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Adjustable Autonomy for Mobile Teleoperation of Personal Service Robots

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***Abstract*— Controlling personal service robots is an important, complex task which must be accomplished by the users themselves. In this paper, we propose a novel user interface for personal service robots that allows the user to teleoperate the robot using handheld computers. The user can adjust the autonomy of the robot between three levels: body control, skill control, and task control. We design several user interfaces for teleoperation on these levels. On the higher levels, autonomous behavior of the robot relieves the user from significant workload. If the autonomous execution fails, or autonomous functionality is not provided by the robot system, the user can select a lower level of autonomy, e.g., direct body control, to solve a task. In a qualitative user study we evaluate usability aspects of our teleoperation interface with our domestic service robots Cosero and Dynamaid. We demonstrate the benefits of providing adjustable manual and autonomous control.**

I. INTRODUCTION

Developing personal service robots with a full spectrum of autonomous capabilities in unstructured environments is a complex and ongoing research topic. While dexterous and versatile robot hardware can be built and impressive demonstrations have been achieved by teleoperation, continuous direct control of the robot is tedious and inconvenient for a user. Instead, the user wants to utilize the robot as an efficient tool that operates as autonomous as possible. Only in difficult situations, in which no autonomous solution exists yet, the user should need to take over direct control of the robot.

In this paper, we propose a user interface for handheld computers such as smart phones, tablets, and slates that allows the user to teleoperate a personal service robot on different autonomy levels and to adjust its autonomy. We identified three levels of autonomy: body level, skill level, and task level autonomy.

On the body level, the user directly controls the motion of body parts such as the drive, the gaze, or the end-effectors. Since the robot provides a set of autonomous skills such as grasping or navigating to a goal pose, the user can configure these skills and trigger their execution on the skill level. Finally, a user interface on the task level composes tasks by configuring sequences of available skills.

We developed the proposed teleoperation interfaces for our domestic service robots Cosero and Dynamaid and evaluated our implementation in a qualitative user study that measured usability factors such as learnability, efficiency, and situational awareness.

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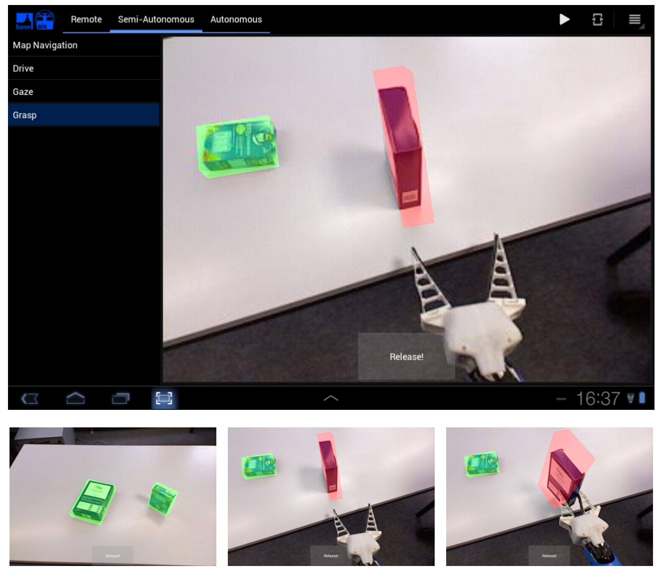

Fig. 1. Skill-level teleoperation user interface for grasping. Top: The UI highlights detected objects by overlaying 3D bounding boxes. The user can select one of the objects by touching it (green: unselected, red: selected). A button at the bottom center lets the user release the object again. Bottom: Sequence from example usage.

II. RELATED WORK

Goodrich et al. [1] introduced the notion of adjustable autonomy. For a navigation task, they noticed that robot effectiveness is highest for direct teleoperation, which requires constant human supervision. When the supervision has some time delay (due to communication latencies or operator neglect), direct teleoperation performance drops sharply. On the other end of the spectrum, fully autonomous behavior is less effective, but does not degrade with neglect. Between these extremes, they proposed different levels of autonomy that give the robot some degree of self-control to reach user-specified subgoals. These approaches tolerate higher neglect times and the performance drop is less sharp, compared to direct teleoperation.

One fundamental question in adjustable autonomy is the adjustment of the level of autonomy. Tambe et al. [2] proposed an optimization approach based on Markov Decision Processes for the transfer of control between agents.

For the problem of driving multiple vehicles, Fong et al. [3] proposed collaborative control, an approach in which humans and robots collaborate to achieve common goals. The human and the robot engage in dialog to exchange information and use each other as a resource to compensate for limitations of autonomy.

Goodrich et al. [4] investigated two managing styles for operating multiple robots. In the sequencing style, the human sequentially attends to individual robots, giving them instructions and then neglecting them for a period of time. In the playbook-style, the human manages clusters or sub-teams of agents, and issues high-level directives that the agents implement in a coordinated manner. The human must plan and select relevant plays, identify agents to cluster into subteams, and act in a supervisory role to determine failures and intervene when necessary. Their experiments suggest that individual and team autonomy benefit from attention management aids, adaptive autonomy, and proper information abstraction.

