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Increasing Flexibility of Mobile Manipulation and Intuitive Human-Robot Interaction in RoboCup@Home

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Abstract. In this paper, we describe system and approaches of our team NimbRo@Home that won the RoboCup@Home competition 2013. We designed a multi-purpose gripper for grasping typical household objects in pick-and-place tasks and also for using tools. The tools are complementarily equipped with special handles that establish form closure with the gripper, which resists wrenches in any direction. We demonstrate tool use for opening a bottle and grasping sausages with a pair of tongs in a barbecue scenario. We also devised efficient deformable registration methods for the transfer of manipulation skills between objects of the same kind but with differing shape. Finally, we enhance human-robot interaction with a remote user interface for handheld PCs that enables a user to control capabilities of the robot. These capabilities have been demonstrated in the open challenges of the competition. We also explain our approaches to the predefined tests of the competition, and report on the performance of our robots at RoboCup 2013.

1 Introduction

The RoboCup@Home league [1, 2] aims at fostering research in intelligent robots that perform tasks in the environments of our daily living. Since 2009, we participate with our team NimbRo@Home and won the competitions in 2011, 2012, and 2013. Our robot system joins lightweight but versatile hardware design with software skills for indoor navigation, mobile manipulation, and human-robot interaction.

At the 2013 RoboCup competition, our robots demonstrated novel abilities in object manipulation: tool use and skill transfer. We also continued the development of a remote user interface for handheld PCs. In this paper, we detail our robotic system and our approaches to perform the predefined tests of the competition as well as the aforementioned novelties.

2 The RoboCup@Home Competition 2013

In the RoboCup@Home competition [3], teams proceed through two stages to select the top five teams that participate in the final. The two stages consist of tests with predefined procedures and open demonstrations in which the teams can show the best of their own research. An additional technical challenge award can be achieved. This year's technical challenge tested the specific capability of recognizing and localizing furniture-type objects. The final is an open demonstration that is judged by an expert jury.

In the predefined tests, basic skills in mobile manipulation and human-robot interaction have to be demonstrated. The robots need to perform the tests at a scheduled time and within a specific time limit. The detailed arena setup is not known to the participants beforehand, but they have to take approaches that robustly work in typical everyday environments. The predefined tests allow for an objective score evaluation according to the achieved sub-tasks. Open demonstrations are evaluated by a jury that is composed of team leaders, or members from the league's executive committee, science, industry, or media.

The *Robot Inspection and Poster Session* is the first test in Stage 1. It tests navigation capabilities of the robots, its visual appearance and safety. In the *Follow Me* test, the robots must keep track of a previously unknown guide in an unknown (and crowded) environment. As in 2012, the robots have to keep track of the guide despite distractions, follow the guide in and out an elevator and find the guide behind a crowd. *Clean Up* tests object recognition and grasping capabilities of the robots. They have to retrieve as many objects as possible within the time limit, recognize their identity, and bring them to their designated locations. The *Cocktail Party* test is set in a butler scenario, where the robot gets called by three persons, learns their identity, and delivers drink orders to them. In the *Emergency Situation* test, a fire in the appartment is simulated. The robot has to detect the fire, and find persons that either stand, sit or lie on the ground and help them out of the appartment. The *Open Challenge* is the open demonstration of Stage 1. Teams can freely choose their 7 min demonstration.

The best 50% teams proceed to stage 2. The *Enduring General Purpose Service Robot* test has been changed from the 2012 test to last over an extended period of time (40 min). Three robots perform the test concurrently in the arena. The robots must understand and execute complex, incomplete, or erroneous speech commands given by an unknown speaker. The commands can be composed from actions, objects, and locations of the regular Stage 1 tests. In the *Restaurant* test, the robots are deployed in a previously unknown real restaurant, where a guide makes them familiar with drink, food, and table locations. Afterwards, the guide gives an order to deliver three objects. The *Demo Challenge* follows the theme "health care" and is an open demonstration.

3 Hardware Design

We designed our service robot Cosero [4] to cover a wide range of tasks in human indoor environments (see Fig. 1). It has been equipped with a flexible torso and

Fig. 1. The cognitive service robot *Cosero*. Left: Cosero receives a pair of tongs during the final of the RoboCup@Home competition 2013 in Eindhoven. Right: Cosero pushes a chair to its location during the Demo Challenge.

two anthropomorphic arms that provide human-like reach. A linear actuator moves the whole upper body up and down, allowing the robot to grasp objects from a wide range of heights—even from the floor. Its anthropomorphic upper body is mounted on a mobile base with narrow footprint and omnidirectional driving capabilities. By this, the robot can maneuver through narrow passages that are typically found in indoor environments, and it is not limited in its mobile manipulation capabilities by holonomic constraints. The human-like appearance of our robots also supports intuitive interaction of human users with the robot.

