Manipulating a Large Variety of Objects and Tool Use in Domestic Service, Industrial Automation, Search and Rescue, and Space Exploration

Sven Behnke

Computer Science Institute VI
Autonomous Intelligent Systems

Robot Competitions

- Provide common test bed for benchmarking
- Promote exchange of ideas
- Foster robotics research

RoboCup @Home

DARPA Robotics Challenge

DLR SpaceBot Cup

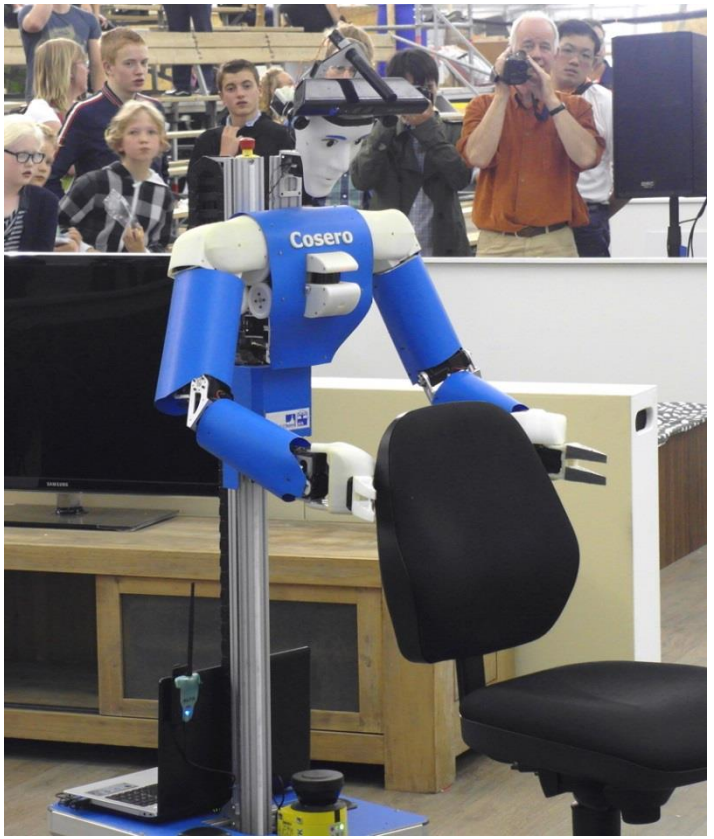
Amazon Picking Challenge

RoboCup@Home

- Since 2006
- Focus on applications in domestic environments and on human-robot interaction
- **Goal:** Develop robots that support humans in everyday tasks
- **Competition:**
  - Predefined tests
    - Follow a person
    - Find and put away objects
    - Fetch drinks
    - Understand complex speech commands
  - Open demonstrations
- Bar is raised every year

Our Domestic Service Robots

Dynamaid



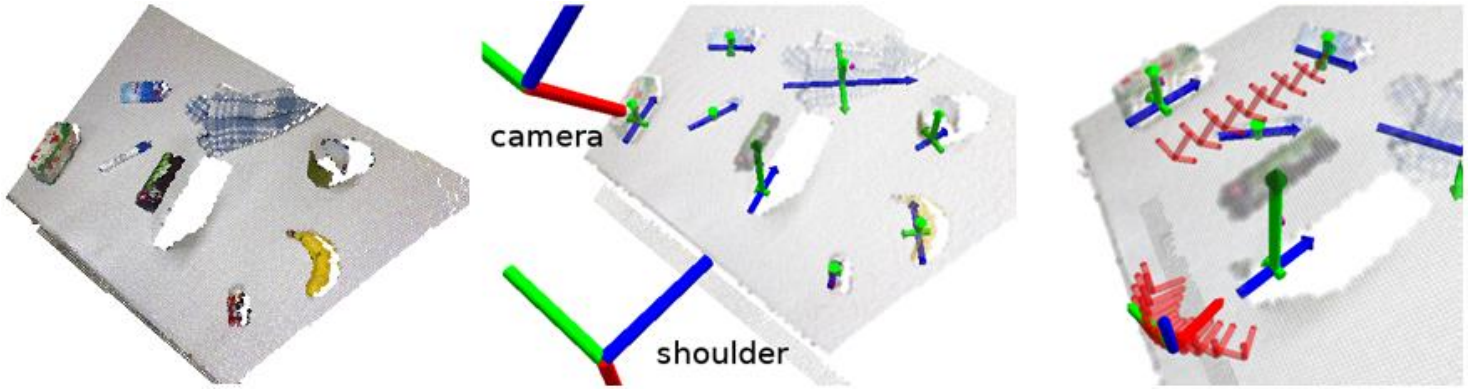
Cosero

- Size: 100-180 cm, weight: 30-35 kg
- 36 articulated joints
- PC, laser scanners, Kinect, microphone, ...

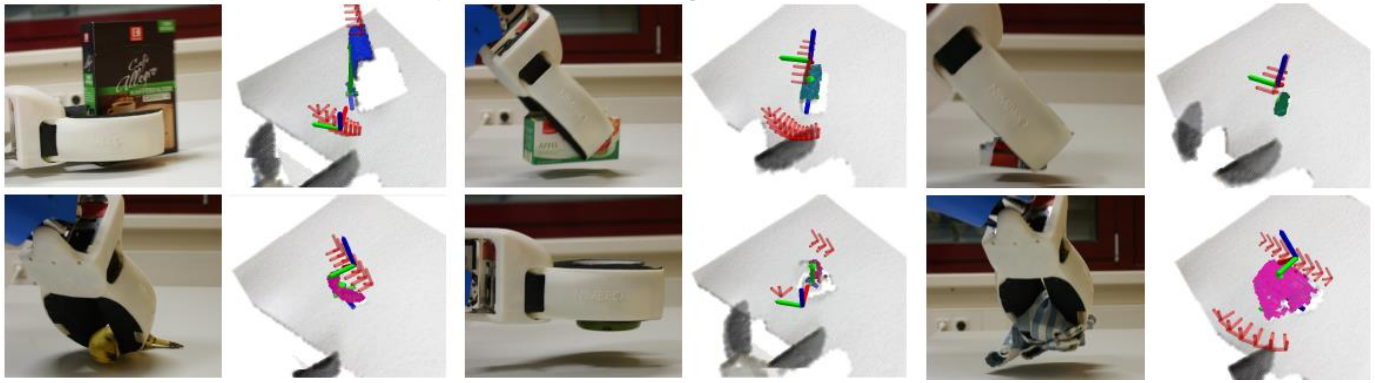
RoboCup @Home 2011 Final

Analysis of Table-top Scenes and Grasp Planning

- Detection of clusters above horizontal plane
- Two grasps (top, side)



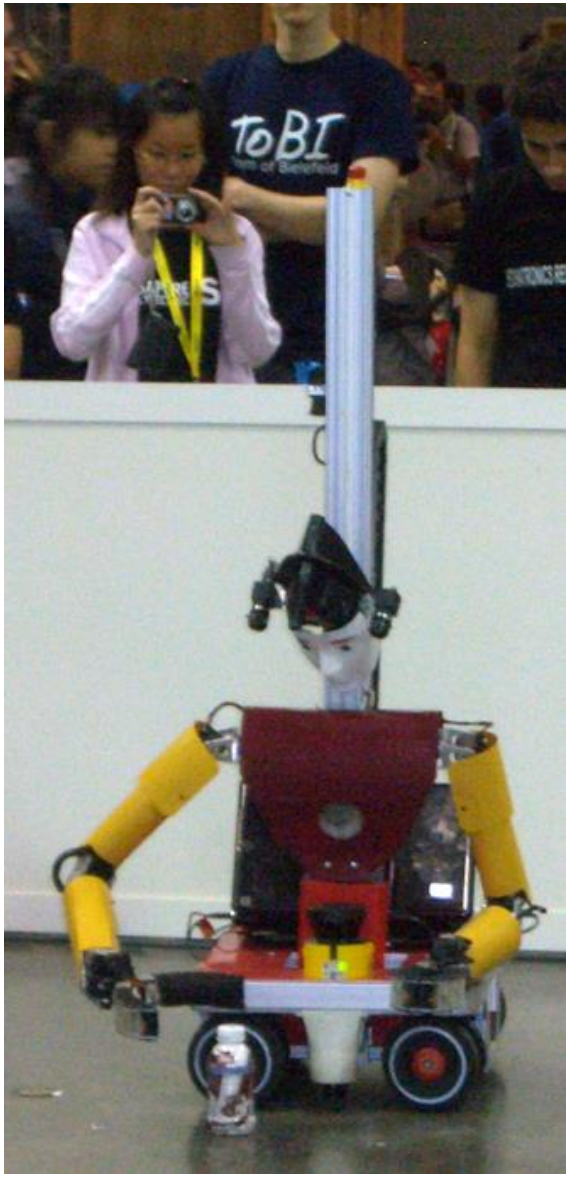
- Flexible grasping of many unknown objects

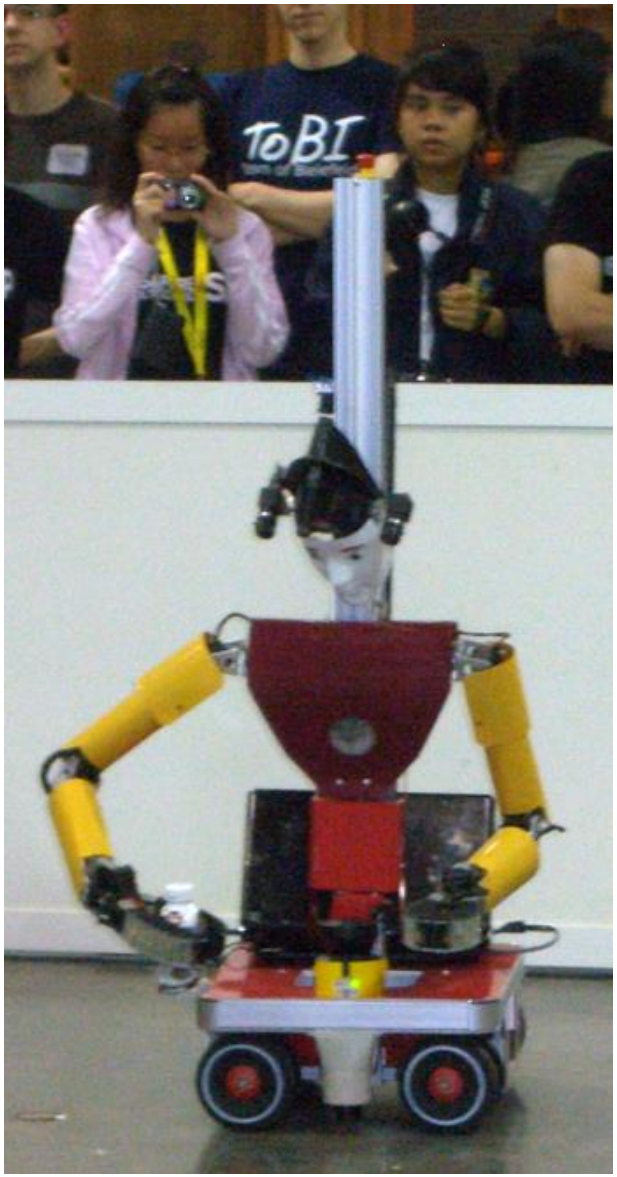


[Stückler, Steffens, Holz, Behnke, Robotics and Autonomous Systems 2012]

RoboCup 2013 Eindhoven

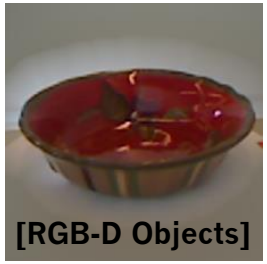
Picking-up Objects from the Floor

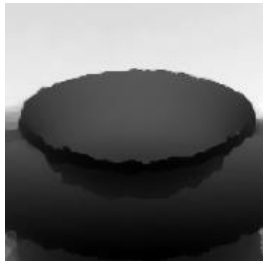
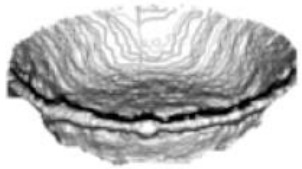
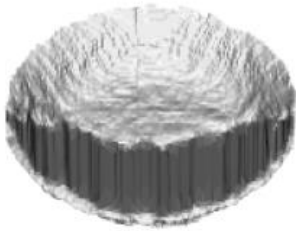
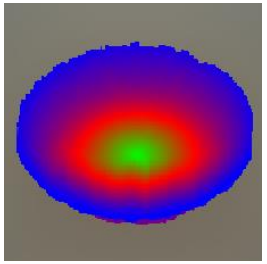




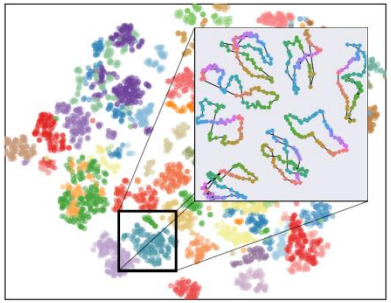
Object Recognition and Pose Estimation

- Rendering canonical views



- Pretrained convolutional neural network

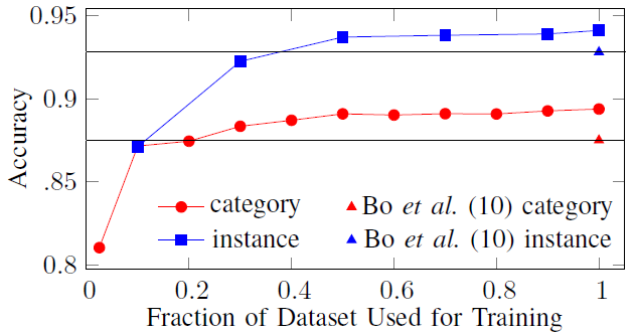



- Linear SVM / SV regression

Method	Category Accuracy (%) RGB	Category Accuracy (%) RGB-D	Instance Accuracy (%) RGB	Instance Accuracy (%) RGB-D
Lai *et al.* (8)	74.3 ± 3.3	81.9 ± 2.8	59.3	73.9
Bo *et al.* (10)	82.4 ± 3.1	87.5 ± 2.9	**92.1**	92.8
Ours	$\mathbf{83.1 \pm 2.0}$	$\mathbf{89.4 \pm 1.3}$	92.0	**94.1**

Work	MedPose	MedPose(C)	MedPose(I)	AvePose	AvePose(C)	AvePose(I)
Lai *et al.* (9)	62.6	51.5	30.2	83.7	77.7	57.1
Bo *et al.* (10)	20.0	**18.7**	**18.0**	53.6	47.5	44.8
Ours – instance level pose regression	20.4	20.4	18.7	51.0	50.4	**42.8**
Ours – category level pose regression	**19.2**	19.1	18.9	**45.0**	**44.5**	43.7

Angular error in °

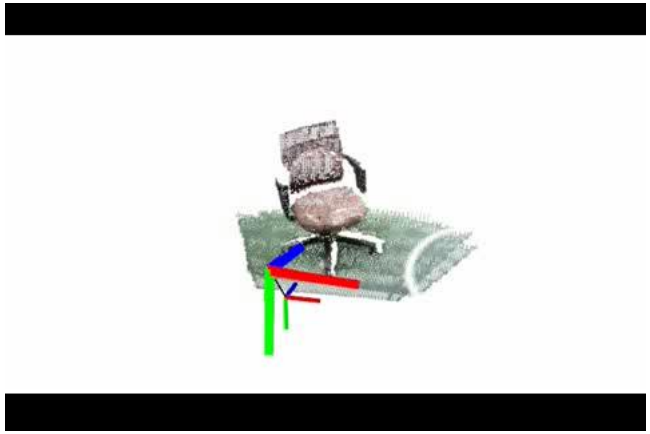


[Schwarz, Schulz, Behnke, ICRA 2015]

