Human-Robot Interaction for Semi-Autonomous Assistive Robots

**Empirical Studies and an Interaction Concept
for Supporting Elderly People at Home**

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At the Faculty of Arts and Sciences at Linköping University, research and doctoral studies are carried out within broad problem areas. Research is organized in interdisciplinary research environments and doctoral studies mainly in graduate schools. Jointly, they publish the series Linköping Studies in Arts and Science. This thesis comes from the Human-Centered Systems Division at the Department of Computer and Information Science.

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Abstract

The present text summarizes the published and submitted articles of my doctoral research in human-robot interaction. The research addresses current shortcomings of autonomous service robots operating in domestic environments by considering the concept of a semi-autonomous robot that would be supported by human remote operators whenever the robot cannot handle a task autonomously. The main research objective was to investigate how to design the human-robot interaction for a robotic system to assist elderly people with physical tasks at home according to this conceptual idea. The research procedure followed the principles of human-centered design and is structured into four phases:

In the first phase, the context of use of the system to be designed was determined. A focus group study yielded characteristics and attitudes of several potential user groups. A survey determined the demands of elderly people and informal caregivers for services a semi-autonomous assistive robot may provide. An ethnographic study investigated the living conditions of elderly people and determined technical challenges for robots operating in this type of environment. Another ethnographic study investigated the work environment in teleassisted service centers and determined the feasibility of extending their range of services to incorporate robotic teleassistance.

In the second phase, two studies were carried out to understand the interaction requirements. The first study determined common types of failure of current autonomous robots and required human interventions to resolve such failure states. The second study investigated how the human assistance could be provided considering a range of potential interaction devices.

In the third phase, a human-robot interaction concept with three user groups and dedicated user interfaces was designed. The concept and user interfaces were refined in an iterative process based on the results of evaluations with prospective users and received encouraging results for user satisfaction and user experience.

In the fourth and final phase the utility of two specific user interface features was investigated experimentally. The first experiment investigated the utility of providing remote operators with global 3D environment maps during robot navigation and identified beneficial usage scenarios. The second experiment investigated the utility of stereoscopic display for remote manipulation and robot navigation. Results suggested temporal advantages under stereoscopic display for one of three investigated task types and potential advantages for the other two.

List of Publications

Publications the present research summary is based on:

Mast, M., Burmester, M., Berner, E., Facal, D., Pigini, L., & Blasi, L. (2010). Semi-autonomous teleoperated learning in-home service robots for elderly care: a qualitative study on needs and perceptions of elderly people, family caregivers, and professional caregivers. *Proceedings of the 20th International Conference on Robotics and Mechatronics, Varna, Oct 2010*, 1-6.

Mast, M., Burmester, M., Krüger, K., Fatikow, S., Arbeiter, G., Graf, B., Kronreif, G., Pigini, L., Facal, D., & Qiu, R. (2012). User-centered design of a dynamic-autonomy remote interaction concept for manipulation-capable robots to assist elderly people in the home. *Journal of Human-Robot Interaction*, 1, 96-118.

Mast, M., Španěl, M., Arbeiter, G., Štancl, V., Materna, Z., Weisshardt, F., Burmester, M., Smrž, P., & Graf, B. (2013). Teleoperation of domestic service robots: Effects of global 3D environment maps in the user interface on operators' cognitive and performance metrics. In G. Hermann et al. (Eds.), *Lecture Notes in Artificial Intelligence: Vol. 8239. Proceedings of the 5th International Conference on Social Robotics (ICSR), Bristol, UK, October 2013* (pp. 392-401). Cham et al.: Springer.

Mast, M., Burmester, M., Graf, B., Weisshardt, F., Arbeiter, G., Španěl, M., Materna, Z., Smrž, P., & Kronreif, G. (in press). Design of the human-robot interaction for a semi-autonomous service robot to assist elderly people. In R. Wichert & H. Klausing (Eds.), *Advanced Technologies and Societal Change: Ambient Assisted Living. 7. AAL-Kongress 2014, Berlin, Germany, January 21-22, 2014*. Heidelberg: Springer.

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Mast, M., Materna, Z., Španěl, M., Weisshardt, F., Arbeiter, G., Burmester, M., Smrž, P., & Graf, B. (2014). *Semi-autonomous domestic service robots: Evaluation of a user interface for remote manipulation and navigation with focus on effects of stereoscopic display*. Manuscript submitted for publication.

Materna, Z., Španěl, M., Mast, M., Beran, V., Weisshardt, F., Burmester, M., & Smrž, P. (2014). *Teleoperating assistive robots: a novel user interface for remote manipulation and navigation relying on semi-autonomy and global 3D environment mapping*. Manuscript submitted for publication.

Qiu, R., Ji, Z., Noyvirt, A., Soroka, A., Setchi, R., Pham, D.T., Xu, S., Shivarov, N., Pignini, L., Arbeiter, G., Weisshardt, F., Graf, B., Mast, M., ..., & Smrž, P. (2012). Towards robust personal assistant robots: Experience gained in the SRS project. *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Vilamoura, Portugal, Oct 2012, 1651-1657.

Further publications:

Albert, D., Mast, M., & Burmester, M. (2009). Nutzererwartungen zur Position von Interface-Elementen auf Webseiten im internationalen Vergleich. In H. Brau et al. (Eds.), *Usability Professionals 2009* (pp. 92-95). Stuttgart: Fraunhofer.

Burmester, M., Jäger, K., Mast, M., Peissner, M., & Sproll, S. (2010). Design verstehen – Formative Evaluation der User Experience. In H. Brau et al. (Eds.), *Usability Professionals 2010* (pp. 206-211). Stuttgart: Fraunhofer.

Burmester, M., & Mast, M. (2010). Repeated web page visits and the scanpath theory: A recurrent pattern detection approach. *Journal of Eye Movement Research*, 3(4), 1-20.

Burmester, M., Mast, M., Jäger, K., & Homans, H. (2010). Valence method for formative evaluation of user experience. *Proceedings of the 8th Conference on Designing Interactive Systems (DIS '10)*, Århus, Denmark, August 2010, 364-367. New York: ACM.

Burmester, M., Mast, M., Tille, R., & Weber, W. (2010). How users perceive and use interactive information graphics: an exploratory study. *Proceedings of the 14th International Conference Information Visualization (IV 2010)*, London,, July 2010, 361-368.

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Mast, M., & Burmester, M. (2011). Exposing repetitive scanning in eye movement sequences with T-pattern detection. *Proceedings of IADIS International Conference on Interfaces and Human Computer Interaction (IHCI)*, Rome, Italy, July 2011, 137-145.

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1 Introduction

People prefer to grow old in the familiar environment of their home rather than in an institution (Eckert et al., 2004; Bayer & Harper, 2000; Lawton, 1982). However, as physical and cognitive abilities often decline with increasing age, many elderly people need to rely on assistance from caregivers. Robots have the potential to reduce elderly people's dependence on caregivers and to prolong the period they can live independently at home. Recent studies have suggested that elderly people are predominantly welcoming towards the idea of a robot in the home (Ezer et al., 2009; Mast et al., 2010; Seelye et al., 2012).

However, the current state of technology does not allow for fully autonomous, multi-purpose, manipulation-capable robots to operate reliably and safely in domestic environments. The environments are unstructured and heterogeneous and thus pose immense challenges to robots. Teleoperated robots, on the other hand, do not suffer from a lack of interpretative or cognitive skills but fail to free human resources, as a teleoperator needs to be present at all times.

A promising middle way is the concept of semi-autonomy (Parasuraman et al., 2000; Martens et al., 2007; Doroodgar et al., 2010; Durand et al., 2010). It combines the strengths of autonomous with those of teleoperated robots to cover a wider spectrum of tasks and to achieve higher reliability. A semi-autonomous robot operates autonomously whenever possible and only involves a human operator when it is confronted with a situation or task it cannot resolve by itself. The human operator then assumes control, carries out the task or solves the problem, and hands back control to the robot. With continuing progress of technology and when combined with human teaching and machine learning, involvement of human operators may decrease over time with the robot becoming more and more autonomous (Campbell et al., 2006; Mason & Lopes, 2011).

The present doctoral research summary describes the design and evaluation of the human-robot interaction for a semi-autonomous, manipulation-capable robot to assist elderly people in the home with activities of daily living. Unless otherwise stated, the work reported here was carried out or supervised by myself. However, as it was embedded in the research project "Multi-Role Shadow Robotic System for Independent Living" (SRS; www.srs-project.eu) with twelve partner institutions in Europe, occasional excursions into the work of others are necessary for understanding the wider context. Most importantly, implementation of the user interfaces, the underlying control architecture, and all other de-

veloped technologies are not the subject of the present work and were realized by the technical partners in the project.

1.1 Research Questions

The starting point was the basic conceptual idea of a manipulation-capable robot helping elderly people at home and receiving assistance from remote human operators when it encounters a situation it cannot handle autonomously. Following the principles of human-centered design (ISO 9241-210, 2010), the context of use was investigated first. Thus, the first set of research questions focused on understanding users, tasks, as well as technical, organizational, and physical environments.

The questions investigated in research phase 1 were:

- What are the characteristics of various potential user groups? This includes needs, abilities, and difficulties of local elderly people as well as various potential remote operator user groups.
- How do potential users perceive and accept the basic conceptual idea of a robot assisted by remote human operators?
- Which potential robot services are demanded and rejected by potential users?
- What are the living and working environments of potential user groups like?

In order to make informed decisions on the type of interaction that was going to be designed, the second research phase investigated how users would interact with the robotic system to be designed.

The questions investigated in research phase 2 were:

- What are common robot failures in task execution and what human interventions would be required to resolve them in a semi-autonomous system?
- How may users perform the required interventions, i.e. with what kind of interactions?
- How would various types of interaction device be suited for performing these interactions?

Subsequently, a requirements specification was developed and in an iterative process of design, development, and testing with users, the human-robot interaction was designed and continuously refined.

The questions investigated in research phase 3 were:

- What roles in the interaction shall be assigned to different user groups with their respective interaction devices?
- Which robot services should be focused?

- What will the user interfaces look like and how will they work?
- What usability problems are inherent in the user interfaces and how can they be resolved?
- How do users judge the usability of and user experience with the interfaces and the usefulness of the robotic system as a whole?

After the final versions of the user interfaces had been implemented, the last research phase focused on investigating specific, potentially innovative and useful aspects of the user interfaces in controlled experiments.

The questions investigated in research phase 4 were:

- In which situations, if any, are global environment maps in the remote user interface useful for resolving challenging robot navigation situations?
- Is stereoscopic display of the user interface advantageous for semi-autonomous remote navigation and manipulation?

1.2 Robotic Platform

The robotic platform used in the project was Care-O-bot 3 from Fraunhofer IPA (Reiser et al., 2009). Its hardware (Figure 1) was left unchanged and all development focused on software. The robot moves on a mobile base with an omnidirectional drive. It has an arm with seven degrees of freedom (DOF) and a three-finger gripper. It is equipped with three 2D laser scanners at the front, back, and top (for sideward scanning) of the base. Its movable head integrates an RGB video camera, an infrared depth camera (Kinect), and a stereo RGB camera. A retractable tray is used for safe handover of objects between human and robot. The robot is further equipped with speakers, microphones, and colored LEDs.

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

Care-O-bot 3 runs on ROS (Robot Operating System; wiki.ros.org). Based on 2D laser scanner data, the robot can build a map of the environment and use it to localize itself and plan navigation paths while avoiding obstacles (Reiser et al., 2009). It can learn and later detect objects such as bottles or cups based on their texture (Fischer et al., 2012). For object manipulation, the robot can identify suita-

ble grasping configurations and plan and execute arm trajectories to the objects to be grasped (Kunz et al., 2010; Jones, 2013).

1.3 Research Procedure

Figure 2 provides an overview of the work carried out and of the main publications it is reported in. It follows the four-phase structure introduced in Section 1.1, which is also reflected in the structure of the chapters. Circles denote research segments with user involvement. Overall 430 prospective users were involved over a course of three years and three months (40% over 65, receiving moderate forms of care). Dotted lines denote segments that were not mainly under my supervision but under the supervision of other project partners.

Figure 2. Research procedure (circles represent research segments with user involvement; dotted boxes represent segments mainly coordinated or carried out by other project partners)

2 Understanding the Context of Use

This chapter describes the first phase of the work carried out. In human-centered design (ISO 9241-210, 2010), a detailed understanding of the context of use is the basis of subsequent design work. This includes understanding users, tasks, and environments. It includes the present as well as the anticipated context of use, with the product to be developed in place. Four studies were carried out in this phase and the chapter is organized accordingly.