While previous work focused on robot navigation, Glas et al. [5] explored the remote operation of multiple social robots. They proposed a user interface for operating a single robot while monitoring several others in the background.

The industrial and medical robotics communities have investigated teleoperation for manipulation. 6D mice (e.g. 3DConnexion SpaceMouse) are useful for controlling the end-effector motion of industrial manipulators.

Wildenbeest et al. [6] investigated the importance of haptic feedback in face of communication latency and low bandwidth. They found that low-frequency haptic feedback is most important for task performance and control effort. Popular haptic displays (e.g. Novint Falcon) use parallel kinematic mechanisms that cover a small 6-DoF workspace.

Teleoperation of anthropomorphic mobile manipulation robots poses unique challenges, due to the many degrees of freedom they have. For this purpose, full-body motion capture devices are frequently employed. Typical optical motion capture systems (e.g. Vicon) require a static mounting. Structured light cameras (e.g. MS Kinect) provide a simpler setup, but they suffer from occlusions and tracking of finger motion is not yet available. Motion capture suits based on inertial measurement units (IMU) (e.g. Xsens MVN) capture the body motion flexibly at arbitrary locations.

Prominent examples of integrated manipulation systems have been developed for space applications. Best known is NASA's Robonaut 2 (R2) [7]. R2 can be teleoperated with a data glove. The device does not provide force feedback and does not capture arm motion. The operator perceives the robot's environment using a head mounted display. Rollin' Justin developed by the German Aerospace Center (DLR) is another impressive example of a mobile manipulation system. DLR has developed a teleoperation interface with haptic feedback using two lightweight arms fixed behind the operator. While such special devices provide good direct control of the robot, they are not suitable for mobile applications, where the user must carry the teleoperation device.

Leeper et al. [8] evaluated different teleoperation strategies for mobile manipulation: direct control—where the operator directly controls the 6D pose of the gripper, waypoint following—where the operator specifies desired gripper waypoints, grasp execution—where the operator only specifies the final grasp pose, and grasp planning—where the operator

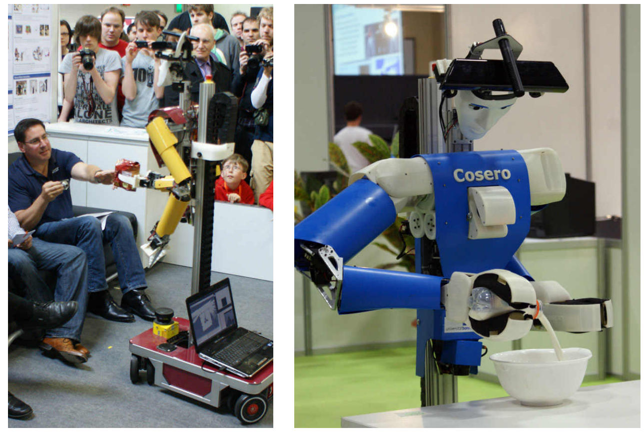

Fig. 2. Our service robots Dynamaid and Cosero in autonomous action.

indicates an area for grasping and selects one of the planned grasp poses. They found that subjects performed best when specifying grasp poses, suggesting that such supervised autonomous operation modes provide a good trade-off between fully teleoperated control and full autonomy.

III. COGNITIVE SERVICE ROBOT SYSTEM

A. Robot Hardware

We embed our teleoperation approach in our domestic service robots Dynamaid and Cosero (see Fig. 2) [9]. We develop our robots for research in autonomous mobile manipulation and human-robot interaction. The robots have an anthropomorphic upper body to operate in environments that have been designed for the human body. Their two anthropomorphic arms resemble average human body proportions and reaching capabilities. A yaw joint in the torso enlarges the workspace. Instead of balancing and moving on two legs, the robots are equipped with wheeled drives that support omnidirectional driving. The mobile bases have a small footprint (Cosero: 59×44 cm) to maneuver through the narrow passages found in household environments. The upper body is attached to the mobile base via a linear actuator that allows it to move vertically. In this way, the robot can manipulate in a wide range of heights—even on the floor.

Our robots are designed to be light-weight (Cosero: ca. 32 kg). We constructed the robots from aluminum parts and their joints are driven by Robotis Dynamixel actuators. Cosero's arms have a maximum payload of 1.5 kg each and its drive has a maximum speed of 0.6 m/sec. The onboard computer is a notebook with an Intel i7-Q720 processor.

The robots perceive their environment with a variety of complementary sensors. They acquire RGB-D images with a Kinect camera in the pan-tilt head. For obstacle avoidance and tracking in farther ranges and larger field-of-views, the robots are equipped with multiple laser-range scanners.

