Design of the Human-Robot Interaction for a Semi-Autonomous Service Robot to Assist Elderly People

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Abstract Service robots could support elderly people's activities of daily living and enable them to live in their own residences independently as long as possible. Current robot technology does not allow reliable fully autonomous operation of service robots with manipulation capabilities in the heterogeneous environments of private homes. We developed and evaluated a usage concept for semi-autonomous robot control as well as user interfaces for three user groups. Elderly people are provided with simple access to autonomous robot services through a handheld device. In case of problems with autonomous execution the robot contacts informal caregivers (e.g. relatives) who can support the robot using semi-autonomous teleoperation. To solve more complex problems, professional teleoperators are contacted who have extended remote access.

Keywords Human-robot interaction · Service robots · Teleoperation · Semi-autonomy · User interface design

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1 Introduction

It is a central desire of elderly people to live as long as possible in their familiar home environment [1]. While the development of cognitive and physical abilities is highly individual [2], many older adults require assistance with activities of daily living at some point. This generates dependence on informal or formal assistance services, associated with effort and financial expenses and reducing the perceived autonomy of elderly people. Service robots may potentially provide assistance and thus enable and prolong independent living in the home environment. Elderly people in several studies have shown a predominantly welcoming attitude towards robots in the home [3–5].

In research projects on robotic assistance to elderly people, three types of robot can be identified [6]: (1) Robots without manipulation capabilities offering information services [7], telepresence [8], or emotional stimulation [9]; (2) Robots optimized for a narrowly defined task, e.g. vacuuming, lawn mowing, or window cleaning robots [10]; (3) Multifunctional robots for a wider range of informational and physical tasks in the home, e.g. PR2 [11] or Care-O-bot 3 [12].

Apartments are heterogeneous and not optimized for service robots (e.g. there are narrow passages and a multitude of different objects like furniture or tableware). They are subject to continuous changes (e.g. through rearrangement of chairs or objects like medicine packages or beverage bottles, temporary obstacles like shopping baskets or laundry baskets). Further, service robots in homes need to operate in the vicinity of people. Autonomous operation currently has many limitations under these difficult conditions. Among the numerous technical challenges are reliable detection of objects, safe navigation and manipulation (e.g. path planning, obstacle avoidance, grasping objects), recognizing and interpreting human behavior, natural interaction with humans, and acquisition of new capabilities (e.g. learning of new objects, navigational strategies, or manipulation sequences).

Many problems of fully autonomous operation can be solved using semi-autonomous operation of the robot. This type of control scheme relies on dynamically alternating control between the robot executing tasks autonomously and interventions of a human teleoperator. The teleoperator supports the robot in situations where autonomous operation fails or when the current functional range of the robot is insufficient or should be extended [13]. Service robots can become more and more flexible over time through the support of humans, learning new behaviors, objects, or manipulation sequences [14, 15]. Through learning, the interventions of teleoperators can decrease over time and the robot's autonomy increase.

In this paper, we describe the development of a usage concept and the interaction design and empirical study of user interfaces for the operation of semi-autonomous service robots by local elderly people and teleoperators. The user interfaces were implemented as part of the European research project "Multi-Role Shadow Robotic System for Independent Living" ("SRS", Grant Agreement No. 247772, [16]).

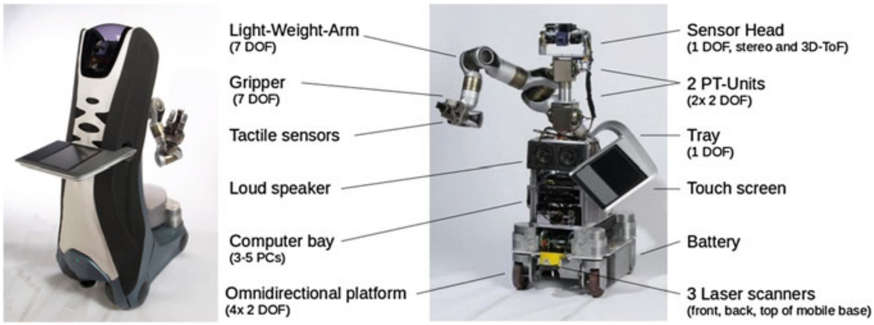

Fig. 1 Care-O-bot 3 and its hardware components

2 Robotic Platform Care-O-bot 3

Care-O-bot 3 from Fraunhofer IPA [12] was the implementation platform in the SRS project. The robot's hardware (Fig. 1) was left unchanged in this project and development focused entirely on software. The robot moves on an omni-directional mobile base. It is equipped with 2D laser scanners at the front, back, and top (for sideward scanning) of the base. It has an arm with seven degrees of freedom (DOF), a three-finger gripper, a movable head with RGB stereo camera and infrared depth camera, as well as a retractable tray for safe handover of objects between human and robot. Further, the robot is equipped with microphones, speakers, and colored LEDs.