An initial focus group study (Section 2.1) with elderly people, informal caregivers, and professional caregivers investigated everyday difficulties of these potential user groups, their expectations and demands, and their attitude towards our conceptual idea of a semi-autonomous robot. Through a survey (Section 2.2), demands for a variety of robot services were quantified. Two ethnographic studies were then carried out. One (Section 2.3) investigated the living conditions of elderly people and associated challenges for robots. This study was carried out by SRS project partners Ingema (Spain) and Don Gnocchi Foundation (Italy) and is therefore only described briefly. The other ethnographic study (Section 2.4) investigated the working environments, competences, and routines of professional telecare assistants, which were considered potential remote operators.

2.1 Focus Group Study on User Characteristics and Perception of Conceptual Idea

2.1.1 Introduction

When designing a robotic system, users' needs must be in the focus of the design work. The goal of this study (Mast et al., 2010) was to gather information on potential user groups and their life situations and to investigate their attitude toward the proposed robotic concept. Related studies (Khan, 1998; Dautenhahn et al., 2005; Ray et al., 2008; Derpmann & Compagna, 2009; Boissy et al., 2007; Faucounau et al., 2009) were carried out under different conditions or with different aims and thus not exhaustively informative (cf., Mast et al., 2010).

The research questions were:

- What are prospective users' relevant characteristics and difficulties in daily life and work with regard to the care situation? This is important to know because a robotic system should improve users' situation.
- How do prospective users perceive the basic conceptual idea of a remotely controlled, partially autonomous robot in the home? Could they imagine using it? If the concept did not appeal to its intended users, it would have to be changed or abandoned.

Also, the study aimed to collect possible services a robot according to the proposed concept could offer and prospective users' attitude towards them. This served as input to a subsequent survey that quantified these demands (see Section 2.2).

2.1.2 Potential User Groups

Following the recommendation of Forlizzi et al. (2004), initially all people within the ecology of elders living at home were considered potential users. The elderly people themselves were to be the primary beneficiaries of the robot. It was thus mandatory to regard this user group as part of the concept and as participating user group in the focus groups. For remote assistance, several further user groups are conceivable: (1) informal caregivers, (2) professional caregivers, (3) healthcare professionals, and (4) professional teleassistants.

Informal Caregivers

Informal caregivers are children, spouses, grandchildren, other relatives, or friends assisting elderly people. Subsumed under this term are here sporadic and potential caregivers who would be willing to provide assistance but do not live nearby, are often at work, or on business trips. The group of potential caregivers with a geographic hindrance could be quite large: in Europe, 51% of adults above 70 have the nearest child living more than 1km away and 16% have the nearest child living more than 25km away (Kohli et al., 2005). There are good reasons for considering informal caregivers as remote users: they know the elderly person and his or her apartment well, their service does not generate extra costs, and they may personally benefit from a robot that takes over some of their assistive tasks in exchange for sporadic remote operation sessions that may be reduced over time with increasing autonomy of the robot due to learning. For potential caregivers living afar, the investigated robotic concept might allow assistance where it was previously not possible. This group was thus invited as participants in the focus groups.

Professional Caregivers

Professional caregivers are people who work in geriatric care. They have usually passed related training and education. In the context of elderly people living at home, professional caregivers either make home visits or were hired for care and live locally. The user group was invited to the focus groups because it is conceivable that their professional duties may be extended to incorporate remote assistance via robots.

Healthcare Professionals

Healthcare professionals are people working in the medical sector, for example physicians or physiotherapists. As medical specialists remotely assisting a manipulation-capable robot during, e.g., household maintenance or mobility assistance tasks, would not correspond with their professional competences of giving medical advice or physical instruction. While they might in the long run receive secondary benefits from the investigated robotic concept, e.g., for remote instruction or telepresence (Kristoffersson et al., 2013; Beer & Takayama, 2011; Michaud et al., 2010), they would not be the ones who are called when a robot fails on a navigation or manipulation task, as foreseen by the conceptual idea of remotely assisting a robot. They were thus not in the focus of the robotic concept.

Professional Teleassistants

The occupation of a professional operator assisting remotely through a robot is as of yet non-existent. Even though related occupations can be found in home emergency telesupport services or telemedical services, the requirements for this potential user group would have to be specified rather than their characteristics understood from a current population. As opposed to the other user groups, it would not be crucial for this user group to personally benefit from the robotic system. If needed in the concept, this user group was considered part of the service. Therefore, the focus group method was not appropriate for this user group.

2.1.3 Method

Eleven focus groups (Merton et al., 1990; Caplan, 1990; Krueger & Casey, 2008) were carried out in Germany (own supervision, six focus groups), Italy (by project partner Don Gnocchi Foundation, two focus groups), and Spain (by project partner Ingema, three focus groups) with a total of 59 participants. During recruitment, a technology project to assist the elderly was mentioned but no reference to robots was given and it was stressed that participants need not have a particular interest in technology to participate. The following groups participated:

Understanding the Context of Use

- Elderly people living at home experiencing some difficulties with the activities of daily living: 4 focus groups in all three countries, 22 participants, 77% female, age 65 to 90 (mean age: 80). Participants did not have severe impairments (e.g. dementia, complete loss of hearing, bedridden).
- Informal caregivers (caring relatives and friends): 3 focus groups in Germany and Spain, 17 participants, 88% female, age 46 to 64 (mean age: 55). Informal caregivers received no payment for their care. Most (60%) cared for their parent but some for grandparents, mother-in-law, or aunt.
- Professional caregivers: 4 focus groups in all three countries, 20 participants, 80% female, age 30 to 61 (mean age: 46). Participants were trained professionals (e.g. geriatric nurses, social pedagogues) working for mobile care services (visiting different elderly in their homes each day), permanently for a single elderly person in the home, and in assisted living facilities.

Participants were first interviewed on their difficulties in the care situation, regardless of technology considerations. In the second phase, the conceptual idea of a remotely assisted dynamically autonomous robot that would improve in its capabilities with continued usage was introduced. To bring the concept close to participants, 15 potential robot application scenarios from a wide range like emergency, housekeeping, and emotional support were explicated and visualized with sketches and videos of robots in action (Figure 3). We asked about participants' opinions and participants discussed their views with each other. Participants were also asked to suggest own application scenarios. Transcripts of the focus group sessions were segmented by participant statements and then grouped to identify common themes.

Figure 3. Examples of illustrations and video scenes presented to participants

2.1.4 Results and Discussion

Results of the focus groups suggested that important psychological characteristics of elderly people are that they wish to be autonomous and independent from caregivers and retain their dignity (cf., Forlizzi et al., 2004). They often feel patronized by caregivers. For the design of a robotic system, this implies giving elderly people as much control as possible. Another frequently mentioned psychological issue mentioned by elderly people was loneliness due to lack of social contact. Reported physical difficulties were often mobility-related (e.g., carrying heavy objects, reaching objects, risk of falling, activities related to shopping such as carrying heavy bags) or related to housekeeping (e.g., cleaning windows, wiping the floor, opening bottles). The findings are generally in line with the literature on age-related difficulties (e.g., Becker et al., 2007; Börsch-Supan et al., 2005; Fisk et al., 2009).

Informal caregivers' difficulties in the care situation showed not to be primarily related to particular activities like shopping or cleaning. Instead, much more frequently, informal caregivers reported difficulties of a psychological nature. They perceive a burden of having to be constantly present at home and reachable because something might happen to the assisted person (cf., Faucounau et al., 2009) and find it difficult to cope with the assisted person's expectations or fear not to meet them. Many feel overly consumed by the care situation. Informal caregivers were experienced in operating computers and other electronic devices like mobile phones, qualifying them for using common contemporary interaction devices. They often reported to lead a busy life. This corresponds with survey results on caregiving children showing that in addition to their care, they work 27 hours per week on average on their normal job (Callegaro & Pasini, 2007). Due to their work, they stated that they would not always be able to answer a remote interaction request.

An important finding of the focus groups was that professional caregivers largely opposed the prospect of providing care remotely through a robot. Their general attitude was that care should be provided by humans. Such notions have also been found in other studies (Boissy et al., 2007; Derpmann & Compagna, 2009). Also, many professional caregivers were afraid that such technology in the long run might make their jobs obsolete (consistent with Derpmann & Compagna, 2009; Ray et al., 2008). Like the group of healthcare professionals, professional caregivers are paid professionals but their main competences and interests do not lie in the use of technology for remote assistance. When considering paying people for providing remote assistance, it seems more suitable to employ professionals who are specialized in such an activity. Therefore, this user group was not focused in the interaction concept later.

Acceptability of the basic conceptual idea was fairly high for both, elderly people and informal caregivers, although some opposed assistive robots in general - usually one or two participants per focus group but more than half of the participants in some Italian focus groups with elderly people. The lower ac-

ceptance by elderly people in Italy could be due to national differences in technology uptake (Cortellessa et al., 2008).

Acceptability by the approving participants showed to be linked to certain conditions. First, both elderly and informal caregivers were strongly interested in personal benefits they would gain through a robot. This finding is consistent with Deegan et al. (2008), Gonzalez et al. (2011), Ezer et al. (2009), and with the philosophy of value-centered design (Cockton, 2005). Acceptability highly depended on the services provided by a robot. Second, elderly and informal caregivers anticipated robots that would not only offer a single service like preparing food and found the idea of multi-purpose robots appealing. They envisioned a robot to replace several other devices in use (e.g., lifter, emergency alerting system, domotic systems) (cf., Sung et al., 2009).

Informal caregivers were generally willing to remotely operate a robot and it appealed to them that they could leave the house while knowing they can still help if something should happen. However, a concern was that the proposed concept could increase rather than decrease their burden of constant availability. For example, they might even have to be available when on vacation or at work. The idea of incorporating dedicated, constantly available professional teleassistance personnel to allow informal caregivers to take a respite without being afraid of neglecting their responsibilities was met with high approval by both, informal caregivers and elderly people.

There were few privacy concerns in view of the remote control aspect, the least among elderly people, which is in agreement with Faucounau et al. (2009) and Khan (1998) but contrary to Boissy et al. (2007), Demiris et al. (2008), and Courtney (2008). However, participants affirmed that it was necessary for the elderly user to authorize each remote interaction session.

2.2 Survey on User Demands for Robot Services

2.2.1 Introduction

Results of the focus groups (Mast et al., 2010; Section 2.1.4) suggested that user acceptance of a robot according to the proposed concept is dependent on the services provided, which has also been found in other studies (Ezer et al., 2009; Deegan et al., 2008). Perceived usefulness is generally an important factor for the acceptance of technology (Davis, 1989; Gonzalez et al., 2011; Cockton, 2005). While people seem to anticipate universal robots that can cover a wide range of services (Sung et al., 2009; Mast et al., 2010), in a real-world development project, certain services will usually have to be prioritized. To ensure that user needs are addressed, special care should be taken when choosing robot services to implement. In order to support such decisions, we wanted to obtain a quantification of user demands for a range of possible robot services. Quantified demands for robot services had previously been generated by Khan (1998), Dautenhahn et al. (2005),

Harmo et al. (2005), Ray et al. (2008), and Faucounau et al. (2009) but in contexts other than elderly care at home, with other user groups, or with smaller ranges of investigated services.

2.2.2 Method

A survey (Mast et al., 2012) was carried out in three countries: Germany (own supervision, 38 participants), Italy (project partner Don Gnocchi Foundation, 19 participants), and Spain (by project partner Ingema, 26 participants). In the focus groups a range of 27 possible robot services was collected. A supplementary literature review (Khan, 1998; Dautenhahn et al., 2005; Harmo et al., 2005; Becker et al., 2007; Boissy et al., 2007; Ray et al., 2008; Faucounau et al., 2009) yielded another seven. The resulting 34 robot services were consolidated to 25 by joining similar ones and by omitting services that required a robot that can leave the house (e.g., taking out the garbage, going shopping) or that were considered unfeasible with current general-purpose domestic service robot hardware (e.g., lifting people requires very specialized robots able to carry heavy weight; Mukai et al., 2010).

A questionnaire was generated, which first explicated the general concept of a robot that would sometimes be remotely assisted by family members or professional operators, and then the 25 robot services, supported by illustrations and still pictures of videos as in the focus groups. Participants were asked to rate the usefulness of each service for their current care situation on a five-point scale with a neutral middle from “not useful at all” (-2) to “very useful” (+2). The services (see Figure 4) can broadly be assigned to the categories of mobility (items 2, 9, 10, 13, 15, 18), housekeeping (items 4, 5, 7, 8, 14, 17, 19, 21, 23), cognitive/sensual (items 3, 6, 11, 12), emergency (item 1), body care (items 20 and 22), and social/emotional (items 16, 24, 25).

Questionnaires were completed in single interviews by 64 elderly people (64% female, age 65 to 92, mean age 77) living at home and experiencing some difficulties with instrumental activities of daily living (IADL; cf., McDowell, 2006) and by 19 informal caregivers (88% female, age 29 to 69, mean age 54), resulting in a total of 83 respondents.