B. Autonomous Capabilities

We develop mobile manipulation and human-robot interaction capabilities for our robots to perform tasks autonomously in everyday environments. This involves the manipulation of objects such as grasping and placing of objects or the opening of doors. The robots are also required to navigate safely through the environment. Finally, the robots interact with humans in several ways: They can interpret speech and gestures such as pointing and stop gestures and also interact physically with humans, e.g., for object hand-over.

1) Body Control: Our robots support omnidirectional driving for dexterous navigation and mobile manipulation [10]. The linear and angular velocity of the drive can be set independently and can be changed continuously. For the anthropomorphic arms, we implemented differential inverse kinematics with redundancy resolution.

2) Navigation: Our robots navigate in indoor environments on drivable surfaces. The main sensor for navigation is the 2D laser scanner on the mobile base. The robots localize in 2D grid maps using Monte Carlo localization [11]. They navigate to goal poses by planning obstacle-free paths in the map. Safe path following and obstacle-free driving incorporates measurements from multiple range sensing devices.

3) Mobile Manipulation: We implemented many mobile manipulation skills for the robots. Grasping objects from flat surfaces is a fundamental capability for which we developed efficient object detection and grasping methods [12].

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 and clustering techniques. The robot recognizes the identity of the objects, and plans a feasible grasp on the object of interest.

4) Human-Robot Interaction: 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. We parse the semantic tags and generate appropriate high-level behavior.

The robots also support the interpretation [13] and synthesis of gestures, and physical interaction through compliant control of the arms [14].

5) High-Level Behavior Control: We implement high-level behavior control in hierarchical finite state machines. On the highest level of the hierarchy, mobile manipulation, navigation, and human-robot interaction skills are executed. We control the execution of skills on the middle level and basic motions on the lowest level.

IV. HANDHELD USER INTERFACES

So far, we presented speech and gestures as natural modalities for face-to-face human-robot interaction. They are used to configure the high-level autonomous behaviors of our robots.

Modern handheld computers such as smart phones, tablets and slates, however, provide complementary user interfaces that add a variety of novel interaction modes:

- They also allow for the teleoperation of behavior on the skill and body control level.
- They improve common ground, since the GUI can be designed to mediate what the robot actually can do. For instance, the user may only be given the choice between possible actions and involved objects and locations.
- They enable remote control without direct auditory or visual connection to the robot. The human user gains situational awareness through the visualization of the robot's view.

For this study, we investigate teleoperation with a handheld computer on three levels of autonomy:

- The human user directly controls the end-effectors, the gaze direction, or the omnidirectional drive on the *body level*.
- On the *skill level*, the user sets navigation goals, points the gaze of the robot to locations in live images, or selects the object to be grasped among detected objects on a flat surface.
- The user configures high-level behaviors that sequence skills autonomously on the *task level*.

Our goal is to design a user interface in which the workload of the user decreases with the level of robot autonomy. The user selects the level of autonomy that is appropriate for the current situation. If the autonomous execution of a task or a skill fails, the user can select a lower level—down to direct body control—to solve the task.

A. Main User Interface Design

The main user interface (UI) contains controls to select between the three levels of autonomy at the upper border of the UI. On the left side of the UI, we display a list of items from which the user can select between the different functionalities in each autonomy level. The user's selection in this list defines the content of the control view that spans the remaining part of the screen.

B. Body-Level Teleoperation

On the body level, we support direct control of drive, gaze, and end-effector. To prevent the robot from being damaged by executing dangerous user commands, these modes include obstacle avoidance. By this, direct control is also safe with regard to communication failures. In order to gain full control of the robot, the user may also switch off obstacle avoidance through a button on the control view.

The body-level controls allow the user to execute actions with the robot that are not covered by autonomous skills and therefore are not supported on higher levels of the teleoperation interface. The user gains situational awareness through the visualization of live images from the robot's RGB-D camera. The user hence perceives the environment from the robot's ego-perspective.

1) Drive Control: The drive control UI displays live camera images from the robot (see Fig. 3), which cover the whole control view. We overlay two virtual joystick panels at the lower left and lower right corner of the control view. The left panel controls linear forward, backward, and sideward velocities. Rotational velocity around the vertical axis of the robot is set through the right panel. A button for toggling

