An Ecosystem for Heterogeneous Robotic Assistants in Caregiving: Core Functionalities and Use Cases

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An Ecosystem for Heterogeneous Robotic Assistants in Caregiving

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***Abstract*—Demographic change and its various implications will be some of the biggest challenges to be faced by society and our health-care systems in the coming decades. While the number of people in need of caregiving is steadily growing in most industrial nations, the number of caregivers does not keep up with this increasing demand. Robotic assistance systems have the potential to mitigate this problem and support caregivers, people in need, and thereby the health-care systems in numerous ways. We present the concept and demonstrate first application scenarios of a holistic ecosystem for robotic assistants in caregiving. This ecosystem involves various robots to cover individual demands, and it combines several robotic technologies ranging from autonomous operation over shared-control to telepresence-modes, in order to deal with the wide variety of situations in the everyday life in caregiving. Working towards this ecosystem we have already implemented its core functionalities on the basis of our robotic prototypes and demonstrate exemplary scenarios to showcase the feasibility of the approach.**

I. Introduction

ROBOTIC technologies in the form of so-called service robots are increasingly finding their way into our everyday lives. Forerunners are robotic vacuum cleaners, pool and window wiping systems, or autonomous lawn-mowing robots. However, while these products showcase how robotic technology can be used to perform tedious household activities, it is also evident that a universal service robot for domestic use is far from being available. Until now, mobile robots with manipulation capabilities are mostly constrained to well-structured, e.g. industrial, applications, for which the systems as well as the environment can be designed according to rather specific needs.

In view of the continuous development of humanoid service robots in many research labs, there is great hope that soon robotics can contribute to fill the ever-growing shortage of personnel in the health and care sectors. The demographic change and its numerous implications are probably some of the biggest challenges our society will be confronted with in the next decades. On the one hand, the number of people in need of care steadily increases. The reasons for that process are multifaceted, with one of the main drivers being the continuous progress in medicine, which enables us to live longer. On the other hand, the number of caregivers does not keep up with this increasing demand. In particular, the basic fact of demographic change in the industrial world exacerbates the ratio between the working and aged population. Moreover, the working conditions in care are often adverse and prevent young people from pursuing this career. As a consequence, the gap between demand and supply grows larger and larger, ultimately posing the risk of collapse for most national health-care systems and society in general.

Fig. 1. Exemplary scenario, showcasing DLR's heterogeneous robotic assistants for care-giving in a laboratory-setting.

Robotic systems have the potential to mitigate this problem, and the immense growth in research on assistive systems reflects this very expectation. When we examine projects working with robotic assistance in care, it quickly becomes clear that this is an incredibly heterogeneous field [1]. Both the range of assistive robotics for care applications and the mere definition of *care* itself are notoriously broad. Naturally, health problems tend to be open-ended and without a 'one size fits all solution' [2]. In terms of robotics, these include a vast array of projects regarding rehabilitation, service, social, and even entertainment applications. In addition, care robotics may seamlessly touch areas that would be more associated with hospitality rather than classic care [3]. One might also link the movement surrounding the idea of *Smart Homes* to the field of care robotics [4]. As well as having a wide array of possible applications, robots can also interact with humans on different levels and by a wide range of stakeholders, including patients, clinicians, and family members [2].

One prominent field related to care is that of socially assistive robots. A well-known example is Paro, a socially assistive robot resembling a baby seal used as therapeutic companion [5]. Paro responds to its environment and to the actions of its users; it repeats behaviors that lead to positive responses and avoids those eliciting negative reactions. Another industrially produced social robot is Pepper, a kid-sized humanoid robot capable of exhibiting body language and interacting with people using multi-modal communication by analyzing human expressions and voice tones [6]. Both Paro and Pepper are commercially available and Pepper's communication skills are

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widely used for a variety of tasks in the field of social robotics and entertainment. During the current Corona crisis, Pepper even reminded people to comply with Covid-19 safety rules in a German supermarket [7].

When it comes to mobile, assistive robots with manipulation capabilities, a wide variety of humanoid systems is known from the literature which could potentially be employed in caregiving such as ASIMO [8], ARMAR-6 [9], or Care-O-Bot 4 [10], just to name a few. Another example that has actually been intended for application in care is ROBEAR [11], a robot specifically designed for lifting tasks, such as transferring a person from the bed into a wheelchair or to provide assistance to stand up. The research platform Hobbit features fall prevention and detection as well as emergency detection and handling [12]. The Hobbit project applies a user-centered concept called *Mutual Care* providing the possibility for the human to take care of the robot like a partner. Swiss personal assistant robot Lio, which is produced in small series, is both a social robot, motivating people to conduct movement exercises, for example, and it is able to grasp certain items with its functional arm [13].

When screening the literature for case studies of robots used in care, it is salient that the majority of projects relates to robots serving in the field of social assistance whereas coverage of physical assistance is lagging behind. We hypothesize that one major reason for that fact is the limitation in reliable autonomous behavior of current humanoid robots, especially in dynamically changing environments such as in domestic settings. Although the autonomous capabilities of robots, which are obviously key components, have experienced significant progress within the past years, a reasonable reliability (close to 100%) to handle all possible situations and scenarios in an autonomous way is unrealistic in the short and medium term.

This reliability issue raises the question of how autonomous robots with manipulation capabilities can make the leap from the laboratory environment to the real world in order to actually contribute to the health-care system. Motivated by this question, we envisioned that a more holistic approach is needed to enable robots to enter real-world applications in the near future.

One technology which can help to bridge this reliability-gap is direct teleoperation, which, in combination with haptic feedback and head-mounted stereo displays, allows a human operator to take full control of a remote robotic avatar.

A high level of autonomy of the robotic system is needed in order to provide support and relief to care-taking personnel. Therefore, we have combined the (shared-)autonomous capabilities of our robots with the option of remote teleoperation as a fallback solution, which is used if the robot cannot deal with the situation on its own. This way, we intend to significantly increase the reliability and usefulness of autonomous robotic agents and thereby help to bring robots into use earlier.