Care-O-bot 3 has a system for autonomous navigation through the environment that avoids obstacles [17]. Also, the robot can recognize objects like bottles or cups [18]. Arm movements and grasping configurations can be planned and executed autonomously [19, 20].

3 Research Process

The SRS project employed a research and development process that extensively integrated potential users [21]. Over all segments of the process in the course of 3 years and 3 months, a total of 430 potential users was involved (40 % of which were people over 65 receiving moderate forms of assistance).

The research process can be divided into three phases. In the first phase several preparatory studies were carried out to understand requirements. This phase included three types of study:

1. User Requirements: We investigated user needs and perception of our intended concept, and collected possible robotic assistance services in focus group studies with a total of 59 participants (elderly people between 65 and 90 years of age experiencing difficulties with activities of daily living; informal caregivers

(mostly family members); formal caregivers) in Germany, Italy, and Spain [4]. In a subsequent questionnaire-based survey, 64 elderly people and 19 informal caregivers rated the perceived usefulness of the previously collected potential robot services [13].

2. Ethnographic Studies: To understand the characteristics of the living environments of elderly people and associated challenges for service robots, we visited 15 elderly people in their homes, recording the living conditions and collecting potential problematic features. In a second ethnographic study [13], we visited telemedical and home emergency teleassistance centers to analyze the workplaces, tasks, and routines. This knowledge is relevant for the design of the workplaces and user interfaces for professional robot teleoperators.
3. Technical Assessments: We carried out three types of technical assessment [13]: In an intervention analysis we identified and analyzed situations where a service robot often fails and cannot complete a task autonomously. This was required for inferring teleoperator tasks. In an interaction analysis, we generated usage scenarios for semi-autonomous robots and inferred and described the necessary interactions. This was used as an input for a study on the suitability various interaction devices.

In the second phase of the research process we developed in an iterative design process a usage concept and three different user interfaces. This phase is the main subject of the present paper. A study on the acceptability of the usage concept with 30 elderly people (mean age 83), 23 informal caregivers, and 5 professional caregivers is described in [13].

In the third phase we carried out controlled experiments on the suitability of several technical innovations developed in the project. One of these studies is reported in Sect. 5.3 and described in detail in [22].

4 Usage Concept

4.1 Robot Services

As a result of the user requirements studies [4, 13] we obtained a number of robot services of high interest for potential users. From these we chose services using the following criteria: A service should (a) require a robot (e.g. reminder functions can be implemented with simpler devices), (b) be feasible to implement with the available hardware, (c) ideally serve as a foundation for other services (e.g. grasping and delivering objects is a foundation for services like “set the table” or “bring medication and a water glass”).

Using these criteria we chose the following three services to be focused in the project: (1.) Fetch and carry objects, (2.) Assistance in cases of emergency where the elderly person can place an emergency call, the teleoperator can navigate the robot to the place of emergency, assess the situation, give instructions to the elderly person, provide emotional support, and trigger emergency measures (e.g. bring medicine or call accident ambulance). (3.) Assistance with carrying heavy objects or reaching objects in problematic places (e.g. objects located too high or on the ground).

4.2 User Groups

Based on the user requirement studies we specified three central user groups [13]:

1. Elderly people living at home in need of assistance with activities of daily living the robot is able to address.
2. Relatives or friends able and willing to assist an elderly person but not currently doing so or only to a limited extent as they do not live on site. In Europe, of 51 % of adults above 70 the nearest child lives more than 1 km away and of 16 % more than 25 km [23].
3. Professional teleoperators available around the clock. We determined that it is feasible, after some training, for current staff of telemedical and home emergency teleassistance centers to assume this role [13].