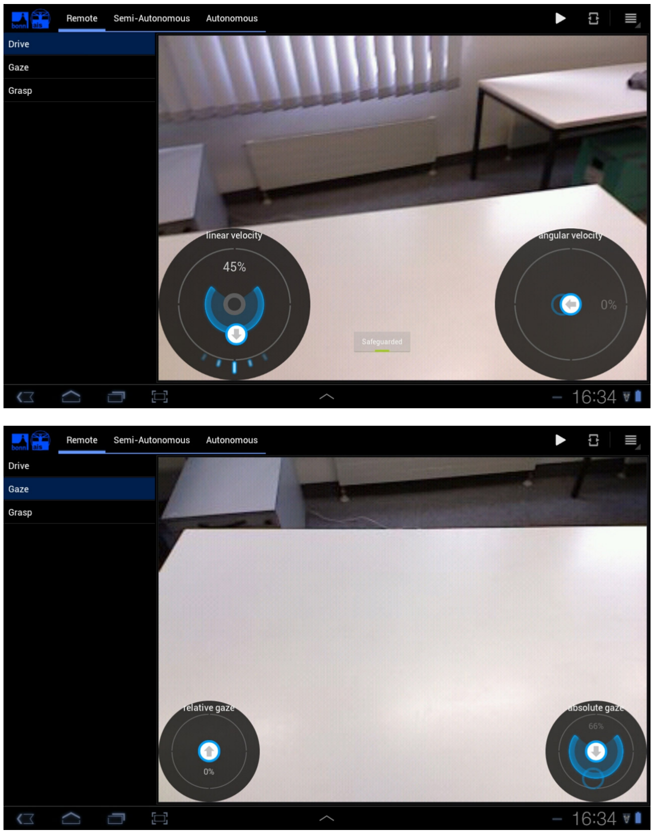

Fig. 3. Body-level teleoperation user interfaces for driving and gazing. Top: The user controls the linear and rotational velocities of the mobile base using the joystick-like panels. Obstacle avoidance can be toggled using the safeguard button. Bottom: The user can steer the gaze of the robot by either controlling the speed of motion in pan and tilt (relative), or by specifying the absolute orientation of pan and tilt (absolute).

obstacle avoidance is located at the bottom of the control view in the center between the joystick panels. We intend the user to hold the mobile device with two hands at its left and right side and to control the UI elements with the left and right thumb.

On this level, the user has full control of the omnidirectional drive. In safe mode, obstacle avoidance decelerates when the user drives onto an obstacle. The controls do not support autonomous driving around the obstacle.

2) Gaze Direction Control: Similar to the UI for drive control, the gaze control UI displays the camera images from the robot in full-screen (see Fig. 3). We again placed two joystick elements in the bottom corners that are to be used with the thumbs. The left joystick controls the relative motion of the head by adjusting pan and tilt angle of the neck joints. The right joystick allows the user to adjust the absolute angles of the pan-tilt unit. We also support swipe gestures on the camera image for changing the gaze direction. This kind of control element follows the proposal by Goodrich and Olsen [15] to manipulate with a control element the visualized world instead of the robot.

3) End-Effector Control: For end-effector control, we overlay two virtual joysticks over the camera image at each side of the handheld display (see Fig. 4). These joysticks

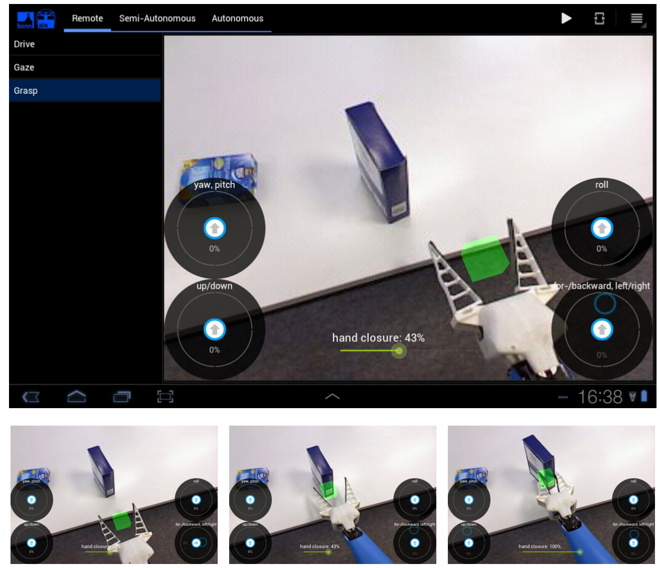

Fig. 4. Body-level teleoperation user interface for end-effector motion. Top: The user can control the motion of the six degrees of freedom of the end-effector through four joystick-like panels. The degree of hand closure can be adjusted using a slider. Bottom: Sequence from example usage.

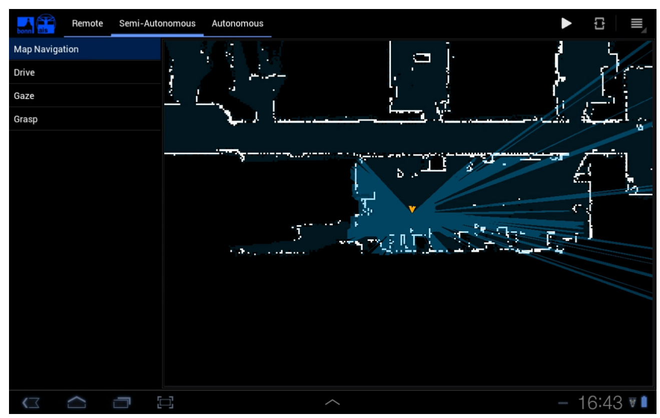

Fig. 5. Skill-level teleoperation user interface for navigation in a map. It visualizes the location of the robot and overlays the current measurements of the navigation laser sensor. The user can specify the navigation goal pose by touching onto the goal position and dragging towards the desired robot orientation at the goal.

control the 6-DoF end-effector pose, while two of them only control one DoF. A centered slider at the bottom lets the user adjust the hand closure. As of speed limitations of the arm joints, the user does not directly control the motion of the end-effector. Instead, the user modifies the target position for the end-effector using the joysticks which is slowly approached by the robot. This target pose is displayed immediately by rendering a visual marker (cube) into the camera image.