In the following we will present and demonstrate an ecosystem for heterogeneous robotic assistance in care-giving. Therein, several aspects describe the main contributions: First, we present an ecosystem which combines various robotic systems (c.f. Fig. 1), which have already proven successful individually, for use in caregiving scenarios. Second, while the user-level interfaces cover a wide variety of requirements demanded by care-giving applications, we have added haptic teleoperation on top, to increase reliability and support in emergency situations. Figure 2 provides a brief glance into the setting utilizing teleoperation, shared-control features, and autonomous operation on several robotic systems matching the specific needs of the individual users. Third, several prototypical experimental implementations demonstrate that the main features of the ecosystem have already been transferred from concept to hardware. Fourth, the ecosystem itself is designed in a way such that it can be efficiently operated and extended. For example, the teleoperator in Fig. 1 can sequentially control the wheelchair and the humanoid using the same haptic interface. In this article we apply the ecosystem on our research platforms to demonstrate its functionality. The proposed concept can be straightforwardly extended in complexity and number of involved people, both on the teleoperator and the user side.

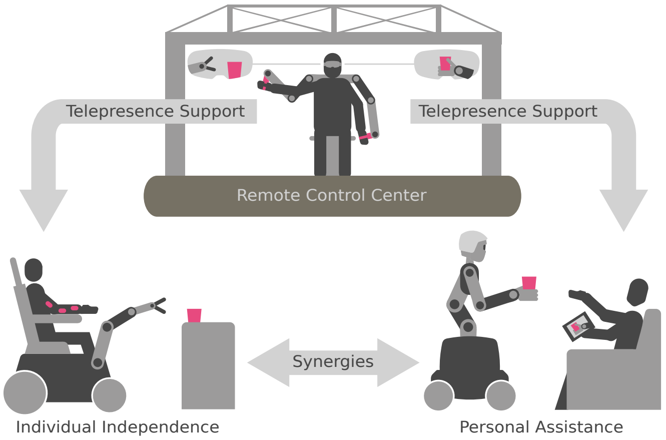

Fig. 2. Illustration of the core elements of the SMiLE ecosystem. Robotic systems such as EDAN and Justin provide individual independence and personal assistance, respectively. Users can control the robots through various interfaces, while an expert can be consulted via telepresence, if needed.

II. Modules of the Ecosystem

Looking at the individual needs of people in care, a diversity of robotic systems will be required in order to provide optimal support. For example, a person with severe mobility impairments will probably favor a robotic wheelchair, while a humanoid service robot may rather serve as a helping hand for an elderly person living at home or in a care facility. Besides the robotic system, also different solutions for user interfaces are needed, adapted to the individual capabilities and preferences of the users.

To reflect this heterogeneity, two research prototypes of robotic systems are currently employed in the realization of the ecosystem: the humanoid assistance robot Justin and the robotic wheelchair EDAN. Furthermore, the ecosystem is completed with the haptic teleoperation device HUG. After briefly introducing these systems and stating their roles within the ecosystem in the following, the user interfaces will be presented. The latter will be conducted following an increasing level of abstraction: from direct commands via joystick over an app-based tablet interface to the most abstract commanding by natural language and its semantic analysis and interpretation.

A. Robotic Systems

The three robots involved are illustrated in Fig. 2 and their roles in the holistic concept are described in the following.

1) EDAN: The idea behind the robotic wheelchair EDAN (EMG-controlled daily assistant) is to serve as supporting technology for people with severe disabilities. Based on a commercial power wheelchair, the system is equipped with a modified torque-controlled DLR lightweight robot with an additional actuated axis. Compared to a classical lightweight robot such as the DLR LWR III, the additional pitch-axis located in the base is pointing laterally our of the seat and significantly increases the reachability of the manipulator [14]. The robotic hand of EDAN is a five-fingered DLR-HIT hand with joint torque interface. EDAN is equipped with an RGB-D camera in order to perceive the environment. Additionally, a pair of stereo cameras is mounted on an actuated pan-tilt unit to allow for remote teleoperation. To provide the user with necessary and task-dependent information, a tablet computer is attached to the wheelchair. The app running on this tablet also allows the user to configure the system and activate or deactivate shared control functions.

All in all, the system thus has three different devices the user can interact with, i. e., robotic arm with hand, wheelchair, and tablet. Selecting the actual device to be controlled is achieved by a head-switch, which cycles through the available entities. The actual commanding of the device can be achieved with a variety of available interfaces, adjustable to the users needs and preferences. As such, EDAN can be controlled with joystick commands, or through decoding of residual muscular activity by means of EMG-sensors, non-invasively placed on the skin of the user's arm [15]. In previous work [16] we have also demonstrated how the robotic arm used in EDAN can be controlled by a person with full tetraplegia through a Brain Computer Interface (BCI). With all of these interfaces it is possible to control EDAN via continuous input signals which allows to efficiently perform a wide variety of tasks. Alternatively, the system can be used in a shared control manner, that is, the human commands are fused with a task-supporting behavior of the system itself. These shared-control capabilities will be explained in Section III-B in more detail.

2) Justin: The humanoid robot Justin [17] was designed for service tasks in space and terrestrial scenarios. Inspired by human kinematics and dynamics, the system meets similar characteristics. The torque-controlled arms and hands of Justin can be used to manipulate objects in a human-like way, which makes Justin a perfect fit for domestic environments. The anthropomorphic upper body (45 kg) is mounted on a wheeled mobile platform (150 kg) that contains all electric and electronic components required for autonomous operation, such as the power supply, battery, and various (real-time) computers. In total, the system features 51 actuated DOF. Extendable legs in the platform base provide the possibility to maximize stability during highly dynamic motions, whereas the footprint can also be minimized if necessary, for example in case of traversing narrow doors. Four RGB-D cameras are mounted all around the platform, allowing for localization and navigation and finding collision-free paths through the room. Additionally, one RGB-D camera and a pair of stereo cameras are integrated into Justin's head to detect objects in the visual field and provide stereo vision for remote teleoperation.

A crucial feature for a robot that is employed in human households is the ability to interact with the environment compliantly and safely. In Justin, as in EDAN, this is achieved through joint-torque sensors in all of the joints (except for the neck joints and the wheeled platform). The lightweight arms feature a payload of 15 kg and can reach from the floor up to a total height of 2.7 m. Justin's hands have four fingers each, which enables human-like object handling and grasping.

