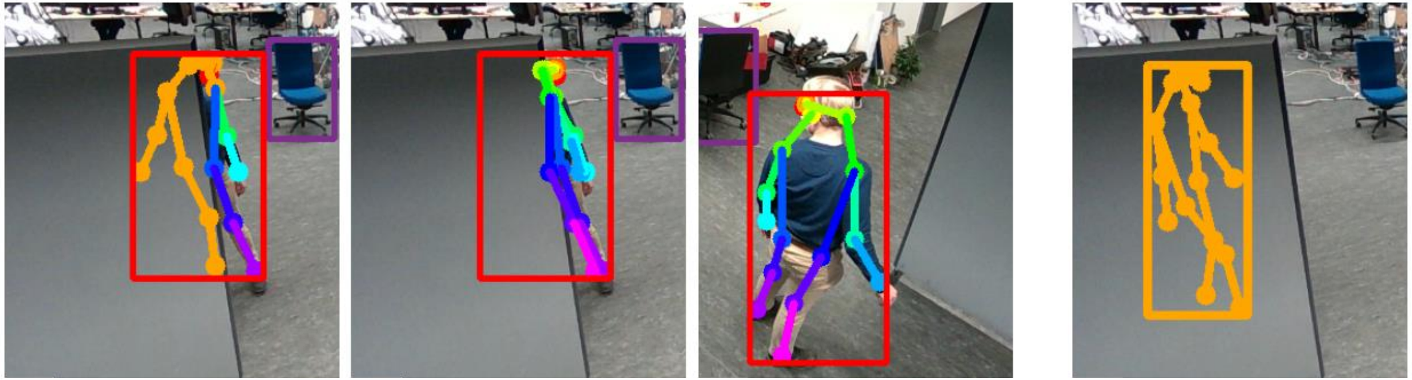


[Bultmann and Behnke: IAS 2022, Hau et al. IRC 2022, Bultmann et al. ICRA 2023]

3D Human Pose Estimation with Occlusion Feedback

- Heavy occlusion causes the pose estimation to collapse to the visible side only
- With occlusion feedback occluded joint detections can be discarded and the local model is completed



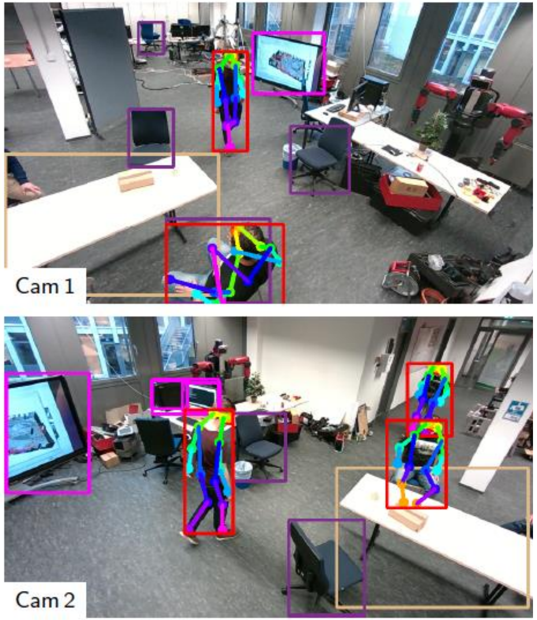


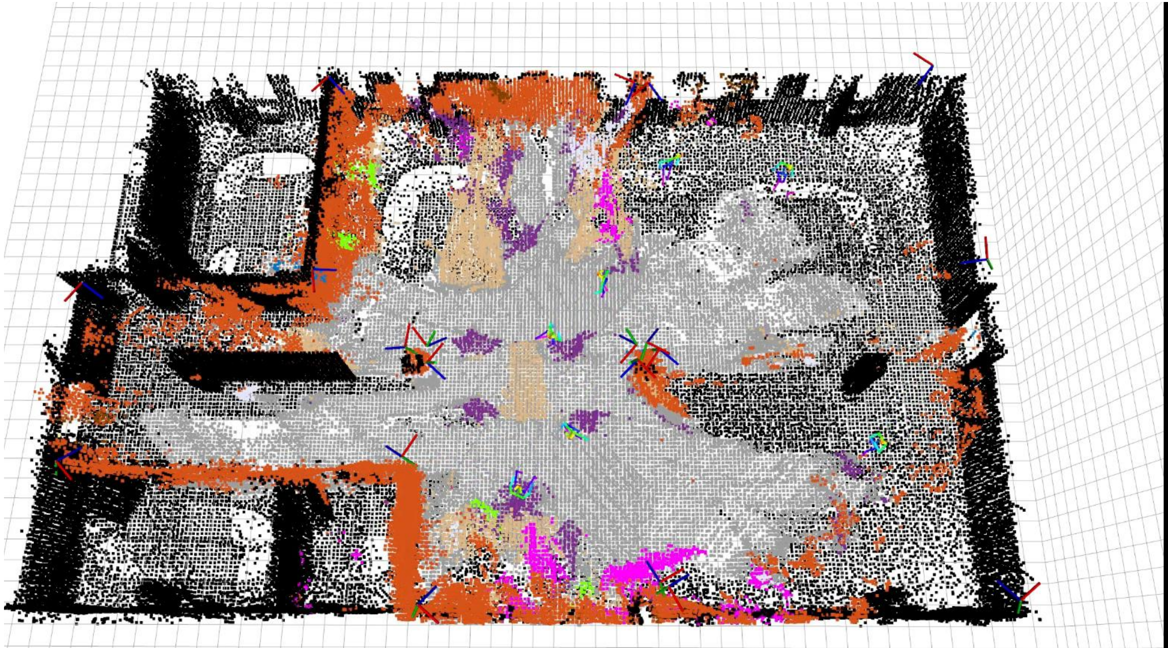
With occlusion feedback | W/o occlusion feedback | Unoccluded reference | Fully occluded

[Bultmann and Behnke: IAS 2022]

Evaluation in Real-World Multi-Person Scenes

- 20 smart edge sensors (4 Jetson NX, 16 Edge TPU), covering 12×22 m area
- Experiments with 8 persons moving through the scene





The sensor network provides a complete 3D semantic scene view and estimates dynamic 3D poses of multiple persons in real time.

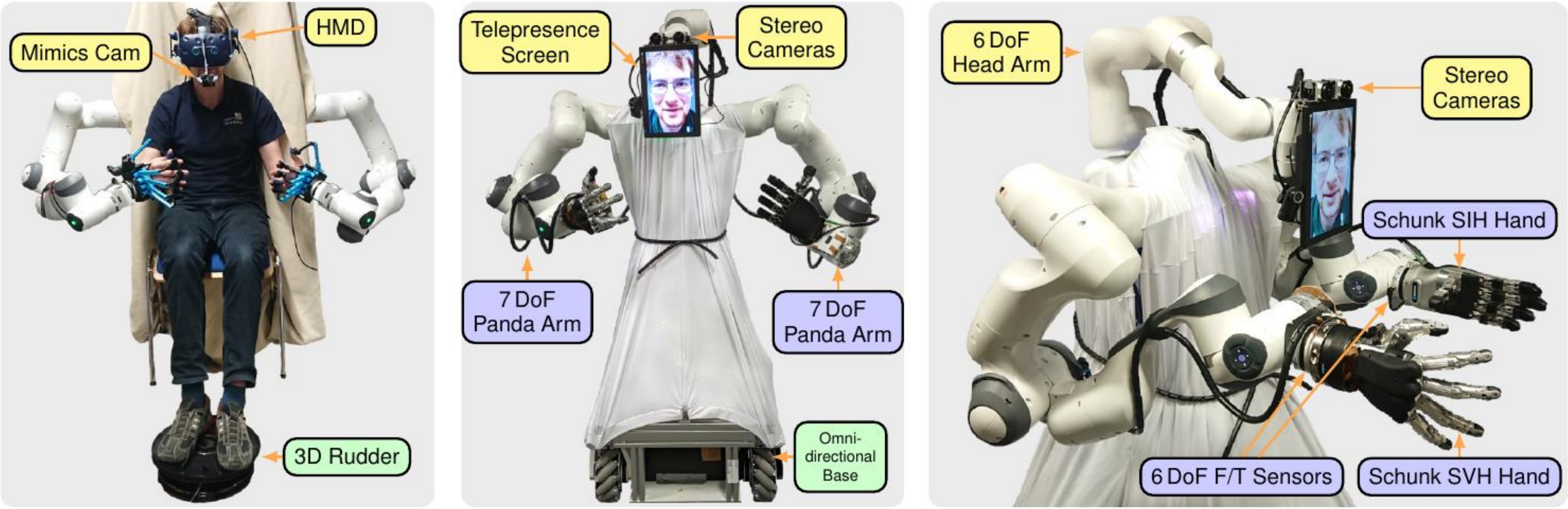
[Bultmann and Behnke: IAS 2022]

