Anthropomorphic Robots for Disaster Response

Sven Behnke
Autonomous Intelligent Systems
Robot Competitions

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

RoboCup Soccer
RoboCup @Home
DARPA Robotics Challenge
DLR SpaceBot Cup

Behnke: Anthropomophic Robots for Disaster Response
DARPA Robotics Challenge

- Motivated by Fukushima

Behnke: Anthropomorphic Robots for Disaster Response
Mobile Manipulation Robot Momaro

- Four compliant legs ending in pairs of steerable wheels
- Anthropomorphic upper body
- Sensor head

[Schwarz et al. Journal of Field Robotics 2016]
Driving a Vehicle

[Schwarz et al. Journal of Field Robotics 2016]
Behnke: Anthropomorphic Robots for Disaster Response
Momaro Leg Design

- Robotis Dynamixel Pro Actuators
  - Hip, knee: 44 Nm
  - Ankle pitch: 25 Nm
  - Ankle yaw: 6 Nm
  - Wheel drive: 2 × 6 Nm
- Carbon composite springs in links
- Omnidirectional driving
- Base height and attitude changes
- Terrain adaptation
- Making steps

[Schwarz et al. Journal of Field Robotics 2016]
Egress

[Schwarz et al. Journal of Field Robotics 2016]

Behnke: Anthropomorphic Robots for Disaster Response
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

[Schwarz et al. Journal of Field Robotics 2016]
Behnke: Anthropomorphic Robots for Disaster Response
Manipulation Operator Interface

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

[Rodehutskors et al., Humanoids 2015]
Opening a Door

[Schwarz et al. Journal of Field Robotics 2016]

Behnke: Anthropomorphic Robots for Disaster Response
Local Multiresolution Surfel Map

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

[Droeschel et al., Robotics and Autonomous Systems 2016]
Filtering Dynamic Objects

- Maintain occupancy in each cell

[Droeschel et al., Robotics and Autonomous Systems 2016]
Allocentric 3D Mapping

- Registration of egocentric maps by graph optimization

[Droeschel et al., Robotics and Autonomous Systems 2016]
Valve Turning Interface

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

[Schwarz et al. Journal of Field Robotics 2016]
Turning a Valve

[Schwarz et al. Journal of Field Robotics 2016]

Behnke: Anthropomorphic Robots for Disaster Response
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

[Schwarz et al. Journal of Field Robotics 2016]
Operating a Switch

[Schwarz et al. Journal of Field Robotics 2016]

Behnke: Anthropomorphic Robots for Disaster Response
Plug Task at DRC

[Schwarz et al. Journal of Field Robotics 2016]

Behnke: Anthropomorphic Robots for Disaster Response
Debris Task

[Schwarz et al. Journal of Field Robotics 2016]
Behnke: Anthropomorphic Robots for Disaster Response
Drive Through Debris

[Schwarz et al. Journal of Field Robotics 2016]

Behnke: Anthropomorphic Robots for Disaster Response
Cutting Drywall

[Schwarz et al. Journal of Field Robotics 2016]

Behnke: Anthropomorphic Robots for Disaster Response
Team NimbRo Rescue

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

[Schwarz et al. Journal of Field Robotics 2016]
Behnke: Anthropomorphic Robots for Disaster Response
Stair Climbing

- Determine leg that most urgently needs to step
- Weight shift
  - Move the base relative to the wheels in sagittal direction
  - Drive the wheels on the ground relative to the base
  - Modify the leg lengths (and thus the base orientation)
- Step to first possible foot hold after height change

[Schwarz et al., ICRA 2016]
Stair Crawling

[Schwarz et al., ICRA 2016]

Behnke: Anthropomorphic Robots for Disaster Response
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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Left grasp</td>
<td>0:44</td>
<td>0:38</td>
<td>0:27</td>
<td>1:20</td>
<td>0:16</td>
</tr>
<tr>
<td>Right grasp</td>
<td>0:45</td>
<td>0:40</td>
<td>0:34</td>
<td>1:04</td>
<td>0:10</td>
</tr>
<tr>
<td>Connect</td>
<td>1:36</td>
<td>1:32</td>
<td>1:07</td>
<td>2:04</td>
<td>0:21</td>
</tr>
<tr>
<td>Total</td>
<td>3:04</td>
<td>2:57</td>
<td>2:21</td>
<td>3:51</td>
<td>0:28</td>
</tr>
</tbody>
</table>

[Rodehutskors et al., Humanoids 2015]
DLR SpaceBot Cup 2015

- Mobile manipulation in rough terrain

[Schwarz et al., Frontiers on Robotics and AI 2016]
Behnke: Anthropomorphic Robots for Disaster Response