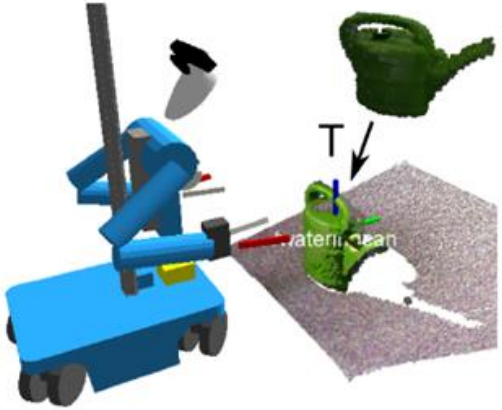
Learning and Tracking Object Models

- Modeling of objects by RGB-D SLAM

[Stückler, Behnke:
Journal of Visual Communication
and Image Representation 2013]

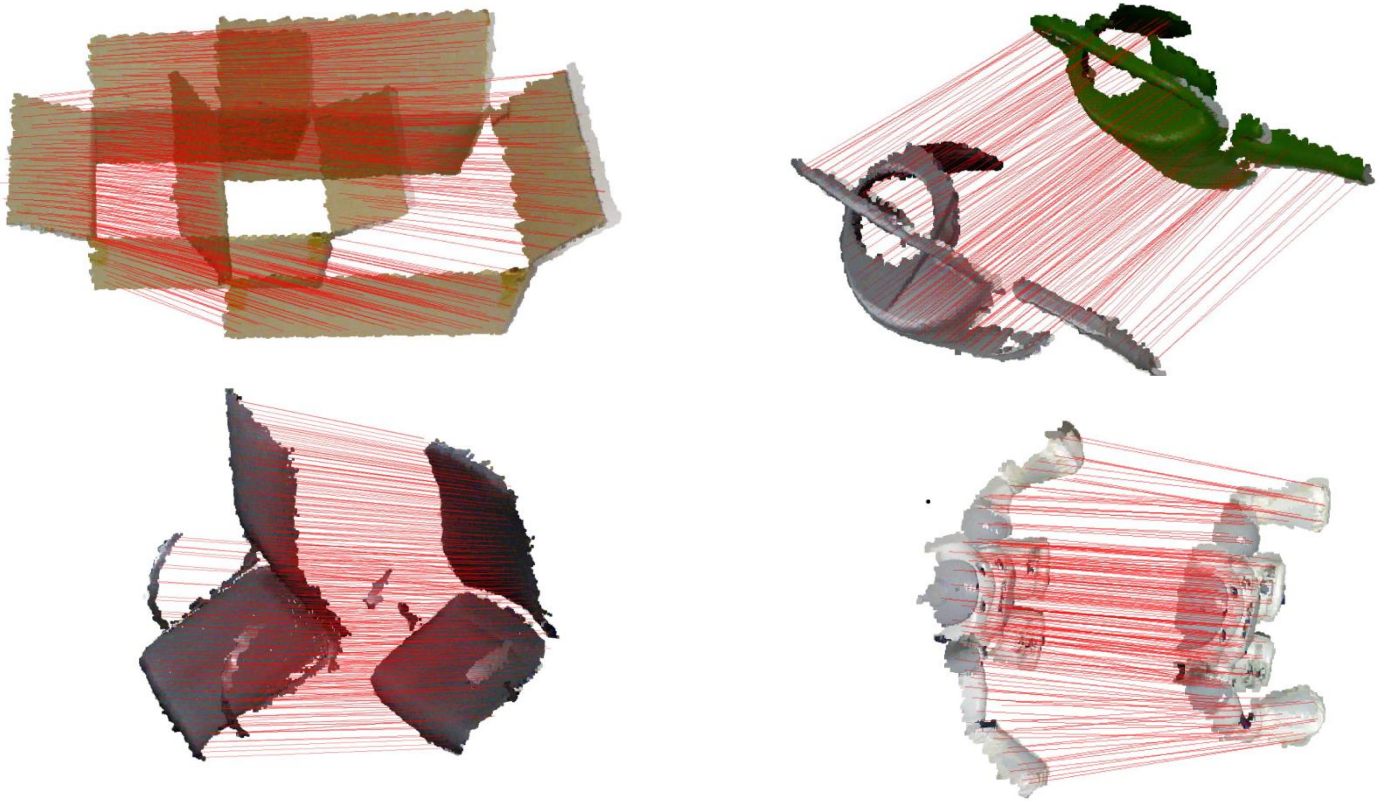


- Real-time registration with current RGB-D image



Deformable RGB-D Registration

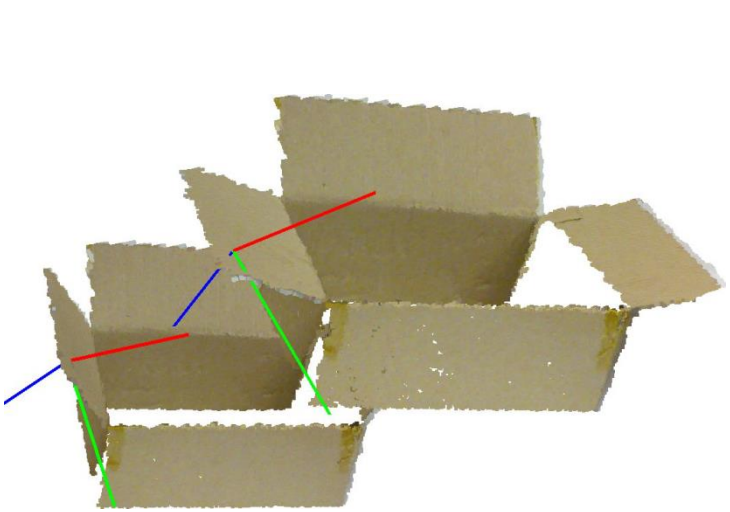
- Based on Coherent Point Drift method [Myronenko & Song, PAMI 2010]
- Multiresolution Surfel Map allows real-time registration

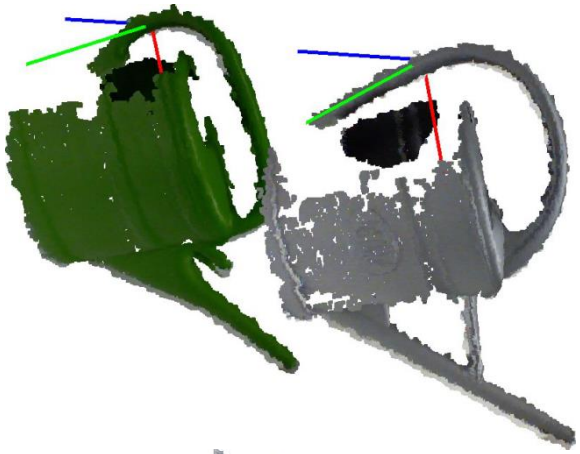


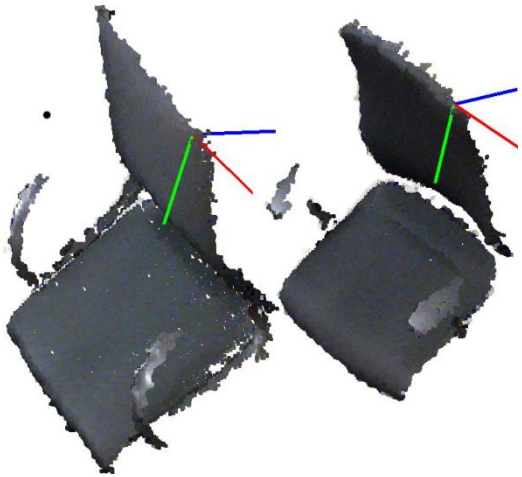
[Stückler, Behnke, ICRA2014]

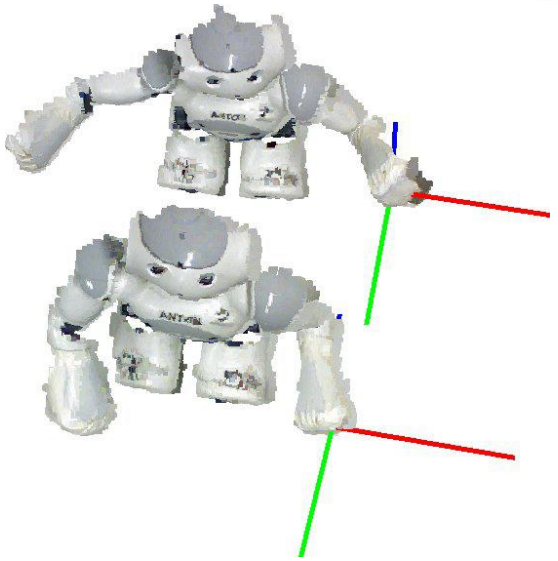
Transformation of Poses on Object

- Derived from the deformation field

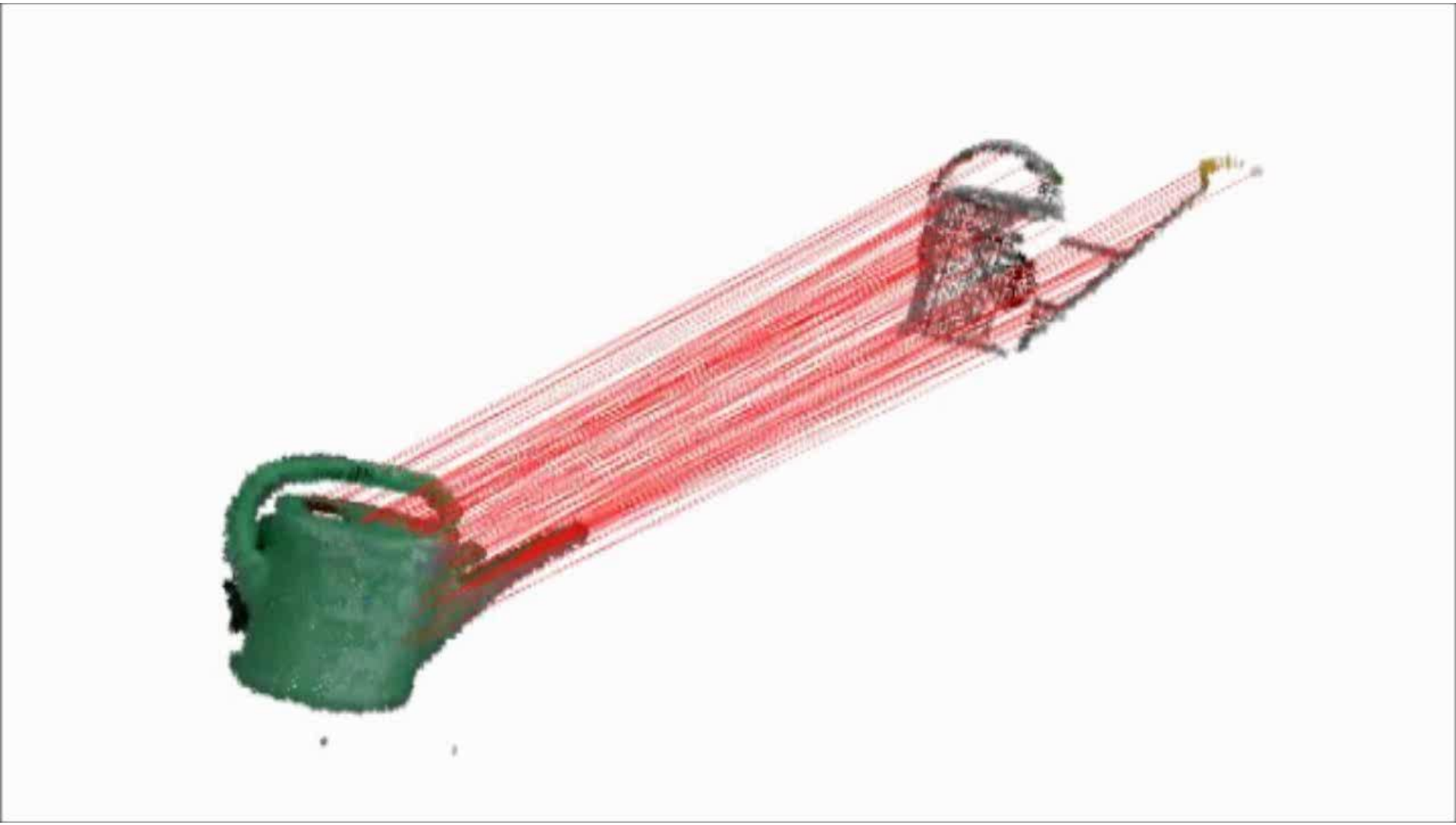








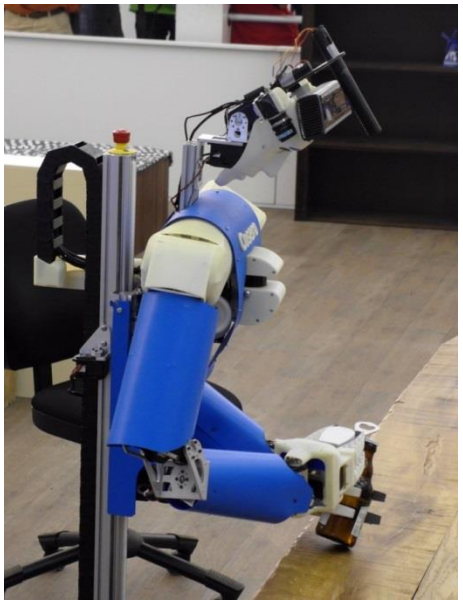
Grasp & Motion Skill Transfer

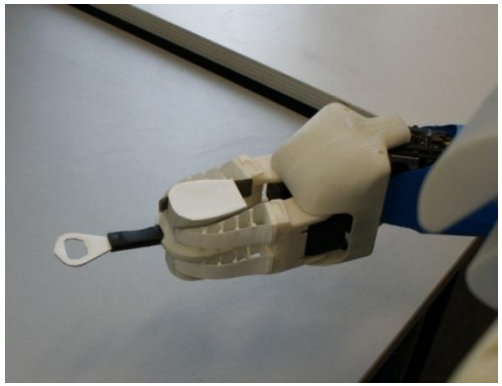


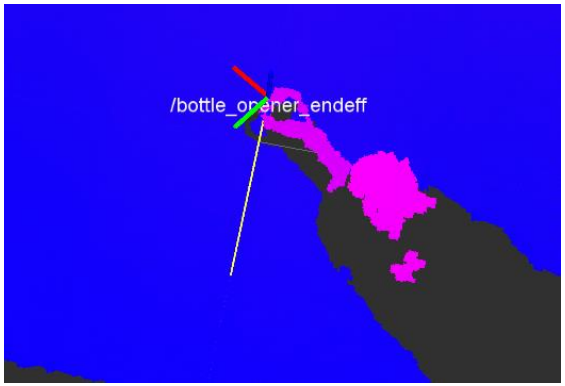
- Demonstration at RoboCup 2013

Tool use: Bottle Opener

- Tool tip perception
- Extension of arm kinematics
- Perception of crown cap
- Motion adaptation