4.3 Concept of the User Interfaces

For the three user groups we specified, designed, and developed dedicated user interfaces (Fig. 2). The usage mode for elderly users is autonomous robot operation. It was necessary to provide a portable interaction device so the robot can be

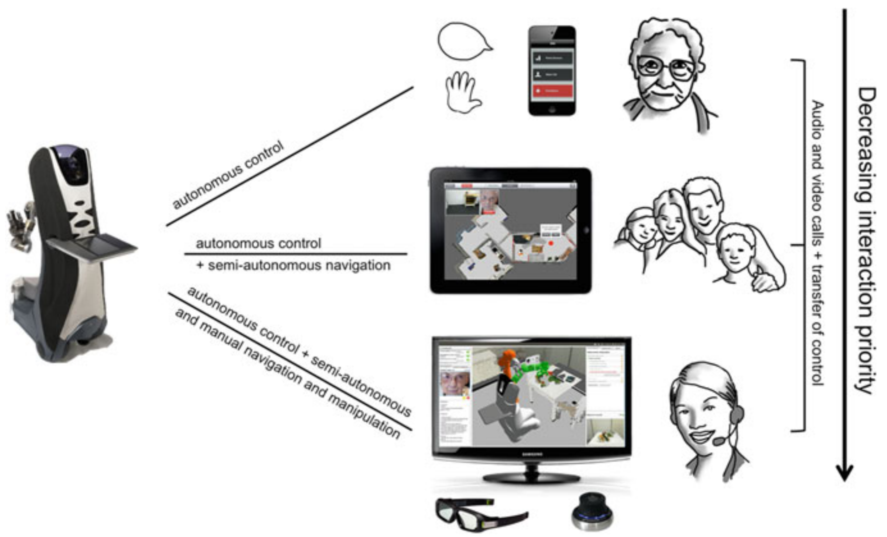

Fig. 2 Concept of the user interfaces for three user groups

commanded from any position in the home and in cases of emergency. We realized this through a portable multi-touch device (a smartphone) as it can easily be carried around and as touch-based interaction can be designed so that it is well accomplishable by elderly people [24]. Considering the current state of the art, it also offers much more reliable interaction than by speech or hand gestures. However, those may be used complimentarily. With the mobile device, elderly people can initiate autonomous services.

If a problem occurs during task execution, the robot by default first tries to reach informal caregivers. These can support the robot with problems that do not require fully manual navigation or fully controllable manipulation. They are equipped with a tablet computer, providing portability too but at the same time, through the larger display, a good overview of the robot's current situation, e.g. by visualizing a room plan including the robot's position and a video image of the robot's camera. Users of this interface mainly have more control over action sequences and navigation. The robot's autonomy is on a medium level for this user interface.

If informal caregivers are not available or the problem to be solved is too complex, a 24 h teleoperation center is contacted. Trained professional teleoperators can use autonomous, semi-autonomous, and if in rare cases necessary, also fully manual operation modes for navigating the robot and executing arm and gripper movements. Their user interface includes a large display, mouse, keyboard, a 3D mouse, and optional stereoscopic 3D glasses.

All three user interfaces have communication features. Before remote access on the robot begins, audio or video communication is initiated between the elderly person and the teleoperator. The elderly person first establishes personal contact to the teleoperator and can then choose to allow remote access. The communication remains active during the intervention of the teleoperator. This is to address ethical requirements e.g. regarding privacy and loss of control [25].

The usage concept further incorporates that the robot acquires new knowledge (e.g. learning and classifying new objects) and abilities (e.g. obstacle avoidance strategies) with the help of teleoperators, either passively learnt by analyzing the teleoperation or by active human teaching. With increasing knowledge and abilities of the robot, the number of necessary teleoperator interventions should decrease over time.

5 Iterative Design and Development of the User Interfaces

The SRS project systematically follows a human-centered design approach [21]. The user interfaces for elderly people and teleoperators gradually evolved from horizontal prototypes (screen sequences) to implemented systems in several iterations and were evaluated with real prospective users. The resulting optimized user interfaces are described in this section.