3) HUG: The DLR HUG [18] is a haptic input device that is applied for tele-manipulation of EDAN and Justin. Alternatively, the device can be used to train a specific procedure with virtual objects and robots in a virtual environment [19]. The haptic interface is built out of two DLR lightweight robots with which the desired poses of the teleoperated robot or the motion of its platform can be commanded, respectively. To allow for a safe interaction with the remote environment, the robotic arms of HUG can provide kinesthetic force feedback to the operator. A force-torque sensor is integrated at the end-effector of each robot, to reduce the effect of the weight of the arms that the human operator has to move. For the sake of safety, the human operator is connected to the robots with safety clutches and operates a foot-deadman-switch. The overall setup involves a head-mounted display with tracking system for the head motion, sensor gloves to command the robotic fingers, and a one-DOF haptic master device that can display grasping forces of the robotic hand to the operator. The stereo-cameras of EDAN and Justin are mounted on pan-tilt units such that the HUG operator can actively change the direction of view by means of the tracking system of the head-mounted display.

B. User-Level Interfaces

Analogously to the robotic systems, the means of control for these systems also need to fit the individual users' needs. Therefore, our current implementation of the ecosystem is built on four different user interfaces, complemented by the additional control option of remote haptic teleoperation by an expert. The range of interfaces and their associated levels of autonomy (see Sec. III) are depicted in Figure 3.

1) Joystick: A joystick presents an intuitive and commonly used interface to achieve direct control of a robot. As such, the device is especially useful in the EDAN use case, where the user is sitting in the wheelchair and can directly observe the robotic motion. The deflection of the joystick can be mapped to a velocity command for the platform or the Cartesian motion of the manipulator such that the pose of EDAN can be precisely set without additional sensors. In case the number of DOF in the joystick is less than six, typically intuitive subsets of the DOF in the robotic end-effector are controlled, with the option to cycle through different subsets (e.g. translation or rotation) using an additional button on the joystick. Since direct control via the joystick can be tedious and leads to high

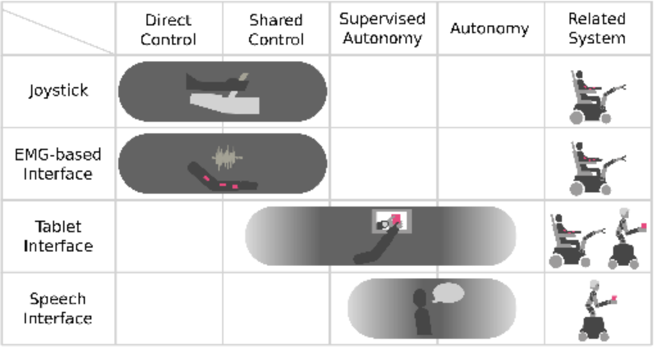

Fig. 3. Illustration of the different kinds of user interfaces in relation to the respective levels of autonomy.

cognitive load requiring permanent attention by the user it is commonly used in combination with shared control (see Sec. III-B). Thus, the joystick interface can be employed in combination with autonomous robot behavior, but it also constitutes a fall-back solution, providing the user with all necessary means of control if the execution of a specific task is not possible in a more autonomous way.

2) EMG-based: In case the user cannot operate a joystick, for example due to a lack of sufficient motor function, EDAN offers an alternative interface based on the recording of muscular activation. So far, this interface has been tested in a pilot study [15] with two subjects suffering from spinal muscular atrophy (SMA). To realize the interface, non-invasive EMG-sensors measure the residual muscular activity by means of electromyography. These signals are then processed to generate a velocity signal, essentially replicating the functionality of a joystick. Therefore, as with the joystick, the EMG-based interface can be used both for direct control and in combination with shared control capabilities.

3) Tablet-based: If the robot system offers a more abstract level of commands, graphical user interfaces are the method of choice. Since app-based tablet or smartphone devices are common, the hardware is inexpensive, highly available, and the handling widely known. Such a graphical interface can provide augmented camera data, click-and-execute functionalities or even a direct interface to the platform motion in an intuitive way. The higher level of abstraction (compared to a joystick interface) and the visualization make it easier to interpret and command the robot and reduce the cognitive load on the user. Furthermore, using commands at a high level of task abstraction frees the operator from the need to continuously monitor the robot or manually set desired trajectories, which allows to concentrate on other activities.

In addition, the interface can be operated over the Internet, as neither minimal latency, interference-free connection nor high bandwidth are required. At the same time it can also be used for bidirectional video/audio communication between the operator and the remote environment of the robot. This way, the remote operator can communicate directly with the person in need of care. This social interaction component can be used for direct interaction with remote friends and relatives as well as health care professionals to monitor and respond to medical emergencies.

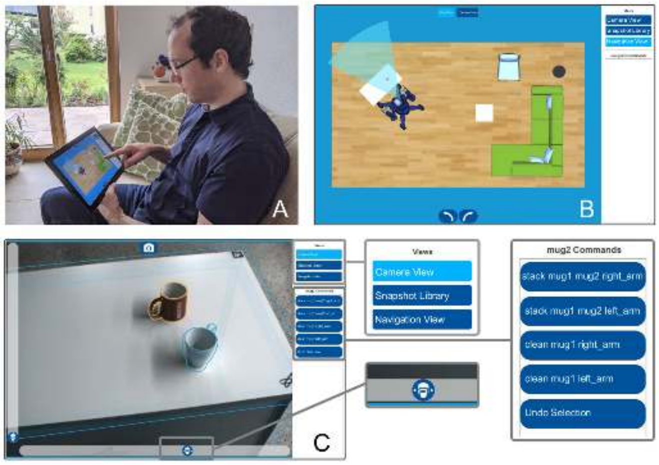

Fig. 4. Tablet interface app for Justin. A: User with tablet-app in map view mode, B: Detailed view of the map view mode, which allows to move the robot in the room, C: Camera view mode which allows to manipulate detected objects, including close ups of the user menu listing available views and actions. The sliders on the bottom and the left of the map view mode allow to change the robots field of view.