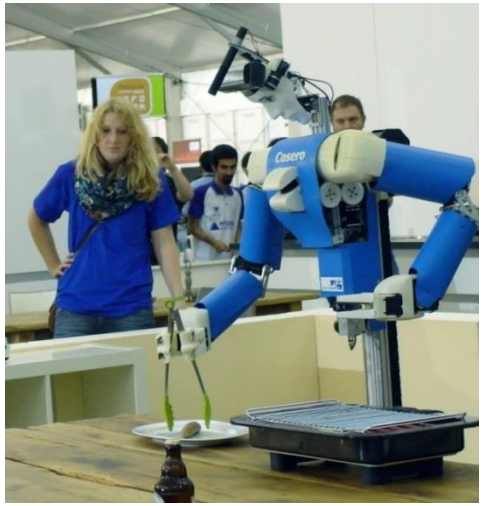






Picking Sausage, Bimanual Transport

- Perception of tool tip and sausage
- Alignment with main axis of sausage

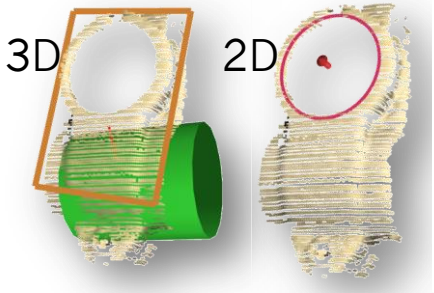


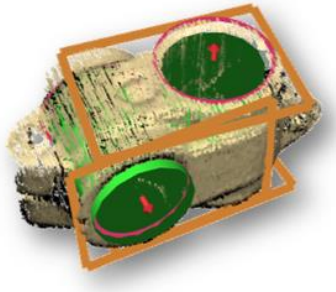
- Our team NimbRo won the RoboCup@Home League in three consecutive years

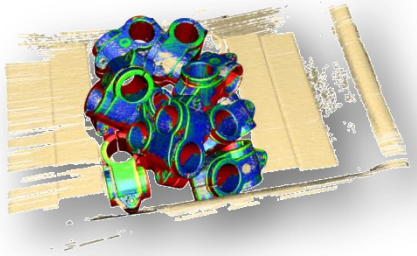
Bin Picking

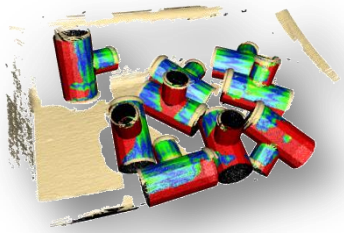
- Known objects in transport box

- Matching of graphs of 2D and 3D shape primitives

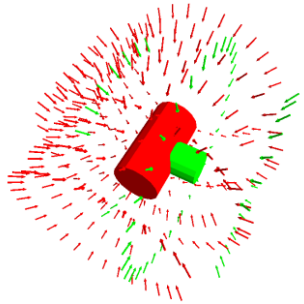


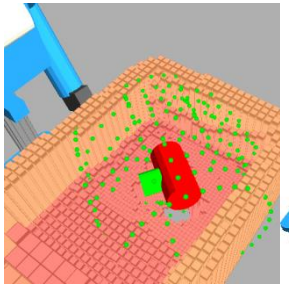


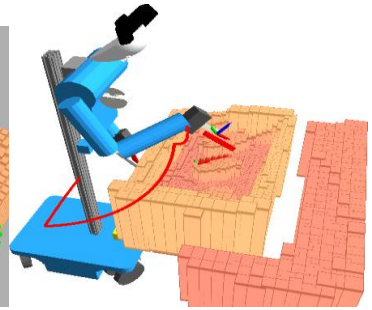




- Grasp and motion planning





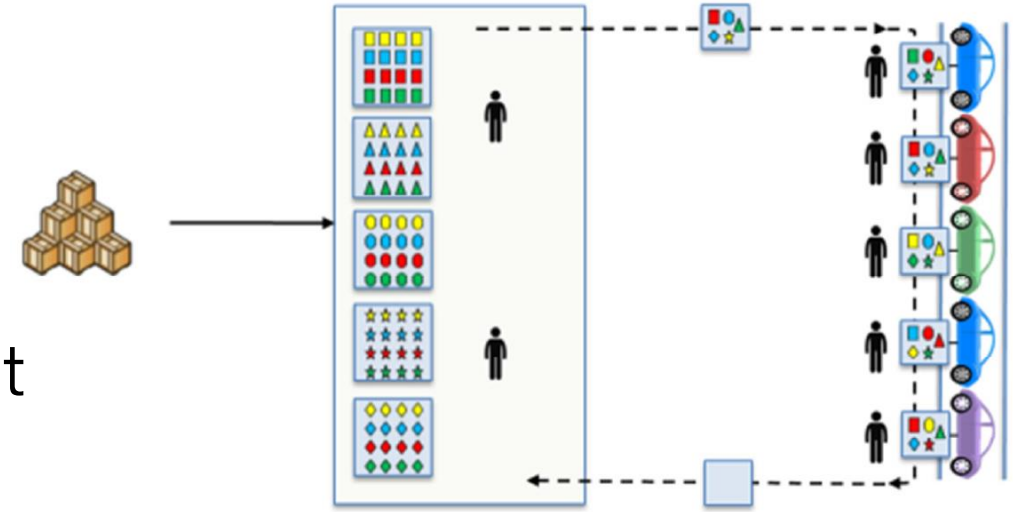


Offline Online

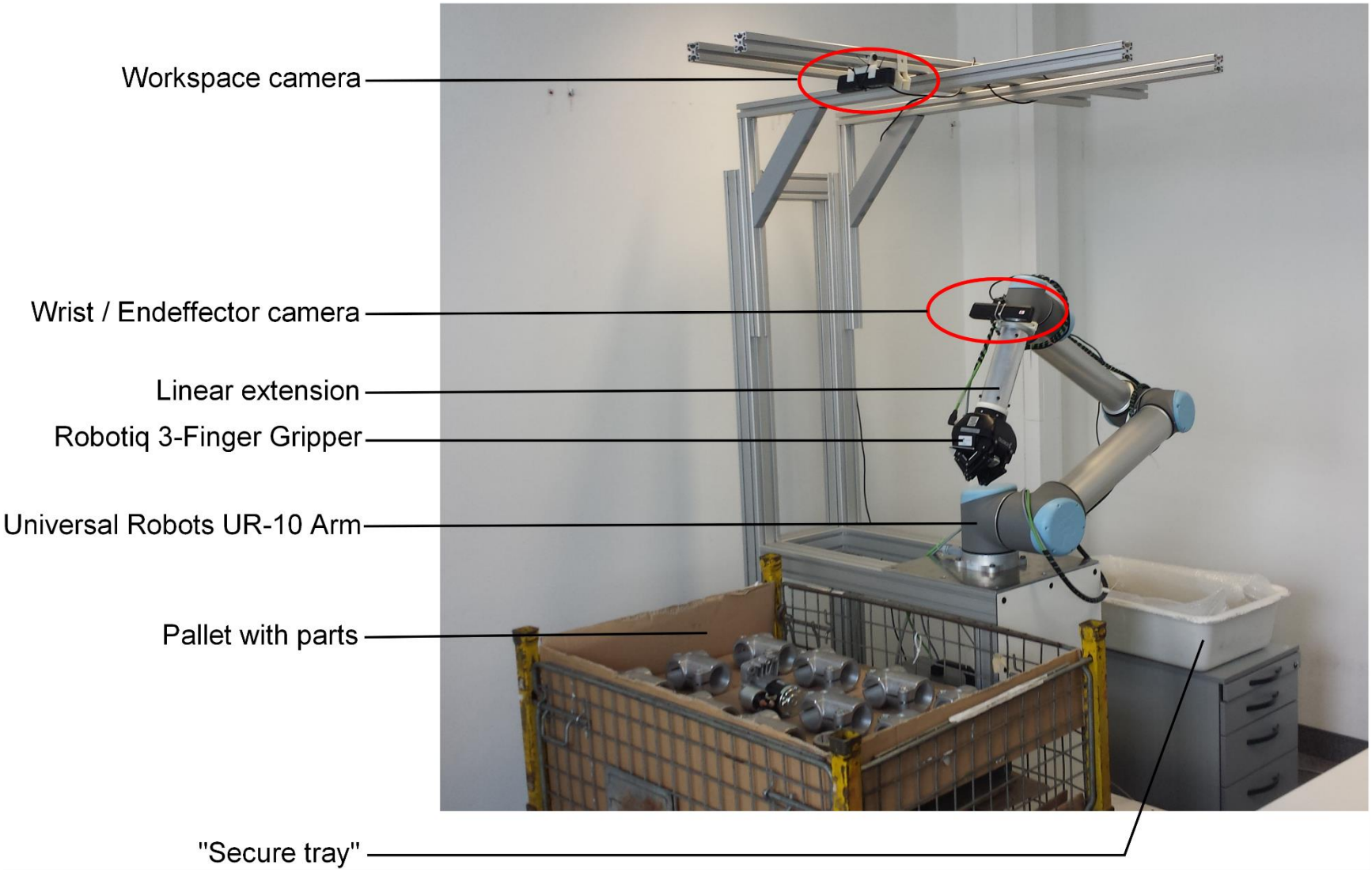
[Nieuwenhuisen et al.: ICRA 2013]

Kitting of Automotive Parts

- Many car variants
- Collect the parts needed for the assembly of a particular car in a kit
- Parts in different variants are available in a supermarket
- Robot needs to
  - navigate to the transport boxes,
  - grasp the parts, and
  - place them in the kit

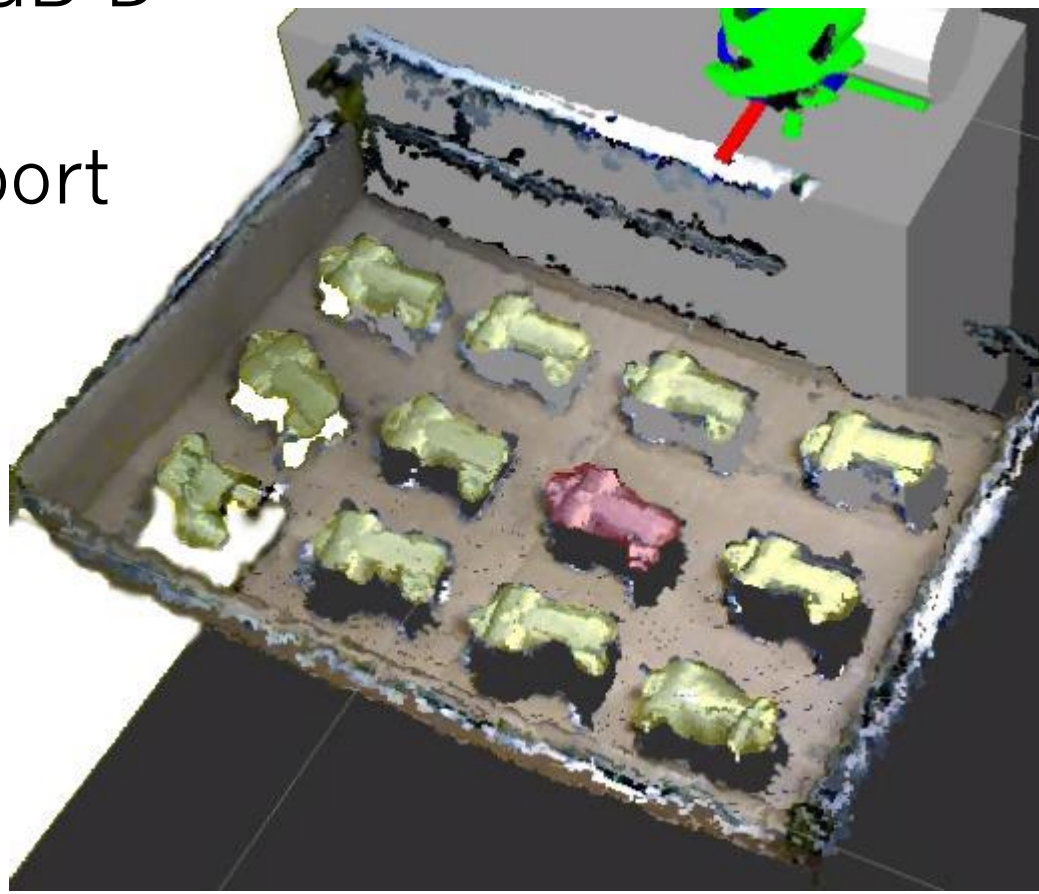


Lab Demonstrator



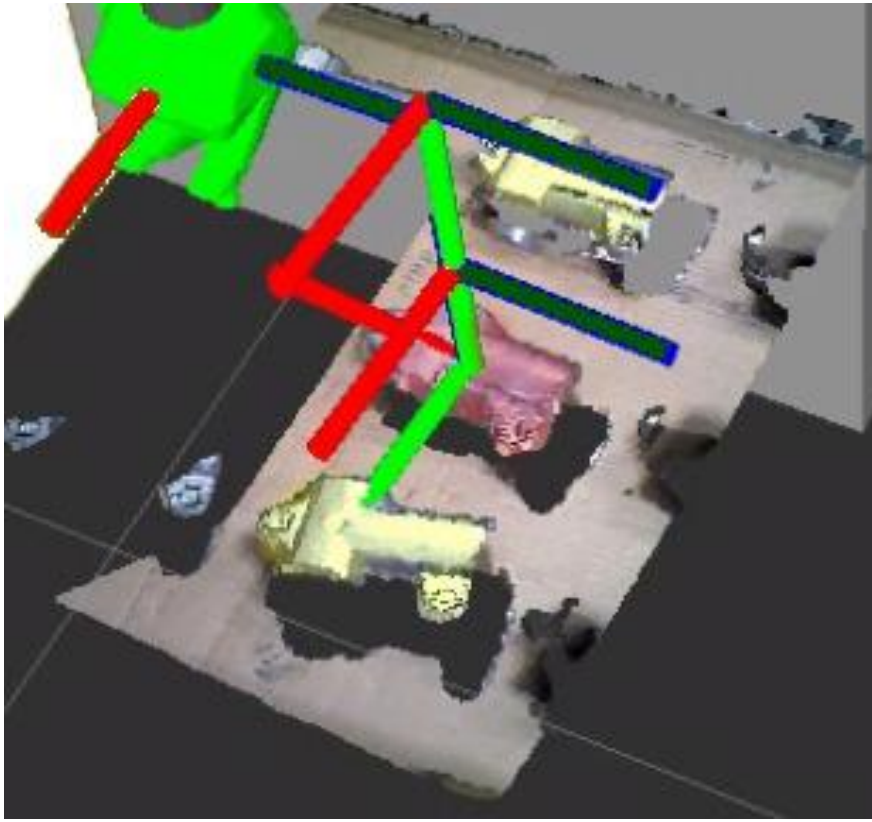
Object Candidate Detection

- Using work space RGB-D camera
- Initial pose of transport box roughly known
- Detect dominant horizontal plane above ground
- Cluster points above support plane
- Estimate main axes