Cosero's grippers consist of two pairs of Festo FinGripper fingers on rotary joints (see Fig. 1). When the gripper is closed on an object, the bionic fin ray structure of the fingers adapts its shape to the object surface. By this, the contact surface between fingers and object increases significantly, compared to a rigid mechanical structure. A thin layer of anti-skidding material on the fingers establishes a robust grip on objects. By having two fingers on each side of the gripper, it supports stable grasps for torques in the direction of the fingers, and forces in the direction between opponent fingers.

For perceiving its environment, we equipped the robot with diverse sensors. Multiple laser scanners on the ground, on top of the mobile base, and in the torso measure objects, persons, or obstacles for navigation purposes. We use a Microsoft Kinect RGB-D camera in the head to perceive tabletop objects and persons.

4 Mobile Manipulation

Several regular tests in the RoboCup competition involve object handling, for which objects are usually placed separated on horizontal surfaces such as tables and shelf layers. The robot needs to drive to object locations, to perceive the objects, and to grasp them. We develop further manipulation capabilities, especially object manipulation skill transfer and tool use, that we demonstrate in open demonstrations.

4.1 Indoor Navigation

Our robots navigate in indoor environments on horizontal surfaces. Hence, we use the 2D laser scanner on the mobile base as the main sensor for navigation. We acquire 2D occupancy maps of the environment using simultaneous localization and mapping (gMapping, [5]). The robots localize in these 2D maps using Monte Carlo localization [6]. They navigate to goal poses by planning obstacle-free paths in the environment map, extracting waypoints, and following them.

Obstacle-free local driving commands are derived from paths that are planned towards the next waypoint in a local collision map. We incorporate 3D measurements of all distance sensors of our robots. The point measurements are maintained in an ego-centric 3D map and projected into a 2D occupancy grid map for efficient local planning.

4.2 Object Perception and Manipulation

Grasping objects from flat surfaces is a fundamental capability for which we developed efficient object detection and grasping methods [7]. Our object detection approach finds objects on planar segments and processes 160×120 range images at about 20 Hz. It relies on fast normal estimation using integral images and efficient RANSAC plane estimation. Points above detected planes are clustered to objects. We consider two kinds of grasps on objects: top grasps that approach low objects from above and side grasps that are suitable for vertically elongated objects such as bottles or cans. We plan grasps by first computing grasp candidates on the raw object point cloud as perceived by the RGB-D camera. The grasp candidates are filtered for collisions during the execution of the grasping motion and are ranked to find the best grasp according to several convenience and stability criteria. The best grasp is finally executed using a parametrized motion primitive for either kind of grasp.

Our robots recognize objects by matching SURF interest points [8] in RGB images to an object model database and by enforcing spatial consistency between the features. In addition to the SURF feature descriptor, we store feature scale, feature orientation, relative location of the object center, and orientation and length of principal axes in the model. During recall, we efficiently match features between an image and the object database according to the descriptor using kd-trees. Each matched feature then casts a vote to the relative location, orientation, and size of the object. We consider the relation between the feature scales and orientation of the features to achieve scale- and rotation-invariant voting. When unlabeled object detections are available through planar RGB-D segmentation (see above), we project the detections into the image and determine the identity of the object in these regions of interest.