2.2.3 Results and Discussion

Results (Figure 4; Mast et al., 2012) showed substantial differences between robot services in their rated usefulness. For many items, participants' responses were heterogeneous, which is reflected in the large confidence intervals in Figure 4. Nevertheless, mean ratings can give an indication of the most widely accepted and rejected services. Analyses of variance showed that the differences between mean item ratings were statistically significant for both, elderly people ($p < 0.0005$) and informal caregivers ($p < 0.0005$).

On average, elderly people rated emergency assistance as most useful (+1.3). It is also evident that many physically strenuous housekeeping and mobility-

related tasks were rated highly by elderly people (e.g., items 2, 4, 5, 7, 9, 10). At the lower end are two items with social and emotional aspects: playing games with relatives through the robot (item 24: -0.3) and companionship by the robot (item 25: -0.4). Informal caregivers rated items related to reminder functions most highly (item 6: +1.8; item 11: +1.8). Walking assistance received the only negative mean score from caregivers (item 18: -0.3).

Items were generally rated higher by informal caregivers than by elderly people. The average per-person mean rating was +1.0 for caregivers versus +0.5 for elderly people. An independent-samples t-test showed this difference to be statistically significant ($p = 0.026$). Looking at differences between single ratings of elderly people and caregivers, per-item independent-samples t-tests revealed statistically significant differences at the .05 level between mean scores for 9 items. Elderly people do not seem to find reminder functions as useful as caregivers. While, as mentioned above, the two reminder items 6 and 11 were the most highly rated ones by caregivers, close to “very useful” (+1.8; +1.8), they were only rated “useful” by elderly people (+0.8; +0.9). Further significant differences were found for items 7 (opening containers), 12 (helping with electronics), 14 (doing the laundry), 16 (video conversation with relative), 19 (tidy up room), 21 (clearing table), and 24 (playing social games). In all cases, caregiver scores were higher. The items with significantly different mean ratings are marked with asterisks in Figure 4.

Overall, according to the results caregivers seem to be somewhat more open to most of the enquired robot services but both user groups’ mean ratings were still largely on the positive side of the scale. General acceptability, despite heterogeneous opinions, of elderly people and caregivers of assistive robots in the home was also found in other studies (Ezer et al., 2009; Meyer, 2011; Faucounau et al., 2009). Elderly people were most willing to accept help by a robot for emergency-related tasks, strenuous physical tasks like cleaning windows, reading aloud, and for reminders. Clearing a table, body care, cooking, social games, and companionship were rated negatively on average by elderly people in the present study. A preference for functional services was also found by Ezer et al. (2009) and by Meyer (2011) and the preference for safeguarding services is consistent with Ezer et al. (2009) and Boissy et al. (2007). In agreement with the present results, Ezer et al. (2009) further found little demand for socially interactive functions. In the present study, informal caregivers most often favored reminder functions and emergency-related functions, which is in agreement with a study by Faucounau (2009) where cognitive stimulation, help calls, and fall detection were rated most highly by informal caregivers. However, none of the referenced studies is directly comparable, as they do not report results for elderly people and caregivers on an extensive range of possible services, as in the present study.

Figure 4. Demands for robot services of elderly people and informal caregivers (means and 95% confidence intervals) sorted by demand of elderly people; 5-point rating scale from "not useful at all" (-2) to "very useful" (+2); asterisks denote statistically significant differences between mean ratings of user groups (* at 0.05 level, *** at 0.001 level); from Mast et al. (2012)

2.3 Ethnographic Study of Elderly People's Homes

2.3.1 Introduction

The main beneficiaries of the investigated robotic system are elderly people in their homes. While informal caregivers' prospective usage environment at home or at work can be assumed to be contemporary and largely known, the goal of this study was to better understand the specific properties of elderly people's homes. There is a body of literature on the living conditions of elderly people, focusing on various aspects like social interactions or assistive product usage (e.g., Forlizzi et al., 2004; Golant, 1984; Ward, La Gory, & Sherman, 1988; Börsch-Supan et al., 2005; Dorfman, 1994). The specific focus of the present study was the possible technical challenges for robots arising in this usage environment, artifacts in use by elderly people, and tasks carried out (in particular such tasks where elderly people expose themselves to safety risks). This study was jointly planned but carried out by project partners Don Gnocchi Foundation and Ingema (Zamora et al., 2011) and is therefore only reported briefly here.

2.3.2 Method

For the ethnographic study (Courage & Baxter, 2005) 15 elderly people's homes (10 in Spain, 5 in Italy) were visited, and the methods of participant observation, diaries of daily routines, photographs, and unstructured interviews employed. 17 elderly participants were interviewed (13 female, 4 male, age 79 to 93, mean age 85).

2.3.3 Results and Discussion

Results showed (Zamora et al., 2011) that the apartments of the visited elderly people often had narrow passages and cramped spaces. This constitutes a challenge for robotic navigation and implies that a robot and technical devices for interacting with it should not use up much space. This seems particularly important given that a substantial number of people live in small apartments. The average number of rooms per person over 50 varies between countries with 1.6 rooms in Greece and 2.7 in Switzerland (Kohli et al., 2005). Many apartments contained carpets and higher doorsills, which can cause problems for wheel-based robotic drives. Delicate items like ceramics in cramped shelves pose challenges for object detection and manipulation. Elderly people expose themselves to risks, for example when reaching objects on a high shelf.

Overall, the ethnographic study showed that elderly people's homes pose even higher challenges to robots than modern homes typical of younger people or model apartments purpose-built for evaluations. Determined technical challenges included narrow passages, carpets, high doorsills, delicate items, difficult illumination conditions, and cramped spaces.

2.4 Ethnographic Study of Teleassistive Service Centers

2.4.1 Introduction

Professional operators were considered a potentially necessary user group for remotely assisting a robot as part of the investigated concept (Mast et al., 2012). This is in part due to the results of the focus group study (Section 2.1; Mast et al., 2010), which showed that informal caregivers have significant time restrictions as they are often at work and thus would not always be available as remote operators. Also, they were often afraid of an increased burden of availability, for example being contacted for remote assistance by an elderly person when on vacation. Further, an interaction analysis (Section 3.2) showed that some required interactions would likely be too complex to handle for untrained users.

However, the profession of a remote operator for assistive service robots does not yet exist. The closest match can be considered teleassistance personnel remotely supporting elderly people who call through emergency alerting systems. We wanted to know if the working environment and staff in teleassistive institutions could be suitable for the task of assisting remotely with a robot. The study's goals were thus to learn about the working environments, competences, tasks and routines, and artifacts in use. While there are published field studies in areas like elderly home telecare (Milligan et al., 2011) and telehealth (Hibbert et al., 2004), I am not aware of previous studies with a similar focus.

2.4.2 Method

An ethnographic study was carried out in four institutions in Germany dealing with the needs of elderly people (Mast et al., 2012): three home emergency teleassistance centers and one telemedical institution. Five participants were interviewed (all female, age 26 to 43, mean age 33) using contextual inquiry (Beyer & Holtzblatt, 1998) in sessions of approximately two hours each. With the contextual inquiry method, the researcher adopts the role of an apprentice and the participant teaches him his or her work. Audio recordings of the interviews were made, photos of the work environment and artifacts in use taken, and the interviewer took notes. The audio recordings were transcribed. Based on the collected data, we produced affinity diagrams of participant statements to identify common themes, sequence models of tasks carried out, physical models (sketches) of the work environments, and personas (Beyer & Holtzblatt, 1998; Cooper, 1999).

2.4.3 Results and Discussion

Interview and observation results suggested (Mast et al., 2012) that professional teleassistants working in home emergency teleassistance centers and telemedical services for assisting elderly people are predominantly females with an education and training as nurses, medical or telemedical assistants, or office clerks. Their responsibilities include answering the call after an elderly person has pressed the

button on an emergency alerting device, to then assess the situation and take measures (around 200 to 500 calls a day, only around 2% real emergencies), GPS-based locating of elders, or monitoring of health-related devices (e.g., related to blood pressure, weight, respiration). Necessary skills are good local language proficiency (e.g., to understand dialects), friendliness, and computer proficiency.

The work is organized as 24-hour shiftwork. In three of the four institutions visited, people worked in regular offices with large desks with conventional PC's and often multiple screens per person, running various computer programs simultaneously, and multiple telephones or headsets (Figure 5, left). The telemedical institution had smaller workspaces, typical of a call center (Figure 5, right). Tele-

Figure 5. Two contrasting workspaces: large office desk with multi-screen setup as found in the home emergency centers (left); small workspace at the telemedical institution (right); from Mast et al. (2012)

assistants used a wide variety of computer programs and all had a technology-friendly attitude. They also need to know the technical specifics of many different devices in use at the elderly people's homes. Some of the computer programs in use provide them with background information on the caller, e.g., name, age, diseases, medication, phone numbers of relatives, or where to find front door keys. As such information is also relevant for the investigated robotic concept, it was incorporated into the user interface (see Section 4.3.4). Feedback on the robotic concept was positive and some suggestions were made by participants. For example, teleassistants stated it would be useful to see the elderly person in case of an emergency (e.g., through the robot's cameras) to better assess the severity of the situation.

In conclusion, results suggested the working environment of present teleassistance centers to be suitable for incorporating robotic teleassistance. It can be considered feasible for at least some individuals to handle remote assistance with a robot, perhaps even for more complex tasks like guiding a robotic arm, after receiving training. Their computer, language, and social skills seem to constitute an adequate professional profile.

3 Understanding User Interaction Tasks

This chapter describes the second phase of the research. Its aim was to understand the tasks that prospective users would carry out with the system to be developed so that appropriate interaction hardware could be selected. A first study determined common instances of failure of autonomous robots and associated human interventions required for resolving such error states (Section 3.1). Building on its results, a second study explored how users might carry out the required assistive tasks and assessed the suitability of a variety of potential interaction devices (Section 3.2).

3.1 Study on Robot Failures and Required Human Interventions

3.1.1 Introduction

While the studies described in the previous chapter focused on users, the study described in this section focused on technical aspects. Since it was part of the concept that human operators assist when robotic autonomous task execution fails, it was necessary to determine the cases in which human intervention would be required. The investigated questions in this study were:

- At which points during autonomous execution of typical household tasks do current service robots typically get stuck in a way that they cannot recover autonomously?
- What would a human operator have to do to allow the robot to resume autonomous operation?

Obtaining this information was important because it determines the range of tasks that users have to carry out with the prospective robotic system using their interaction devices.

3.1.2 Method

An analytical study was carried out on failures that can occur during autonomous task execution by manipulation-capable service robots. Based on four exemplary autonomous action sequences involving manipulation (e.g., sequence 1: take a meal out of a fridge, place it in the microwave, operate the microwave to heat it, serve meal), a team of four roboticists first decomposed the sequences and listed all single actions involved in tables. For each action, robotic components concerned, pre-conditions, and post-conditions were identified. Table 1 shows an example of the task of opening a fridge.

Table 1. Part of a decomposed action sequence (finding a fridge and opening it) used as a basis for identifying possible failures in autonomous execution

Task	Action	Components	Pre-Conditions	Post-Conditions
Find fridge	Move base to scan position	Navigation	Target position specified	Position reached
	Build 3D map	Environment perception		3D map generated
	Locate fridge	Environment perception	3D map available	Fridge extracted
Move base to fridge	Move base to fridge	Navigation	Target position specified	Target position reached
Open fridge	Locate handle	Object detection Environment perception	Object is in knowledge base Robot is in “find object” position	Object recognized
	Move arm to pre-grasp position	Manipulation	Pre-grasp position reachable (object position) Pre-grasp position specified	Pre-grasp position reached
	Move gripper to open position	Manipulation	Pre-grasp position reached Grasp configuration available	Gripper open
	Move arm to grasp position	Manipulation	Gripper is open Grasp position reachable Grasp position specified	Grasp position reached
	Move gripper to close position	Manipulation	Gripper is open Grasp position reached Grasp configuration available	Object grasped
	Move arm and base synchronously to open door	Manipulation Navigation	Object grasped Door open trajectory available / possible	Door open position reached

The analysis was initially based on Care-O-bot 3 and then supplemented considering experience in other projects and differences compared to other service robots (e.g., PR2 (Bohren et al., 2011), Twendy-One (Iwata & Sugano, 2009), Tokyo University’s assistive cleaning robot (Yamazaki et al., 2011)) such as one versus two manipulators, different degrees of freedom, gripper types, dexterities,

sensors, or omni-directional versus differential drives. Thus, although robots' components and capabilities differ, the aim was to obtain fairly generic results.

Based on the tables of actions, pre-conditions, and post-conditions, common failures in autonomous execution were determined. A failure was considered a cause for not meeting a necessary pre-condition or post-condition. To begin executing an action, certain pre-conditions have to be met and when an action has been completed, a post-condition has been reached. Whenever a pre-condition or post-condition is not met, a failure occurred. In the event of a failure, a human operator would have to intervene to solve the problem and reach the anticipated condition. For each failure case, required interventions were identified. An analysis of this kind cannot be exhaustive as there is, depending on the level of granularity, a nearly endless number of failure cases and ways to resolve them. The focus was on identifying frequent and common cases and feasible interventions.