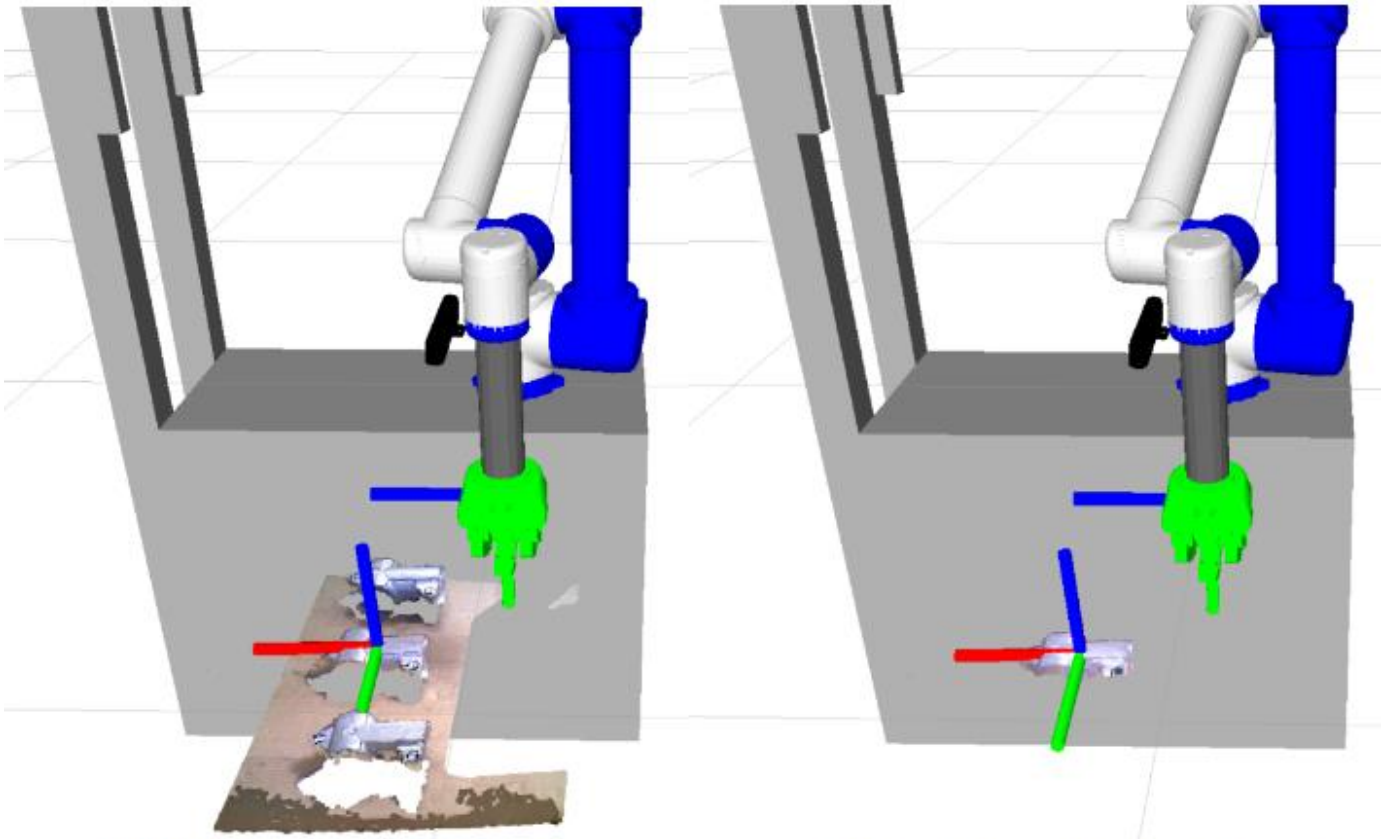
Object View Registration

- Wrist RGB-D camera moved above innermost object candidate
- Object views are represented as Multiresolution Surfel Map
- Registration of object view with current measurements using soft assignments
- Verification based on registration quality



Registered Object Model

- Registration yields the object pose

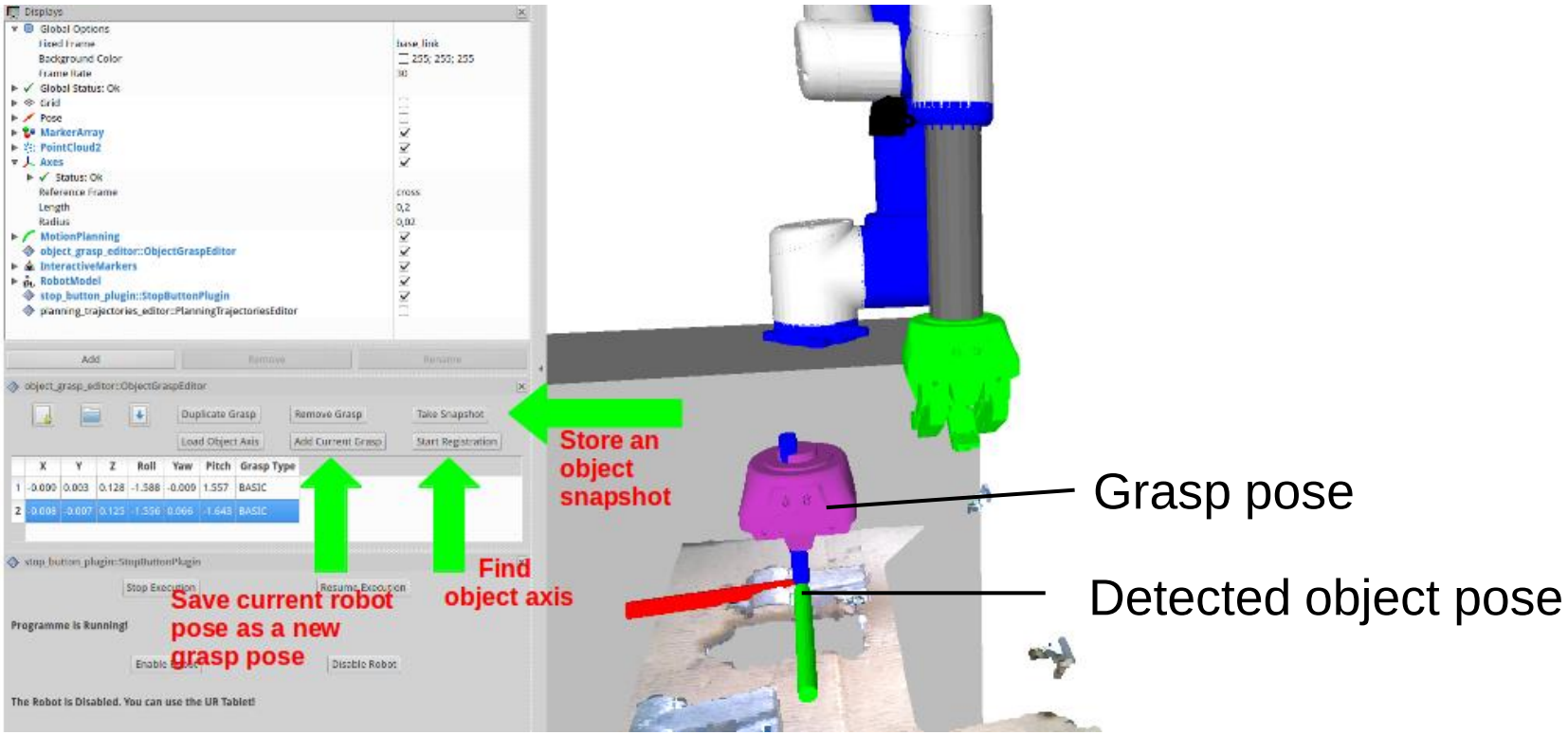


Detected Object Pose

Object Model and Pose

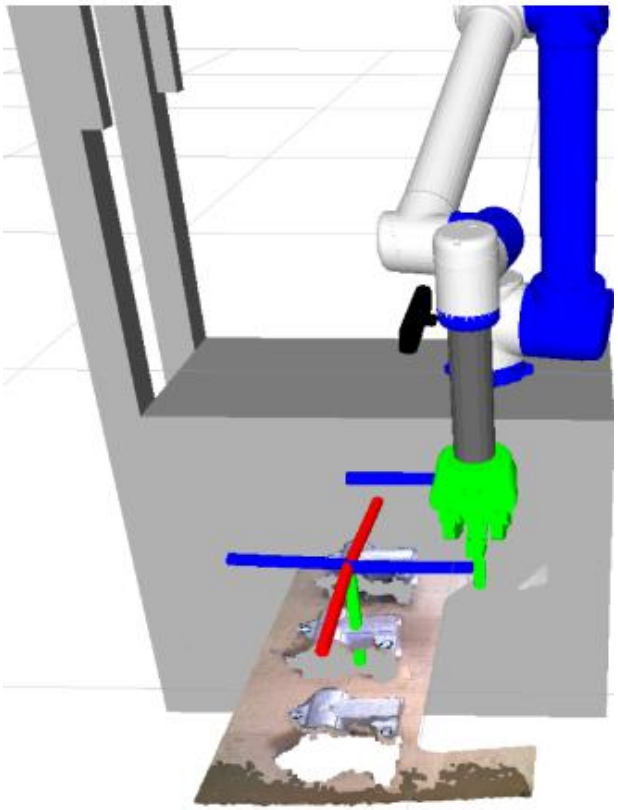
Grasp Definition

- GUI for object model acquisition and grasp definition, relative to object model

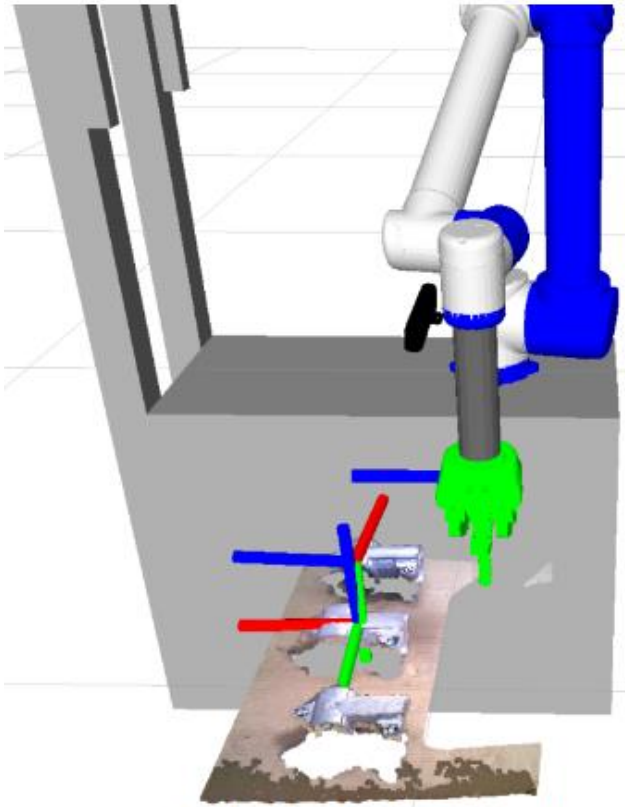


Grasp Selection

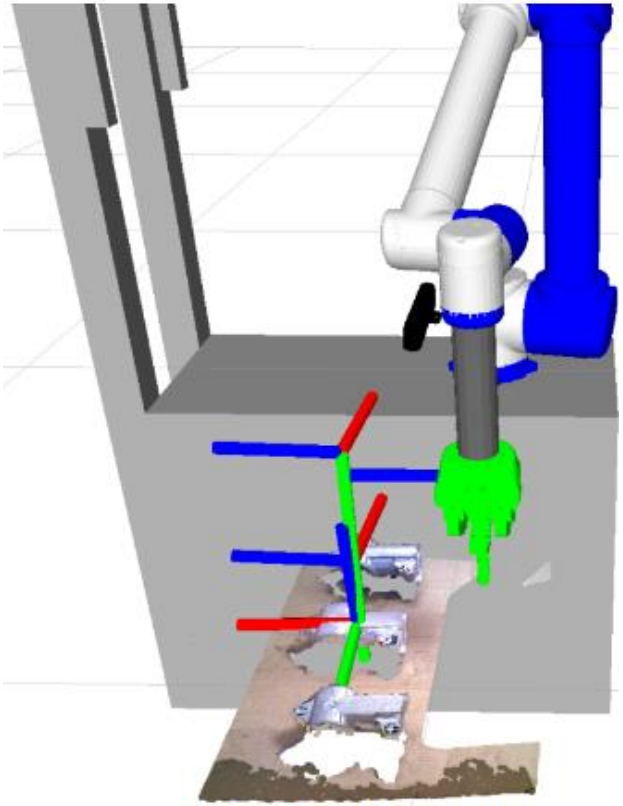
- Grasps are selected according to object pose