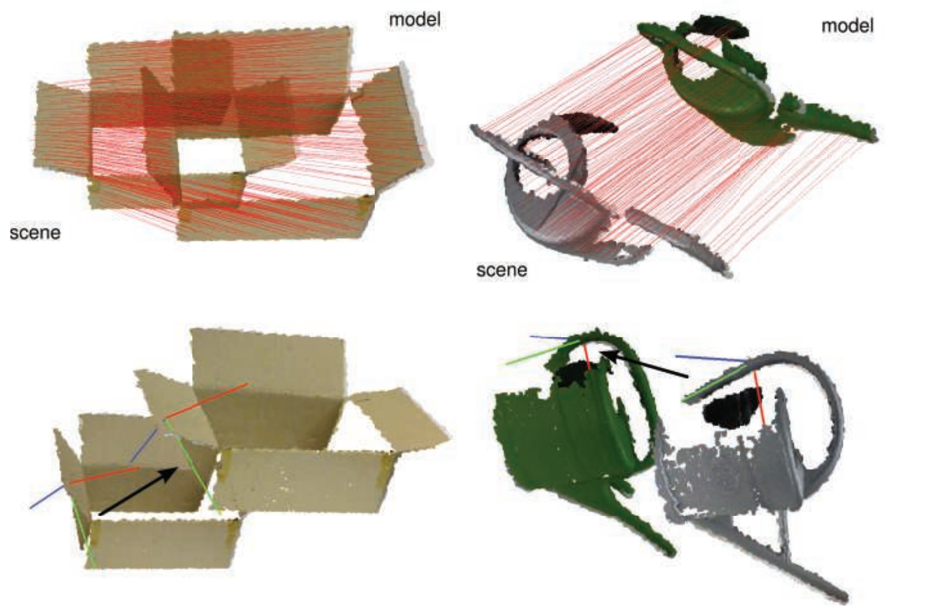

Fig. 2. Deformable registration for object manipulation skill transfer. Top: Deformable registration between two differently shaped watering cans and deformed instances of a box. Bottom: Local transformations estimated at selected points between the objects.

Our robots also support placing objects on planar surfaces and throwing objects into trash bins.

4.3 Object Manipulation Skill Transfer

In previous years, we showcased object perception and manipulation based on the tracked pose of the objects such as cooking plates, chairs, and watering cans. The manipulation skills were tailored to specific instances of the object. This year, we have shown how manipulation capabilities designed for a specific object instance can be transfered to other instances of the same class but with different shape. For this purpose, we developed efficient deformable registration between the shape of a perceived object with a model object (see Fig. 2).

We propose a multi-resolution extension to the coherent point drift (CPD) method [9] to deformably register RGB-D images efficiently. Instead of processing the dense point clouds of the RGB-D images directly, we utilize multi-resolution surfel maps (MRSMaps) [10] to perform deformable registration on an aggregated image representation. This image representation stores the joint color and shape statistics of points within 3D voxels (coined surfels) at multiple resolutions in an octree. The maximum resolution at a point is limited proportional to its squared depth according to the disparity-dependent noise of the RGB-D camera.

Fig. 3. Tool Adapters. We designed special adapters for tools to establish stable grasps that resist forces and torques in any direction. Left: Adapter attached to bottle opener. Center: Cosero's gripper design. Right: Grasp on the bottle opener adapter.

In effect, the map exhibits a local multi-resolution structure which well reflects the accuracy of the measurements and compresses the image from 640×480 pixels into only a few thousand surfels. We also support the aggregation of multiple images into a single MRSMap, in effect overlaying the local multi-resolutions of the individual images.[1] We further improve the run-time performance of the CPD algorithm by aligning maps from coarse to fine resolutions. The registration on finer resolutions is initialized from the result on the coarser one. In addition to depth, we also utilize cues such as color and contours.

For the integrated skill transfer demonstration, we first segment the object of interest in the RGB-D image using techniques such as support-plane segmentation [7]. The RGB-D image segment is then transformed into a MRSMap and a reference object model MRSMap is aligned with the image. The grasp poses and motion trajectories are defined in terms of local coordinate frames relative to the object's reference frame. We assume that the poses and trajectories are close to the reference object's surface, and, hence, we find the local rigid transformation from the reference object towards the image segment. Finally, the motions are executed according to the transformed grasp and motion trajectories. Further details can be found here [11].

4.4 Tool Use

We implemented skills for using a bottle opener and a pair of tongs in a barbecue scenario. For a firm grip on the tool that can also resist torques along the finger direction, we augment the tools with specialized adapters (see Fig. 3). When the gripper is closed on the adapter, the fingers bend around the shape of the adapter and establish form closure. The ridge in the center of the adapter fits between the space of the fingers. It fixates the adapter for exerting torques in pitch direction. For some tools such as pairs of tongs, the opening of the gripper is also used to operate the tool. To create form closure with the fingers at various opening angles of the fingers, the adapters are equipped with flat springs for each finger.

[1] Our MRSMap implementation is available open-source from http://code.google.com/p/mrsmap/ .

Fig. 4. Tool perception. For the opening of a bottle with a bottle opener tool, Cosero perceives the tip of the bottle and the tip of the tool.