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

3D Mapping & Localization

Mission plan

Navigation plan

Object perception

Grasping

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

Behnke: Anthropomorphic Robots for Disaster Response
Navigation Planning

- Costs from local height differences
- A* path planning

[Schwarz et al., Frontiers in Robotics and AI 2016]
3D Map of Disaster-like Scene

[Droeschel et al., Robotics and Autonomous Systems 2016]
Considering Robot Footprint

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

[Klamt and Behnke, under review]
3D Driving Planning $(x, y, \theta)$: A*

- 16 driving directions
- Orientation changes

$\Rightarrow$ Obstacle between wheels

[Klamt and Behnke, under review]
Making Steps

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

[Klamt and Behnke, under review]
Hybrid Driving-Stepping Plan

Path Planning Example

Scenario: Momaro has to step up a height difference and manoeuvre around a small wall.

[Klamt and Behnke, under review]
Detailed Realization of Steps

[Klamt and Behnke, under review]

Behnke: Anthropomorphic Robots for Disaster Response
Semantic Terrain Classification

Disparity map (from registered Velodyne scans)

RGB image

Geometric classifier

Visual classifier

Fused classifier

Classes
- Drivable (blue)
- Rough (yellow)
- Obstacle (red)

[Chen, Schilling et al.]
Upgraded Sensor Head

- Continuously rotating Velodyne Puck VLP-16
  - 300,000 3D points/s
  - 100 m range
  - Spherical field of view
- Three wide-angle color cameras (total FoV $210 \times 103^\circ$)
- Kinect V2 RGB-D camera on pan-tilt unit
3D Map of Indoor+Outdoor Scene

[Droeschel et al., Robotics and Autonomous Systems 2016]
3D Map of Indoor+Outdoor Scene

[Droeschel et al., Robotics and Autonomous Systems 2016]
3D Map of Indoor+Outdoor Scene

[Droeschel et al., Robotics and Autonomous Systems 2016]

Behnke: Anthropomorphic Robots for Disaster Response
Global and Local Navigation

Navigation in allocentric laser map (colored points)
Using a Wrench to Turn a Valve
Manipulation Trajectory Optimization

- Extended stochastic trajectory optimization (STOMP)
- 8 DoF (including torso yaw)
- Weighting multiple objectives
- Speed limits depend on distance to obstacles

[Pavlichenko et al.]
Momaro Reaching for an Object

[Pavlichenko et al.]
Behnke: Anthropomorphic Robots for Disaster Response
Workspace Perception Data Set

129 frames, 6 object classes

https://www.centauro-project.eu/data_multimedia/tools_data
Deep Learning Object Detection

- Adapted DenseCap [Johnson et al. 2015] pipeline

- Transfer learning needs only few annotated images
  
  [Schwarz et al.]

Behnke: Anthropomorphic Robots for Disaster Response
Tool Detection Results

Average precision:

<table>
<thead>
<tr>
<th>Min overlap</th>
<th>Clamp</th>
<th>Door handle</th>
<th>Driller</th>
<th>Extension box</th>
<th>Stapler</th>
<th>Wrench</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>81.2</td>
<td>21.7</td>
<td>80.7</td>
<td>100.0</td>
<td>85.2</td>
<td>57.6</td>
</tr>
<tr>
<td>0.2</td>
<td>93.3</td>
<td>67.6</td>
<td>97.0</td>
<td>100.0</td>
<td>95.2</td>
<td>85.7</td>
</tr>
</tbody>
</table>

[Schwarz et al.]

Behnke: Anthropomorphomic Robots for Disaster Response
Tool Detection Examples
Semantic Segmentation

- **Deep CNN**

[Husain et al. RA-L 2016]

Pixel-wise accuracy:

<table>
<thead>
<tr>
<th></th>
<th>Clamp</th>
<th>Door handle</th>
<th>Driller</th>
<th>Extension box</th>
<th>Stapler</th>
<th>Wrench</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>92.0</td>
<td>83.3</td>
<td>93.1</td>
<td>98.8</td>
<td>98.5</td>
<td>88.9</td>
</tr>
</tbody>
</table>
3D Object Modeling and 6D Pose Estimation

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

[Aldoma et al., ICRA 2013]

Behnke: Anthropomorphic Robots for Disaster Response
Schunk SVH

- Anthropomorphic hand
- 9 DoF
Conclusion

- Compliant wheeled-legged base
  - Large adjustable support polygon
  - Omnidirectional driving
  - Terrain adaptation, weight shift, steps
- Anthropomorphic upper body
  - Human-like manipulation
  - Bimanual handling of large objects
  - Tool use
- Teleoperation is flexible, but demanding and error-prone
- Developing autonomy for common navigation and manipulation tasks