Grasp Candidates

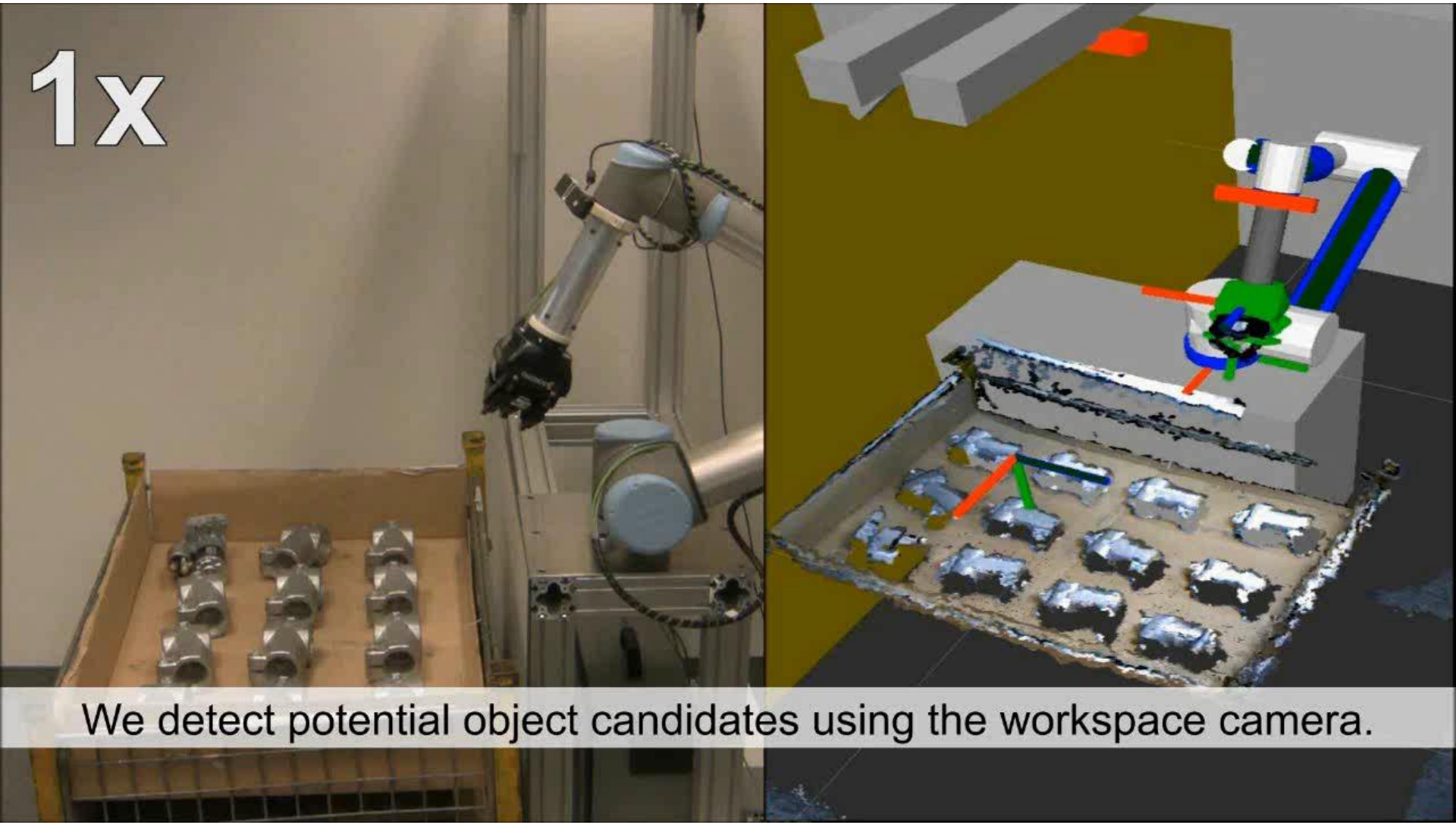


Selected Grasp and Object Pose



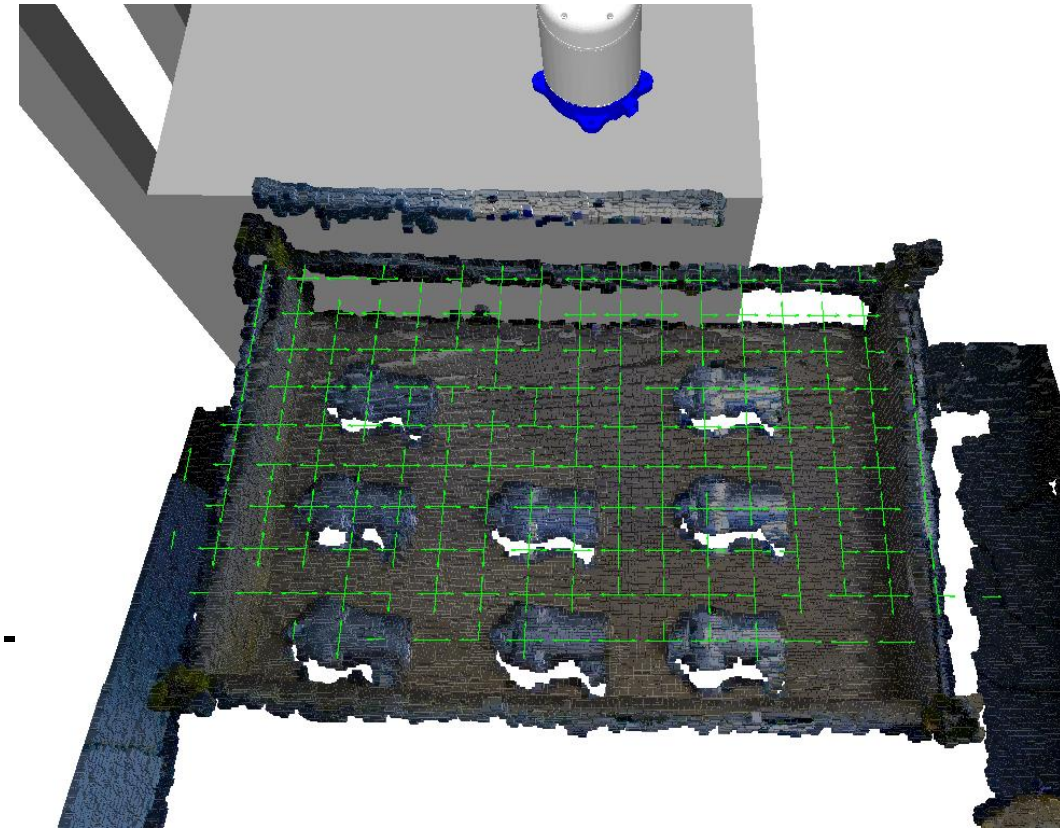
Pre-Grasp, Grasp and Object Pose

Part Detection and Grasping



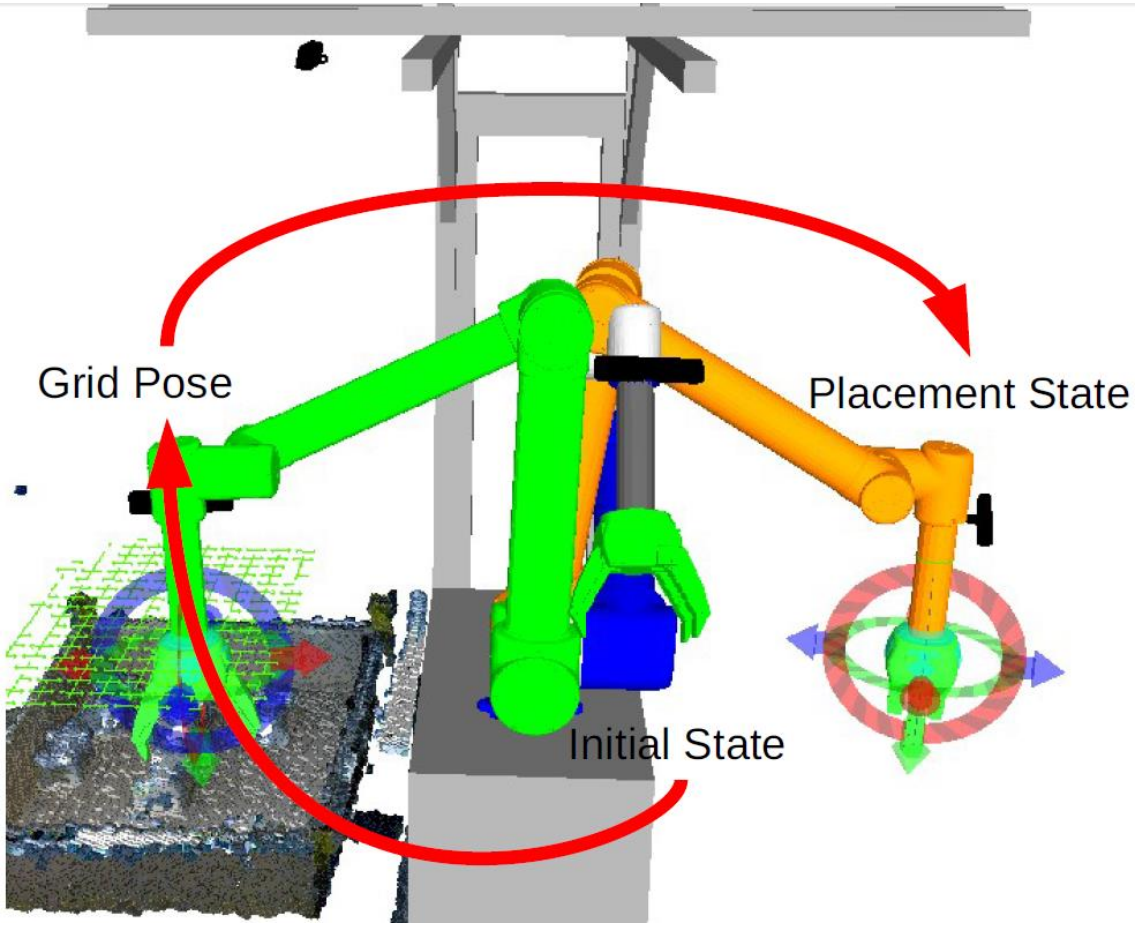
Motion Planning

- Use ROS MoveIt for motion planning and execution
- Predefined poses (initial, placement) and grid of poses above the objects
- Preplanned paths
- Only short trajecto-ries must be planned online



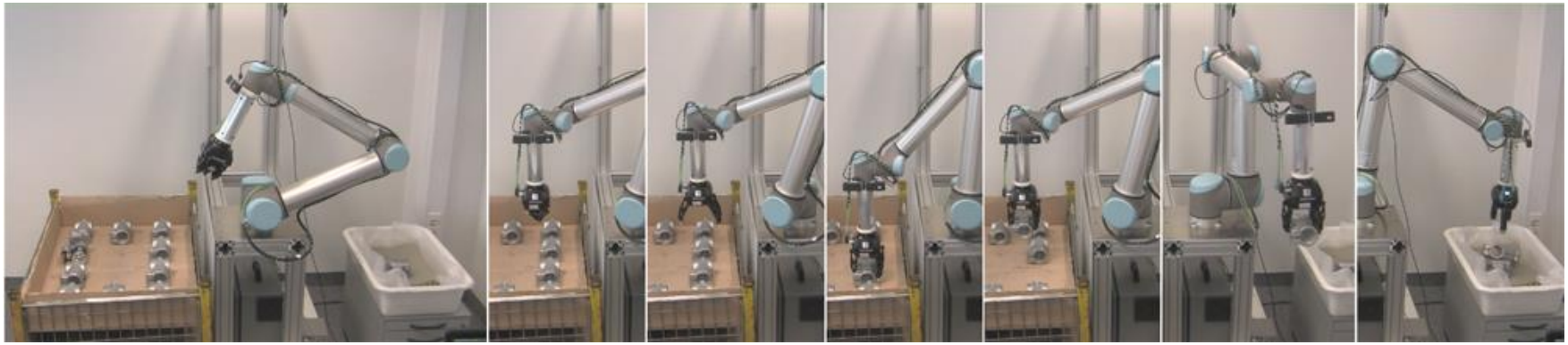
Concatenation of Motion Segments

- Interpolation for smooth segment transitions



Depalletizing of Starters

Depalletizing Results: 10 Runs



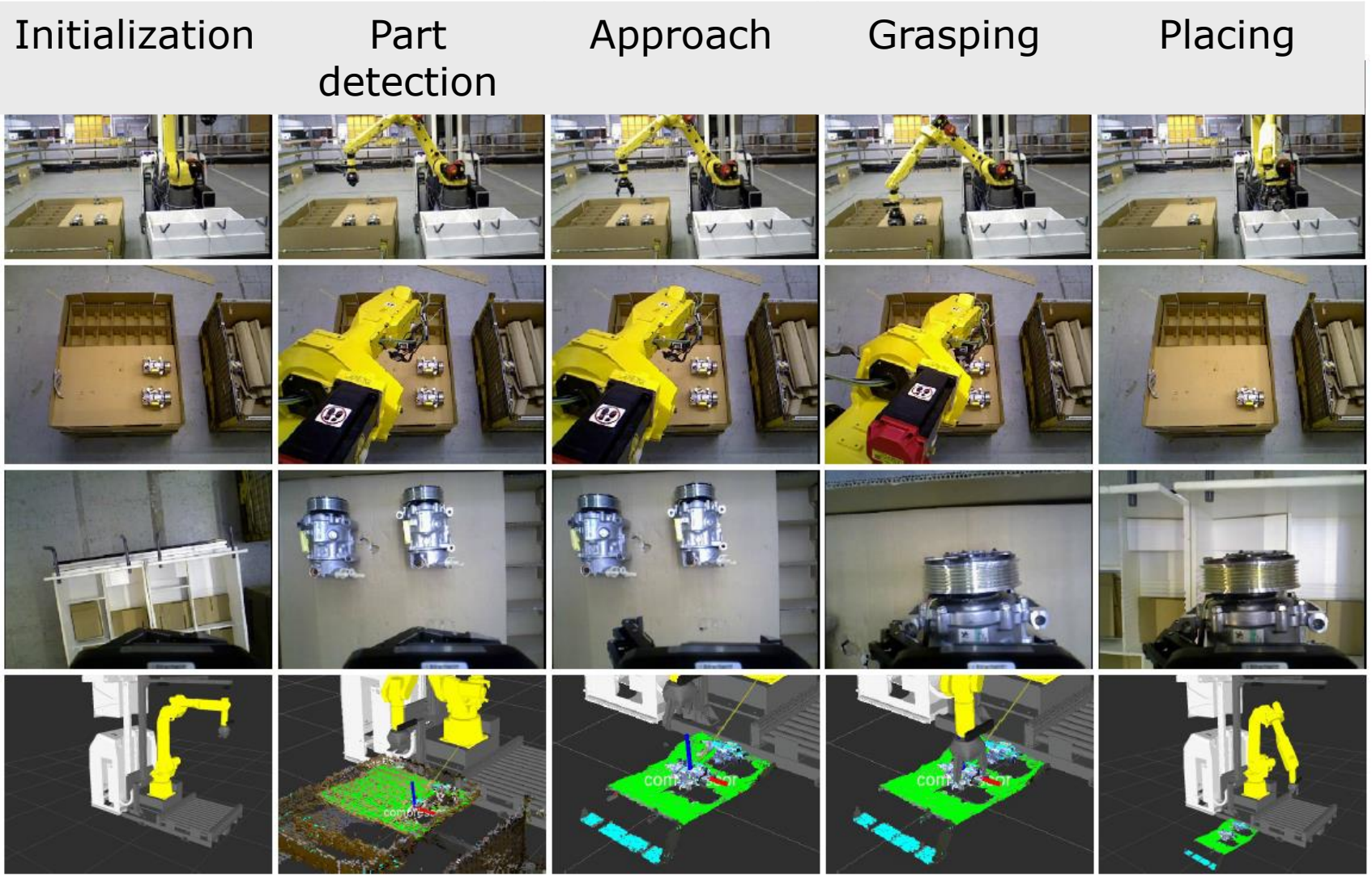
- Total time

Component	Mean	Std	Min	Max
Object detection and grasping	13.84 s	1.89 s	10.42 s	23.81 s
Full cycle (incl. release and returning to initial pose)	34.57 s	3.01 s	29.53 s	49.52 s

- Component times and success rates

Component	Mean	Std	Min	Max	Success Rate
Initial object detection	26.3 ms	10.3 ms	0.02 ms	38.5 ms	100 %
Detecting that the pallet is empty					100 %
Object localization & verification	532.7 ms	98.2 ms	297.0 ms	800.1 ms	100 %
Identifying wrong objects					100 %
Grasping a found object	7.80 s	0.56 s	6.90 s	10.12 s	99 %