Simple open-loop control is not feasible for tool use due to several sources of imprecisions. Firstly, an exact calibration between the robot's sensors and its end effector may not be known. Also, the pose of the tool in the gripper or the manipulated object cannot be assumed to be known precisely. We therefore implemented perception of the tips of the tool and the manipulated object using the head-mounted RGB-D camera (see Fig. 4). During manipulation, Cosero looks at the tool and the manipulated object, segments the objects from the surrounding using our efficient segmentation method (see Sec. 4.2), and detects the endings of the objects in the segments. For grasping sausages from a plate or a barbecue, we segment the sausages using plane segmentation and adapt the grasping motion to the position and orientation of the sausages. An adaptive motion then uses this information to perform the skill.

5 Human-Robot Interaction

A key prerequisite for a robot that engages in human-robot interaction is awareness of the whereabouts of people in its surrounding. We combine complementary information from laser scanners and vision to continuously detect and keep track of people. Using the VeriLook SDK, we implemented a face enrollment and identification system.

Our robots interact naturally with humans by means of speech, gestures, and body language. For speech, we use the Loquendo SDK. Its speech synthesis supports colorful intonation and sounds natural. Loquendo's speech recognition is speaker independent and is based on predefined grammars that we attribute with semantic tags for natural language understanding. The robots also support the interpretation [12] and synthesis of gestures.

Physical interaction between users and the robot occurs, for instance, when handing objects over, or when collaboratively working with objects. A key feature for this kind of interaction is compliant control of the arms [13, 14]. When handing an object over to the user, the robot keeps the end effector compliant in the forward and upward direction such that the user can reach for the object and pull it. The robot detects the pulling and releases the object.

5.1 Specification of Tasks by Spoken Dialogue

Our robots support spoken dialogues for specifying complex commands that sequence multiple skills. The ability to understand complex speech commands, to execute them, to detect failures, and to plan alternative actions in case of failures is assessed in the *Enduring General Purpose Service Robot* test.

We decompose skill-level capabilities into a set of primitive skills that each are attributed only with a single object and/or location. The skill navigate_to_location, for example, depends on a goal location, while fetch_object_from_location both is determined through a target object and an object location.

The robot knows a set of specific objects with attached object labels which are used in spoken commands. Known specific objects are included in the visual object recognition database. It is also possible to define an unspecific object using labels such as "unknown", "some object", or the label of an object category (e.g., "tool"). If multiple skills with object references are chained, the reflexive pronoun "it" refers to the last object that occurred in the task command. Hence, objects are referred to by labels and may have the additional attributes of being specific, unspecific, and reflexive. Persons are handled in a similar way, but the notion of a person category is not included in our system. Our robots can enroll new persons and link their identity with their face appearance in the database of known persons.

Specific locations, location categories, unspecific locations, or location-specific adjectives (like "back") can be indicated by the user as well. We provide sets of navigation goal poses for specific locations as well as location categories. Different lists of poses are used for the purposes of object search, exploration for persons, or simple presence at a spot.

We utilize semantic tags in Loquendo's grammar specification to implement action, object, and location semantics in speech recognition. We appropriately designed the grammar such that recognition provides its semantic parse tree as a list of actions with attributed objects and locations.

Behavior control interprets the recognized semantic parse tree and sequences actions in a finite state machine. The robot executes this state machine and reports progress through speech synthesis. In case of a failure (e.g., desired object not found), the failure is recorded, the robot returns to the user, and reports the error through speech.

5.2 Convenient Remote User Interfaces

We develop handheld user interfaces to complement natural face-to-face interaction modalities [15, 16]. Since the handheld devices display the capabilities and perceptions of the robot, they improve common ground between the user and the robot (see Fig. 5). They also extend the usability of the robot, since users can take over direct control for skills or tasks that are not yet implemented with autonomous behavior. Finally, such a user interface enables remote interaction with the robot, which is especially useful for immobile persons.

Fig. 5. Handheld user interface. Top left: Complete GUI with a view selection column on the left, a main view in the center, and a configuration column on the right. Top right: The user composes a task as several skills in a sequence by selecting skills from a list and configuring the involved objects and locations. Lower right: 3D external view. Lower middle: The navigation view displays the map, the estimated location, and the current path of the robot. Lower right: The sensor view displays laser scans and the field-of-view of the RGB-D camera in the robot's head.

The user interface supports remote control of the robot on three levels of autonomy. The user can directly control the drive and the gaze using joystick-like control UIs or touch gestures. The user interface also provides selection UIs for autonomous skills such as grasping objects or driving to locations. Finally, the user can configure high-level tasks such as fetch and delivery of specific objects.