3.1.3 Results

Overall, 27 common failures and 51 corresponding human remote operator interventions to resolve them were identified. The failures and interventions can be assigned to four categories: manipulation, navigation, object detection and modeling, and environment perception. Examples of determined failures are failing to determine positions, failing to plan trajectories, failing to recognize the environment or objects, colliding with the environment or objects, or poor or unavailable sensor data or models.

Examples of corresponding human interventions are specifying manipulation target object locations, manually navigating the robot, changing a planned navigation path, removing obstacles, or changing environmental conditions (e.g., light, position of robot) and re-initializing automatic procedures like object detection or grasping. Table 2 provides an example.

Table 2. Example of identified failures and human interventions for action "move arm from gripper open position to pre-grasp position"

Pre-condition: Pre-grasp position specified	
Failure or Error State	Possible Remote Operator Interventions
Pre-condition not met (pre-grasp position not specified)	Previous step in action sequence has to be repeated or corrected
Pre-grasp position not reached due to (potential) collision with environment	Remove obstacles Manual arm trajectory Update obstacle map and re-plan Choose alternative pre-grasp position
Pre-grasp position not reached due to (potential) collision with target object	Manual arm trajectory Choose alternative pre-grasp configuration Re-locate object
Pre-grasp position reached but turned out not to be appropriate	Choose alternative pre-grasp configuration Manual arm trajectory
Post-condition: Pre-grasp position reached	

3.2 Study on Required Interactions and Suitable Devices

3.2.1 Introduction

The analysis described in the previous section elicited the tasks that a user needs to carry out (interventions) and the goals to reach so the robot can resume autonomous operation in a variety of situations. The study however did not elaborate *how* these tasks would be carried out. There is a variety of possible interaction approaches and hardware for controlling a robot remotely. The complexity of the interactions may vary, not all users may be capable of handling all interactions, and not all interaction hardware may be suitable. The present study therefore investigated the following questions:

- Which types of interaction for providing assistance with a robot and resolving its failure states would be required?
- Which interaction hardware is suitable for the specific interactions and for the different user groups?

3.2.2 Method

Figure 6 provides an overview of the procedure followed. The previously determined human interventions (see Section 3.1) along with the knowledge on users obtained in the previous user studies (see Sections 2.1 - 2.4) informed a process of scenario-based design (Rosson & Carroll, 2008). 60 university students of information design in 13 teams produced 13 detailed user interaction scenarios by means of text, illustrations, low-fi interaction prototypes, and videos, where users resolved robot failure states in concrete daily life situations. Another eight scenarios were generated by myself and SRS project partners. User interaction scenarios are “sketches of use” intended to capture the essence of the interaction design of a future system with a storytelling approach (Rosson & Carroll, 2008). The inter-

Figure 6. Procedure followed for determining user interactions and suitable interaction hardware

action scenarios were based on precursory user task analyses (Kirwan & Ainsworth, 1992; Hackos & Redish, 1998) and problem, activity, and information scenarios (Rosson & Carroll, 2008). While the intervention analysis (Section 3.1) determined *what* a user would have to do in cases of robotic failure, the scenarios focused on *how* this assistance would be provided using potential interaction devices. An example of an intervention would be to specify the correct location of an object that could not be found at its expected place. Resulting interactions could be to use a room plan and click on the living room with a mouse and after the robot has arrived there, to manually navigate the robot to the table where the object (e.g., a bottle) is located using a joystick or on-screen navigation elements.

The scenarios employed user-demanded robot services that achieved higher scores in the survey (see Section 2.2) as themes. In each scenario, a local elderly user interacted with a robot and autonomous task execution failed at several steps. A remote user then intervened to resolve the failure state. In addition to direct interaction of the local user with a robot through speech, gestures, or a touch screen on the robot, several types of remote interaction hardware solutions were employed in the scenarios (assigned to varying user groups). A requirement for the remote interaction hardware employed was commercial availability, so no dedicated hardware would have to be developed. The following hardware solutions were evaluated:

- (1) A standard PC with mouse, keyboard, and webcam
- (2) A standard PC additionally equipped with one (for robots with one manipulator) or two (for robots with two manipulators) high-precision stylus-based haptic 3D manipulation devices (e.g., SensAble Phantom) and standard joystick for low-level navigation
- (3) A standard PC additionally equipped with a 3D mouse (e.g., 3Dconnexion SpaceNavigator) and standard joystick
- (4) A high-definition television and a PC with a controller-free gesture recognition device (e.g., Microsoft Kinect)
- (5) A high-definition television and a PC with an accelerometer-based motion tracking device (e.g., Nintendo Wii Remote)
- (6) A touchscreen tablet computer with video camera and state-of-the-art sensors like accelerometer, gyroscope, electronic compass (e.g., Apple iPad)
- (7) A smartphone-sized handheld touchscreen device with video camera and state-of-the-art sensors
- (8) Local human-robot interaction through speech, gestures, or robot-mounted touchscreen

In the second step, the interactions and user interface functions contained in the scenarios were isolated and consolidated. Due to the implementation in real-life contexts, not only interactions directly related to resolving failure states became evident but also a variety of supporting interactions and user interface functions

like the initiation of audio or video communication between the local user and the remote operator.

In the third step, a suitability assessment was made of the different hardware solutions for each of the determined interactions and functions. Two user interface design experts and two roboticists rated suitability on a 5-point scale (from “very unsuitable” to “very suitable”). To support the rating process, we also carried out practical tests with the less common hardware solutions 2, 3, 4, and 5 to better assess suitability for navigation, manipulation, and GUI usage. Considering the required interactions, the strengths and weaknesses of the hardware solutions, and the abilities and expertise of users, suitable hardware was chosen for each user group and the interactions allocated to them.

3.2.3 Results

User Interactions

84 required user interactions and user interface functions were isolated from the scenarios. They served as requirements for implementation and as the basis for the subsequent hardware evaluation. Examples of user interactions and user interface functions isolated from the scenarios are:

- Start autonomous robot service as local user (also when located in a different room than the robot)
- Initiate assistance request and specify suitable remote operator
- Locate user in apartment (or ask for location)
- Interact with objects augmented in a video stream or point cloud (detected objects, surfaces, door handles); associated actions like pick up, place, open, close
- Semi-autonomous manipulator and gripper control: specify target position in 3D; open, close, and rotate gripper
- Manually specify navigation target for autonomous navigation by indicating in a room plan
- Low-level manual navigation
- Teach new objects or surfaces (if necessary and possible, depending on the particular robot's capabilities): assign name and category
- View and edit library of previously taught (possibly by another user) action sequences, objects, locations, etc.
- Assist multiple customers simultaneously as a professional user (e.g., when waiting for a robot to finish an activity)
- Receive indication of robot's current status: current activity, failure state, battery level, etc.

- Audio or video conversation between users during an assistance session (e.g., to obtain information from local user about wishes or the location of objects, and to increase trust)

Hardware Suitability and Allocation to User Groups

The hardware suitability assessment brought the following central findings:

- Different hardware is suitable for different interactions. A single solution that would fit all requirements could not be determined and it was therefore concluded that multiple types of hardware are necessary within the concept.
- Some interaction will likely require specialized interaction devices and trained users, especially in the field of remote manipulation where high precision, navigation in 3D space, and to some degree technical knowledge of the robot (e.g., on its sensors) is required.
- Portability and always being connected to the internet are important requirements for both, local and family users. It is also beneficial if their devices are affordable. Only solutions 6 (tablet computer) and 7 (phone-sized touchscreen device) fulfill all of these requirements.
- Some interactions and functions are difficult to implement on small screens, for example navigation using a room plan or interaction with recognized objects augmented to the video stream of the robot's cameras. This particularly applies to solution 7 (phone-sized device). The added screen space of solution 6 (tablet computer) was considered necessary for realizing some required remote assistance functions.
- The local elderly user should have a "remote" interaction device too to call the robot when in a different room and because speech interaction is error-prone and currently does not live up to the expectation of most users to converse naturally.
- Localization of the elderly user, especially when in a room other than the robot, is beneficial but technologically challenging. As a workaround the local user can specify his location manually. To do this, again a dedicated mobile device for the elderly user would be advantageous.
- There is a high amount of conventional graphical user interface interaction involved in high-level interaction (e.g., to specify objects to be fetched or to change the order of items in action sequences). Hardware solutions 4 and 5 are not very suitable for that. Further, they do not offer sufficient precision for manipulation tasks.

In conclusion, an approach with different interaction devices for each user group, scaling in portability and spectrum of functions, was considered most suitable. A phone-sized touch screen device (solution 7) can offer mainly autonomous services and simple functions to the elderly user. Touchscreen devices have shown to be suitable for elderly people (Kobayashi et al., 2011; Findlater et al., 2013) and

the device type is small enough to carry constantly and to use it in case of an emergency or to call the robot from a distant room. A tablet computer (solution 6) is still portable but due to its larger screen size can offer advanced semi-autonomous functionality to informal caregivers like interacting with objects in the robot's video stream without pre-defined action sequences.

Remote manipulation tends to require more sophisticated devices due to required high precision and navigation in 3D space. The suitability of interaction devices depends on the realization approach (e.g., how much autonomy is involved) and potentially also on the specific robot (e.g., number of manipulators, degrees of freedom, gripper dexterities). From a generic perspective, we considered a conventional PC most adequate, with appropriate interaction devices for remote manipulation with the chosen interaction approach for the specific robot. For our implementation we chose a 3D mouse as the main interaction device. A major advantage compared to more specialized devices like stylus-based haptic devices is its affordability.

4 Designing and Evaluating the Interaction

This chapter describes the third phase of the research. The results of all studies described in Chapters 0 and 3 were the basis for developing a requirements specification (Section 4.1; primarily carried out by other project partners). In an iterative process, a usage concept (Section 4.2) as well as user interfaces (Section 4.3) were designed, developed, and refined at several stages based on the results of evaluations with users (Mast et al., 2012; Mast, Burmester, et al., 2014, in press; Mast, Materna, et al., 2014; Materna et al., 2014). The present chapter focuses on the final outcome of these efforts but also provides an overview of the evaluations carried out and describes some of the design changes introduced based on the results.

4.1 Underlying Requirements Specification and Basic Concept Decisions

Based on the results of the context of use studies, the results of the studies on user interaction tasks, conceptual goals, and technical feasibility, we made basic concept decisions and produced a requirements specification (Thayer & Dorfman, 1990) with 57 requirements including user interface requirements and requirements for other technical aspects (e.g., decision making, environment perception). The requirements specification was under the supervision of several other project partners and is therefore not described in detail here. Table 3 provides examples of the link between study results and user interface requirements or concept decisions. The requirements specification was complemented by a description of the context of use, e.g. including personas (Cooper, 1999) of the different user groups.

Table 3. Examples of study results and their link to user interface requirements and concept decisions (adapted from Mast et al., 2012)

Study Result	User Interface Requirement or Concept Decision
Focus group study: Elderly people stated they often feel patronized by caregivers and they long to be independent and self-reliant (finding is also supported by literature)	Concept decision: Elderly user shall have as much control over the system as possible UI requirement: UI for elderly user shall support full control over autonomous services (e.g., start, stop, choosing objects to fetch) UI requirement: Elderly user shall be able to choose which remote operator to call for assistance
Focus group study: Informal caregivers were willing to remotely operate a robot and it appealed to them that they could leave the house while knowing they can still help if something should happen to the assisted elderly person	Concept decision: The concept shall include informal caregivers as a user group
Focus group study: Informal caregivers felt consumed in their care and were afraid of increased burden of reachability with the proposed system (e.g., when on holidays) User interaction study: Some required interactions were considered too complex to be handled by untrained users	Concept decision: The concept shall include trained professional remote assistants as a user group, available 24 hours a day
Survey on robot service demands: There were substantial differences in user-rated usefulness of robot services	Concept decision: The concept shall focus on user-demanded services as much as possible, considering also other factors (see Section 4.2.1)
User interaction study: It will be important for the elderly user and remote user to communicate during an assistance session (e.g., because elderly person is most knowledgeable about own goals and objects in the apartment)	UI requirement: The user interfaces shall support audio and video communication between users
Ethnography on teleassistance centers: Teleassistants rely on caller information such as medications or the location of door keys.	UI requirement: The user interface for professional users shall have a free text field for writing comments on customers

4.2 Usage Concept

4.2.1 Robot Services

As a result of the survey on user demands for robot services (Section 2.2), we were aware of users' priorities regarding robot services. However, when choosing robot services for implementation in a development project, there are further criteria to take into consideration. We chose robot services to be focused based on the following criteria (Mast et al., 2012; Mast, Burmester, et al., 2014, in press):

- High user demand
- Should require a robot (e.g. reminder functions can be realized with much simpler technology and can easily be integrated into a robot)
- Should be feasible to realize with the current robot hardware
- Should ideally be the foundation for further services (e.g. fetch and carry of objects is a foundation for setting a table or bringing medication)

Applying these criteria, we settled to focus on the following robot services:

- Fetch and carry of objects
- Assistance in cases of emergency (e.g., elderly person after a fall can place an emergency call, remote operator navigates the robot to the person, assesses the situation and health status, give instructions to the person, may call an ambulance, make the robot open the apartment door for the ambulance, or fetch medicine)
- Assistance with carrying heavy objects or objects difficult to reach (e.g., objects located too high or too low)

4.2.2 User Groups

Drawing on the results of the focus group study (Section 2.1), the ethnographic study on teleassistive service providers (Section 2.4), and the user interaction tasks study (Section 3.2), three user groups were specified as target groups (Mast et al., 2012; Mast, Burmester, et al., 2014, in press):

- Elderly people living at home, in need of assistance with activities of daily living the robot is able to address, having no or only mild cognitive impairments
- Informal caregivers (relatives, friends) caring for an elderly person or willing to provide assistance but currently unable to or only to a limited extent (e.g., because they do not live nearby or are often away)
- Professional teleoperators as part of a 24-hour service (e.g. staff of current home emergency teleassistance or telemedical services, having received training on robotic teleoperation)

4.2.3 Concept of the User Interfaces

For each of the three specified user groups, we designed, developed, and evaluated a dedicated user interface (Figure 7). The user interfaces scale in their capabilities and in the degree of system autonomy. Capabilities and controllability by the user both increase from top to bottom. Higher-capability user interfaces also include all functionality of the lower-capability user interfaces.