The app used in the presented ecosystem is illustrated in Fig. 4. The operator accesses the possible actions provided as context-specific robot commands via a tablet interface. The live video of the camera of the robot is displayed to the operator and supplemented by transparent 3D models of the objects in the environment (Fig. 4C). This allows the operator to easily assess the validity of the internal world model of the robot by comparing the orientation of virtual objects with their real counterparts in the video-stream.

By selecting an object overlay on the tablet screen, like one of the mugs in the scene shown in Fig. 4C, the operator receives the object-specific command set that displays only the current commands of interest (see Fig. 4C on the right). After selecting one of the commands, e. g., to clean a mug or to stack them, the robot performs the task autonomously. This technology has already been successfully validated in space missions as remote control tool. In particular, several astronauts located on the International Space Station (ISS) have used this intuitive interface to control the humanoid robot Justin remotely from the orbit [20].

Using the mission control system developed for the ISS experiments, the user interface can be adapted to the user's level of experience:

- It can provide novice users with an intuitive user interface that displays only the most important abstract commands.
- Experienced users can access more complex robot functions and manually parameterize the autonomous task execution.
- In the future, trained healthcare professionals may be able to perform patient-specific medical diagnostic or therapeutic procedures.

4) Natural language: Ultimately, the use of natural language combined with an audio interface promises to be the most natural and intuitive manner of interaction with a robotic assistant. Thus, the cognitive load can be further reduced and the ease of interaction is improved. For the current generation of elderly people who are partially not familiar with smartphones or tablets yet, a natural language interface may be most appropriate. So far, the automated semantic analysis of natural language commands does not cover a wide variety of tasks. As such, speech recognition can be used to trigger autonomous functions of a robot, which are known to the user, but full speech-based commanding is not yet achievable.

All the aforementioned interfaces are designed to provide the designated users of the assistive systems with control capabilities. Additionally, the ecosystem allows for direct haptic teleoperation of the systems. This additional interface is intended for professionals, i.e. trained teleoperators, to access and command the system in case of emergency, or when the user-level functionalities do not suffice to fulfill a task.

III. LEVELS OF AUTONOMY

BESIDES user-specific interfaces, the level of autonomy of the robot also needs to be tailored to the particular requirements given by the user. Currently the ecosystem is composed of four user-level control modes offering different levels of robot autonomy (see Fig. 5). Analogously to the interfaces, these control modes are complemented by a telepresence option in which an expert takes control over the system.

A. Direct Control

The most basic control scheme is direct control, in which the user instantly commands the pose of the end-effector of the robot via an appropriate user interface. Actually, for wheelchair-mounted robot arms, similar to EDAN, direct control based on joystick commands is the most commonly used mode of operation. Typically, a joystick provides two or three continuous velocity commands, which are mapped to subsets of the task-space DOF of the end-effector. An additional trigger signal makes it possible to switch between different sets of *input mappings*, also including the tool or gripper, to provide the user with full control over the system. Many activities of daily living can be performed with the approach of direct control, essentially transferring the task of motion planning to the human operator.

In EDAN, direct control is achieved with a 3-DOF input device, either based on a joystick, or on measuring residual muscular activity. In combination with the trigger signal, this enables the user to switch between purely translation control, rotational control, or opening and closing of a specific grasp type of the robotic hand. Using this cycle of control modes (see Fig. 5 top row) in combination with the EMG-based interface, even users with severe physical disability can perform a variety of tasks that require dexterous manipulation [15].

B. Shared Control

Direct control is rather time-consuming, even in comparably simple tasks. For one, this is because the DOF of the task space usually exceed the number of control signals available from the interface. Moreover, tasks that require synchronous Cartesian motions (in directions of translation and orientation) can barely be executed sequentially. Shared control methods can support the user to perform complex tasks of daily living where high accuracy or coordinated motion is required. Examples are the pouring of water into a glass or the opening of a door. The main idea of shared control is that the user still has full control authority over the system at any time but the robot supports task execution in a transparent and intuitive way.

In EDAN, shared control is achieved by transforming the user's commands in a goal directed manner, which effectively reduces the number of coordinates the user needs to control in a task to fit the DOF of the interface. Two basic principles are used to realize the shared control capabilities, namely input mapping (IM), which assigns DOF of the user interface to coordinates in task space, and active constraints (AC), which restrict the resulting robot pose according to task specific needs, cf. [21] and Fig. 5, second row. Currently, the interfaces designated for use with EDAN offer three DOF and therefore shared control features are modeled accordingly. However, IMs and ACs could also be defined in order to work with interfaces of lower or higher dimensionality.

Based on these principles, a shared control skill is built up by phases wherein each phase has an individual set of IMs and ACs. Transition between the phases are triggered according to different available metrics that relate two frames in space, typically distances between the end-effector and a frame on the object of interest. Additionally, transitions can also depend on external forces estimated via the joint torque sensors, e.g. when pressing a door handle.

To stick with the example of opening a door, in a first phase, the IM allows for translational control in three DOF to move the end-effector of the robot towards the door handle. At the same time, an AC enforces the robotic hand to converge to a specific orientation when close to the handle, as well as reaching a specific grasp point on the handle. Once the robot-hand is above the handle, the next phase is activated in which the door handle needs to be pushed down, which is achieved by defining the IM to allow for downward motion only. Finally, when opening the door after pressing the handle, the robot end-effector is constrained to a circular motion which corresponds to the path described by the door handle. While opening the door, the IM is defined such that the user essentially only needs to create control signals in a single DOF, namely the direction towards the door handle. As a result, the complete six-dimensional Cartesian control of the end-effector is automatically handled by the shared control algorithm.

To enlarge the kinematic reachability of the arm, especially in tasks that require a large range of motion, EDAN is extended with a whole-body control approach [22]. This approach coordinates the motion of the wheelchair and the manipulator, either in shared control tasks, or even in direct control if desired by the user. Especially in an assistive system, such as EDAN, whole-body control allows to perform tasks which require a coordinated motion of the mobile base and the manipulator, e.g. when opening a door and passing through.