$10M ANA Avatar XPRIZE Competition

- Requires mobility, manipulation, human-human interaction
- Focuses on the immersion in the remote environment and the presence of the remote operator

NimbRo Avatar Semifinals System

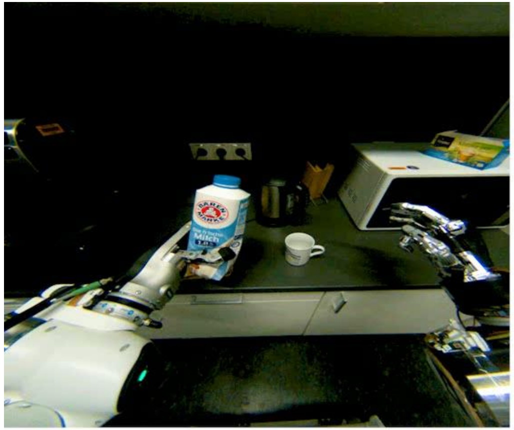
- Two-armed avatar robot designed for teleoperation with immersive visualization & force feedback
- Operator station with HMD, exoskeleton and locomotion interface



[Schwarz et al. IROS 2021]

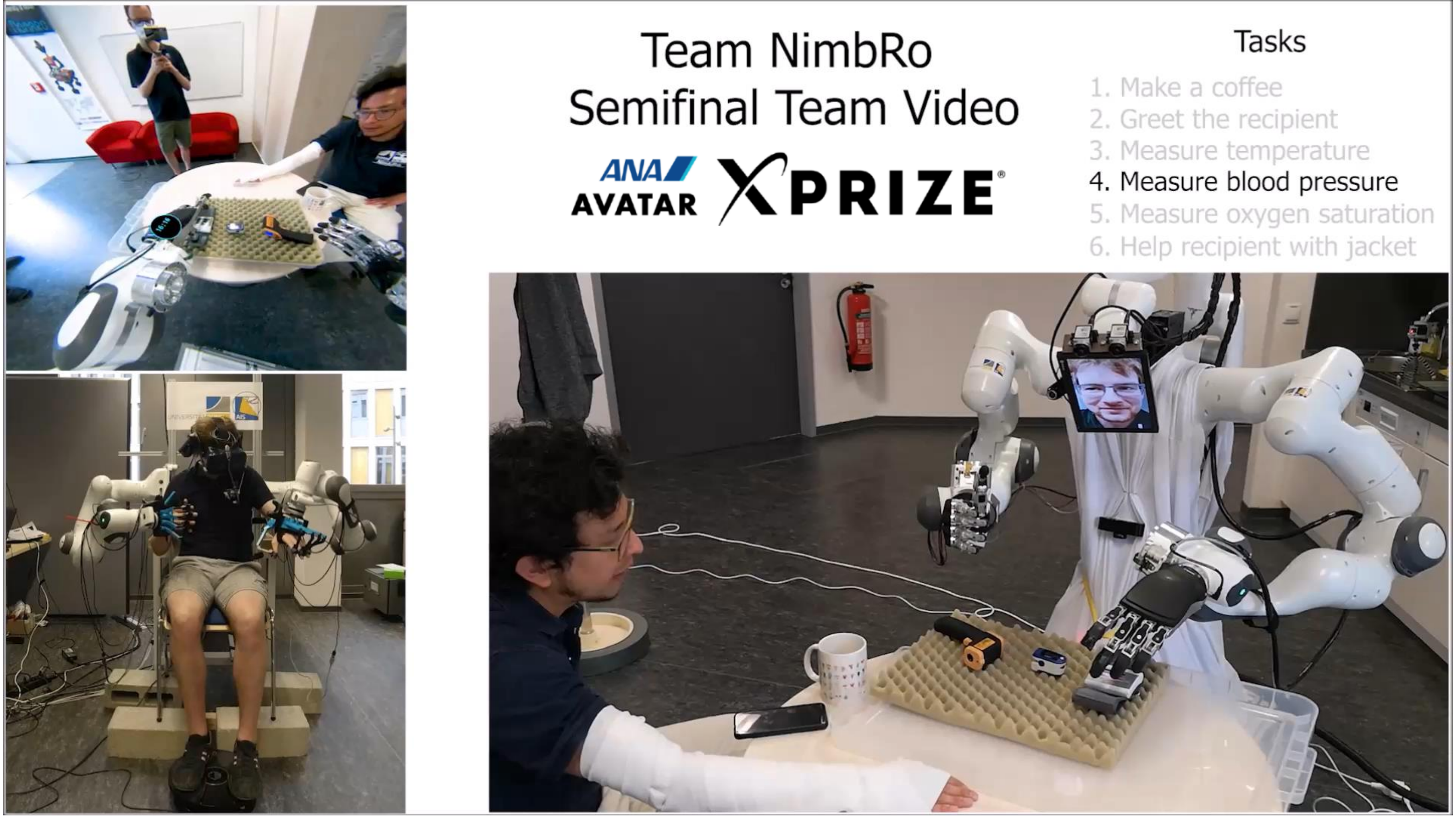
Team NimbRo Semifinal Submission

ANA AVATAR XPRIZE



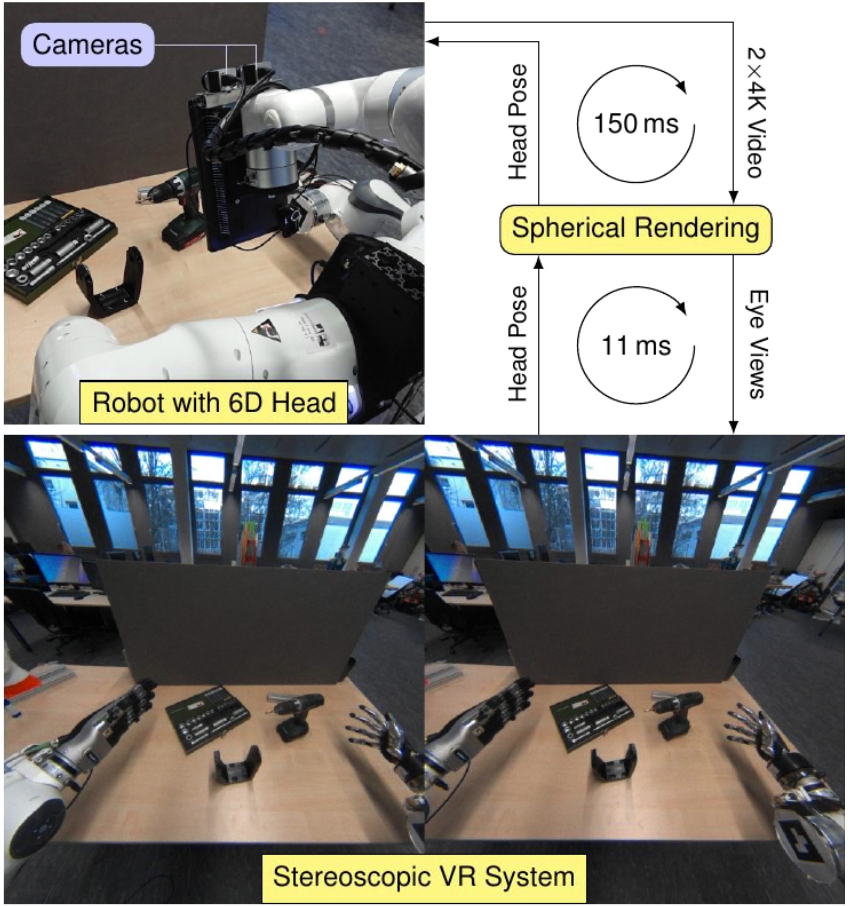
[Schwarz et al. IROS 2021]

UNIVERSITÄT BONN AIS

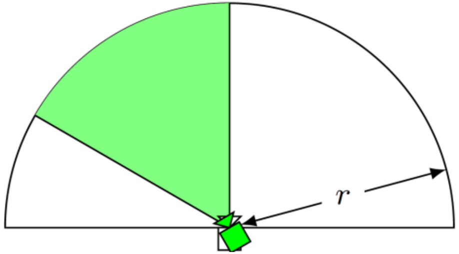


[Schwarz et al. IROS 2021]

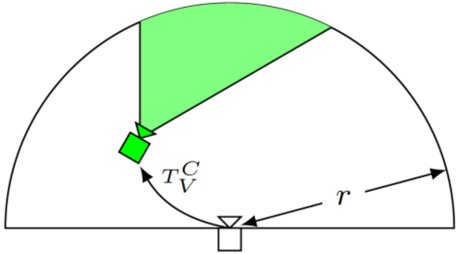
NimbRo Avatar: Immersive Visualization



- 4K wide-angle stereo video stream
- 6D neck allows full head movement
  - Very immersive
- Spherical rendering technique hides movement latencies
  - Assumes constant depth



Exact for pure rotations

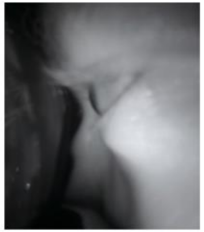


Distortions for translations

[Schwarz and Behnke Humanoids 2021]

NimbRo Avatar: Operator Face Animation

- Operator images without HMD
- Capture mouth and eyes
- Estimate gaze direction and facial keypoints