Elderly users are equipped with a smartphone-sized touchscreen device. Touch-based user interfaces have shown to be well usable by elderly people if appropriately designed (Kobayashi et al., 2011; Findlater et al., 2013). While this interaction device is highly portable (in order to command the robot from any place in the apartment and to be able to place emergency calls), it only allows for initiating autonomous services (e.g., fetching an object) in order to keep the complexity of the interaction reasonable (cf., Section 4.3.2). At the current state of the art, compared to direct forms of interaction like speech or hand gestures, a major advantage of the touchscreen device is reliability. However, the concept generally includes complementary direct interaction, depending on the specific robot’s capabilities. We chose not to rely on direct interaction for the implementation on Care-O-bot 3.

Figure 7. Concept of the user interfaces for the three user groups elderly people, informal caregivers, and professional teleoperators (from Mast, Burmester, et al., 2014, in press; Mast, Materna, et al., 2014)

If the robot encounters a problem or a function is not available in the user interface of the elderly person (e.g., an object to be fetched is not yet in the database of learned objects), a remote operator can be called. This can be initiated by the robot’s control architecture after recognition of a failure state (Qiu et al., 2012), or

by the elderly user. By default, it is suggested that informal caregivers be called first, before professional operators, as their service is free of charge.

The user interface for informal caregivers is realized on a tablet computer. The larger screen size allows for additional semi-autonomous functions such as robot navigation by room plan and it offers a more detailed view of the robot's environment, e.g., through a video image and other sensor data. Informal caregivers can support the robot on problems that do not require fully manual navigation or highly controllable manipulation. The autonomy level for this user interface can be described as medium.

If informal caregivers are unavailable, if the problem to be solved is too complex to be handled with their device, or if the elderly user prefers, a 24-hour tele-assistance center is contacted. Their user interface includes a conventional PC with keyboard and mouse, a large display, a 3D mouse in case of our implementation with Care-O-bot 3 (other interaction devices for manipulation are conceivable, cf., Section 3.2), and optional stereoscopic 3D glasses. Beyond the capabilities of the user interface for informal caregivers this user interface most importantly allows semi-autonomous remote manipulation and a range of remote robot navigation modes with different autonomy levels.

All three user interfaces have communication features. Before a remote operation session, personal contact is established between the teleoperator and the elderly user. The elderly user then may choose to allow remote access. This is to address ethical concerns regarding the privacy of elderly people and loss of control (Sharkey & Sharkey, 2012). During remote operation, there is ongoing communication to increase trust and to help clarifying issues such as the elderly user's objectives, the location of objects, or potential obstacles in the apartment.

The concept includes that the robot acquire new knowledge (e.g. learning and classifying new objects) and abilities (e.g. obstacle avoidance strategies) either through passive learning or through teaching by users (Campbell et al., 2006; Mason & Lopes, 2011). This way, the robot's autonomy can increase over time, gradually reducing the need for human involvement.

4.2.4 Acceptability Study

After the usage concept had been specified, we carried out an acceptability study (Mast et al., 2012). We were interested how prospective users would respond to the usage concept, also considering the concerns over our early conceptual ideas elicited in the focus group study (cf., Section 2.1). This study was coordinated by project partner Don Gnocchi Foundation and carried out mutually in Italy, Spain, and Germany.

The concept was brought to life with illustrated user interaction scenarios (Rosson & Carroll, 2008; cf., Section 3.2.2). We detailed various usage situations with elderly, family, and professional users operating the envisioned interaction devices in everyday life to control robots (e.g., elderly person in the home calls daughter for assistance with a robot problem, daughter at work answers, asks for

permission to control the robot, etc.). 30 elderly people over 65 (mean age 83, from Italy, Spain, and Germany), 23 informal caregivers (from Italy, Spain, and Germany), and 5 professional teleassistants (from Germany) working in elderly telesupport centers were interviewed about their perceptions face to face and using a questionnaire.

Results suggested that the changed parameters in the refined concept have a positive effect on user perceptions. Having incorporated a 24-hour professional service center in the concept, there were no more objections from informal caregivers about increased burden due to constant availability with such a system. Further, participants could now more clearly see personal benefits, presumably as the presented scenarios were themed around user-demanded robot services (cf., Section 2.2). Informal caregivers reported willingness to teach the robot. Professional teleassistants were pleased about the ability to see their elderly customers through the cameras of the robot or of their handheld interaction device as this would in many cases improve the teleassistant's ability to assess the remote situation.

While the feedback was predominantly positive, it should be considered that we presented ideal usage situations of the robotic system. An implemented system would likely show diminishing aspects due to technological constraints. Nevertheless, the feedback showed that the basic conceptual parameters had now been acceptably chosen and we could proceed to applying the concept to the Care-O-bot platform.

4.3 User Interfaces

Following the human-centered design approach (ISO 9241-210, 2010), the user interfaces evolved from horizontal prototypes (screen sequences simulating a real user interface) to implemented user interfaces in several iterations (cf., Figure 2). Each user interface prototype was tested for usability problems with real prospective users at three or more stages of development and improved based on the results. The present section describes the final, optimized user interfaces as well as selected evaluation results and corresponding design changes.

4.3.1 Evaluations

To find areas of improvement in the user interfaces, we carried out a total of ten formative usability studies (Dumas & Fox, 2008), using the methods of think-aloud, observation of behavior, and interviews (Mast et al., 2012; Mast, Burmester, et al., 2014, in press). Participants worked on realistic tasks with the user interface prototypes in sessions of approximately 60 to 90 minutes. After each usability study, we created a problem report and determined necessary design changes for the next user interface iteration. Overall 86 participants from the three user groups were involved in these studies. We exposed a total of 138 usability problems in the three user interfaces and addressed them in subsequent

phases of development. We also carried out quantitative assessments of the user experience using the AttrakDiff questionnaire (Hassenzahl et al., 2003; Hassenzahl & Monk, 2010). The instrument measures pragmatic quality (usability), hedonic quality (stimulation, identification), as well as overall attractiveness of a product.

The evaluations were carried out at five different sites. The first set of studies was carried out at Stuttgart Media University's User Experience Research Lab (own supervision), initially with horizontal prototypes and in the second stage with early implementations of the user interfaces, connected to the Gazebo robot simulator (Koenig & Howard, 2004). Through connection to the simulation, users were able to see the actions of the robot resulting from their user interface operation. A realistic Gazebo apartment model was developed (available on wiki.ros.org/srs_user_tests). It has three rooms (living room, bedroom, kitchen) connected by corridors and over 80 furniture items and household objects with realistic physical properties like weight and friction resistance (Figure 8). It resembles the environment used in later experimental investigations in reality (see Chapter 5).

Figure 8. Gazebo simulation environment model developed for evaluations (top left: apartment over-view; top right: kitchen; bottom left: living room; bottom right: bedroom)

With further progression of the project, evaluations were increasingly carried out in real-world environments: initially in a model kitchen at Fraunhofer IPA in Germany (own supervision), then in an inhabited apartment of elderly people in Germany (own supervision), in an apartment purpose-built for user evaluations in Italy (supervised by project partner Don Gnocchi Foundation), and finally in a purpose-built apartment with living room, bedroom, and kitchen at Fraunhofer IPA (own supervision). Figure 9 shows impressions of the evaluations.

Figure 9. User interface evaluations: in Gazebo simulation (top left), model kitchen (top right), and real apartments (bottom) (similar in Mast, Burmester, et al., 2014, in press; and Mast, Materna, et al., 2014)

4.3.2 User Interface for Elderly People

The user interface for elderly people (Mast et al., 2012; Mast, Burmester, et al., 2014, in press) offers access to autonomous functions only. The main menu (Figure 10a) contains three large buttons: “Robot Services” brings the user to a menu of offered autonomous functions to choose from. Through “Make Call”, the user can ask a remote operator for support (as opposed to the standard case where the robot’s semi-autonomous control system suggests to initiate such a call when autonomous task execution has failed). “Emergency Call” initiates (after confirmation) a call to medically trained staff. They can take control of the robot to assess the situation, help physically with the robot (e.g., fetch medicine), or send an ambulance to the apartment.

Figure 10 shows the beginning of the interaction sequence for having the robot fetch an object. After tapping “Robot Services” (Figure 10a), the user is offered a choice of autonomous services (Figure 10b). When tapping on “Bring objects”, the user is asked to specify the object and the delivery destination in the apartment (Figure 10c). The robot will normally search for the object at the last known location or the user can specify the location. Tapping on “Select object” brings up a list of known objects in the robot’s database (Figure 10d). When the service has been fully specified, it can be started.

Figure 10. User interface for elderly people: a) main menu; b) robot services menu; c) access to object and destination selection; d) object selection (similar in Mast et al., 2012; and Mast, Burmester, et al., 2014, in press)

Usability Studies

Over the course of development, the user interface for elderly people was evaluated in four usability studies (the first three in Germany under my supervision and the last in Italy under the supervision of project partner Don Gnocchi Foundation) with a total of 34 participants (mean age 78, living at home and experiencing difficulties with activities of daily living). A total of 41 usability problems were identified in these studies and addressed in later phases of development.

Elderly people were able to use the user interface in its final iteration without major issues. Some design decisions based on usability study results were to use fewer hierarchical menu levels, a step-by-step interaction rationale with only currently relevant information on the screen, large buttons and text, and no technology-oriented or foreign language in the localized versions. Also, semi-autonomous functions, present in earlier prototypes, were abandoned. For example, there was a function where the user was asked to tap on an object in a presented scene to narrow down the search space when the robot could not recognize the object (e.g., due to clutter). Participants did not understand nor were willing to provide this type of assistance and expected an intelligent robot to recognize objects by itself.

User Experience Assessment

Results of the final assessment of user experience with the AttrakDiff questionnaire (Hassenzahl et al., 2003; Hassenzahl & Monk, 2010) are shown in Figure 11. The data were collected at the end of the last usability study, carried out by project partner Don Gnocchi Foundation. 16 elderly people participated in this study (mean age 80, 69% female, 31% male). While there was still room for improvement in all rated dimensions (Figure 11, right), the overall result in the area “desired” (Figure 11, left) can be considered very encouraging. Participants rated pragmatic and hedonic qualities as well as overall attractiveness highly. Elimina-

tion of the remaining usability problems after the study may have further improved pragmatic quality and attractiveness.

Figure 11. Results of final user experience assessment for the user interface for elderly people: AttrakDiff portfolio with mean values for pragmatic and hedonic quality on the left (P denotes mean; orange rectangle denotes 95% confidence intervals); mean values for dimensions on the right (PQ: pragmatic quality; HQ-I: hedonic quality identification; HQ-S: hedonic quality stimulation; ATT: attractiveness)

4.3.3 User Interface for Remote Informal Caregivers

In addition to the autonomous functionality as in the user interface for elderly people, the user interface for remote informal caregivers (Mast et al., 2012; Mast, Burmester, et al., 2014, in press) offers a higher degree of user control through semi-autonomous navigation and autonomous manipulation based on augmented live visualizations of the apartment. Also, action sequences can be designed and new objects taught to the robot. Such new knowledge is made available to all other user interfaces, so e.g., the elderly person will be able to use the action sequence designed by the caregiver.