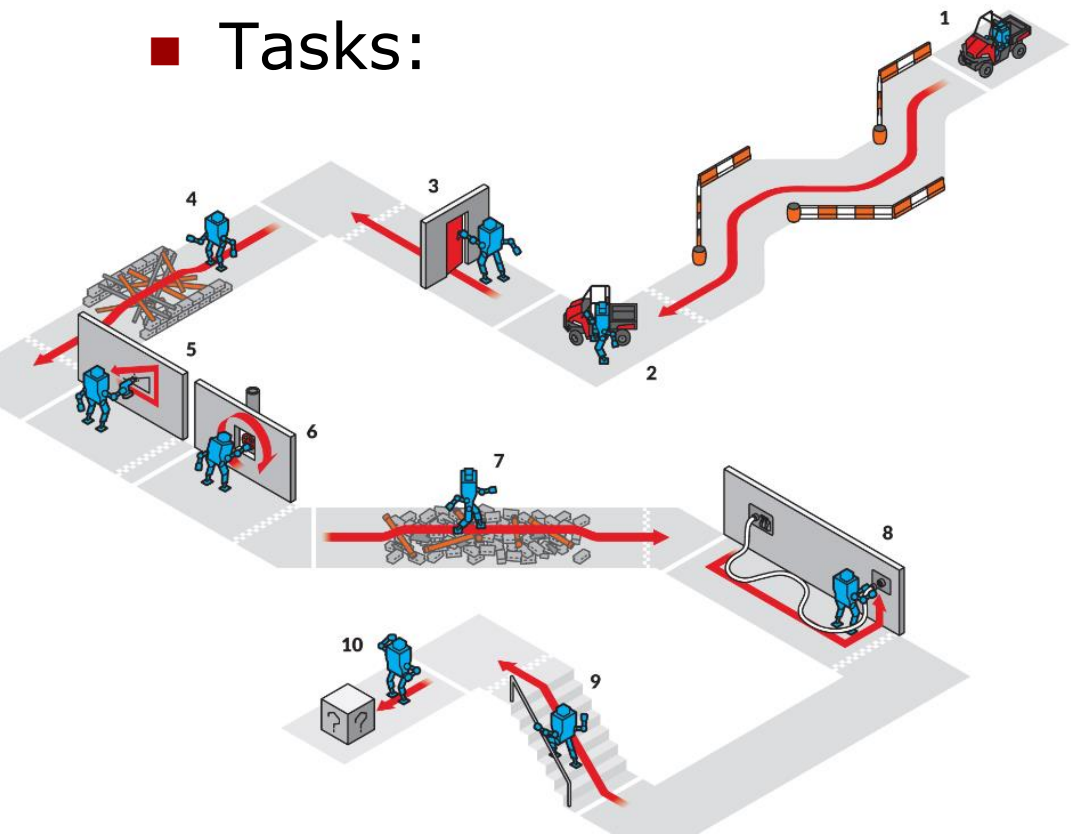
Integrated Mobile Manipulation Robot



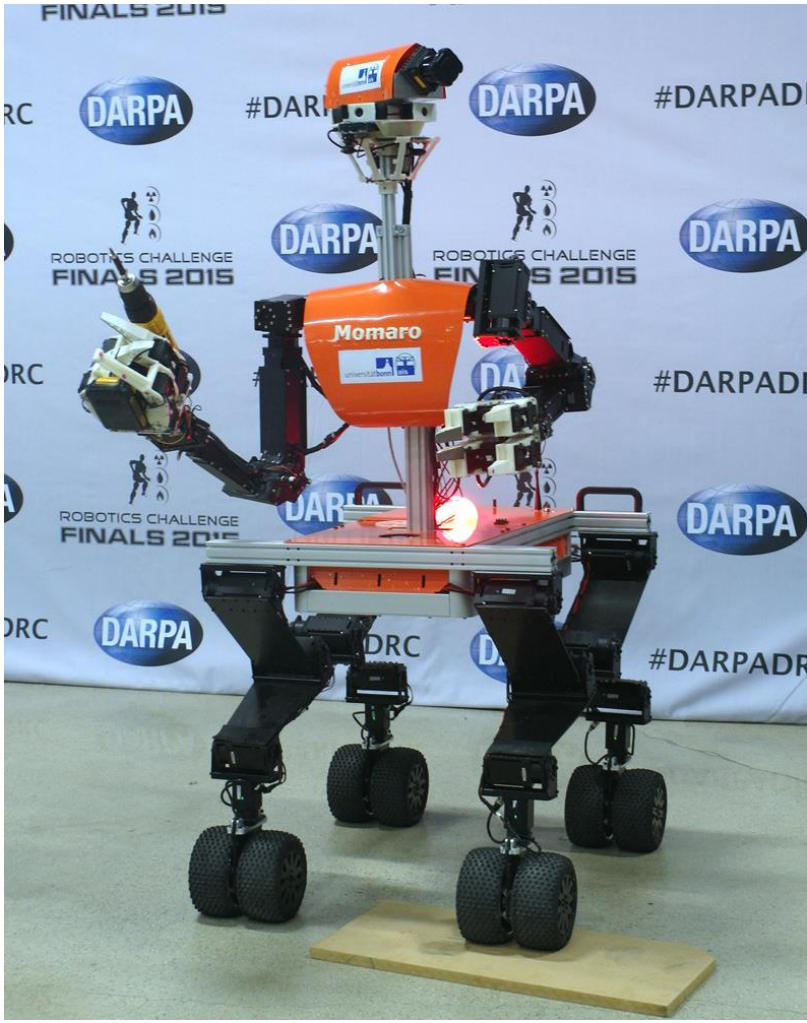
[Holz et al., ETFA 2015]

DARPA Robotics Challenge

- Tasks:



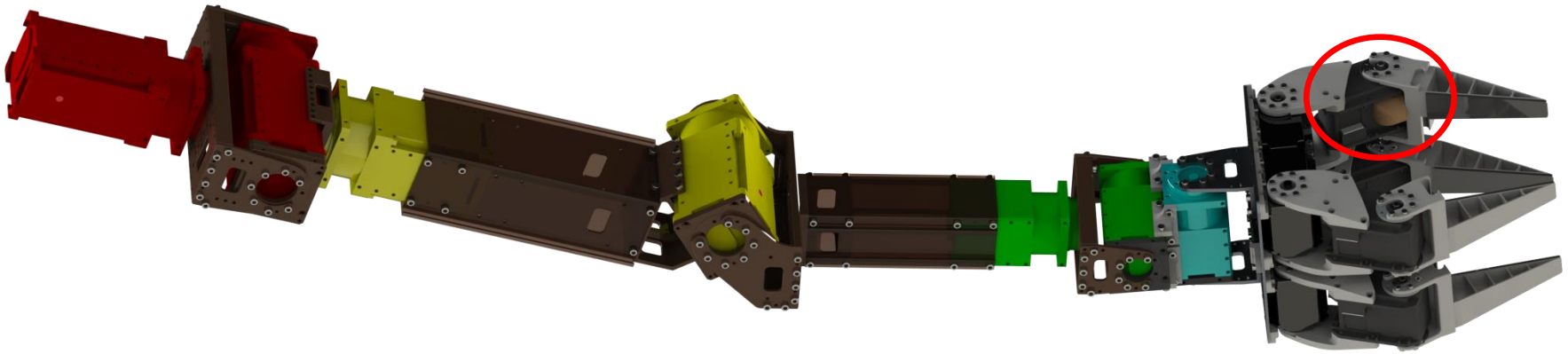
- Mobile manipulation robot Momaro



[Schwarz – Behnke, ICRA 2016; Rodehutskors et. al., Humanoids 2015]

Momaro Arm Design

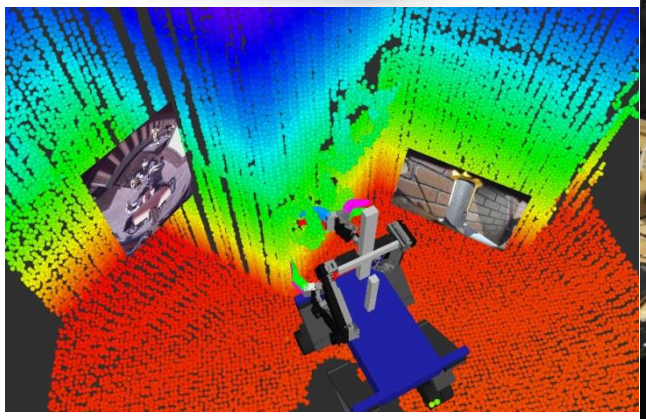
- Seven Robotis Dynamixel Pro actuators
  - Shoulder roll & pitch 2x 44.2 Nm, yaw 25 Nm
  - Elbow 24.8 Nm
  - Wrist roll & pitch 6.3 Nm, yaw 1.4 Nm



- Four fingers with two Dynamixel actuators
  - Proximal 8.4 Nm, distal 6.0 Nm
  - Bump for pushing tool trigger

Manipulation Operator Interface

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

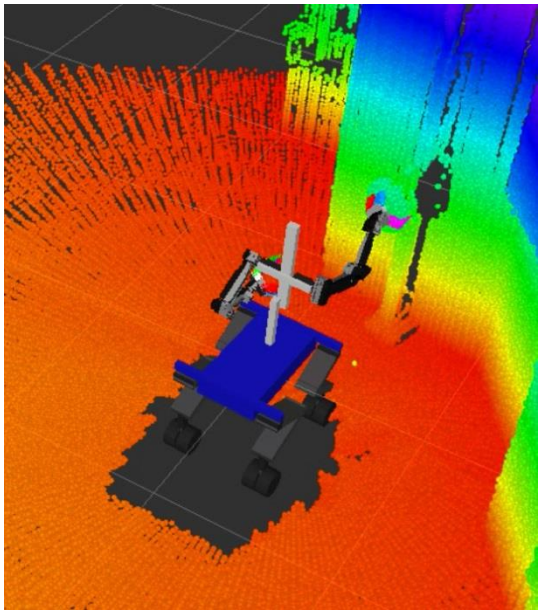


[Rodehutskors et al., Humanoids 2015]

Door Opening at DRC

Valve Turning Interface

- Align wheel model with 3D points using interactive marker
- Turning motion primitive

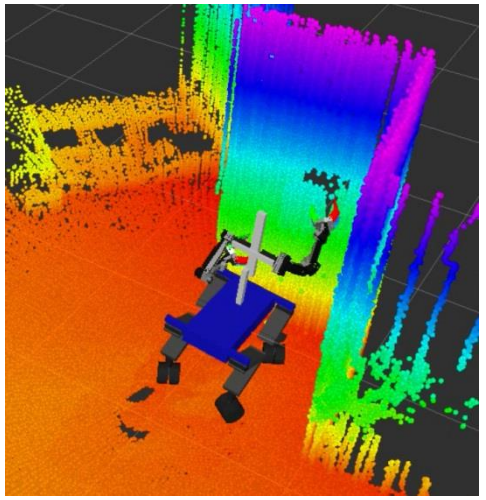


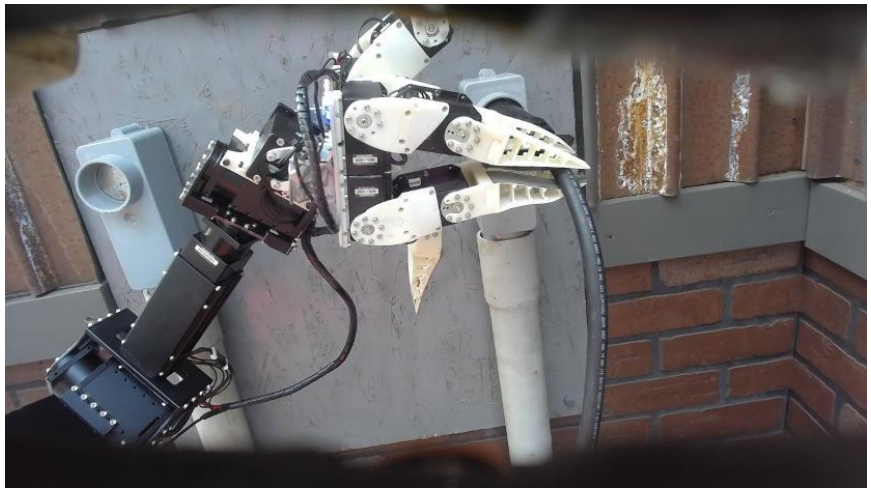
Valve Turning at DRC

DRC Team NimbRo Rescue:
Mobile Manipulation Robot
Momaro

Surprise Tasks

- Direct control of manipulation
- Open a cabinet and push a button
- Operate an electric switch
- Pull a plug and insert it into another socket

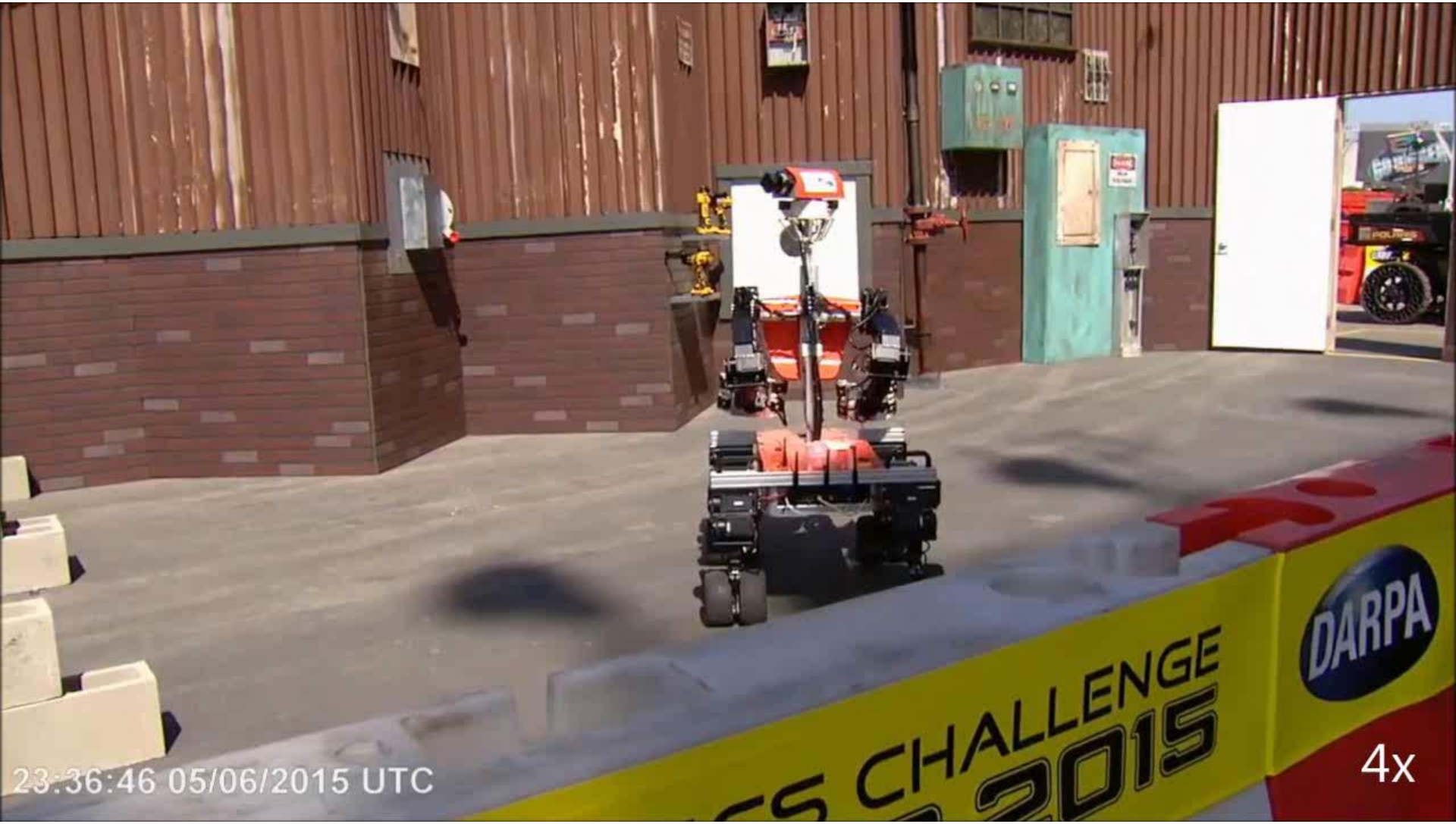




Operating a Switch at DRC

Plug Task at DRC

Cutting Drywall at DRC



Team NimbRo Rescue

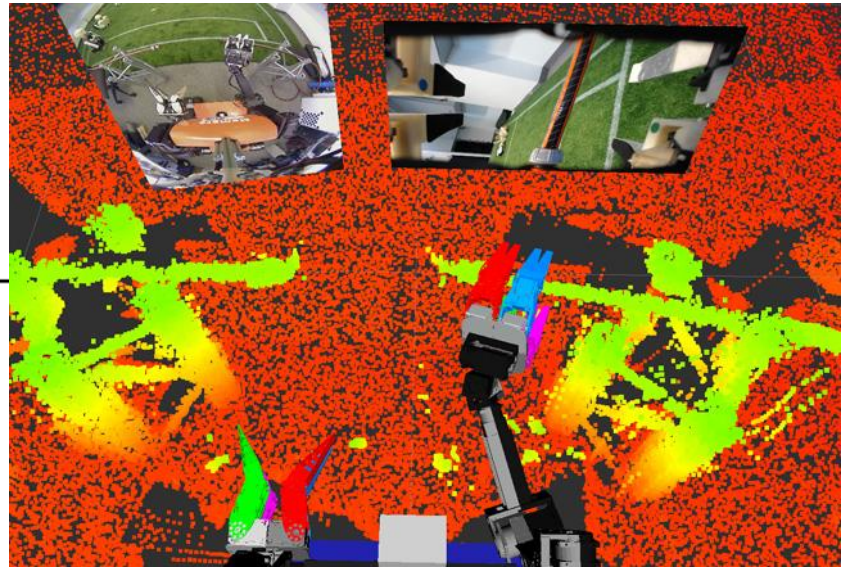
Best European Team (4th place overall), solved seven of eight tasks in 34 minutes