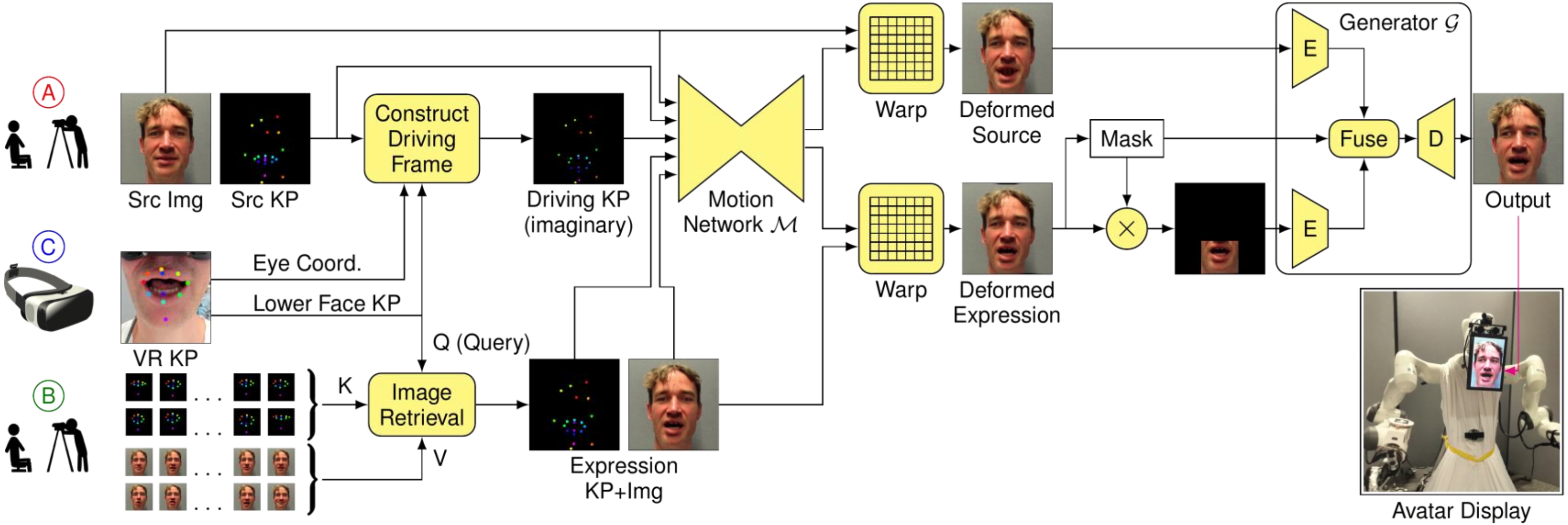


Left Eye

Mouth

Right Eye

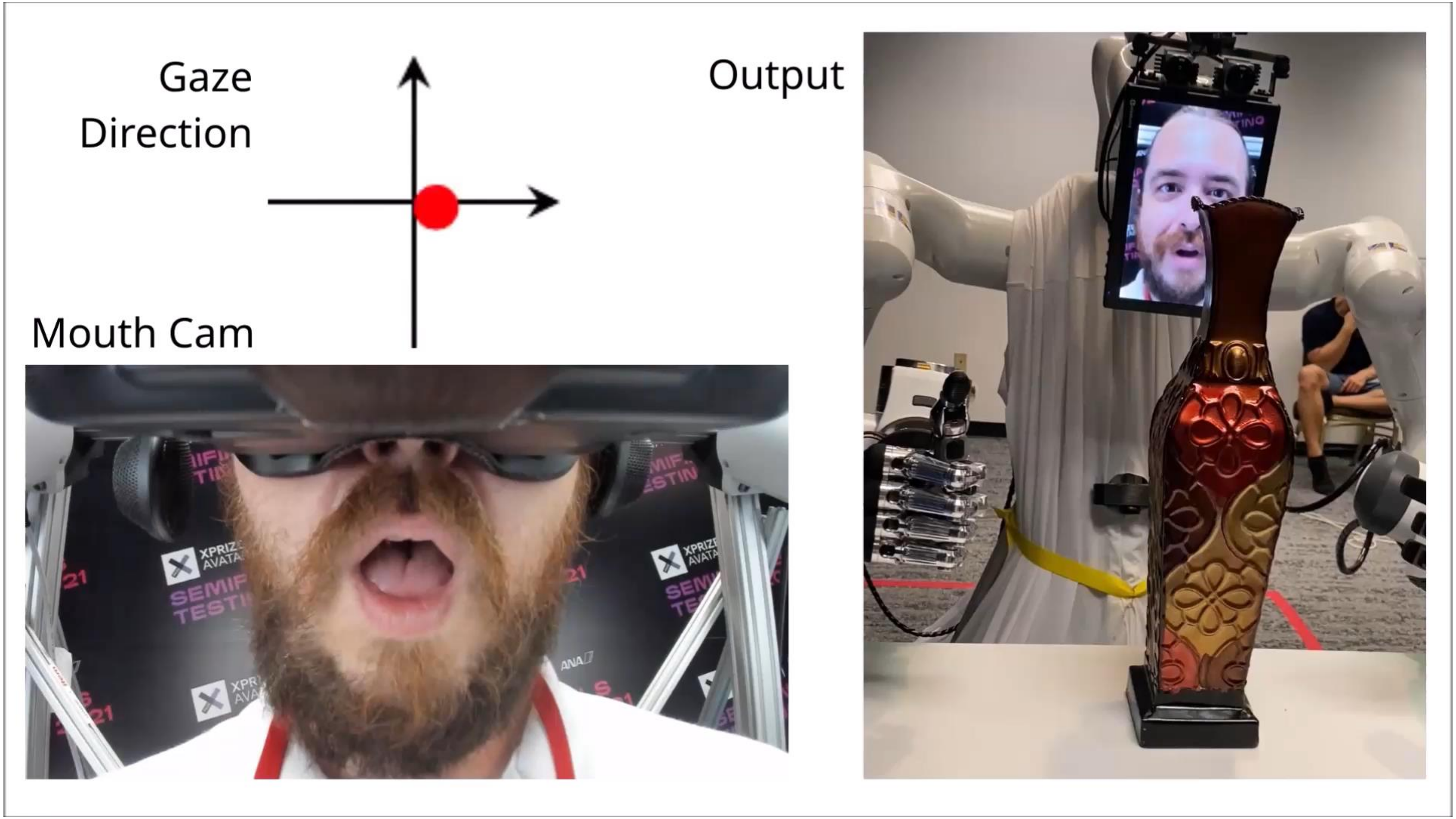
- Generate animated operator face using a warping neural network



[Rochow et al. IROS 2022]

UNIVERSITÄT BONN AIS

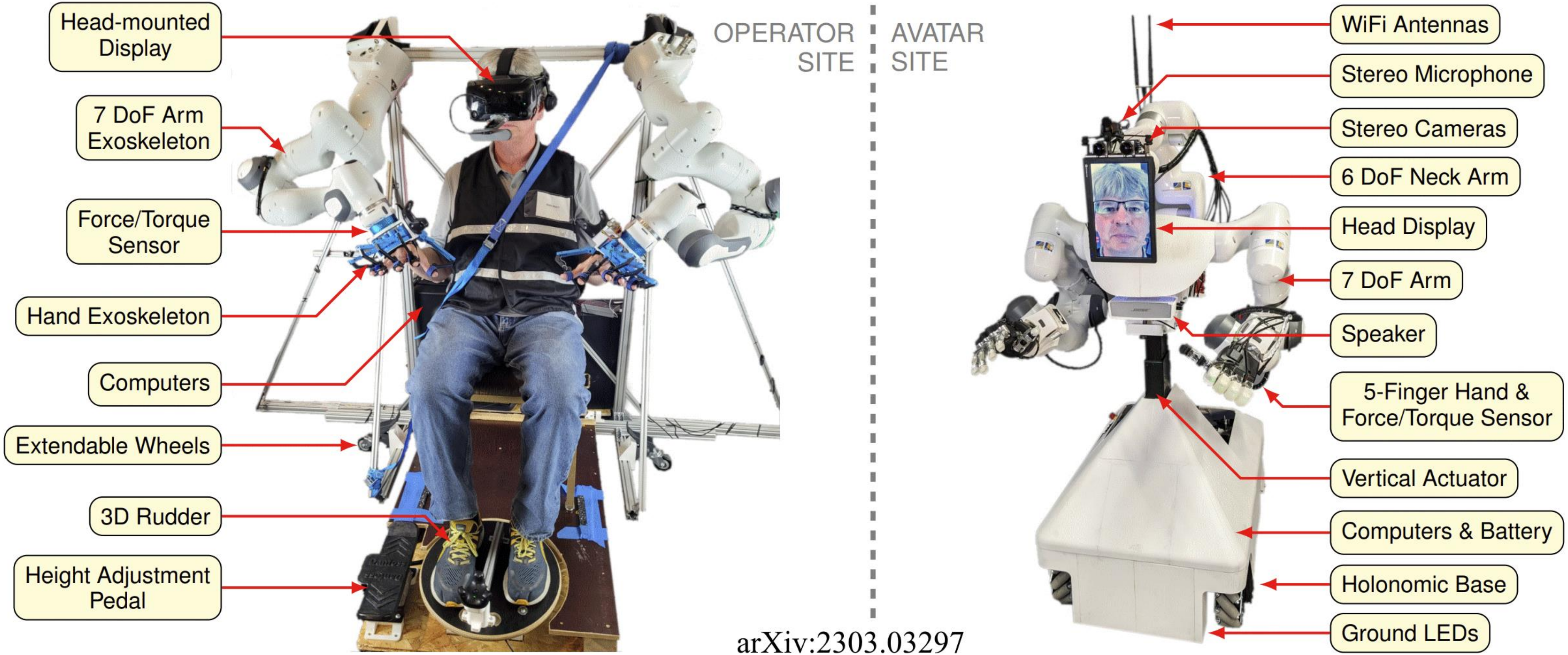