C. Skill-Level Teleoperation

The skill-level user interface configures robot skills that require the execution of a sequence of body motions. The robot controls these body motions autonomously. By that, the workload on the user shall be reduced. While the robot executes the skill, the user can supervise its progress. Compared to body-level control, the skill-level UI does require less communication bandwidth, since images and control commands have to be transmitted with less frequency. Hence, this mode is less affected by low quality or low bandwidth communication.

On this level, the user has access to the following autonomous skills of the robots:

- navigation to goal poses in a map,
- navigation to positions in the current camera image,
- gazing to locations in the image, and
- grasping objects in the view of the robot.

1) Map Navigation: The map navigation control view displays the 2D occupancy grid map that is used by the robot for localization and path planning (see Fig. 5). To visualize the pose estimate of the robot, we mark this pose by an arrow head at the robot's location that points into the orientation of the mobile base. The user can scroll on the map using swiping gestures. Zooming in and out is supported using spread and pinch two-finger gestures.

To let the robot navigate to a goal pose, the user touches the goal position on the map and drags her/his finger into the desired goal orientation. The robot will then plan a path to the specified goal pose and start driving, if it found a valid path. The planned path is displayed in the map and the user can follow the progress of the robot.

We also visualize the current laser scan of the robot. By this, the experienced user can identify localization errors or examine why the robot might not find a valid path, e.g., if an obstacle blocks its way.

2) Navigation to Visible Locations: In this control mode, we display the current camera image of the robot. In the image, the user can simply touch where the robot is supposed to navigate to. If a depth measurement is available at the selected location in the RGB-D image, the robot plans a local obstacle-avoiding path to the specified location and drives towards it. The selected goal location is displayed by rendering a marker into the image.

3) Gazing to Visible Locations: We also implemented a UI that lets the user point the gaze of the robot towards selected image locations. The user simply touches on the desired location in the displayed image. We retrieve the relative 3D location of the image point from the depth channel of the RGB-D images. Afterwards, a virtual marker is rendered at this 3D location into the camera image.

4) Object Grasping: Controlling the end-effector directly using body-level controls can be time-consuming. In this UI, we therefore integrate object detection and grasping capabilities of the robot into a convenient tool for fetching objects. The user is presented with the object detections of our real-time object segmentation algorithm (see Fig. 1). The bounding boxes of the detected objects are displayed in the current image of the robot as virtual transparent markers. The user selects the target object by touching it. If she/he wants to release the object, she/he simply presses a button which is located at the bottom of the view.

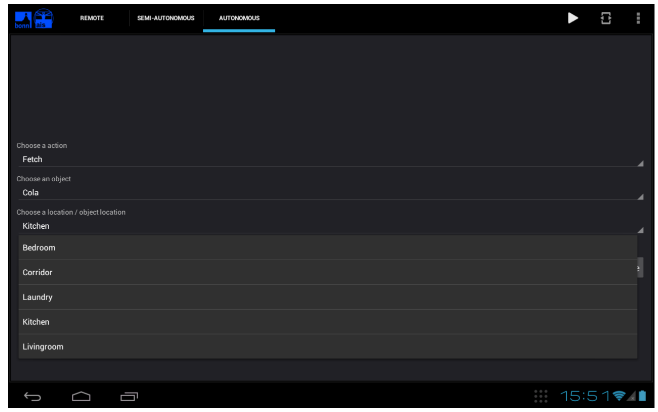

Fig. 6. Task-level teleoperation user interface. The use can select actions and involved objects and locations from combo boxes.

D. Task-Level Teleoperation

The task-level teleoperation UI is intended to provide the high-level behavior capabilities of the robot. These high-level behaviors typically sequence multiple skills in a finite state machine. The user shall be able to compose actions, objects, and locations similar to a speech-based implementation of the parsing of complex speech commands (see Fig. 6). This speech-based capability is required, for instance, in the RoboCup competitions for the General Purpose Service Robot tests.

V. IMPLEMENTATION

We implemented the UIs on Android. For sufficient space to place UI elements without limiting the view, we chose a 8.9 inch tablet. We interface the handheld with the robot via wireless Ethernet communication. The application is implemented in Java to be able to use the whole functionality the Android platform provides. Since we employ the Robot Operating System (ROS) [16] as middleware and software communication infrastructure for our robots, we used ROSJava in the application.