The user interface is split into a main interactive view in its center and two configuration columns on the left and right side (see Fig. 5, top). One view displays live RGB-D camera images with object perception overlays (Fig. 5, top left). The user may change the gaze of the robot by sweep gestures, or select objects to grasp. A further view visualizes laser range scans and the field-of-view of the RGB-D camera (Fig. 5, bottom right). The navigation view shows the occupancy map of the environment, the pose of the robot, and its current path (Fig. 5, bottom center). Finally, we also render a 3D external view (Fig. 5, bottom left). The user can also choose to execute navigation or object manipulation skills. For fetching an object, for instance, the user either selects a specific object from a list, or chooses a detected object in the current sensor view.

High-level tasks such as fetch and delivery can be configured in a task specification UI (Fig. 5, top right). The task-level teleoperation UI is intended to provide the high-level behavior capabilities of the robot. These behaviors sequence multiple skills in a finite state machine. The user can compose actions, objects, and locations similar to a speech-based implementation of the parsing of complex speech commands as detailed in Sec. 5.1.

6 Results and Lessons Learned at RoboCup 2013

6.1 Competition Results

On the first competition day, our robots Cosero and Dynamaid [4] went through the inspection and registration test. Together with a poster presentation of the team, we achieved the highest score in this test. In the *Follow Me* test, Cosero lost track of the guide when a person was closely walking in front of the guide, such that we could not score. Cosero demonstrated that it could recognize the names of persons in the *Cocktail Party* test. In *Clean Up*, Cosero found two objects and brought one of it to its correct place. It got the highest score in this test, while only two out of 21 teams could score at all. The new *Emergency Situation* test was tackled by many teams. Here, Cosero achieved the third best score by finding a standing person, asking, if he requires help, and guiding him to the exit. Stage 1 was concluded by the *Open Challenge*, in which Cosero demonstrated the usage of a watering can, while we had predefined grasps and watering motion for another instance of cans. Cosero estimated the shape deformation between the two object instances, and transfered the manipulation skill to the new can. It grasped the watering can from a table, watered a plant, and placed the watering can back. Afterwards, Cosero was intended to push a chair to its location, but could not reach a good position for grasping it. The demonstration was well received by the jury of team members, and received 1361 points, only 11 points behind the team WrightEagle@Home from China. After Stage 1, we were closely behind team WrightEagle@Home which had about 2 % advantage in points.

Stage 2 began with the *Enduring General Purpose Service Robot* test. Cosero understood a complex speech command, fetched an object, and delivered it. A second command with missing information was also understood, for which it asked questions to retrieve the missing information. We achieved the best score in the test. In the *Restaurant* test, Cosero was shown the environment and the location of food and drinks, which it later found again. Cosero gained the second best score, behind WrightEagle@Home. The last test in Stage 2 was the *Demo Challenge*. We demonstrated a care scenario, in which the robot extended the mobility of a user with its mobile manipulation capabilities. Cosero moved a chair to its location and attempted to open a bottle. We also showed our teleoperation interface to the jury.

We reached the finals on the second place with 98% of the score of team WrightEagle@Home. In the final, Cosero demonstrated tool use. He used a pair of tongs to cook a sausage on a barbecue and a bottle opener to open a beer that he served to a person. This demonstration convinced the high-profile jury which awarded the highest number of points. Together with the results of Stage 1 and 2, the final normalized score was 99 points for NimbRo, followed by WrightEagle@Home (China, 86 points) and TU Eindhoven (Netherlands, 73 points).

6.2 Lessons Learned

Developing complex service robot systems as tested in the RoboCup@Home league is a challenge. Many individual skills must be integrated into a complete system. Implementing the procedures of the predefined tests is not solely programming a sequence of skills, but the unforeseeable setup of the arena and the unpredictable behavior of persons requires robust navigation, mobile manipulation, and human-robot interaction skills as well as robust high-level behavior control.

The competition tests the generality of the approaches by the teams. Typically, a test fails, if an assumption made during the development is not fulfilled in the actual competition scenario. For instance, in the *Follow Me* test, we did not foresee that the distracting person that crosses between the robot and the guide, would stand very close at the guide and both persons would stop. This made our person tracking approach fail which relies on tracking laser scan features. In future work, we plan to develop person detection and segmentation in RGB-D images, which still is a research challenge in the above situation.

In the *Cocktail Party* test, the place where the robot would get familiar with the persons in the scenario was not well chosen by us. After the persons introduced themselves, the implemented solution was expecting the persons to walk out of sight of the robot to trigger the fetching of the drinks. This problem could be resolved with a better design of the high-level behavior of the robot.