Hose Connecting Task

- Bimanual task
  - Grab the left hose with the left gripper,
  - Grab the right hose with the right gripper, and
  - Connect both hoses
- 10/11 trials successful
- Execution time

Task	Time [min:s]				
	Avg.	Median	Min.	Max.	Std. Dev.
Left grasp	0:44	0:38	0:27	1:20	0:16
Right grasp	0:45	0:40	0:34	1:04	0:10
Connect	1:36	1:32	1:07	2:04	0:21
Total	3:04	2:57	2:21	3:51	0:28

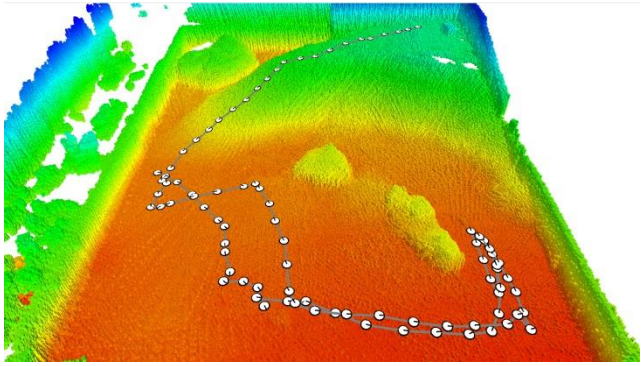
[Rodehutskors et al., Humanoids 2015]



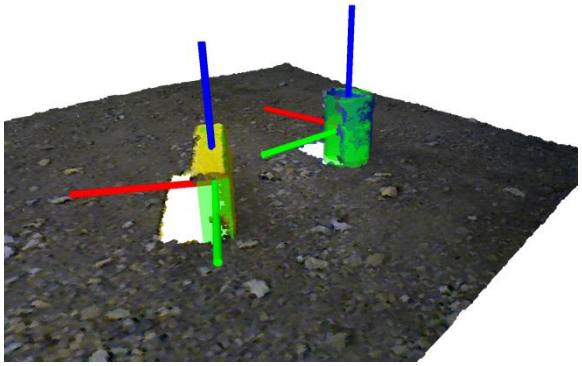
DLR SpaceBot Camp 2015

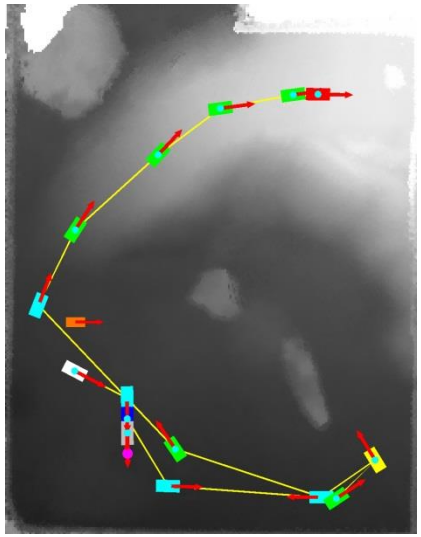
Autonomous Mission Execution

3D Mapping & Localization

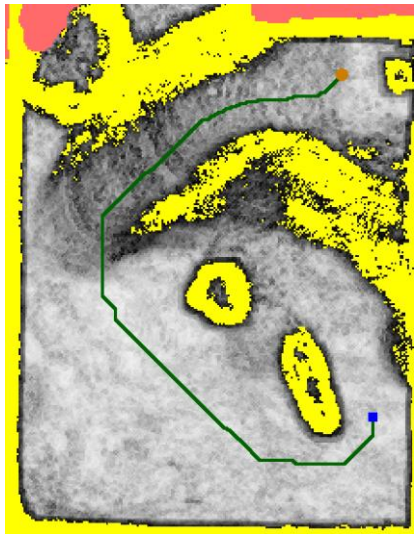


Object perception

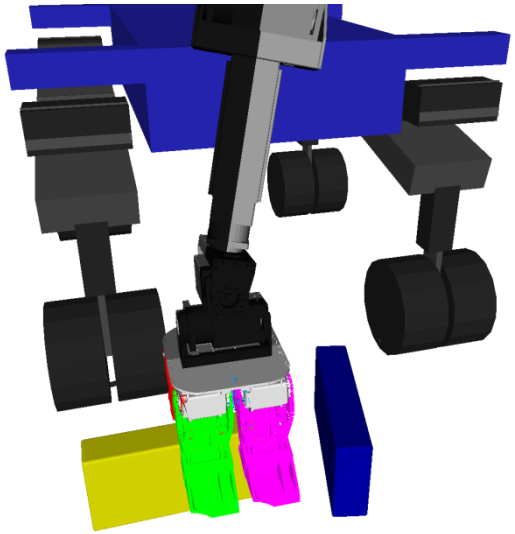




Mission plan



Navigation plan

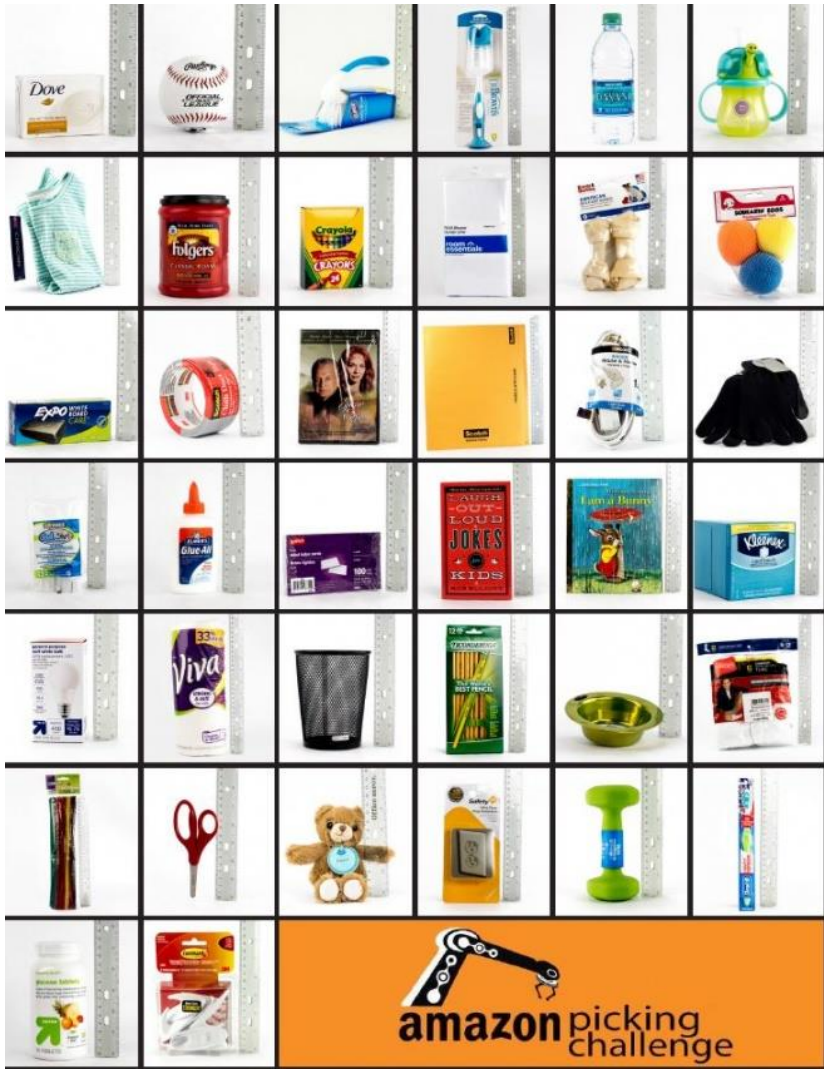


Grasping

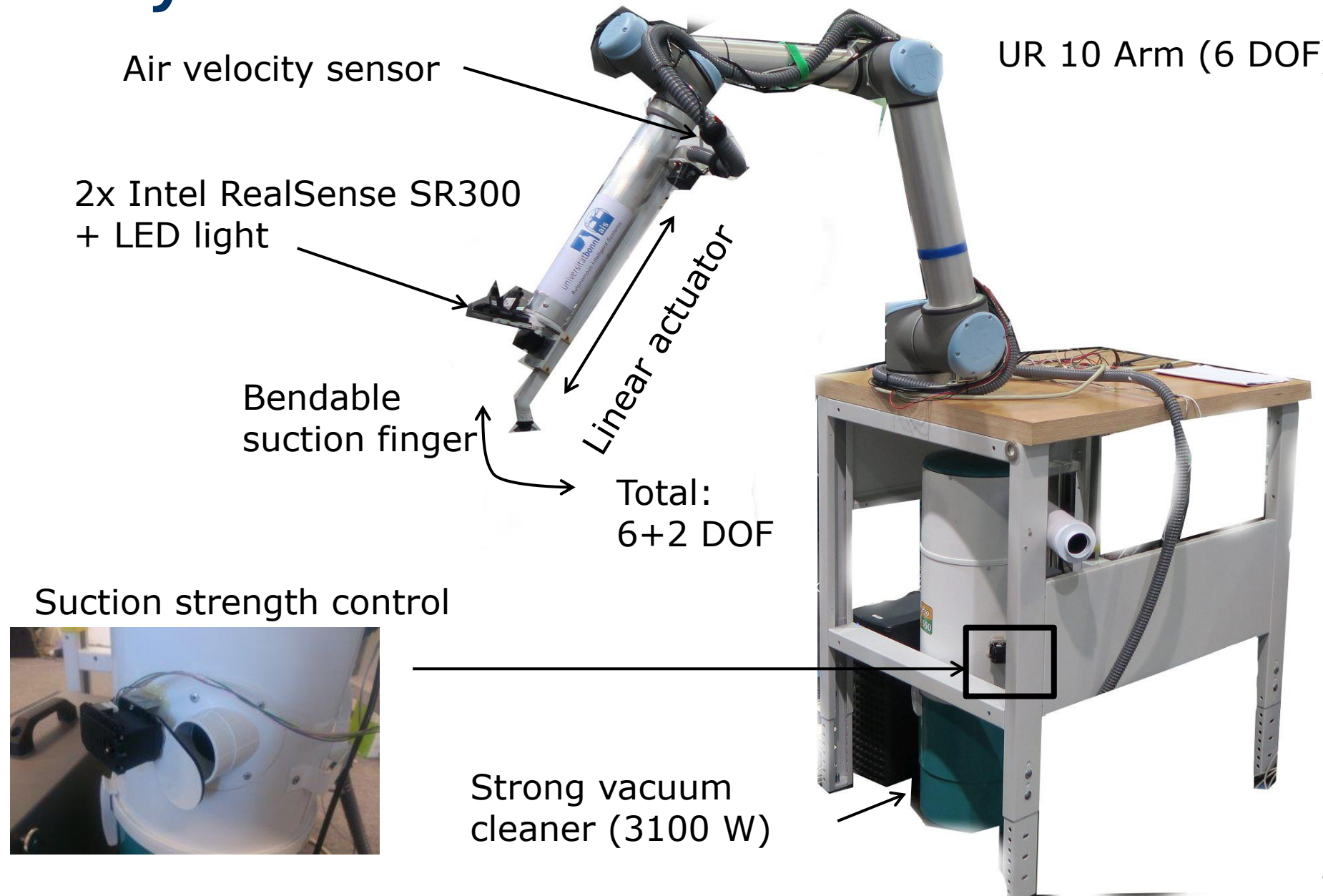
[Schwarz et al., Frontiers in Robotics and AI 2016]

Amazon Picking Challenge 2016

- Large variety of objects
- Different properties
  - Transparent
  - Shiny
  - Deformable
  - Heavy
- Stowing task
- Picking task



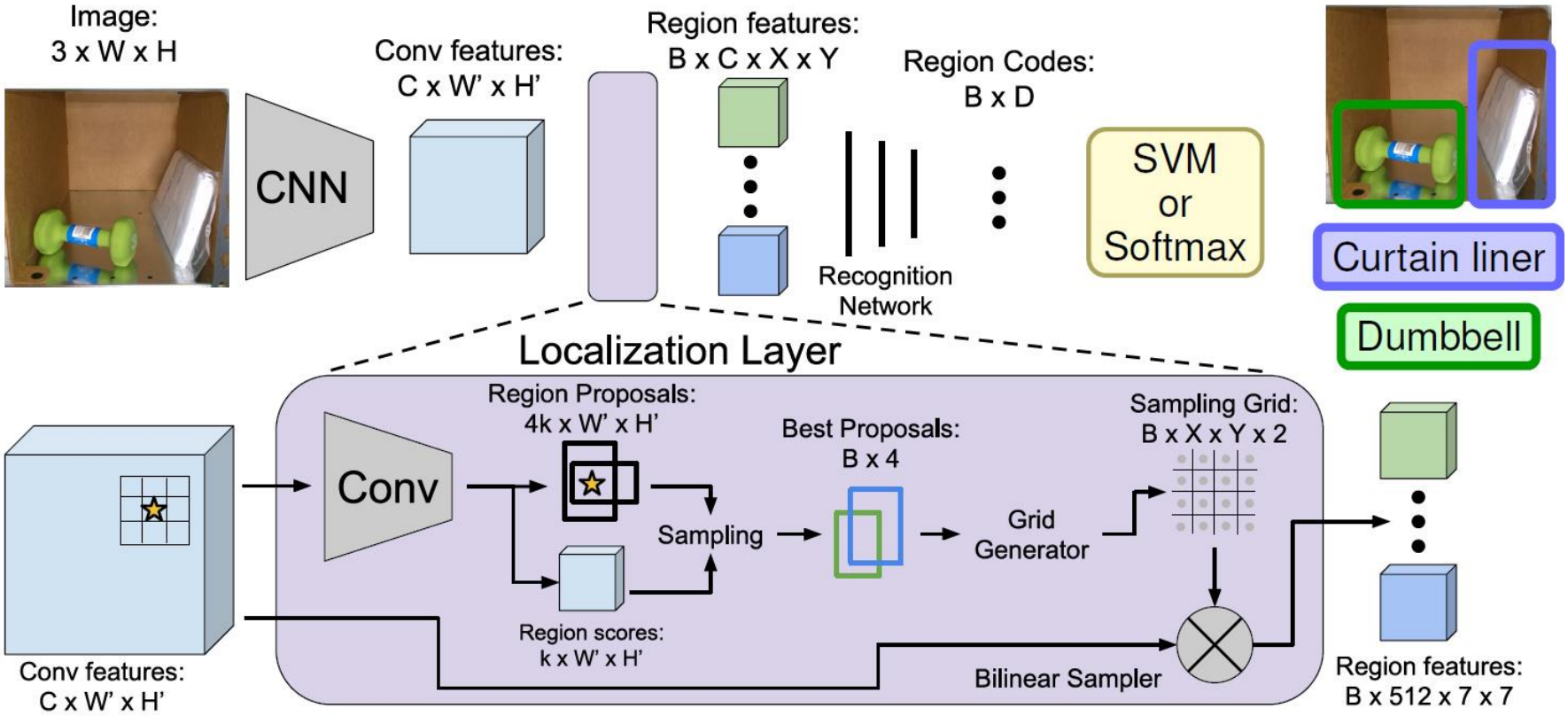
System


Air velocity sensor
2x Intel RealSense SR300
+ LED light
Bendable
suction finger
Linear actuator
Total:
6+2 DOF
UR 10 Arm (6 DOF)
Suction strength control
Strong vacuum
cleaner (3100 W)