The user can choose from three main functional areas in the menu bar (Figure 12a, top center): “Robot Status”, “Control”, and “Robot Services”. “Robot Status” shows information like battery status, connection quality, and additions and changes to the robot’s knowledge base. The latter is important because multiple users can teach the robot new knowledge and capabilities (e.g., new objects, surfaces, action sequences). “Control” is the main functional area, further described in the next paragraph. Under “Robot Services”, autonomous functions are available as well as teaching and editing functionality for action sequences and the object database.

In the “Control” area (Figure 12a) the user can navigate the robot by tapping on a destination in the room plan. The planned path is then visualized and the robot moves along it. The user keeps contact with the elderly person and can monitor the robot’s movement in the continuously updated room plan and in the camera picture in the upper left. Sensor data, e.g. from the laser scanners, shows current obstacles, which the robot avoids autonomously. The robot’s position and orientation can be fine-tuned in the room plan with dragging and rotation ges-

tures or in the maximized video view. Recognized objects are augmented in the room plan and video image and by tapping on them the robot reaches and grasps them autonomously.

Figure 12. User interface for remote informal caregivers: a) Navigation by room plan with video of robot's camera and open call with elderly person in upper left; b) action sequence editing (as in Mast, Burmester, et al., 2014, in press)

Figure 12b shows the interaction concept for creating and editing individual configurable robot services. Using actions such as “bring” and place indicators like “from” or “go to”, as well as objects from the database, e.g. “glass”, and variable like “ask for object”, the user can design robot services, which are then automatically made available to all system users, including the elderly person at home.

Usability Studies

The user interface was evaluated in three usability studies (the first two in Germany under my supervision and the last in Italy under the supervision of project partner Don Gnocchi Foundation) with a total of 31 participants (mean age 49). 66 usability problems of varying severity were identified in those studies and addressed in later phases of development.

As an example of an identified problem, the first implemented version of the user interface featured a fully manual navigation mode (without autonomous obstacle avoidance) based on on-screen controls in the maximized video camera view. This turned out to be highly error-prone with the robot often hitting walls or colliding with obstacles. The camera's narrow field of view and network latency are likely causes. We subsequently specified semi-autonomous, map-based navigation with automatic obstacle avoidance as the standard navigation mode, extended its functionality, and restricted use of the video-based control mode to fine-tuning the robot's position.

User Experience Assessment

Results of the final assessment of user experience with the AttrakDiff questionnaire (Hassenzahl et al., 2003; Hassenzahl & Monk, 2010) are shown in Figure 13.

The data were collected at the end of the last usability study, carried out by project partner Don Gnocchi Foundation. 12 informal caregivers participated in this study (mean age 54, 50% female, 50% male). The result in the upper right area of “neutral” (Figure 13, left) can be considered neither overwhelming nor disappointing. Mean values are similar for all dimensions (Figure 13, right). The not fully convincing results for this user interface are likely due to remaining technical problems and features not fully implemented by the responsible project partner until the end of the project.

Figure 13. Results of final user experience assessment for the user interface for informal caregivers: AttrakDiff portfolio with mean values for pragmatic and hedonic quality on the left (P denotes mean; orange rectangle denotes 95% confidence intervals); mean values for dimensions on the right (PQ: pragmatic quality; HQ-I: hedonic quality identification; HQ-S: hedonic quality stimulation; ATT: attractiveness)

4.3.4 User Interface for Professional Teleoperators

As the last instance in the concept of user interfaces (Figure 7), the user interface for professional teleoperators (Mast et al., 2012; Mast, Burmester, et al., 2014, in press; Mast, Materna, et al., 2014; Materna et al., 2014) offers the most extensive functionality. The user interface relies on an integrative visualization of sensor data in a 3D scene with freely adjustable viewpoints. Its most important distinguishing feature compared to the other user interfaces is semi-autonomous manipulation.

Functional Areas and Visualization Approach

Figure 14 shows the functional areas of the user interface. The left pane is dedicated to functionality and information regarding the elderly customers. It shows incoming calls (teleoperation requests and general support calls), open calls (multiple teleoperation sessions can be handled simultaneously, as there are wait times, e.g. when the robot moves to another room), and a text field for comments on the customer such as required medication. Customer management functions are available when changing to a second tab.

Figure 14. Overview of user interface for professional teleoperators

The right pane contains information and functionality related to the robot. The tab “Current sequence” shows the procedural steps the robot went through when executing the current task, the step where it failed including the required operator intervention, and subsequent steps it will execute after the operator intervention. The tab “Robot services” provides access to autonomous services as in the user interface for elderly users and caregivers. The tab “Objects” provides access to the robot’s object database including editing and teaching functions. A resizable and movable RGB video of the robot’s camera is shown in the lower right.

The core functionality is realized in the central area of the user interface. The visualization is based on the concept of ecological interfaces (Nielsen et al., 2007), where affordances of the environment (Gibson, 1979; Norman, 1988), i.e. what it offers (possible robot actions, e.g. passable regions, objects that can be grasped), can be directly inferred from the scene without further cognitive effort. Data from various sensors as well as various indicators are integrated into a single 3D scene with a freely adjustable viewpoint (rotation, translation, zooming). The chosen approach addresses several problems of conventional user interfaces based on a 2D map, video, and sensor data in different screen areas, such as limited field of view (Labonté et al., 2010; Nielsen et al., 2007), unawareness of the robot’s surroundings (Drury et al., 2003; Yanco & Drury, 2004), and divided attention (Bruemmer et al., 2005; Nielsen et al., 2007; Yanco & Drury, 2004). Figure 15 shows and describes the visualization elements of the 3D scene (Mast, Materna, et al., 2014).

Figure 15. Visualization elements of the 3D scene. Left: (1) robot with realistic shape and dimensions, (2) safety-relevant area around robot (“footprint”; yellow rectangle), (3) 2D floor map based on laser data (grey and black), (4) live 2D laser data from all three scanners (red), (5) obstacle map (recent laser data; purple). Added elements in the middle: (6) colored point cloud of fused depth and RGB data in the robot camera’s current field of view, (7) field of view boundaries (two yellow lines), (8) global 3D environment map outside the robot’s field of view. Right: (9) in-scene collision indicators for translational (top) and rotational movements (bottom) appearing when navigating the robot towards an obstacle. (from Mast, Materna, et al., 2014)

A central innovation of this user interface is its ability to display a 360-degree 3D environment representation despite the 3D sensor capturing only a limited field of view in front of the robot (57° horizontally and 43° vertically). This is achieved through global 3D environment mapping. While the robot moves around, it generates and continuously updates a three-dimensional environment map. Two techniques are available: The voxel-based technique (Figure 15, center; Mast et al., 2013; Mast, Materna, et al., 2014; Materna et al., 2014) is based on the OctoMap framework (Hornung et al., 2013) that uses octrees to represent 3D occupancy grids. As an alternative, a geometric technique is available (Arbeiter et al., 2012; Mast et al., 2013), which consumes less network bandwidth.

The chosen environment visualization allows an operator to assess what is behind, right, and left of the robot, which has been a major problem in robot teleoperation (Drury et al., 2003; Yanco & Drury, 2004). The automated mapping techniques are an improvement over previous approaches that relied on manually modeled or extrapolated 3D visualizations (Nielsen et al., 2007; Labonté et al., 2010; Livatino et al., 2010). An experiment on the usefulness of global 3D environment mapping is described in Section 5.1 and in Mast et al. (2013).

For improved depth perception, an optional stereoscopic viewing mode is available, relying on Nvidia 3D Vision 2 shutter glass technology. An experiment investigating potential benefits of stereoscopic viewing with the present user interface is described in Section 5.2 and in Mast, Materna, et al. (2014).

Robot Navigation

The user interface offers four remote navigation modes with varying robot autonomy:

- **Go-point mode:** The user sets a go-point by clicking on a location in the scene and the robot autonomously plans a path to get there, avoiding obstacles autonomously. By planning several smaller paths rather than one large path, the user can attain some degree of control over the robot's behavior. This mode offers the highest robot autonomy.
- **Follow mode:** The user drags a disc that the robot attempts to follow while autonomously avoiding obstacles. Fine movement cannot be controlled in this mode but it can be helpful e.g., to quickly navigate the robot along an approximate path through obstacles. The robot's autonomy is medium in this mode.
- **In-scene control mode:** In this mode, the operator uses arrows around the robot for translational movement and a ring for rotational movement. The robot's movement can be controlled precisely but since only one degree of freedom is active at a time, it can be difficult to navigate the robot out of a cluttered passage. Collision avoidance is optional in this mode and robot autonomy low.
- **3D mouse mode:** This mode relies on the SpaceNavigator 3D mouse (using only three of the device's six degrees of freedom). The user can choose between user perspective control (default mode) and robot perspective control. The user perspective control mode was designed to avoid cognitive effort and associated negative impact on task performance due to display-control misalignment (Chintamani et al., 2010). Collision avoidance is optional in this mode and robot autonomy low.

Manipulation

Another central innovation of the user interface is its approach for semi-autonomous remote manipulation (Materna et al., 2014; Mast, Materna, et al., 2014). It uses collision-free arm trajectory planning (Jones, 2013) based on a global environment map (Materna et al., 2014; Mast et al., 2013; Hornung et al., 2013) and offline motion execution. This makes the user interface robust to transmission delay, which has been a long-standing problem in robotic telemanipulation (Sheridan & Ferrell, 1963; Stassen & Smets, 1997; Franken et al., 2011).

Figure 16 shows the sequence of interactions and resulting robot actions for reaching and grasping an object unknown to the robot or that the robot was not able to recognize. In this scenario, the robot was commanded to fetch an apple juice box but failed to recognize it (e.g., because the scene is cluttered or because the juice box is tilted) (step 1). In steps 2 to 4, the user first defines the outer boundaries of the target object by adjusting a geometric primitive using the mouse.

Figure 16. Sequence of interaction steps and robot actions for reaching and grasping an object unknown to the robot or unrecognized (from Mast, Materna, et al., 2014)

Once the object has been defined, the operator positions a virtual gripper around it using the 3D mouse in user perspective mode (steps 5 to 7). The arm turns red if position is unreachable or if the arm would collide with the environment (step 6). When the position has been specified, the arm trajectory is planned and shown as an animation in the user interface first (step 8). The operator may check if the trajectory seems appropriate or if it perhaps might come too close to critical objects.

When satisfied with the trajectory, the operator executes it and monitors it in realtime in the 3D scene and RGB video image. Execution can be interrupted in case of an emergency. After the movement has been completed, the operator executes the grasp (step 9). After the local problem has been solved, control is normally handed back to the robot, which attempts to finish the service task autonomously (step 10).

The operator also has further means of intervention, such as editing the 3D collision map with an approach similar to steps 2 to 4 in Figure 16. This is useful in case sensor noise has been identified as the problem or to specify regions the arm is meant to touch (e.g., soft objects) while still avoiding all real obstacles.

Usability Studies

The user interface was evaluated in three usability studies (the first and last in Germany under my own supervision, the second in Italy under the supervision of project partner Don Gnocchi Foundation) with a total of 21 participants (mean age 32). 31 usability problems of varying severity were identified in those studies and addressed in subsequent phases of development.

As an example of a design measure based on an identified problem, we abandoned a previous split of the central user interface area into four views showing different sensor data and perspectives. In its place we introduced the single ecological environment representation described above.

User Experience Assessment

Results of the final assessment of user experience with the AttrakDiff mini questionnaire (Hassenzahl et al., 2003; Hassenzahl & Monk, 2010) are shown in Figure 17. The data were collected during the experiment on stereoscopic display (see Section 5.2; Mast, Materna, et al., 2014), which represented the user interface's final evaluation. Results in Figure 17 represent the 15 participants in the stereo group (mean age 26).

As illustrated in the AttrakDiff portfolio, the user interface overall falls into the “desired” range, which can be considered a highly encouraging result. The diagram of mean values shows that users particularly rated the user interface to be stimulating (HQ-S) but ratings for usability (PQ), identification (HQ-I), and overall attractiveness (ATT) are rather high as well.

Only for hedonic quality a statistically significant difference between the stereo and mono display groups was found, with lower ratings in the mono group (mean aggregated HQ rating of 0.6 versus 1.5; see Mast, Materna, et al., 2014). This may in part be due to the novelty of experiencing the user interface under stereoscopic display. Results overall indicate that users have a positive impression of the user interface while there is also still some potential for improvement in all dimensions.