The most complex test is the *Enduring General Purpose Service Robot* test. Our performance demonstrates that we developed a complete system that integrates complex speech processing and person awareness with indoor navigation and mobile manipulation skills. It is a challenge to design dialogue engines and high-level behavior control that can react to all kinds of complex speech commands which involve the many possible actions, objects, locations, and speech expressions.

Our robots performed well in many tests. The fact that our robots won the competition for the third time in a row makes apparent that this is not a coincidence, but we developed a well-balanced and comparably robust system.

7 Conclusions

In this paper, we presented the contributions of our winning team NimbRo to the RoboCup@Home competition 2013 in Eindhoven. We advanced the mobile manipulation capabilities of our robots and demonstrated generalization of object manipulation skills and tool use. Our robots scored in many tests of the competition and came in second to the finals, only a few points behind the leading team WrightEagle@Home. In the final, our robot Cosero convinced the high profile jury with its tool-use skills demonstrated in a barbecue scenario, and won the competition. In future work, we aim at further increasing the robustness and generality of our approaches to navigation, object manipulation, and human-robot interaction.

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References

1. T. van der Zant and T. Wisspeintner. RoboCup X: A proposal for a new league where RoboCup goes real world. In *RoboCup 2005: Robot Soccer World Cup IX*, LNCS 4020, pages 166–172. Springer, 2006.
2. T. Wisspeintner, T. van der Zant, L. Iocchi, and S. Schiffer. RoboCup@Home: Scientific competition and benchmarking for domestic service robots. *Interaction Studies*, 10(3):393–428, 2009.
3. M. R. Elara, D. Holz, L. Iocchi, F. Mahmoudi, J. R. del Solar, J. Stückler, K. Sugiura, S. Wachsmuth, J. Xie, and T. van der Zant. RoboCup@Home: Rules & regulations. http://www.robocupathome.org/rules, 2013.
4. J. Stückler, I. Badami, D. Droeschel, K. Gräve, D. Holz, M. McElhone, M. Nieuwenhuisen, M. Schreiber, M. Schwarz, and S. Behnke. NimbRo@Home: Winning team of the RoboCup@Home competition 2012. In *RoboCup 2012: Robot Soccer World Cup XVI*, Lecture Notes in Computer Science. 2013.
5. G. Grisetti, C. Stachniss, and W. Burgard. Improved techniques for grid mapping with Rao-Blackwellized particle filters. *IEEE Trans. on Rob.*, 23(1):34–46, 2007.
6. D. Fox. KLD-sampling: Adaptive particle filters and mobile robot localization. *Advances in Neural Information Processing Systems (NIPS)*, pages 26–32, 2001.
7. J. Stückler, R. Steffens, D. Holz, and S. Behnke. Efficient 3D object perception and grasp planning for mobile manipulation in domestic environments. *Robotics and Autonomous Systems*, 2012.
8. H. Bay, A. Ess, Tinne Tuytelaars, and Luc Van Gool. Speeded-up robust features (SURF). *Computer Vision and Image Understanding*, 110(3):346–359, 2008.
9. A. Myronenko and Xubo Song. Point set registration: Coherent point drift. *IEEE Trans. on PAMI*, 32(12):2262–2275, 2010.
10. J. Stückler and S. Behnke. Multi-resolution surfel maps for efficient dense 3D modeling and tracking. *Visual Communication and Image Representation*, 2013.
11. J. Stückler and S. Behnke. Efficient deformable registration of multi-resolution surfel maps for object manipulation skill transfer. In *IEEE International Conference on Robotics and Automation (ICRA)*, 2014.
12. D. Droeschel, J. Stückler, and S. Behnke. Learning to interpret pointing gestures with a time-of-flight camera. In *Proceedings of the 6th ACM International Conference on Human-Robot Interaction (HRI)*, 2011.
13. J. Stückler and S. Behnke. Following human guidance to cooperatively carry a large object. In *Proceedings of the 11th IEEE-RAS International Conference on Humanoid Robots (Humanoids)*, pages 218–223, 2011.
14. J. Stückler and S. Behnke. Compliant task-space control with back-drivable servo actuators. *RoboCup 2011: Robot Soccer World Cup XV, Springer LNCS*, 2012.
15. S. Muszynski, J. Stückler, and S. Behnke. Adjustable autonomy for mobile teleoperation of personal service robots. In *Proc. of the IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*, 2012.
16. M. Schwarz, J. Stückler, and S. Behnke. Mobile teleoperation interfaces with adjustable autonomy for personal service robots. In *9th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, 2014.