5.1 Interaction of Elderly People with the Robot

Figure 3 shows part of an interaction sequence for having the robot fetch an object (e.g. a water bottle) with the portable handheld device of the elderly person in the apartment. Figure 3a shows the main menu where users can initiate autonomous robot services, call teleoperators for assistance, or place an emergency call with a medically trained teleoperator. Choosing “Robot Services” in this screen brings the user the screen shown in Fig. 3b. For fetching an object the user taps on “Bring objects”. This brings up the screen shown in Fig. 3c where the user can specify the object and destination. Choosing “Select object” brings up a list of known objects sorted by category (Fig. 3d). When the service has been fully specified, it can be started.

Over the course of the development this user interface was evaluated with a total of 34 elderly people (mean age 78; experiencing difficulties with activities of daily living and still living at home) in four usability tests [26] at different points in time to identify usability problems. In early stages these tests were carried out using the “Gazebo” robot simulator [27] at Stuttgart Media University’s User Experience Research Lab, later with the real robot in a model kitchen at Fraunhofer IPA and in real apartments of elderly people in Germany and Italy. Figure 4 shows impressions of the different study phases.

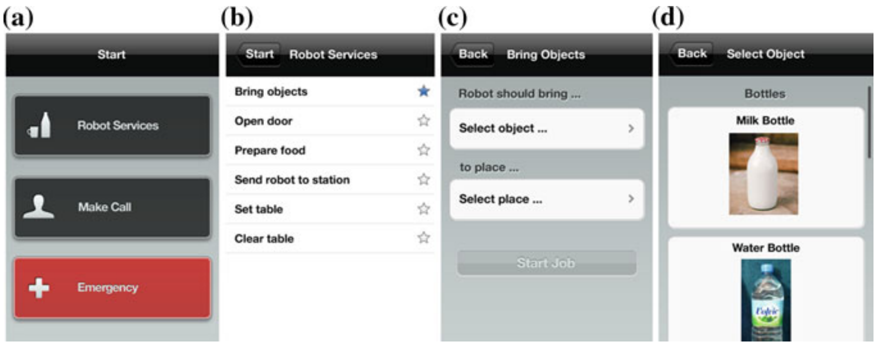

Fig. 3 User interface for elderly people, **a** main menu, **b** choosing a robot service, **c** access to object and destination selection, **d** choosing an object

Fig. 4 Evaluation of the user interface for elderly people. **a** Lab evaluation where robot simulation showed robot actions in modeled home environment. **b** Evaluation in model kitchen. **c** and **d** Evaluation in real homes of elderly people

The user interface was overall well usable for elderly people. Over the course of the project, we identified 41 usability problems and addressed them in subsequent stages of development. Along with minor presentation and interaction problems, we found that elderly people sometimes had difficulties assessing the capabilities of the robot. For example, the first version of the user interface included a semi-autonomous function where the user was asked to identify an object in a scene when the robot could not find or recognize the object. Purpose and necessity of this form of assistance were questioned by the elderly users because they strongly expected an "intelligent" robot to recognize objects by itself. We subsequently removed this functionality and restricted its use to the user interfaces for teleoperators.

5.2 Interaction of Private Teleoperators (Informal Caregivers) with the Robot

Beyond the ability to initiate pre-defined autonomous services, the user interface for private teleoperators (Figs. 5 and 6) offers free and spontaneous semi-autonomous navigation and autonomous manipulation based on live visualizations of the apartment. Complex action sequences can be composed and saved. Further, new objects can be taught to the robot.

As with the user interface for elderly people, our intention was to avoid complex menu structures. The user can choose from three main areas: "Robot Status", "Control", and "Robot Services" (Fig. 5 top center). "Robot Status" shows information like battery and connection status as well as changes to the robot's knowledge base. The latter is important as multiple users have access to the robot and can teach it new knowledge and capabilities (e.g. new objects, places, action sequences).

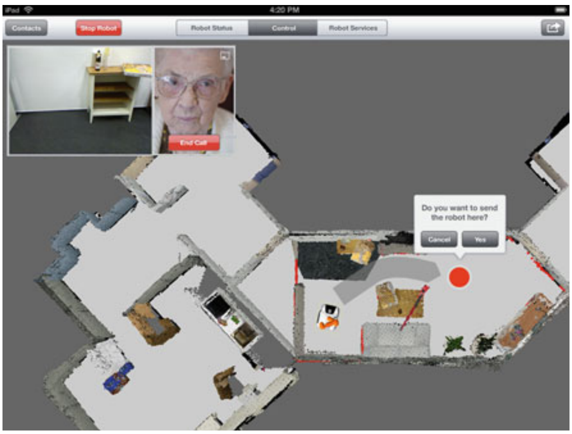

Fig. 5 Navigation to a target destination in the room plan. *Upper left* video of robot's front view, open call with local elderly person