ROSJava is an implementation of ROS which allows convenient development of ROS nodes in Java. All communication between robot and Android handheld, e.g., subscription of topics, service calls, or publication of data, is executed by the ROS peer-to-peer message system. Due to missing UDP support, the dropping of outdated messages is not possible. This requires sufficient bandwidth and latency of the wireless connection. To safe bandwidth and computation time, we preprocess as much as possible on the robot.

The communication with the robot is implemented as a background service. This is necessary to preserve high responsiveness of the UI thread. The UI is organized in different views and overlays. For example, one overlay is used to project the bounding box of reachable items into the camera image. The rendering pipeline uses a double buffer technology to allow the user to select items. The autonomous levels are accommodated in Android fragments. Due to the usage of standard tools like the Android SDK, an easy distribution of the application through platforms such as the Google Play Store is possible.

VI. Evaluation

We evaluate our user interface in a qualitative usability study. For comparability, all users were studied during their interaction with our robot Cosero. We measure the factors learnability, neglect tolerance, efficiency, situational awareness, and satisfaction with the UI.

We embed our evaluation into a scenario with a defined user profile. The evaluation comprises three exercises and involves 20 test subjects from whom ten subjects had previous experience with autonomous robots or computer games.

In a gazing exercise, the subjects are asked to span the environment by controlling the robot's gaze into all directions. The subjects are asked to apply the body-level gaze control UI. If a subject does not use finger gestures, she/he is asked to also try gestures.

In the driving exercise, the subjects shall teleoperate the robot to a designated target location at 5m distance in three different ways. In a first attempt, the subjects use the body-level UI to reach the target in a straight line without obstacles. In the second test, the subjects have to drive the robot around an obstacle to the same location. Finally, the subjects use the skill-level UI to command the robot to the target location.

For the grasping exercise, the subjects are instructed to grasp an object from a table. At first, they use the skill-level UI to grasp the target object. Afterwards, they directly control the end-effector using the body-level UI.

During the exercises which were the same for all test persons, the subjects have been asked to verbalize their thoughts while they are executing the tasks. After each exercise, we evaluated specific usability aspects. After all exercises have been accomplished, we evaluated general usability aspects. The users were issued a questionnaire with several multiple choice questions, and were then asked to select the most fitting response.

We assume the fulfillment of the following conditions for the tests:

- wireless communication between the robot and the handheld is available at all times,
- the robot only needs to navigate on flat ground,
- the objects to grasp are located on flat surfaces and are clearly separated from each other. They are in manipulation range of the robot and are freely accessible, i.e., they are not placed inside of closed cabinets.

During the tests, the user cannot directly observe the robot. Instead, she/he has to gain situational awareness through the user interface.

A. User Profile

We define the user profile "limited mobility" for our evaluation. It may not be possible or inconvenient for the user to move around its home for performing tasks such as fetching a beverage. The main purpose of the robot in our study is the execution of fetch and carry tasks.

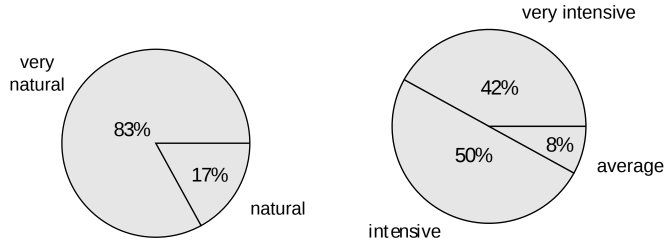

Fig. 7. Evaluation of gestures during the gazing exercise. Left: Subjective sensation of naturalness of gestures (possible choices: very natural, natural, average, unnatural, very unnatural). Right: Degree of usage of gestures compared to virtual joysticks (possible choices: very intensive, intensive, average, extensive, very extensive).

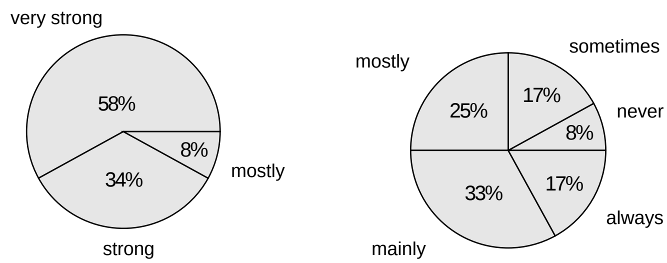

Fig. 8. Evaluation of neglect tolerance. Left: Confidence of the subjects in the robot's ability to perform skills autonomously (possible choices: very strong, strong, mostly, weak, very weak). Right: Subjective reliability of the robot to avoid dangerous situations (possible choices: always, mainly, mostly, sometimes, never).

We assume average user experience with computer systems. Since the user is supposed to be situated in her/his home, the subjects will be allowed to familiarize themselves with the test environment prior to the exercises.