NimbRo Avatar: Operator Face Animation



[Rochow et al. IROS 2022]

NimbRo Avatar System for ANA Avatar XPRIZE Finals

- New requirements: tetherless, remote perception of haptics, reliability



arXiv:2303.03297

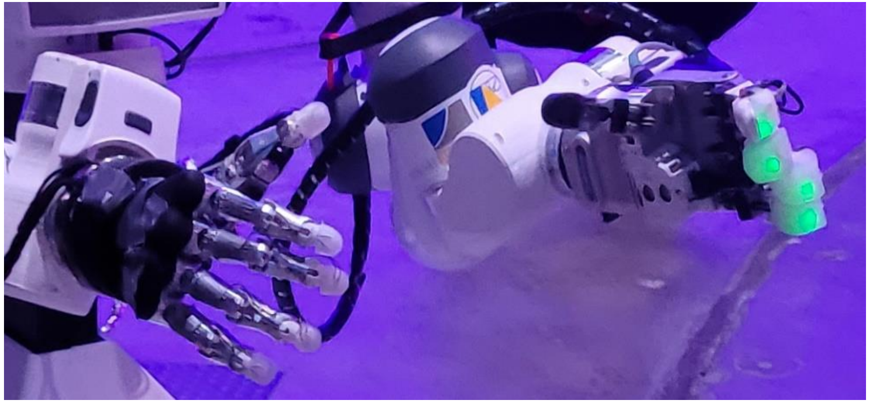
[Schwarz, Lenz et al.]