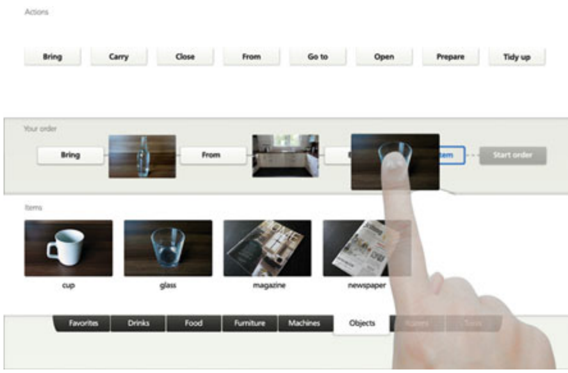

Fig. 6 Configuration of an individual fetch-carry service with drag-and-drop gestures

For navigating the robot around the apartment, e.g. when searching for an object, the user can tap on a target destination in a room plan. After confirming, the robot moves along an autonomously planned and visualized path (Fig. 5). Simultaneously, the user keeps contact with the elderly person and can monitor the robot's movement through the continuously updated room plan and a video image of the robot's camera (Fig. 5 upper left). Sensor data, e.g. from the laser scanners show potential obstacles, which the robot avoids autonomously. For fine-tuning the robot's position, drag-and-drop and rotation gestures can be used in the room plan view. Using the room plan view or a maximized video view, known objects augmented in the user interface can be reached and grasped autonomously.

We developed an interaction concept for individually configurable, more complex robot services (Fig. 6). The user starts with an empty template. At the top various elements for defining the service can be found, such as actions ("Bring") or place indicators ("From" or "Go to"). The central area contains the action sequence to be defined. For example, the user can first drag "Bring" and then "Bottle" into the action sequence. If the location of the object is known to the robot, it is automatically inserted. Through a further "Bring", a glass could be added, etc., until the sequence is complete and can be executed. Through variables like "Ask for object" flexible services can be created and later be used by the elderly person too.

The user interface was evaluated at three stages in the project for usability problems with a total of 31 informal caregivers (mean age 49), initially using a robot simulator and later in real apartments. Overall, we found 66 usability problems of varying severity and designed solutions in the course of development. As an example of a problem, an early prototype contained a direct manual navigation mode realized through graphical interaction elements overlaid on the video image. Safe and reliable navigation was not possible using this type of control. The video image's narrow field of view, network latency, and other factors kept users from attaining accurate awareness of the remote environment, so the robot often hit walls or collided with obstacles. We subsequently specified semi-autonomous, map-based navigation with automatic obstacle avoidance as the main navigation mode and extended its functionality.

5.3 Interaction of Professional Call Center Teleoperators with the Robot

The user interface for professional teleoperators provides extensive control over the robot's functionality. Most importantly it allows semi-autonomous environment manipulations.

The user interface employs a large high-resolution display with optional stereoscopic 3D display using shutter glasses for tasks that require precise depth assessments (e.g. when reaching for and grasping objects). Graphical user interface elements are operated with a conventional computer mouse. For navigating the robot and controlling the manipulator arm, a 3D mouse is used (we implemented control with the 3Dconnexion SpaceNavigator device).

Figure 7 shows the user interface, which is divided into three areas. The left pane contains all functions relating to the local elderly customers. The upper left shows incoming assistance requests of robots experiencing problems. Any operator can take the call and operators can work on multiple problems alternatingly (e.g. there are idle times when a robot needs to move from one end of the apartment to the other). The center of the left tab shows active calls and provides access to customer management functions via a tab. Individual comments on the customer (e.g. on living situation, health problems, medication) can be entered in a text field in the lower left.