B. Learnability

In the gaze exercise, we evaluate the learnability of our handheld user interface. The subjects stated easy and intuitive learning of the user interface. While the subjects reported that the virtual joystick provides a more accurate control method, they found gestures natural and used them intensively (see Fig. 7).

C. Neglect Tolerance

We evaluated the confidence of the subjects in the robot's ability to autonomously perform skills (see Fig. 8). We also asked the subjects for the perception of the reliability of the robot to avoid dangerous situations. High results in confidence and reliability suggest that the users are willing to neglect the robot while it is acting on their commands. This reduces the workload on the user and the utility of the teleoperation interface increases with the autonomy level.

D. Efficiency

1) Driving Exercise: To quantify efficiency, we measured the interaction times during the three modes of the driving exercise (see Fig. 9). It is clearly visible, that control on the skill level requires only little interaction with the handheld. In direct control, the subjects require much more time to steer the robot to the destination. It can also be seen,

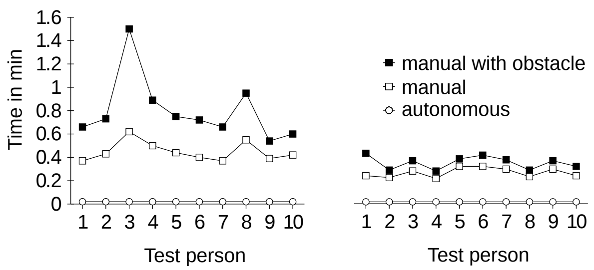

Fig. 9. Interaction time during driving exercise. Left: Subjects without previous experience with mobile robots or computer games. Right: Subjects with previous experience with mobile robots or computer games.

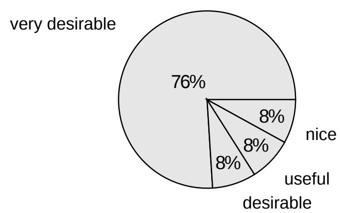

Fig. 10. Evaluation of usefulness of autonomous skill execution (possible choices: very desirable, desirable, useful, nice, unnecessary).

that experienced users perform the task much faster than unexperienced ones. The subjects required in average about 25% more time to drive around an obstacle than driving on a straight line. The subjects noted that in body-level control mode, they had to supervise the robot for almost the complete task duration. All the test subjects found the autonomous execution of skills useful (see Fig. 10).

2) Grasping Exercise: The measured execution times for the grasping exercise in Fig. 11 demonstrate that especially for unexperienced users, autonomous behavior brings an advantage in the overall time to complete the task. Direct body-level control of the end-effector has been perceived mostly unconfident and strongly laborious. On the other hand, the subjects felt confident during teleoperation at skill level and were only weakly involved.

E. Situational Awareness

During the driving exercise, we asked the subjects, how well they were able to assess collisions using the camera images, and if they would regard the display of laser scans

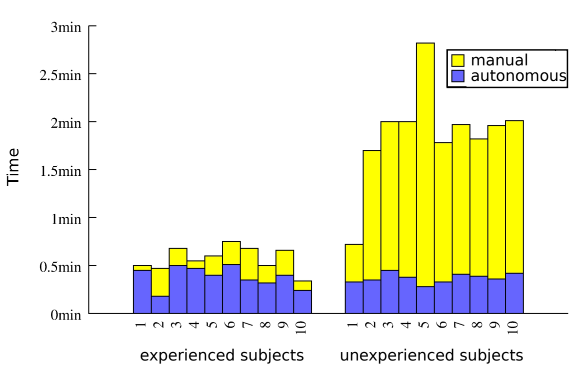

Fig. 11. Execution time for grasping exercise.

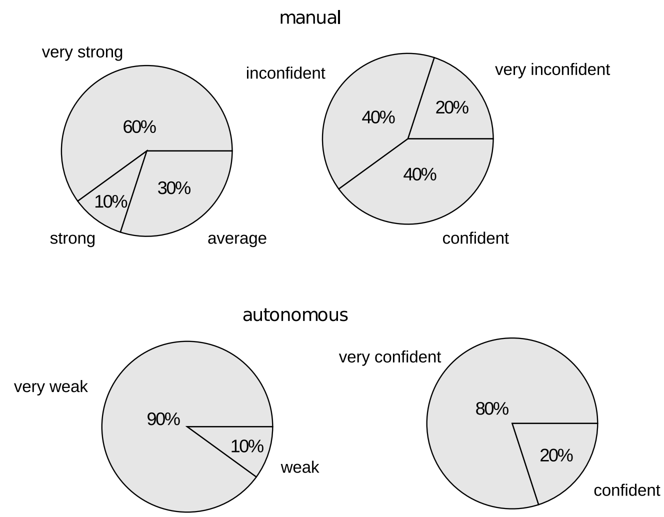

Fig. 12. Evaluation of workload (left, choices: very strong, strong, average, weak, very weak) and confidence (right, choices: very confident, confident, moderate, unconfident very unconfident) during grasping exercise. Top: Direct body-level control. Bottom: Autonomous skill-level control.