Finals Test Run Day 1

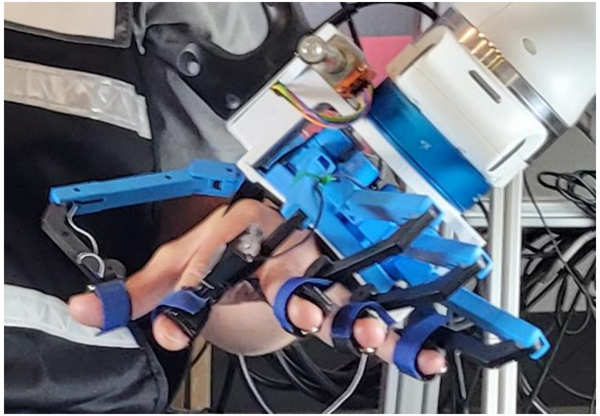
[Schwarz, Lenz et al. arXiv:2303.03297]

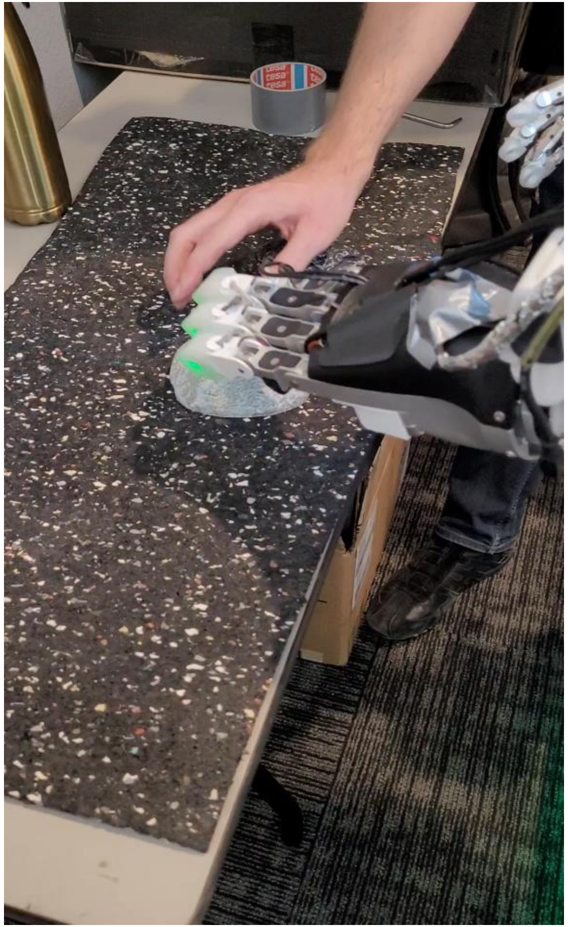
Haptic Perception

- Sensors in the finger tips



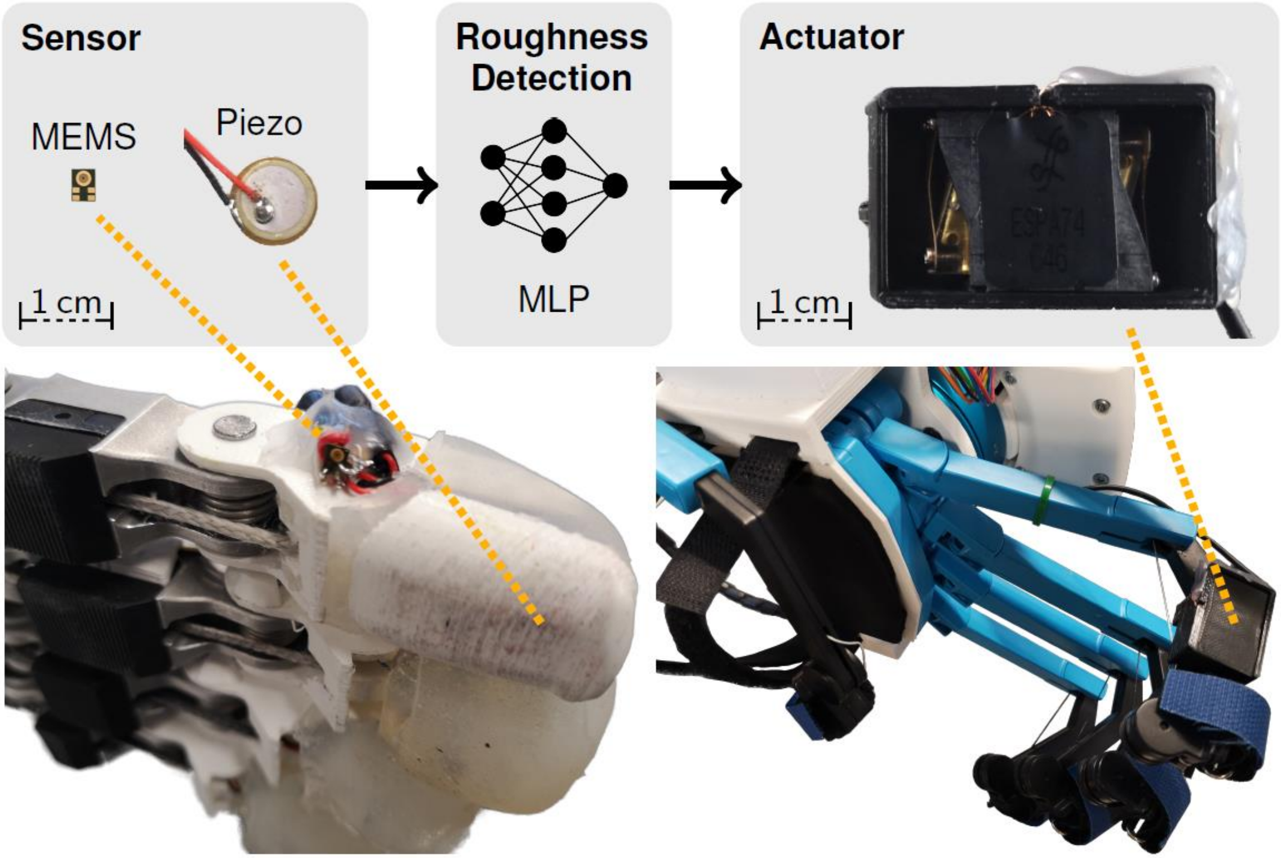
- Actuators on the hand exoskeleton





[Pätzold et al. arXiv:2303.07186]

Roughness Perception



Data set of
rough and smooth objects

[Pätzold et al. arXiv:2303.07186]

Finals Day 2 Testing

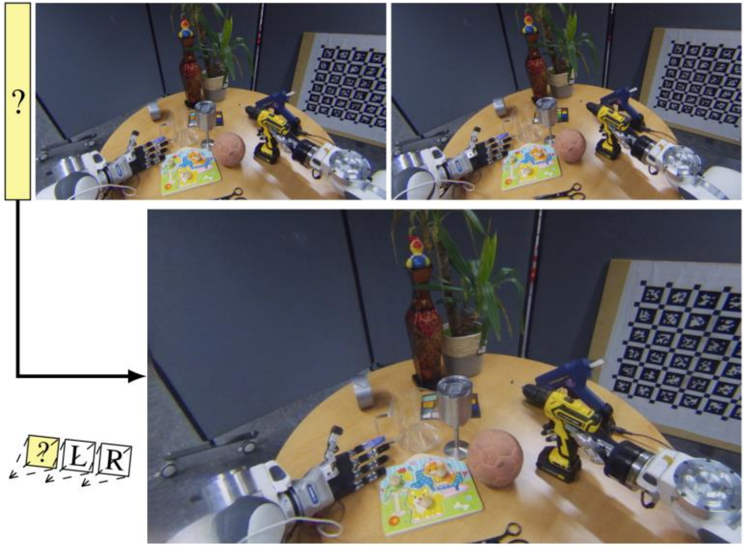
[Schwarz, Lenz et al. arXiv:2303.03297]