In EDAN, a variety of shared control skills are implemented to support execution of every day tasks. In our framework, shared control skills are object-centered and stored in an object database (ODB) as human readable YAML-files. Besides skill definitions, the ODB also provides information such as name, class affiliation, geometry, or grasp and tool frames for each

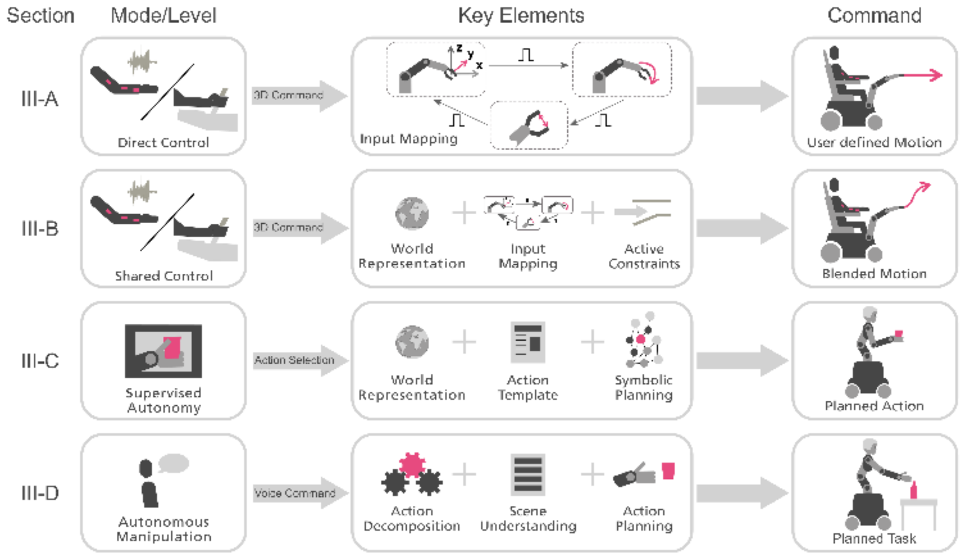

Fig. 5. Overview of the user-level control modes with their respective level of autonomy available in the ecosystem. Each row relates to a specific control mode as described in the Sections III-A – III-D.

object. Objects stored in the ODB can be localized using the RGB-D camera(s) and a perception pipeline based on a bounding box detector followed by a pose estimator algorithm as described in [23]. For objects with a support plane like doors or drawer handles, the plane equation is estimated from depth data and intersected with the object bounding box for a more refined pose.

Once an object has been detected within the reachable workspace, it is stored in the robot's world representation and shared control skills associated with the object become available. The user can choose to activate a skill directly from EDAN's tablet computer, or have it automatically activated as soon as the end-effector is moved into close vicinity of the object of interest. Accordingly, the user can abort the currently active task by moving away from the object of interest. Information about available tasks and possible activation are visualized on the tablet computer.

C. Supervised Autonomy

Direct and shared control are suitable modes for assistive systems such as EDAN, which follow a human-in-the-loop approach. In service robots, like Justin, a different strategy is required since the robot is supposed to execute tasks without continuous human interaction. As a result, the system needs to operate on a higher level of autonomy, and simultaneously, the user interface must work on a higher level of abstraction. This leads to the control mode of supervised autonomy as it is employed in the Justin system.

Based on the findings obtained during the METERON SUPVIS Justin experiments (Multi-purpose End-To-End Robotics Operation Network) [20], the interface, initially designed for astronaut-robot teams, is repurposed for elderly care scenarios. The user interface relies on highly abstract commands generated by the robot autonomy layer. This system uses an object-centered knowledge representation to plan the execution of a task:

The knowledge about objects in its environment is stored in our common knowledge base ODB. This knowledge base contains object-specific *Action Templates* [24] that provide the robot with symbolic and geometric descriptions of the respective manipulation task. For application in elderly care, we have added numerous objects and action templates to the ODB to allow the robot to interact with its new environment. A hybrid planning framework utilizes this information to solve the given task symbolically and find a suitable geometric solution for the intended course of action, cf. Fig. 5 third row. The planning is carried out according to the actual symbolic and geometric state of the environment and uses robot-specific planning modules such as motion planning and controller parameterization [25]. If the robot does not find a suitable geometric solution, the action is re-evaluated by means of geometric and symbolic backtracking to find alternative solutions.

Besides symbolic and geometric planning another key aspect to achieve autonomous operation is self-localization and navigation. In Justin, a 3D map of the indoor scene is created for localization purposes. During operation, recently obtained sensor readings are compared to this map. This is done by sampling multiple random pose hypotheses based on the last position of the robot and the commanded movement. For each hypothesis the expected sensor output (here: depth images) is generated and compared to the actual measurements. Since Justin is equipped with four RGB-D sensors, redundant sensor information is available. This feature can be exploited to resolve ambiguous situations and increase the robustness of the indoor localization. In the end, the most probable pose hypothesis is selected as the current pose.

With the obtained pose the navigation module can plan a collision-free path to a selected destination. This target can be either directly selected by a human or be part of the autonomy of the robot. Here a standard A* (A star) algorithm is applied to plan the shortest path to the target. The algorithm works on a graph that connects all safely traversable positions and takes the configuration of the robot into account, as for certain areas

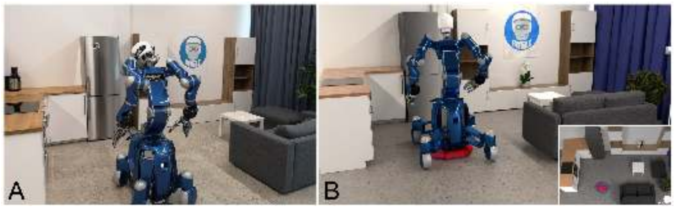

Fig. 6. Localization based on the 3D model of the environment. A: Photo of the actual scene, B: Rendering of the robot localized in the kitchen area. The colored dots below the robot, and in the inserted birds-eye view, depict the hypothesis of the localization.

the arms may have to be folded.