The right pane contains information and functions related to the current robot. The tab "Current Sequence" shows what steps the robot went through recently and at which step in the action sequence it encountered a problem (red cross marks; e.g. the robot may not have been able to identify suitable grasping points of a recognized object). Via the tab "Robot Services" the user can start autonomous robot services as in the user interface for elderly people and edit action sequences as in

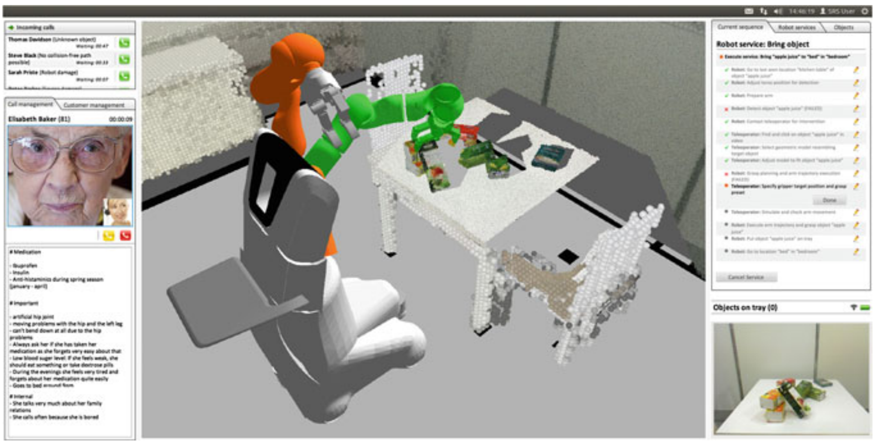

Fig. 7 User interface for professional teleoperators

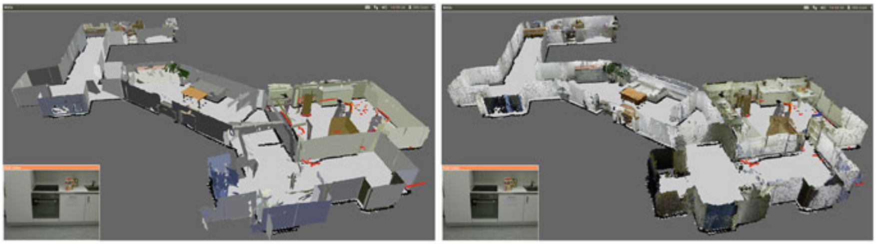

Fig. 8 User interface for professional teleoperators with central area maximized and in zoomed-out perspective. *Left* Environment visualization with geometric 3D mapping. *Right* Environment visualization with voxel-based 3D mapping

the user interface for private teleoperators. The tab “Objects” provides access to the database of known objects, where objects can be managed and new objects taught. The lower part of the right pane shows the video image of the robot’s current view.

The area in the center is the main working area. The robot and its environment are visualized in 3D. The perspective can be freely adjusted and zoomed using mouse manipulations. The 3D visualization is the main tool for assessing the remote environment when solving manipulation and navigation problems. The central working area can be maximized (Fig. 8) so the operator can use the whole screen to assess the situation.

Designed following the principle of ecological interfaces [28] and realized with RViz [29], the 3D scene consists of the following visualization components, each of which can be switched on and off individually (see Figs. 7, 8, and 9): laser sensor-based 2D floor map (grey and black), obstacles according to laser data (red, Figs. 8 and 9), current colored 3D point cloud of the robot’s field of view, historic global 3D environment map, robot with accurate shape and dimensions, collision safety-relevant footprint around the robot (yellow rectangle, Fig. 9), and collision warning indicators around the robot, lighting up when approaching obstacles (red circular segments, Fig. 9 center).

A central innovation is the full 360-degree 3D environment representation. While the robot moves around, it generates and continuously updates a 3D model of the environment using a 3D depth camera and a conventional video camera. The 3D environment visualization therefore contains real-time 3D data in the robot’s current

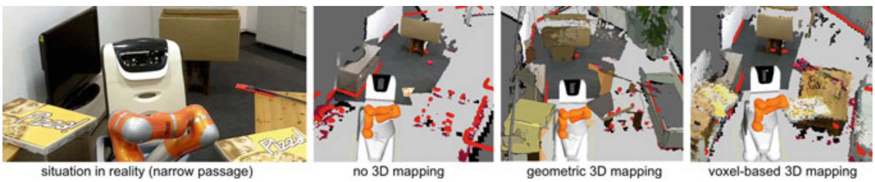

Fig. 9 Comparison of 3D visualization techniques when solving a navigation problem (making the robot pass through a narrow passage)

field of view as well as global historical data for the rest of the scene. Two mapping techniques are available. The voxel-based technique uses a probabilistic approach based on octrees (OctoMap [30]). Voxels are visualized as balls in a point cloud, which creates a solid appearance and a realistic environment representation. A disadvantage of this technique, however, is that it has relatively high network bandwidth requirements. Less bandwidth is required with the geometric technique [31], where point clouds are reduced to homogeneous planes and geometric primitives. The two techniques are contrasted in Fig. 8 with a fully mapped home environment.