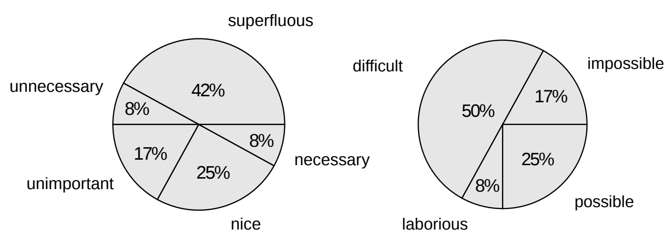

Fig. 13. Evaluation of situational awareness during driving exercise. Left: Assessment of necessity of displaying laser scans (possible choices: nice, necessary, unimportant, unnecessary, superfluous). Right: Situational awareness about possible collisions (possible choices: quite possible, possible, laborious, difficult, impossible).

necessary to improve situational awareness. From Fig. 13 we see that most subjects did not find a laser scan necessary. However, subjects with experience with mobile robots regarded laser scans as a useful tool. Most subjects also replied that the camera image alone is not sufficient to maintain awareness of the collision situation around the robot. Some of the subjects considered the movement of the head to look around the robot, but some of them stated that this would be laborious.

F. Satisfaction

Fig. 14 summarizes our assessment of the satisfaction of the subjects with the user interface design. The subjects have been mostly content with the placement of the control elements and perceived its appearance homogeneous. They remarked that it is difficult to estimate the posture of the head relative to the base. This could be fixed with an additional display element. The subjects also found it mainly easy to switch between functionalities.

G. Public Demonstration

We demonstrated our concept of mobile teleoperation on the skill and task levels during the RoboCup@Home

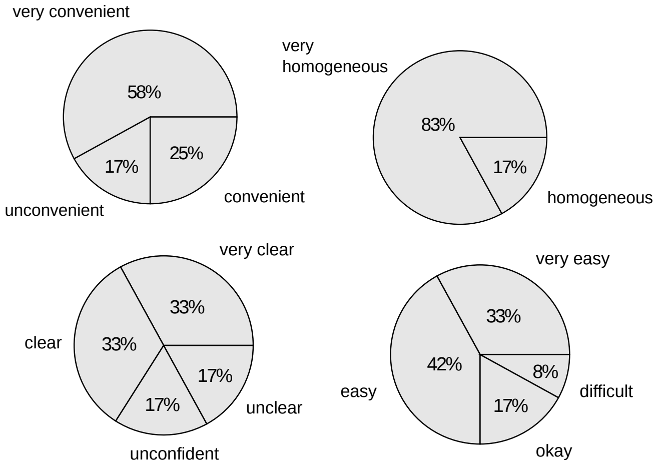

Fig. 14. Evaluation of satisfaction with user interface design. Top left: Position of control elements (choices: very convenient, convenient, moderate, inconvenient, very inconvenient). Top right: Appearance of user interface (choices: very homogeneous, homogeneous, moderate, inhomogeneous, very inhomogeneous). Bottom left: Awareness of camera orientation relative to mobile base (choices: very clear, clear, moderate, unconfident, unclear). Bottom right: Change between functionalities (choices: very easy, easy, okay, difficult, very difficult).

competition at RoboCup 2012. In the Demo Challenge, we showed an elderly-care scenario in which a user commanded the robot to fetch a drink from another room. At first, the person used a task-level control UI to let the robot fetch a specific beverage. The robot drove to the assumed location of the drink, but since it was not available, the user had to take a different choice. The user switched to the skill-level control UI and selected one of the other beverages that were perceived by the robot on the table and displayed in live images on the UI. Finally, the robot grasped the selected drink and brought it to the user. The demonstration was well received by the jury consisting of the league's technical and executive committee members. Overall, our team NimbRo@Home won the competition.

VII. CONCLUSIONS

In this paper, we proposed mobile teleoperation interfaces for adjustable autonomy of personal service robots. We identified three levels of autonomy and designed various handheld computer user interfaces on these levels. On the body level, the user can control body motions such as omnidirectional driving, gaze, and end-effector motion. To prevent the robot from executing potentially damaging user controls, we integrated obstacle avoidance capabilities on this level. Using these controls, the user can execute tasks with the robot that are not covered by autonomous functions.

The next higher level allows the execution of robot skills. These skills require a sequence of body motions and perception capabilities which are executed autonomously by the robot. The user can monitor the progress of the robot using the UI.

Finally, we propose to sequence skills in a task-level UI. The task-level UI is designed to configure high-level behavior similar to complex speech commands.

In a qualitative user study, we evaluated our user interface and demonstrated the efficiency gained from the configuration of autonomous skills over the manual control of body motion. While the situational awareness of the users can still be improved by specialized telepresence sensors on the robot, the users successfully performed gazing, driving, and grasping tasks.

In future work, we will integrate further functionality into our user interface and investigate the use of speech as a complementary input modality for the handheld.

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