Figure 17. Results of final user experience assessment for the user interface for professional teleoperators: AttrakDiff portfolio with mean values for pragmatic and hedonic quality on the left (P denotes mean; orange rectangle denotes 95% confidence intervals); mean values for dimensions on the right (PQ: pragmatic quality; HQ-I: hedonic quality identification; HQ-S: hedonic quality stimulation; ATT: attractiveness)

5 Experiments on User Interface Aspects

This chapter describes the final phase of the research. After the design and development of the user interfaces had been completed, the research focus turned to specific user interface features and their impact on operators' task performance, cognitive load, situation awareness, and quality of their spatial mental models. This served the optimization of the design of robot teleoperation user interfaces. Two controlled experiments were carried out and are recapitulated in this chapter. The first experiment (Mast et al., 2013) investigated the utility of global 3D environment maps in the user interface for remote robot navigation. The second experiment (Mast, Materna, et al., 2014) included both, remote navigation and manipulation tasks. It investigated potential advantages of using stereoscopic display in the user interface. This experiment also served as a final evaluation of the user interface for professional teleoperators, some results of which have been reported in Section 4.3.4.

5.1 Experiment on Global 3D Environment Maps for Remote Navigation

5.1.1 Introduction

Conventional robot teleoperation user interfaces relying on the display a video stream from the robot's camera and a 2D map, or sensor data in various parts of the screen have shown to be insufficient for attaining good situation awareness and effectively accomplishing remote navigation (Drury et al., 2003; Nielsen et al., 2007; Bruemmer et al., 2005). The video camera's narrow field of view is a particularly limiting factor. To provide operators with a more complete representation of the remote environment, various approaches have been explored such as using multiple or panospheric cameras (Fiala, 2005; Keyes et al., 2006). However, these approaches impose a high load on network bandwidth and do not provide users with truly three-dimensional environment representations. Others have explored enriching 2D map and video with schematic 3D room models, manually

modeled or extrapolated from 2D laser data, and partially obtained encouraging results with regard to user performance (Bruemmer et al., 2005; Labonté et al., 2010; Livatino et al., 2010). However, the level of detail in these visualizations is low and manual modeling for each new apartment (and after changes in the apartment) is inefficient.

Recent advances have made 3D depth sensors affordable and techniques for realtime global 3D environment mapping have emerged (Hornung et al., 2013; Yguel & Aycard, 2011; Arbeiter et al., 2012; Kakiuchi et al., 2011). While the robot moves around, it generates and keeps updating a 3D map of the environment. When visualized in a teleoperation user interface, such maps have the potential to provide operators with recent information on objects all around the robot.

The experiment investigated potential advantages of displaying to the remote operator during robot navigation global 3D environment maps generated with two different techniques implemented in the user interface for professional users. The voxel-based technique (Materna et al., 2014; Figure 18, left) utilizes the OctoMap framework (Hornung et al., 2013), a probabilistic approach that uses octrees to represent 3D occupancy grids. The geometric technique (Arbeiter et al., 2012; Figure 18, right) segments consecutive point clouds, derives geometric primitives, and merges them into a map. The latter technique tends to offer less detail due to a simplified environment representation. Also, some artifacts and inaccuracies are introduced due to additional data processing. However, a significant advantage is that it consumes substantially less network bandwidth and fewer computational resources for display.

Figure 18. Visualizations resulting from the two types of global 3D mapping implemented in the user interface for professional users (zoomed-out perspective with apartment-sized environment mapped): voxel-based visualization on the left, geometric visualization on the right (similar in Mast, Burmester, et al., 2014, in press; Mast et al., 2013; Mast, Materna, et al., 2014)

The goal of the experiment was to identify scenarios of remote robot navigation where global 3D mapping would be advantageous and scenarios where it would not or even be detrimental to task performance. The experiment had an explorative character due to a range of different tasks investigated and due to a relatively high number of different cognitive and performance measures employed.

5.1.2 Method

The user interface for professional users as described in Section 4.3.4 was used in this experiment with the 3D mouse navigation mode based on the user perspective and active 2D-laser-based collision avoidance. There were three experimental groups: a control condition without global 3D environment mapping, voxel-based global 3D mapping, and geometric global 3D mapping (cf., Figure 20). 27 people (mean age 26) participated – 9 in each group. Participants had no previous experience with robots. They underwent several vision tests and a spatial ability test (Peters et al., 1995) and were assigned to experimental conditions in a balanced way based on the results. All participants were male to avoid a confounding effect due to gender differences in spatial problem solving (Jones & Healey, 2006). For further details on participants, see Mast et al. (2013). The experiment site (overview in Figure 18) had three rooms (kitchen, living room, bedroom, connected by corridors) equipped with 80 household and furniture items. After a 45-min training employing the simulation (with a different environment than later in reality), participants in each group carried out four tasks (Figure 19):

- Task 1: Searching for a large object (chair) in the kitchen and approaching it with the robot – the room was not illuminated but grayscale depth data was available in field of view and global maps generated during daytime
- Task 2: Navigating the robot through elevated obstacles in the living room (the robot’s 2D laser-based collision avoidance does not avoid elevated obstacles); shown in Figure 20
- Task 3: Navigating the robot through obstacles on the floor in the corridor (collision avoidance works for obstacles on the floor)
- Task 4: Searching for a small object (a tea box) under normal illumination

1. search task (large object) 2. obstacle task (high) 3. obstacles task (low) 4. search task (small object)
Figure 19. Robot at the beginning of the four tasks (similar in Mast et al., 2013)

Figure 20. Comparison of visualizations in the three experimental conditions during high-obstacle navigation task (similar in Mast et al., 2013; Mast, Burmester, et al., 2014, in press; Materna et al., 2014)

A number of objective and subjective measures (see Mast et al., 2013) were used. For brevity and because some of the measures are likely correlated, the ones considered here are: task completion time, perceived workload rated post-task with NASA-TLX raw (Hart & Staveland, 1988), number of collisions in the elevated-obstacles task, obstacles recalled post-task in the two obstacle tasks, and perceived spatial mental model rated post-experiment using the subscale “spatial situation model” (SSM) from the Spatial Presence Questionnaire MEC-SPQ (Wirth et al., 2007).

Results were analyzed using two-tailed independent-samples *t*-tests for pairwise group differences and a two-tailed Wald test assuming Poisson distribution for the collision metric. Due to the exploratory nature of the experiment, no adjustment for multiple testing was made.

5.1.3 Results and Discussion

Selected results are shown in Table 4 (for all results see Mast et al., 2013). There were strong benefits of using either type of global 3D mapping technique when searching for the large object (task 1). This is also reflected in significantly less perceived workload and in further metrics reported in Mast et al. (2013). In case of searching for the small object (task 4), benefits were only clearly present when using the voxel-based technique. An interpretation of these results is that in task 1, the target object was sufficiently large to be easily detected by participants in both types of map whereas they had to navigate the robot to arbitrary locations in the room to find the object in the control condition. However, in task 4, the object was small and hardly identifiable in the coarser geometric visualization but marginally identifiable in the voxel-based visualization.

When navigating around obstacles, no significant differences were found for any of the recorded measures in case of task 3 where participants navigated around obstacles on the floor that the robot was able to avoid autonomously. Presumably, the reason is that all obstacles were also visible in the 2D laser scanner visualization in the user interface. Differences were however found for task 2 where participants navigated around elevated obstacles that the robot did not automatically avoid. While participants were fastest in the control condition, this came at the cost of significantly more collisions with objects compared to both mapping-enabled conditions. It seems that participants rushed through the obstacle course, unaware of the existence or proximity to obstacles. This is corroborated by the fact that participants recalled significantly fewer obstacles in the control condition. Perceived workload was highest in the geometric condition, which could be attributed to additional mental effort due to ambiguity inherent in this type of visualization.

The perceived quality of the spatial situation model was highest in the voxel-based mapping condition. Considering also the results on obstacle recall, this suggests that the availability of global 3D mapping tends to support the formation of accurate mental models of the remote site but not necessarily in all sit-

uations, as shown by the results for task 3 where there were no advantages for either type of mapping technique.

Table 4. Selected results for experimental conditions C (control condition without 3D mapping), V (voxel-based 3D mapping), G (geometric 3D mapping) (adapted from Mast et al., 2013)

	Metric	Means with 95% confidence intervals	Diff. betw. means
1. Search (large object)	Task completion time	C: 235s V: 109s G: 126s	C vs. V: $p = 0.001^{**}$ C vs. G: $p = 0.004^{**}$ V vs. G: $p = 0.376$
	Perceived workload (0-100)	C: 40.4 V: 16.8 G: 23.1	C vs. V: $p = 0.002^{**}$ C vs. G: $p = 0.029^{*}$ V vs. G: $p = 0.115$
2. Navigate (high obstacles)	Task completion time	C: 121s V: 171s G: 206s	C vs. V: $p = 0.029^{*}$ C vs. G: $p = 0.001^{**}$ V vs. G: $p = 0.154$
	Perceived workload (0-100)	C: 36.8 V: 34.9 G: 52.0	C vs. V: $p = 0.754$ C vs. G: $p = 0.010^{*}$ V vs. G: $p = 0.003^{**}$
	Object collisions	C: 1.7 V: 0.6 G: 0.9	C vs. V: $p = 0.044^{*}$ C vs. G: $p = 0.013^{*}$ V vs. G: $p = 0.352$
	Obstacles recalled	C: 2.1 V: 3.3 G: 3.4	C vs. V: $p = 0.001^{**}$ C vs. G: $p = 0.001^{**}$ V vs. G: $p = 0.771$
3. Navigate (low obstacles)	Task completion time	C: 139s V: 155s G: 160s	C vs. V: $p = 0.333$ C vs. G: $p = 0.195$ V vs. G: $p = 0.722$
	Perceived workload (0-100)	C: 37.1 V: 30.9 G: 33.2	C vs. V: $p = 0.230$ C vs. G: $p = 0.515$ V vs. G: $p = 0.737$
	Obstacles recalled	C: 2.9 V: 3.3 G: 2.8	C vs. V: $p = 0.264$ C vs. G: $p = 0.748$ V vs. G: $p = 0.057$
4. Search (small object)	Task completion time	C: 215s V: 97s G: 174s	C vs. V: $p = 0.001^{**}$ C vs. G: $p = 0.317$ V vs. G: $p = 0.014^{*}$
	Perceived workload (0-100)	C: 42.5 V: 21.6 G: 36.9	C vs. V: $p = 0.017^{*}$ C vs. G: $p = 0.547$ V vs. G: $p = 0.021^{*}$
Post-experiment	Perceived quality	C: 3.6 V: 4.3 G: 3.9	C vs. V: $p = 0.006^{**}$ C vs. G: $p = 0.190$ V vs. G: $p = 0.031^{*}$
	spat. situat. model (1-5)		

Overall, the results suggest that global 3D environment mapping visualized in the user interface in many settings allows for a better assessment of the remote situation and for navigation with less errors. User performance was overall best with the voxel-based technique but due to its technical advantages, the geometric technique could be considered in situations where identifying small detail is not crucial. The results are broadly in agreement with previous studies that found benefits of 3D-enhanced user interfaces but used less advanced techniques (Nielson et al., 2007; Labonté et al., 2010). The automated sensor-based map generation with recent and detailed environment data offered by the here employed techniques can be considered a significant advancement over earlier approaches.

5.2 Experiment on Stereoscopic Display for Remote Manipulation and Navigation

5.2.1 Introduction

Since operators act in a remote three-dimensional environment, judging e.g. distances and object sizes, depth perception has been an important issue in telerobotics (Liu et al., 1993; Lee & Kim, 2008; Edmondson et al., 2012; Chen et al., 2007; Stassen & Smets, 1997). Binocular disparity, realized through stereoscopic display technology, can be a powerful cue to depth (Howard & Rogers, 2012). A stereoscopic display mode is available as an option in the user interface for professional users (see Section 4.3.4), which was investigated in this study.

Studies have suggested that stereoscopic display improves users' task performance and environment judgments in such domains as reaching for objects, positioning and resizing objects, and path tracing in virtual environments (Arsenault & Ware, 2004; Hubona et al., 2004; Sollenberger & Milgram, 1993; Ware & Franck, 1996; Barfield et al., 1999), or in video-based robotic telemanipulation (Edmondson et al., 2012; Drascic, 1991; Hutto et al., 2004), video-based remote robot navigation (Lee & Kim, 2008; Livatino et al., 2008; Chen et al., 2014), and remote robot navigation based on egocentric 3D visualizations extrapolated from 2D laser scanner data (Livatino et al., 2010).

However, there is also experimental evidence suggestive of no or little merits of stereoscopic display if certain other depth cues are already present, e.g. occlusion cues (Liu et al., 1993), perspective cues (Kim et al., 1987), haptic feedback cues (Lee & Kim, 2008), or object shadows (Hubona et al., 2004). Varying results have been obtained on the merits of stereo display in the presence of motion-based cues, with some studies suggestive of merits (Sollenberger & Milgram, 1993; Ware & Franck, 1996; Hubona et al., 2004) and others not (Doshier et al., 1986; Ware et al., 1993; Naepflin & Menozzi, 2001; van Schooten et al., 2010). In addition to the presence of other depth cues, the value of binocular disparity has also shown to depend on such factors as task (Edmondson et al., 2012; Arsenault & Ware, 2004; Bradshaw et al., 2000), distance of the perceived objects (Arsenault & Ware, 2004; Bradshaw et al., 2000; Bradshaw & Glennerster, 2006; Surdick et al., 1997), and orientation of the scene (or perspective of the viewer) (Kim et al., 1987; Fujiwara et al., 2011).