To assess the suitability of the two 3D mapping techniques for solving challenging navigation situations, we carried out an experiment under controlled conditions with 27 participants and three experimental conditions (control condition without 3D mapping; geometric mapping; voxel-based mapping) in a real environment with three rooms (living room, bedroom, kitchen), realistically equipped with over 80 household furniture items and objects. Participants worked on various realistic tasks such as searching an object in the room or making the robot pass through a narrow passage.

Figure 9 shows a task in the living room where participants were asked to navigate the robot through several protruding obstacles without colliding. On the right in Fig. 9, it can be observed that 3D mapping allows e.g. to judge higher objects on the left and right of the robot, outside the field of view of its cameras, which was beneficial for solving this task. Results of this study suggested that global 3D mapping in many settings allows for a better assessment of the remote situation and for navigation with less uncertainty. User performance overall was best with the voxel-based technique but due to its technical advantages, the geometric technique may be preferable in situations where the identification of small details in the scene is not crucial.

Another central innovation is the technique for semi-autonomous manipulation. It avoids the problems associated with fully teleoperated real-time manipulation such as interaction complexity due to many degrees of freedom of the robot's arm and gripper and environment collisions due to insufficient safety features.

Figure 10 shows the procedure. A use case could be that the elderly person commanded the robot to fetch a book. Objects are inside of other objects (as the book in the surrounding shelf) can be challenging for a robot's object detection and therefore object recognition failed and the teleoperator was contacted. The teleoperator first

Fig. 10 Interaction sequence for semi-autonomous reaching and grasping of an object unknown to the robot

defines the outer boundaries of the target object by fitting a geometric 3D primitive (a cube in this case) to the target object using the mouse. Using the 3D mouse, the operator then defines the target position of the gripper. If the arm is green, the target position can be reached. If it turns red, the target position is in collision or not reachable.

In the next step, the robot plans the arm trajectory, which for safety reasons is first simulated as an animation in the user interface. The teleoperator can view the arm movement from several perspectives and judge if it is safe or if the arm might come too close to fragile objects or people. When the teleoperator is satisfied with the suggested trajectory, he executes the movement and watches it live in the 3D scene and video. The operator can interrupt the movement at any time. Once the robot has grasped the book, control is transferred back to the autonomous system and the robot continues with the action sequence, bringing the book to the elderly person.

The user interface for professional teleoperators was evaluated in several phases of its development. Overall 76 prospective users took part in these evaluations. An early prototype without global 3D environment visualization was evaluated with seven telemedical assistants. Eighteen usability problems were found. Among other measures, based on the results, we abandoned a previous split of the main user interface area into four areas showing different sensor data and perspectives. In its place, we introduced the described ecological visualization with freely adjustable viewpoints (Fig. 7). Later studies investigated dedicated questions on specific innovations such as the mentioned experiment on 3D mapping [22]. Participants' success rates for navigation and manipulation tasks were close to 100 % in later studies, i.e. participants were nearly always able to solve the problems—differences showed primarily in the time to completion. Participants rated usability and user experience of the user interface very highly with an overall result of the AttrakDiff instrument [32] in the area "desired".

6 Conclusion

We developed a usage concept for teleoperators to support robots in situations where autonomous operation is not possible. User interfaces for local elderly people as well as private and professional teleoperators were developed and evaluated with a systematic human-centered approach. As a result, we obtained iteratively optimized user interfaces that can be used as a model for similar service robot concepts.

We currently analyze the results of a further experimental study on the professional user interface where we investigated stereoscopic display and semi-autonomous manipulation. To further develop the usage concept and user interfaces in the future, it would be interesting to bring service robots into apartments for a long-term study of usage behavior. Such a study should focus on usability, usefulness, and subjective experience. Results may show how long-term usage affects the perception of these systems and elderly people's quality of living.

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