Based on *Action Templates* and Navigation skills, the Justin system can be commanded with a high degree of abstraction, where available actions depend on the current state of the environment and the objects relevant to the task, which are stored in the world representation. We continued to use the autonomy system from the METERON experiments unchanged, as the object-centered knowledge representation has proven to be useful and easy to translate into the user interface.

D. Autonomous Manipulation

Supervised autonomy makes it possible to adjust the level of autonomy of the robotic system as well as the complexity of the interface to the preferences and capabilities of the user. However, for some tasks, like searching for a specific object, a higher level of autonomy, e. g., in combination with voice commands, may be desirable. To enable a robot to perform a task fully autonomously, 3D visual perception, fast whole-body motion planning, and their close interaction are crucial. That is particularly true in household environments with challenging and ever-changing geometrical constraints.

To allow for this, a precise 3D environment model is generated in real-time (30 Hz frame rate) using GPU-based probabilistic fusion algorithms [26], [27] that integrate the stream of depth images from the head-mounted Kinect camera into a dense voxel model, which reaches a precision of 2 mm in a typical manipulation distance of up to 2 m.

These 3D models are the basis for an optimization-based motion planner that plans a collision-free motion for all 19 upper-body DOF and the mobile platform in less than 1 s [28]. To speed up the solver convergence and avoid local minima, we developed an informed multistart approach which draws guesses for the initial trajectories using a generative neural network (GAN). The GAN is conditioned on the current 3D model, and the start and target configurations and is trained in batch-mode from numerous example planning problems.

The high-resolution 3D model is also used for pose estimation of objects to be grasped and manipulated. Our algorithm predicts a number of point correspondences to a given 3D model of the target object. From a moderate number of correct predictions, the object pose can be estimated using classical robust techniques (such as RANSAC) even if contaminated with a high number of outliers. Multiple pose hypotheses are generated from groups of predicted point correspondences and evaluated for their fit to the scene model, thus optimizing the three rotational and three translational DOF. As usually a large number of point correspondences are predicted for each scene, not all of them being correct, a prediction method is required that delivers a meaningful confidence measure along with each prediction. With this consideration in mind, we decided to use *Extremely Randomized Trees* for the correspondence prediction, a method previously used in a similar problem setting [29]. Only high-confidence correspondences are then regarded in the generation of pose hypotheses.

To be able to autonomously find a target object from large distances, we implemented a combined exploration and detection strategy. For the object detection, a *RetinaNet* [30] detector was trained on various appearances of the target objects in RGB images, viewed from distances of about 1–3 m and under various lighting conditions. Combined with our realtime 3D environment modeling and fast motion planning algorithms, the robot is able to move around in a room while streaming RGB images at 1 Hz to the detector, in search of the target object. For the object detected in an RGB image, a synchronous depth image is used to transform the image coordinates of the object into 3D space, i.e., the target location for the robot for fetching the object.

E. Telepresence

Besides the control modes designed for the users of the robots, the ecosystem provides the opportunity of control via telepresence by an expert, utilizing the sensory channels provided by HUG (see Section II-A3). A high level of immersion or transparency, respectively, enables the operator to perceive the remote environment with his/her own senses in a way such that it feels like being on the remote site. The senses that are generally considered in telepresence systems provide visual, audio and haptic (kinesthetic and tactile) information of the remote environment. In the ecosystem, DLR HUG is used as the main telepresence device, providing the operator with the required manipulation and sensing capabilities. Using HUG, the operator can control all DOF of the avatar system and simultaneously feel the forces exerted on the environment, which is visually perceived through a pair of stereo cameras mounted on the avatar.

For safe and high-performance teleoperation the quality of haptic and visual feedback is known to be more relevant than the one of the audio channel. Therefore, the visual feedback to the operator provides high camera resolution, sufficient light and depth of focus, stereo information, and a large field of view. In contrast to tactile feedback (which is only required for very specific tasks), kinesthetic force feedback provides safety-critical information on the physical interaction of the remote robotic arm with its environment.

Telemanipulation has its origins in the atomic industry. The first basic telerobotic system was developed in 1945 in the Argonne National Laboratory for radioactive environments to replace humans in harmful environments. Since then and especially with the development of torque-controlled robots, the technology was further developed for space applications, and is nowadays even applied in surgical scenarios due to micro-manipulation capabilities and tremor filtering. Despite the market maturity, safety of the persons in the robot environment but also of the human operator in the control center remain of utmost priority in the development process. Additional safety measures include the observation of the quality in the communication channel, passivity-based handling of interaction forces, and the overall control stability despite time delay [31]. Still, delay itself is the limiting factor for human perception and performance. To ease complex procedures and reduce the workload of the operator, different augmentation approaches have to be considered for demanding tasks [32].

In our prototypical implementation, direct haptic teleoperation of the assistive robotic systems is possible. Upon teleoperation request, the control authority of the avatar is taken through HUG. Since EDAN features only one manipulator, only one arm of HUG is needed for manipulation, whereas the other arm is used as a joystick to control the motion of the nonholonomic platform. In Justin, both robot arms can be teleoperated in parallel. To control its pseudo-omnidirectional mobile base a differential steering method is realized where both arms of HUG serve as joysticks.

Within the ecosystem, HUG is combined with the previously described tablet interface that provides the teleoperator with the autonomous capabilities whenever needed. This extended telepresence technology is applied for two reasons. For one, teleoperation via telepresence can effectively increase the deployability of autonomous robots, as these systems will not achieve 100% reliability in the near future. In case of failure or malfunction in autonomous operation the teleoperator can take over control and either finish the incomplete task, or bring the robot to a safe state and start remote diagnosis and repair in case of technical problems. On the other hand, haptic teleoperation can be used in scenarios and tasks, in which autonomous capabilities are not preferred. This could, for example, be the case when conducting medical examinations remotely or when emergency situations occur. Here, we particularly envision use cases such as medical emergencies in which the teleoperator administers medication, and gathers as well as provides information about the medical condition of the patient to the emergency doctor prior to arrival on site.

To offer this telepresence service in an effective way, the ecosystem envisions a teleoperation control center, in which human operators (cf. Fig. 7) can connect to all available avatars whenever needed. As intervention via teleoperation will only be needed when the autonomy of a system fails, or in case of a medical emergency, the number of teleoperators needed is low compared to the number of robots at use. Using this call-center-like approach it will be possible to manage a large number of robotic systems which can be located in different facilities anywhere around the world.