As stereoscopic display is usually associated with some drawbacks like the need to wear glasses, to dim lights, or potential feelings of discomfort after prolonged use (Lambooj et al., 2009; Camposeco et al., 2011), it is important to verify its benefits for a particular usage scenario. Characteristics of the present user interface potentially affecting the merits of stereoscopic display are:

- **User-adjustable viewpoints:** This feature introduces uncertainty as it is a priori unknown how often and for how long users will use it and thus have motion-based depth cues available.

- **Realistic sensor-based 3D visualization:** This means that rich environmental cues are available, including e.g. textures and shadows, which have shown to affect the merits of stereo display. However, such cues are also available in video-based displays, where studies have suggested stereoscopy to be beneficial (Lee & Kim, 2008; Edmondson et al., 2012; Drasic, 1991; Hutto et al., 2004; Livatino et al., 2008).
- **Various, partially novel task types:** As task is an influential factor (Edmondson et al., 2012; Arsenault & Ware, 2004; Bradshaw et al., 2000), effects may vary according to the task.

A literature review did not yield any previous studies investigating effects of stereoscopic display under parameters similar to the present user interface, namely robotic remote manipulation and navigation tasks with point cloud visualization of real indoor scenes and fully user-adjustable viewpoints including rotation, panning, and zooming. The goal of this experiment was therefore to determine how stereoscopic display affects users' task performance and cognitive workload for this contemporary type of user interface. As mentioned before, this study also had the objective of an overall assessment of the user interface and system. Some of these results have been reported in Section 4.3.4 and this aspect is henceforth not further focused (for all results, see Mast, Materna, et al., 2014).

5.2.2 Method

The experiment site was identical to the one in the previous experiment, with kitchen, living room, and bedroom, equipped with 80 household and furniture items (overview shown in Figure 18) but objects were arranged differently for the tasks. The experimental design employed display type (mono, stereo) as a between-subject variable. Effects of display type were investigated for three types of task (within-subjects):

- **Manipulation subtask 1:** defining the shape of the target object (cf., steps 2 to 4 in Figure 16 on page 40)
- **Manipulation subtask 2:** positioning the gripper at its target position (cf., steps 5 to 7 in Figure 16)
- **Robot navigation around elevated obstacles**

The two manipulation subtasks were performed in two environments each, i.e. in two rooms with different objects. The first environment is shown in Figure 16 on page 40 (the target object was an apple juice box) and the second in Figure 21 (target object was the gray book in the shelf). Subtasks were considered completed when the participant had reached a pre-defined precision criterion (see Mast, Materna, et al., 2014 for details). The navigation task was similar to task 2 in the previous experiment (see Figure 19 and Figure 20 on page 45) but with an additional obstacle to increase the difficulty. It was considered completed once the robot had passed a finishing line. Prior to the trials, participants underwent a 1-

hour training on the robot and for the specific task types in simulation. Voxel-based global 3D environment mapping (cf., Sections 4.3.4 and 5.1) was enabled for all tasks.

Figure 21. Robot and user interface at the beginning of manipulation task in bedroom (similar in Mast, Materna, et al., 2014)

28 people participated in the experiment, 14 in each group (mean age 26, all male due to gender differences in spatial problem solving (Jones & Healey, 2006)). Participants had no prior experience with robot teleoperation and were not extensive 3D gamers or extensive users of professional 3D applications. They underwent vision tests (including a Lang I stereopsis test) and a spatial ability test (Peters et al., 1995) and were assigned to experimental conditions in a balanced way based on the results. Full details on the sample are provided in Mast, Materna et al., (2014).

The main dependent variables were task completion time, perceived cognitive workload (measured post-task using NASA-TLX raw; Hart & Staveland, 1988), and for the navigation task also number of collisions. For each of the manipulation subtask types, analyses of variance were carried out for each metric. For the navigation task, two-tailed independent-samples *t*-tests were carried out for task completion time and perceived cognitive workload, and a Wald test for the collision metric. Bonferroni correction for multiple testing was applied.

5.2.3 Results and Discussion

All participants were able to complete all tasks. Results for task performance and cognitive workload are shown in Table 5 (for all results, see Mast, Materna, et al., 2014). For the task of defining the target object (manipulation subtask 1), at the adjusted significance level of $\alpha = .007$ there was no main effect of display type on either task completion time or cognitive workload. However, without multiplicity correction there was a significant main effect on task completion time with participants in the stereo group completing the task faster. This can be interpreted as an indication for potential advantages that would need to be confirmed in further studies. For the task of positioning the gripper (manipulation subtask 2), there was a significant main effect of display type on task completion time but not on cognitive workload. Participants in the stereo group were faster at positioning the gripper. For the navigation task, no significant differences between means

were found for any dependent variable after multiplicity correction. Without correction, participants in the stereo group completed the task significantly faster, which can again be interpreted as a potential advantage to be confirmed.

Table 5. Results for task performance and cognitive workload for the three task types: means, standard deviations, 95% confidence intervals, p -values for ANOVA main effects of display type and t -test differences between means (adjusted significance level: $\alpha = .007$) (adapted from Mast, Materna, et al., 2014)

Task type	Metric		<i>M</i>	<i>SD</i>	<i>M</i> and 95% CI	<i>p</i>
Manipulation subtask 1: target object shape definition	Task completion time (sec)	Mono	285	110.1		.045
		Stereo	219	79.0		
	Cognitive workload (0-100)	Mono	31.0	15.7		.145
		Stereo	38.8	14.3		
Manipulation subtask 2: gripper positioning	Task completion time (sec)	Mono	239	72.2		.001
		Stereo	172	44.8		
	Cognitive workload (0-100)	Mono	27.7	14.5		.555
		Stereo	30.8	14.9		
Robot navigation	Task completion time (sec)	Mono	282	67.3		.025
		Stereo	221	69.0		
	Number of collisions	Mono	0.64	0.63		.319
		Stereo	0.93	0.92		
	Cognitive workload (0-100)	Mono	45.4	22.0		.969
		Stereo	45.1	17.5		

Overall, the most prominent finding of the experiment was the highly significant temporal advantage of stereo viewing for positioning the gripper. The estimated advantage is between 30 and 104 seconds, based on 95% confidence intervals for differences between means. This can be considered relevant for practical applications. It shows that even for a contemporary user interface relying on semi-autonomy, point cloud display, and free viewpoint adjustment, stereoscopic display can be beneficial. Previous studies on robotic telemanipulation suggesting benefits of stereo display have relied on video-based displays with a fixed viewpoint and no or little system autonomy (Edmondson et al., 2012; Drascic, 1991; Hutto et al., 2004).

The nominally significant temporal advantage of stereo display for both other task types suggests further investigations are necessary. Potential reasons why

statistical significance after correction was not reached for the shape definition task are that participants changed viewpoints more often or for longer durations, compared to the gripper-positioning task. Some studies have suggested no or little benefits of stereo display when motion-based depth cues are present (Barfield et al., 1999; Doshier et al., 1986; Ware et al., 1993; Naepflin & Menozzi, 2001; van Schooten et al., 2010). Another reason could be a lack of stereoscopic adaptation of the mouse pointer, which should be addressed in future versions of the user interface (see Mast, Materna, et al., 2014).

Comparing the navigation task to the gripper-positioning task, potential reasons why no significant difference between display conditions was found for the navigation task are less uncertainty in depth judgment as the robot moves along a visible 2D plane, or zoomed-out perspectives chosen by participants in the navigation task. Compared to previous studies that found advantages of stereo display when navigating with video-based or egocentric 3D user interfaces (Lee & Kim, 2008; Livatino et al., 2008; Chen et al., 2014; Livatino et al., 2010), the additional environment data available through the point cloud display and global 3D environment mapping in the user interface may explain why the present study did not find significant differences between display conditions.

In conclusion, the results suggested stereoscopic display not to be an essential feature for the present type of user interface, as participants were able to complete all tasks under mono display too within reasonable time, at least at the here employed level of task difficulty. However, stereoscopic display can be considered a useful optional display mode that may be relied upon in difficult or time-critical situations, e.g., in cases of emergency – particularly for the task of positioning the gripper.

6 Summary of Research Contributions

In summary, the main contributions to the research field made by the work described are:

- **Results of a focus group study with potential users of a semi-autonomous service robot to assist elderly people (Mast et al., 2010):** This study yielded important characteristics of elderly people and caregivers to be considered when designing a remotely supported robotic system. Elderly people and informal caregivers perceived the conceptual idea of a semi-autonomous robot predominantly positive, while professional caregivers were more skeptical, in part due to the potential loss of their job due to a robot. Informal caregivers often feel consumed by the care situation and perceive it as a burden having to be constantly present and available. As they lead a busy life, a robotic concept cannot assume that this user group will always be available. A robotic system should thus improve their situation, e.g. by supporting their mobility with portable devices or by incorporating backup personnel in case informal caregivers are unavailable. The study also suggested that acceptability of a robot by elderly and caregivers largely depends on the services provided by the robot.
- **Results of a survey on user demands for robot services (Mast et al., 2012):** This study provided quantified demands by elderly people and informal caregivers for a range of 25 services a semi-autonomous robot could potentially provide. The results can be used as a guideline for what to consider for implementation when designing a robotic system. Elderly people were highly willing to accept help by a robot in emergency situations and for strenuous physical tasks like cleaning windows but most rejected robotic help for tasks like body care, cooking, or providing companionship. Informal caregivers regarded reminder functions and emergency services as important. Both user groups were supportive of most investigated services with informal caregivers' ratings generally higher than those of elderly people.

- **Results of an ethnographic study on teleassistive service centers (Mast et al., 2012):** This study provided information on the appropriateness of extending the service range provided by current telemedical and home emergency teleassistance service centers to robotic teleassistance. Results suggested staff to be generally qualified for this type of work due to their background often being in care and their experience with a relatively wide range of hardware and computer programs. It seems feasible that some individuals could undergo training for robot teleoperation. The study also suggested this user group to be supportive of the concept of semi-autonomous robots. They saw particular personal benefits such as being able to visually judge the remote situation in cases of emergency.
- **A user-validated human-robot interaction concept for semi-autonomous robots to assist elderly people (Mast et al., 2012; Mast, Burmester, et al., 2014, in press):** The concept specifies three user groups with corresponding interaction devices and user interface functionality. It is based on extensive involvement of prospective users with a total of 430 participants involved in studies on user requirements, concept acceptability, usability, and user experience. Moreover, it is based on an analysis of common failures in robots' autonomous task execution and corresponding required human interventions, and a study on interaction requirements. The iteratively developed concept and user interfaces in the final evaluations achieved encouraging results regarding user satisfaction and user experience and can be used in other research projects as a model and starting point.
- **Results of an experiment on global 3D environment maps for remote robot navigation (Mast et al., 2013):** The experiment investigated potential benefits of displaying global 3D environment maps – an innovative feature in the user interface for professional users – during remote navigation of service robots in domestic environments. Two different variants, a voxel-based and a geometric mapping technique were compared to a control group without global 3D mapping. Results suggested a strong temporal advantage of either type of global 3D mapping when searching for a large object, a temporal advantage of using the voxel-based technique when searching for a small object, better awareness of the remote situation when navigating through elevated obstacles using either type of map, and no benefits of using either type of mapping technique when navigating through obstacles on the floor, which are also visible in 2D laser scanners.
- **Results of an experiment on stereoscopic display for remote manipulation and navigation (Mast, Materna, et al., 2014):** Depth perception has been an important issue in robot teleoperation and stereoscopic display can offer a powerful cue for depth judgments. Previous studies investigated the utility of stereoscopic display for conventional video-based user interfaces or using

virtual environments and also obtained ambiguous results. The aim of this experiment was therefore to investigate the utility of stereoscopic display for the developed user interface for professional users, representing a contemporary type of user interface relying on semi-autonomy, sensor-based 3D visualization, and user-adjustable viewpoints. Results suggested clear temporal benefits of stereoscopy compared to a control group using monoscopic display for one of the three investigated task types, namely positioning the gripper at the grasping position. For the other two task types, i.e. defining the target object's shape as the first step for grasping of objects unknown to the robot and navigating the robot through elevated obstacles, no temporal advantages were found after correction for multiple testing. However, without correction there were temporal advantages of using stereoscopy for both task types, implying potential less pronounced benefits that would have to be verified in further studies. No significant differences were found between display conditions regarding the cognitive workload experienced by the teleoperators.

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