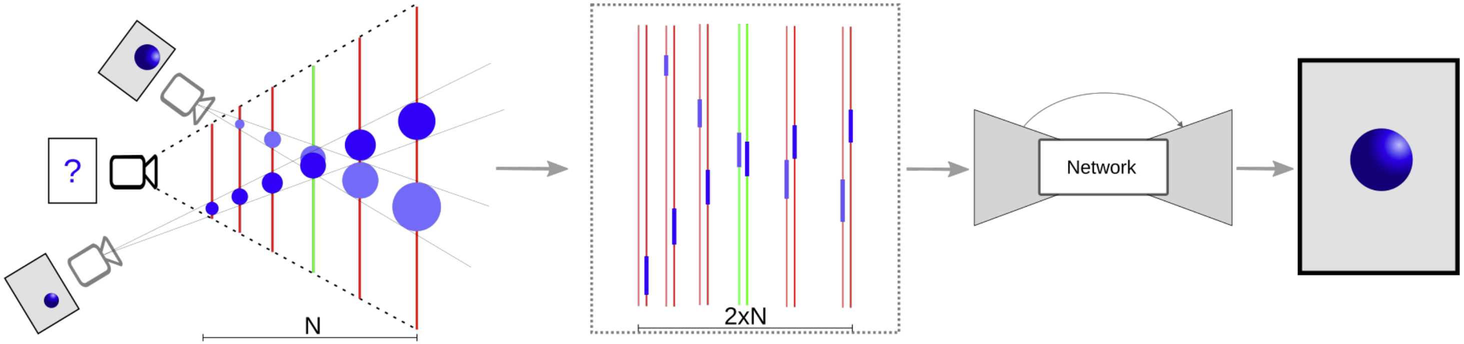
Team NimbRo

[Schwarz, Lenz et al. arXiv:2303.03297]

FaDIV-Syn: Fast Depth-Independent View Synthesis

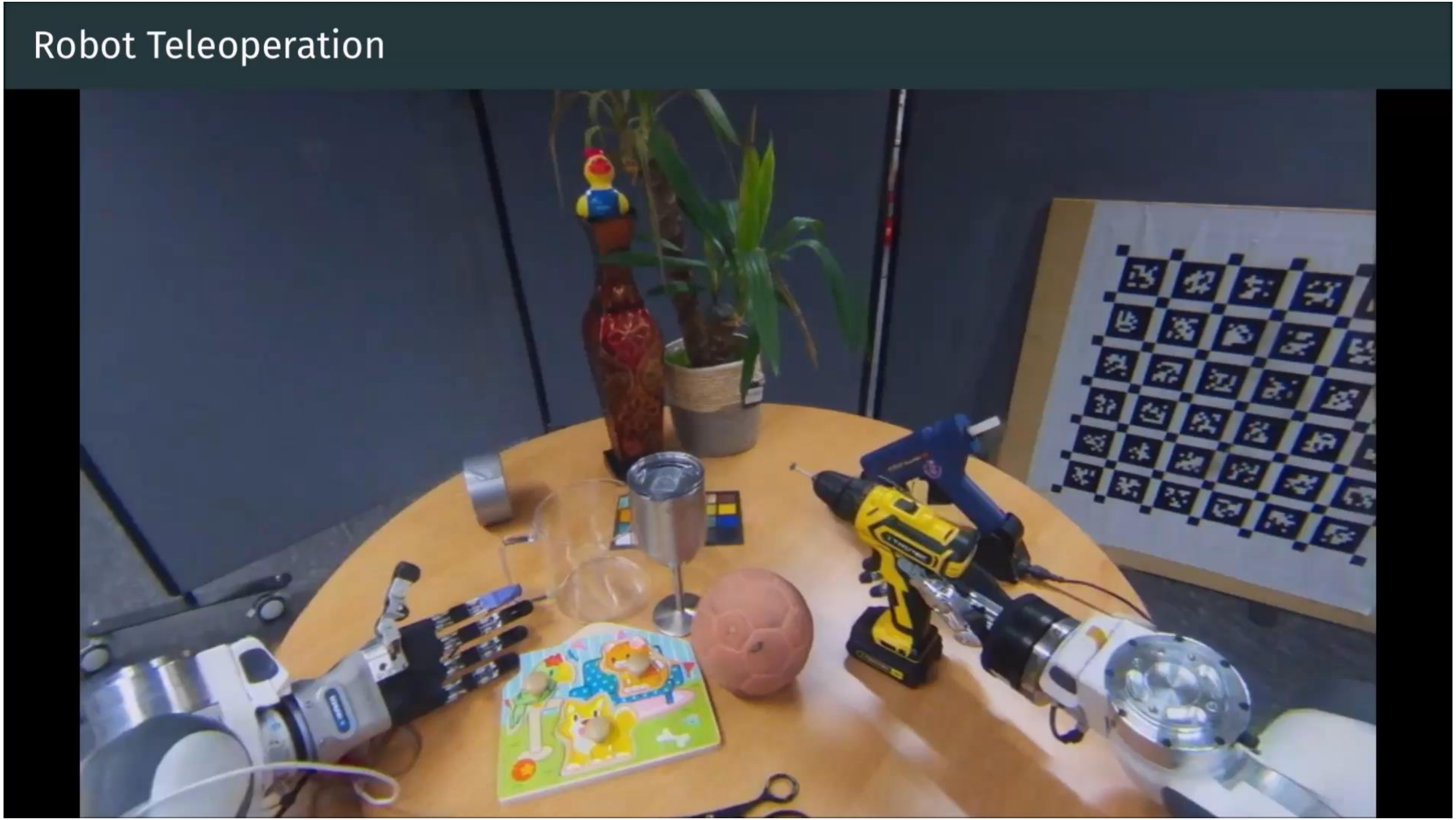
- Two input views
- Generate novel view from different pose
- Does not require depth
- Handles occlusions, transparency, reflectance, moving objects, …





[Rochow et al. RSS 2022]

FaDIV-Syn: Fast Depth-Independent View Synthesis



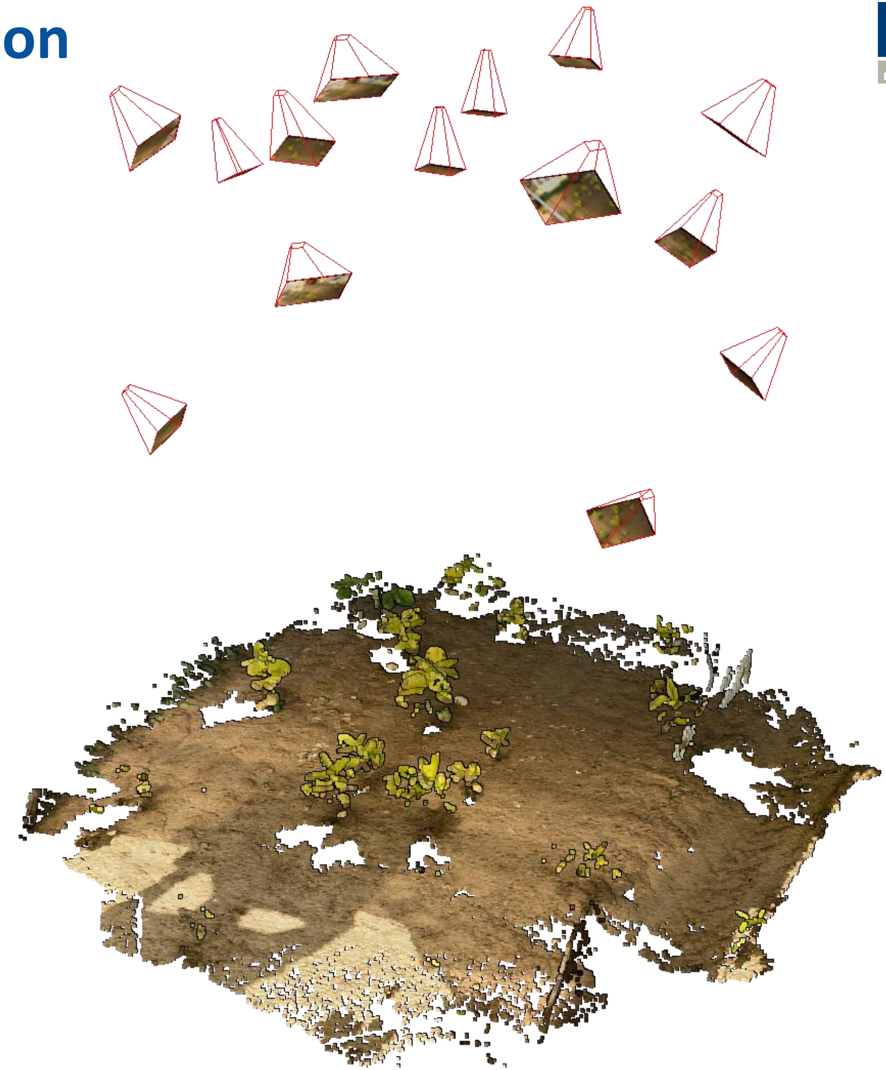
[Rochow et al. RSS 2022]