IV. CASE STUDIES

To demonstrate the features of the ecosystem, we have created exemplary scenarios that showcase typical situations people in need of care may experience in daily living and in which robotic assistance can be beneficial. In order to address the actual needs of daily nursing care that could be supported by robots, it is important to identify and define the actual goals together with all stakeholders involved. Therefore, the scenarios are based on interviews conducted with nurses and those to be nursed, in order to identify useful applications.


Fig. 7. Teleoperation Setup with DLR HUG (in the background) and the robotic system Justin (in the foreground)

People in need of care, caregivers, and relatives are considered as potential primary and secondary users of the robots in the ecosystem. To get a first hand impression, representatives of all groups were asked about the requirements and wishes for functions and properties but also about the challenges they see. The sentiment of potential users shows that assistance robots in care are seen as positive and promising means in some specific areas of application. This is especially the case for fetch-and-carry tasks as well as small chores such as opening a window. For this class of tasks a robot is seen as a potential help by both caregivers and caretakers. For the group of severely physically disabled people, food and drink preparation was named as well as generally increasing the mobility of the individual. Another positively rated scenario was the robotic ability to provide help or call for external support in emergency situations.

However, concerns were also expressed. In particular these related to social contacts and human attention. Both nurses and those to be nursed criticized that robots may decrease the amount of social interaction. The elderly also fear a faster physical degradation if too much activity is taken away from them by a robot. On the other hand, many tasks that were desired by the potential users are technically not yet achievable with humanoid robots to a satisfying degree, for example, putting on socks or support in heavy lifting.

Based on these impressions a set of tasks was defined, which is in accordance with the users' requirements and, at the same time, enables demonstration of the capabilities of the ecosystem. Table I provides an overview of the demonstrated tasks, which can be clustered in three user-related scenarios regarding individual independence, personal assistance, and telepresence support.

A. Individual Independence

Scenarios of individual independence are mainly related to users with severe motor disabilities, who are usually in need of 24h care. Assistive systems such as EDAN can provide this group of users with the capability to physically interact with their environment again. As described in Section III-B, EDAN is equipped with shared control capabilities. To demonstrate the functionality of the robot within the ecosystem, two activities of daily living have been adopted as shared control skills. The first one is to pour liquid into a mug and drink from it, while the second one is to open a door and move through it. These two scenarios demonstrate the feasibility of the approach as these supposedly simple tasks would need a long sequence of commands to be performed in a manual control mode, especially in those tasks combining mobility and manipulation as needed in driving through a door. Since EDAN can be controlled either by a 3D joystick or the EMG-based interface (cf. Fig. 3) each mode is demonstrated once.

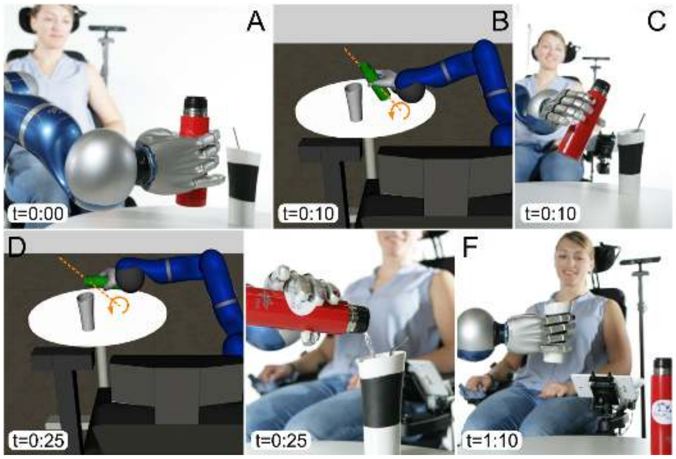

Fig. 8. Individual Independence: Pouring a drink. A: moving towards the mug with a grasped bottle, B-C: in this phase of pouring, the bottle is rotated around its center when coming closer to the mug, D-E: rotation around the tip of the bottle resulting in the actual pouring motion, E: grasping the mug for drinking. Performing this task takes about 1:10min. Note that this is a demonstration with a non-disabled user.

Pouring: The pouring task is actually comprised of three individual subtasks, namely grasping a bottle, the actual pouring, and placing the bottle on the table again. All of these tasks are supported by shared control skills, which get activated in close vicinity to the target object. Once the bottle is grasped (see Fig. 8 A), the user can freely move the end-effector by means of the given interface (EMG in this example). In the close vicinity of the mug, the shared control skill of pouring gets activated, which results in the rotation of the bottle about its vertical axis to approach a natural pouring orientation. Moving closer to the mug, the actual pouring motion is automatically superimposed onto the user's commands, where first, the bottle is rotated around its center, to move the lid above the mug, see Fig. 8 B-C. Once close enough to the mug, the rotation happens around the tip of the bottle as depicted in Fig. 8 D-E, in order to allow the actual pouring. The user can determine the amount of liquid to pour through specifying the degree of rotation of the bottle by means of moving towards or away from the mug. Once the liquid has been poured, the user can retract the bottle from the mug and place it on the table surface again. Afterwards, the user can intentionally pick up the mug, again with support of the shared control system (Fig. 8 F), and finally drink from it.

TABLE I
OVERVIEW OF THE PRESENTED CASE STUDIES

Use Case	System	Interface	Autonomy Level	Task
Individual Independence (Sec. IV-A)	EDAN	EMG	Shared Control	Pour a drink
	EDAN	Joystick	Shared Control	Open door & pass through
Personal Assistance (Sec. IV-B)	Justin	Tablet	Supervised Autonomy	Fetch & carry dispenser
	Justin	Voice\ Tablet	Autonomous Manipulation	Find & bring spectacle case
Telepresence Support (Sec. IV-C)	EDAN	HUG	Telepresence	Operate microwave
	Justin	Tablet & HUG	Supervised Autonomy & Telepresence	Administer injection

Door opening and passing through: The task of opening a door and passing through it is composed of three parts: at first, the wheelchair needs to be aligned normal to the door plane. Since system-transparency plays a major role when providing assistive robots with shared control capabilities, the task of aligning the wheelchair to the door has to be manually activated by the user. Therefore, upon detection and localization of the door handle from the RGB-D data, the subtask of aligning becomes available on the user's graphical interface and can be activated by use of the head-switch and the continuous interface.