RGB-D Cameras

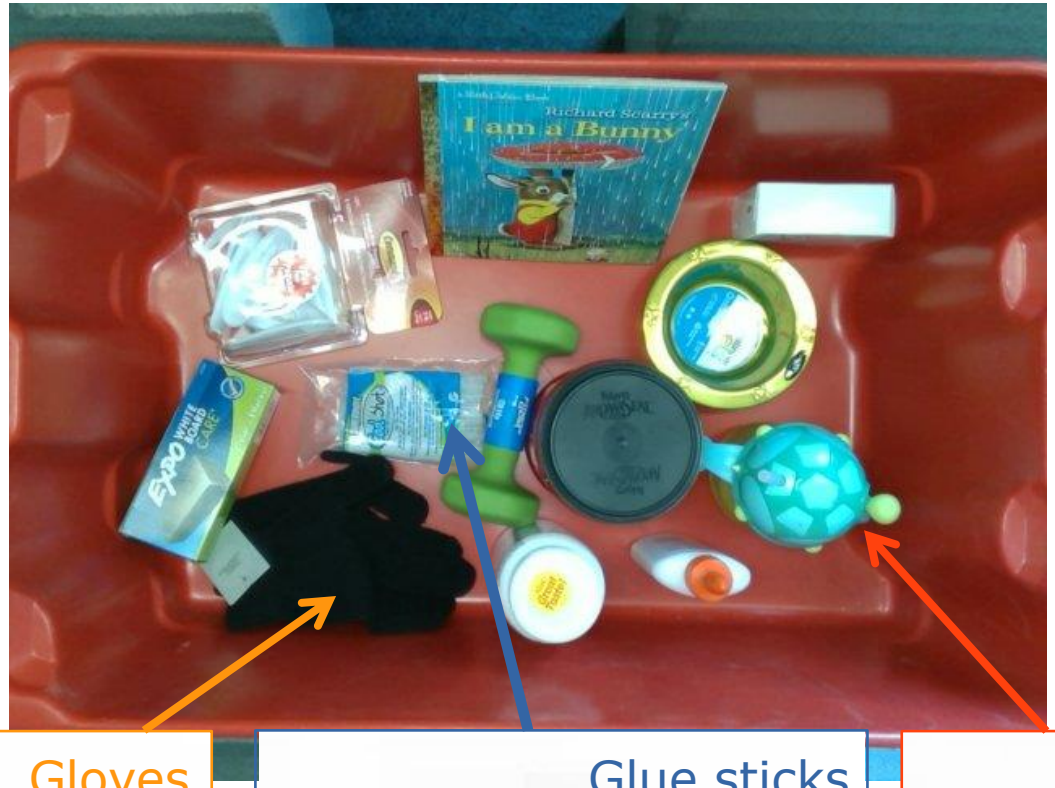
- 2x Intel RealSense SR300
- Fusion of three depth estimates per pixel (including RGB stereo)

Object Detection



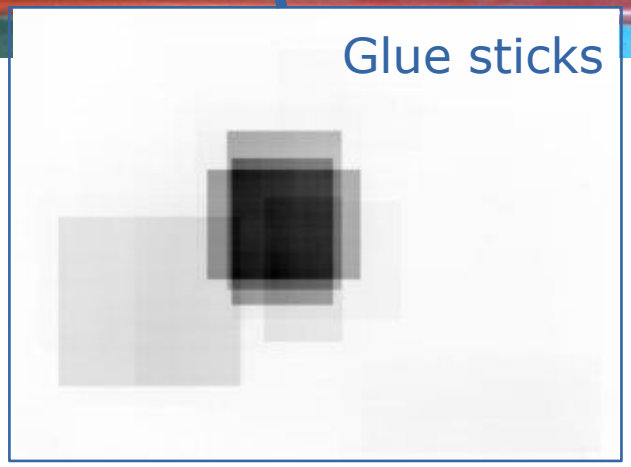
[Adapted from Johnson et al. CVPR 2016]

Example Detections



Gloves

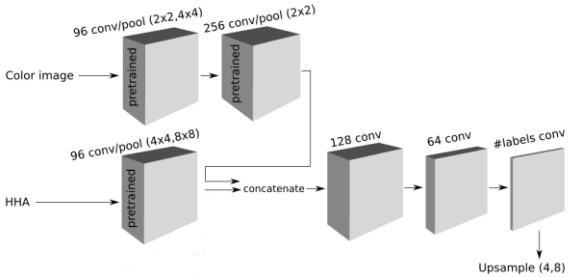
Glue sticks



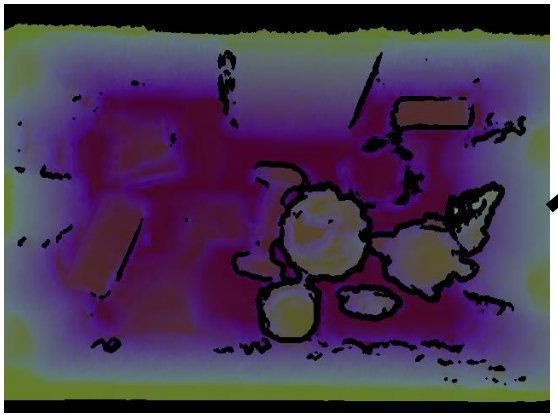
Sippy cup

Semantic Segmentation

- Deep Convolutional Neural Network



RGB



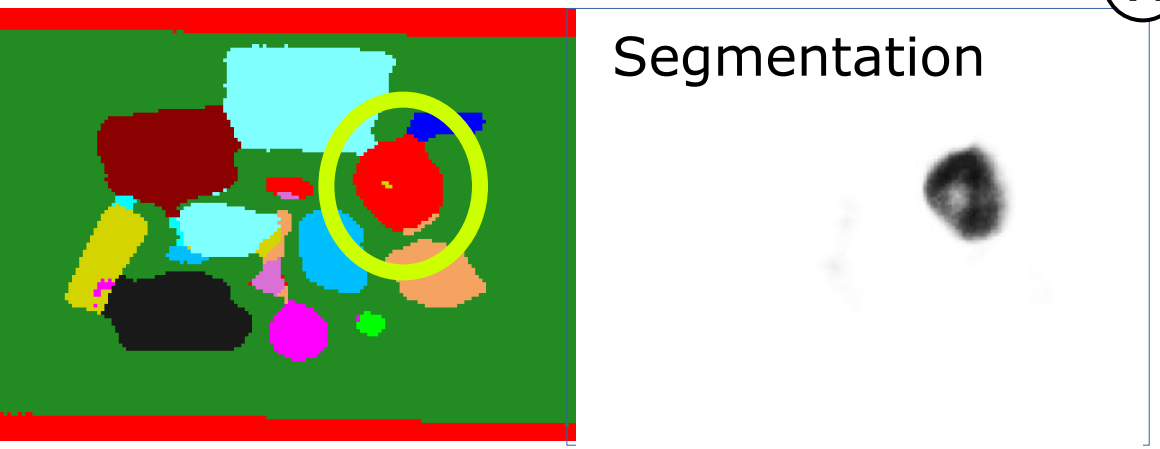
HHA

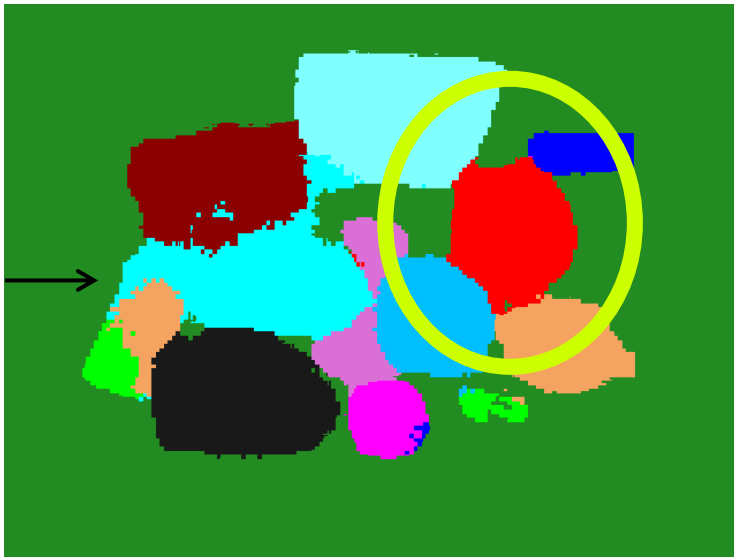
Result

[Husain et al. RA-L 2016]

Combined Detection and Segmentation

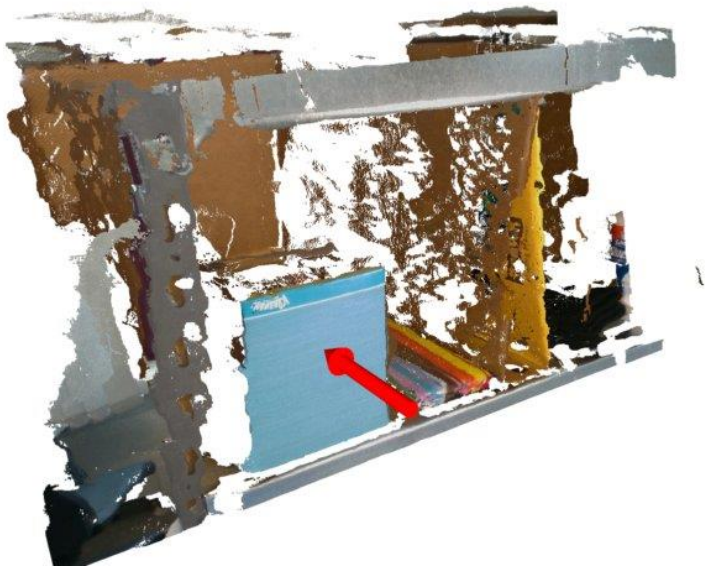
- Pixel-wise multiplication





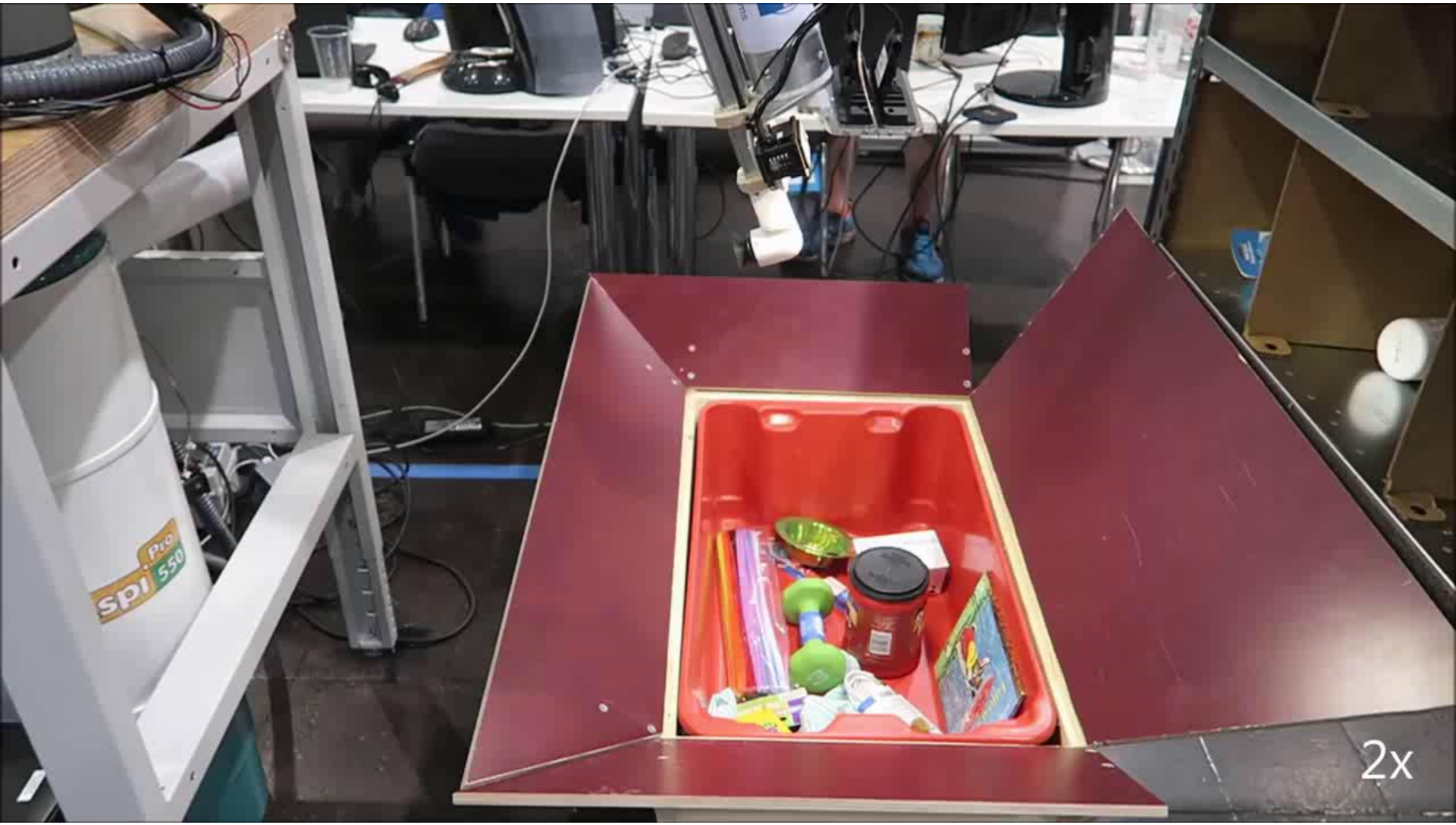
Grasp Pose Selection

- Center grasp for “standing” objects:
  - Find support area for suction close to bounding box center



- Top grasp for “lying” objects:
  - Find support area for suction close to horizontal bounding box center

Example Stowing Top Grasp



Example Picking Grasps

6D Pose Estimation

- Capture item on turn table
- Build 3D model
- Generate proposals
- Register to test image

[Aldoma et al., ICRA 2013]

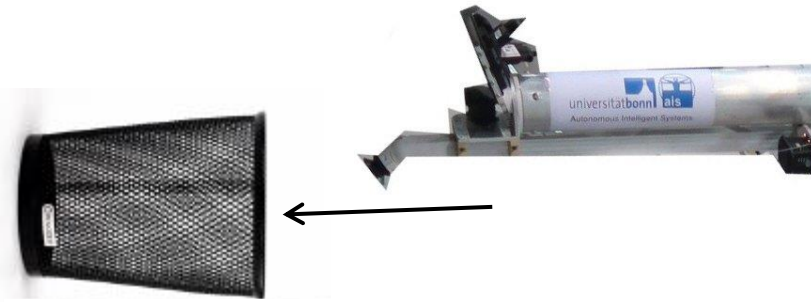
Tricky Items

- Heavy / Large

Ensure that grasp is on **center of mass**!

- Many holes / Meshes

Grasp one ball



Knock over and suck on bottom

Grasping the Pencil Cup

Team NimbRo Picking

- 2nd place stowing, 3rd place picking

Conclusion

- Developed methods for manipulating objects and tool use in
  - Domestic service,
  - Industrial automation,
  - Search and rescue, and
  - Space exploration
- Challenges
  - Variability of objects
  - Space restrictions
  - Task constraints
- Need for further research
  - Gripper design
  - Perception
  - Grasp planning
  - Learning

Thanks for your attention!

Questions?