Multi-view Plant Reconstruction

- 14× Nikon Z7 DSLR camera
  - 45 MP
  - 64–25600 ISO
  - 24-70 mm Lens

Multi-view Plant Reconstruction

- Recovered camera poses and semi-dense point cloud through Multi-View-Stereo



[Rosu 2022]

Implicit Surfaces on Permutohedral Lattices

- Geometry represented as Signed Distance Field (SDF)
- Color represented as a direction-dependent color field
- Transform SDF into radiance [1] and train similar to NeRF

Geometry

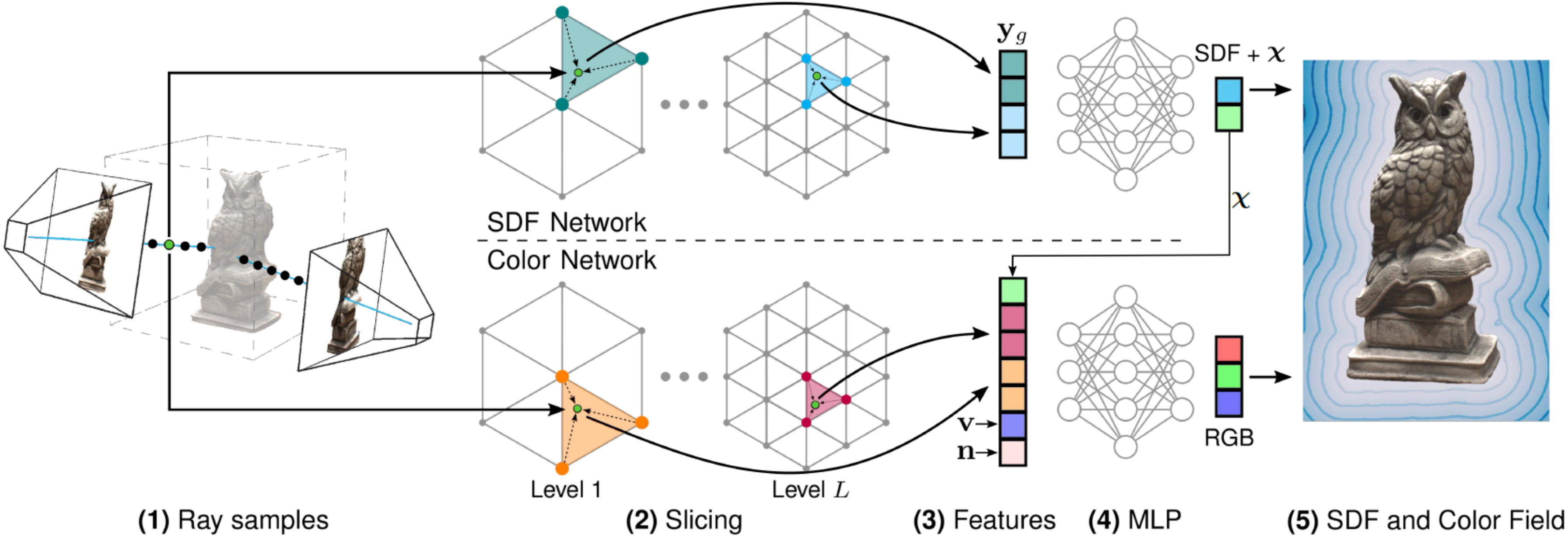
Color at the zero level-set of the SDF

[Rosu and Behnke, CVPR 2023]

[1] Wang et al. NeuS: Learning Neural Implicit Surfaces by Volume Rendering for Multi-View Reconstruction, NeurIPS 2021.

Implicit Surfaces on Permutohedral Lattices

- Geometry represented as Signed Distance Field (SDF)
- Color represented as a direction-dependent color field
- Transform SDF into radiance [1] and train similar to NeRF



[Rosu and Behnke, CVPR 2023]

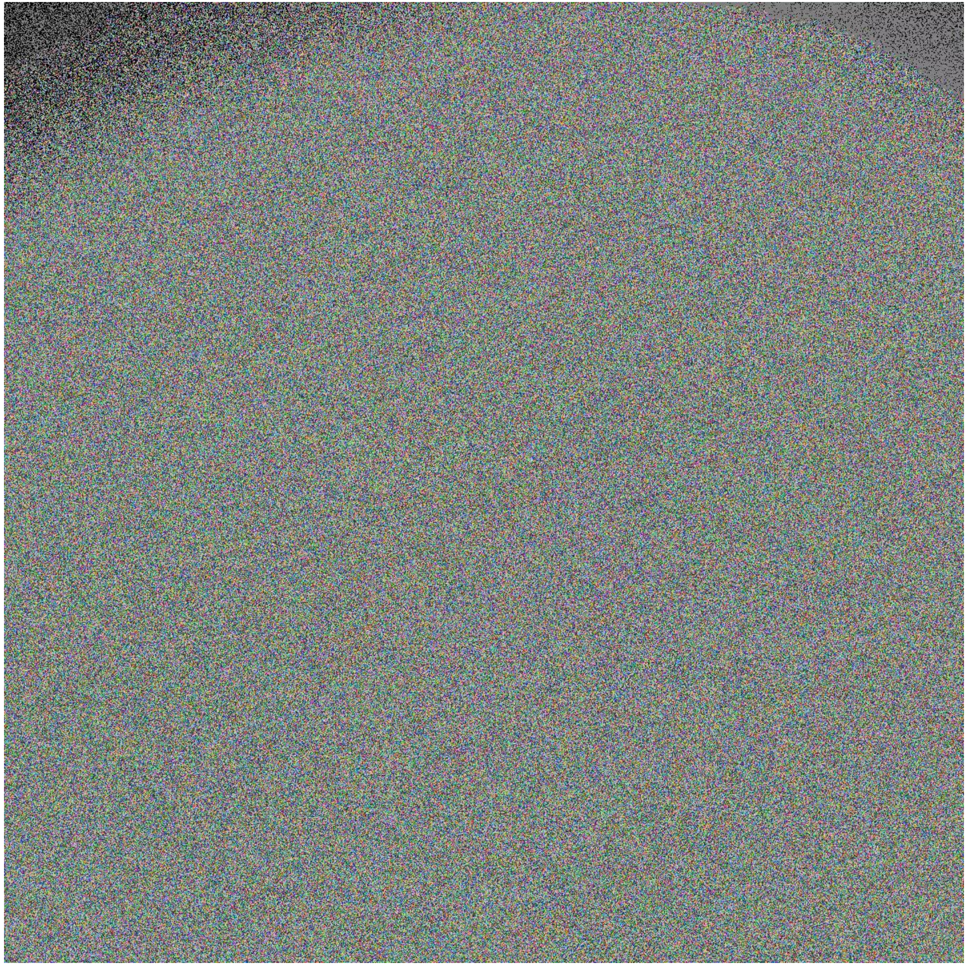
[1] Wang et al. NeuS: Learning Neural Implicit Surfaces by Volume Rendering for Multi-View Reconstruction, NeurIPS 2021.

Multi-view Plant Reconstruction

- InstantNGP with a Multiresolution Hash Encoding [2]
- Permutohedral lattice
- Small MLPs for SDF and color
- 25 M parameters
- 1 h training on Nvidia RTX 3090 GPU

[2] Müller et al. Instant Neural Graphics Primitives with a Multiresolution Hash Encoding ACM Transactions on Graphics (SIGGRAPH 2022)

Surface normals

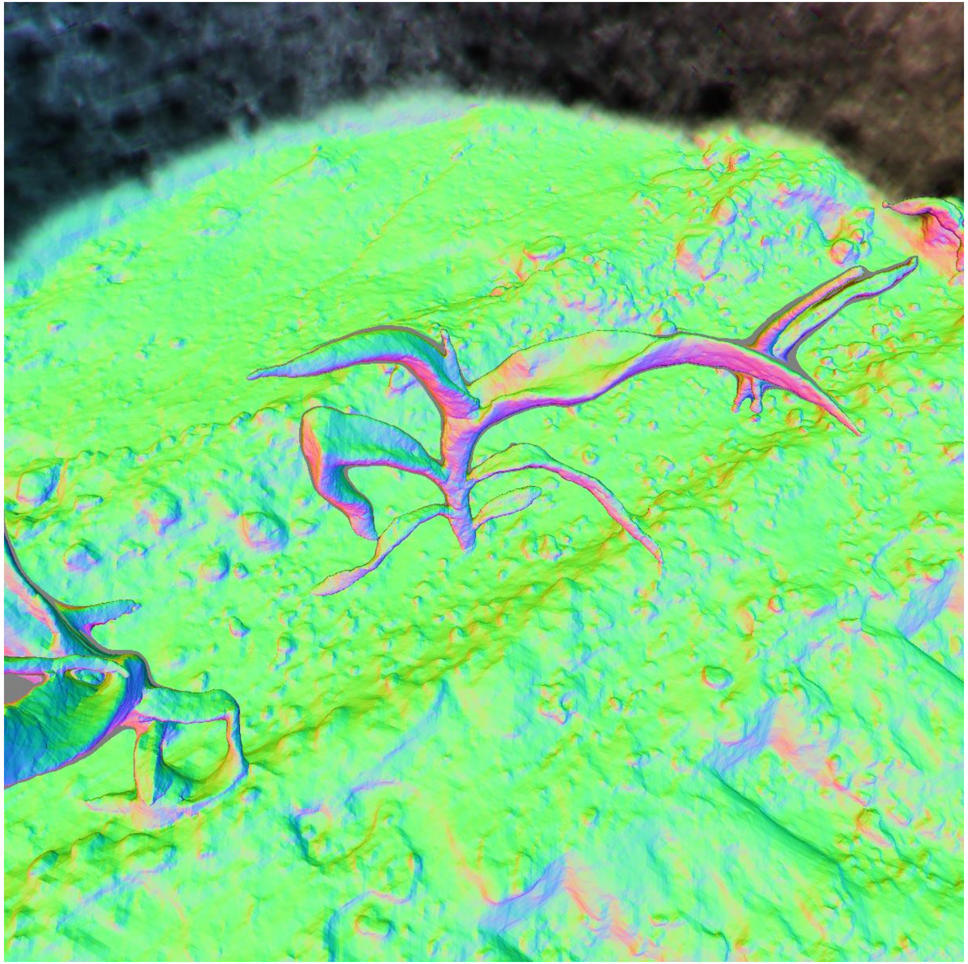


 [Rosu and Behnke, CVPR 2023]

Multi-view Plant Reconstruction

- InstantNGP with a Multiresolution Hash Encoding [2]
- Small MLPs for SDF and color
- 25 M parameters
- 1 h training on Nvidia RTX 3090 GPU

[2] Müller et al. Instant Neural Graphics Primitives with a Multiresolution Hash Encoding ACM Transactions on Graphics (SIGGRAPH 2022)



Surface normals

[Rosu and Behnke, CVPR 2023]

Multi-view Plant Reconstruction

- Rendered novel views

 [Rosu and Behnke, CVPR 2023]

Plant Reconstruction over Multiple Days

Volumetric renders through
SDF + color

[Rosu and Behnke, CVPR 2023]

Plant Reconstruction over Multiple Days

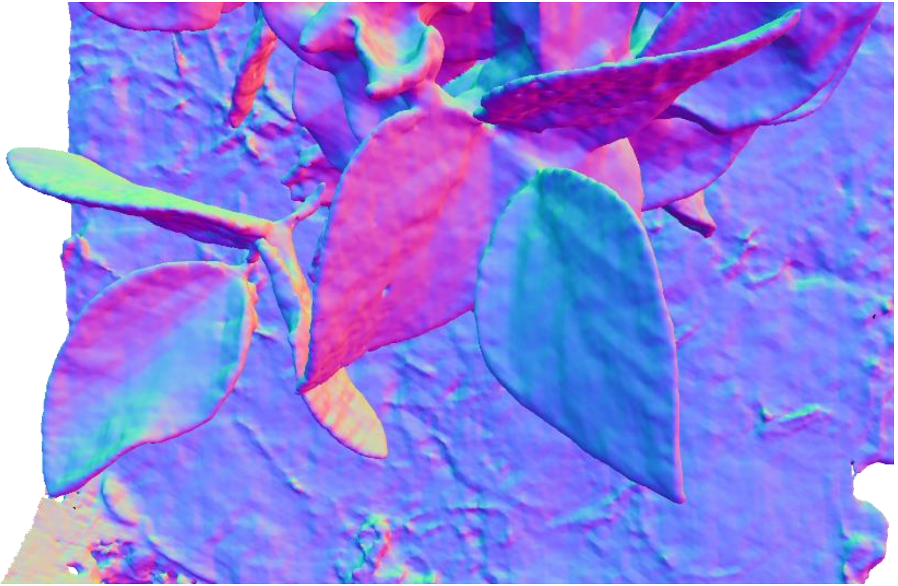
Predicted depth

[Rosu and Behnke, CVPR 2023]

High Geometric and Texture Detail

- Marching cubes on the SDF to recover mesh
- Learnable texture to match color images
- Rendering in real time

Textured mesh



Mesh normal vector

[Rosu and Behnke, CVPR 2023]

Conclusions

- Developed capable robotic systems for challenging scenarios
  - Bin picking
  - Humanoid soccer
  - Disaster response (UGV, UAV)
  - Plant reconstruction
- Challenges include
  - 4D semantic perception
  - High-dimensional motion planning
- Promising approaches
  - Prior knowledge (pretrained models, inductive bias)
  - Shared experience (fleet learning)
  - Shared autonomy (human-robot)
  - Instrumented environments