Once selected, the wheelchair automatically aligns to the door such that only pure forward motion is needed to pass through the door (Fig. 9 A). After aligning, the shared control task to open the door is automatically activated. At this point the user can command the end-effector of the robot while the shared control constraints provide guidance to reach for the handle, automatically enforcing the correct orientation of the robotic hand (Fig. 9 B-D). Once at the handle, the user commands the manipulator to press down and finally open the door, while the shared control module forces the robotic hand to stay on the path described by the handle (Fig. 9 E-G). As a result, the user does not need to take care of the coordinated motion of the arm and the wheelchair but instead only has to provide a forward command to progress in the task. During all these activities, the wheelchair motion is coordinated by a reactive whole-body-controller [22], [33] to ensure reachability of the robotic arm, and at the same time, maneuver the wheelchair through the door. Once the door is fully open, the user can release the handle by commanding the end-effector upwards and fully drive through the door controlling the wheelchair directly. Afterwards, the door can be pushed until it is closed making use of the whole-body control behavior again while freely commanding the end-effector, see Fig. 9 H.

B. Personal Assistance

Other than in the previous section, the scenario of personal assistance is meant for people who still have some level of mobility and independence but still require support in everyday activities. A typical use case for a robotic personal assistant are fetch-and-carry services of household objects. As an example, a person may request the robot to bring a remote control or a medicine. Of course, the medicine could also be served in a time-dependent manner without the need of additional user request. In our prototypical implementation of the ecosystem, the humanoid robot Justin serves as personal assistant. It is

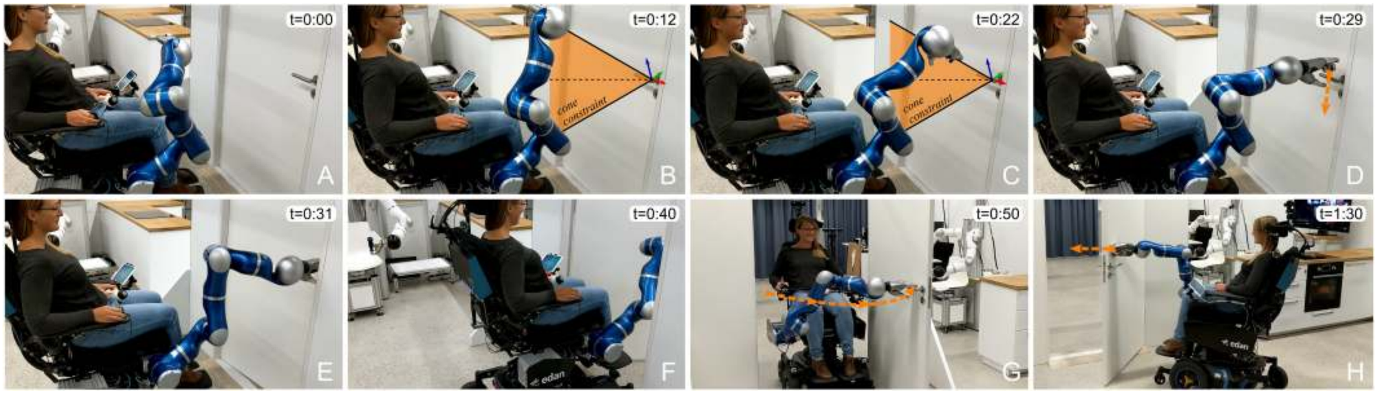

Fig. 9. Individual Independence: Opening a door and passing through. A: approaching the door, B-C: a cone-shaped constraint guides the end-effector to the door handle, and aligns to the handle accordingly, D: downwards motion makes the robot press the latch, E-G: opening the door and driving through, while the end-effector follows the motion of the door handle, H: closing the door by pushing on it. The task is executed by means of shared control and whole-body control on EDAN. Performing this task takes about 2:00 minutes. Note that this is a demonstration with a non-disabled user.

Fig. 10. Personal assistant: fetch-and-carry service of a medicine dispenser. A: opening of the drawer, B: grasping the dispenser, C: closing the drawer, D: carrying the dispenser. Execution time of this task is less than 2:00min.

commanded in supervisory control via a tablet interface, either by the person in need directly, or remotely by a relative.

In this scenario, the medicine is located in a kitchen drawer. Using the graphical user interface (GUI) on the tablet one can command the robot to move to the kitchen and localize the drawer of interest. The robot recognizes objects and their locations in the environment autonomously. Once objects are localized, possible actions involving the respective target objects are proposed in the GUI. This way the user can choose to open the drawer, upon which the robot plans and executes a collision-free motion to fulfill the requested task (see Fig. 10 A). When the drawer is open, the medicine dispenser can be localized and the robot grasps and places it on the kitchen counter upon user's request (Fig. 10 B-C). Afterwards, the robot is commanded to close the drawer and transfer the dispenser to the person in need (Fig. 10 D).

In other fetch-and-carry scenarios it is also conceivable that the user does not know where the object is located, for example, when searching for a spectacle case. Given that the personal assistance robot has a database of objects belonging to the user, the task is one of finding a known object in a domestic environment, moving there, grasping the object, and bringing it to a placement area close to the user. Within the ecosystem, this task is demonstrated using 3D modeling and object recognition capabilities, as described in Section III-D.

Once the request to retrieve the spectacle case is issued by the user, e.g., via voice command, the robot creates a 3D model of the room and starts scanning for the requested object (see Fig. 11 A-B). Upon successful localization of the spectacle case in RGB images, the 3D room model is used to autonomously navigate close to the object (see Fig. 11 C) so that its pose can be estimated (see Fig. 11 D) and it can be autonomously grasped (see Fig. 11 E); then the object is brought to the user or placed somewhere safe (Fig. 11 F).

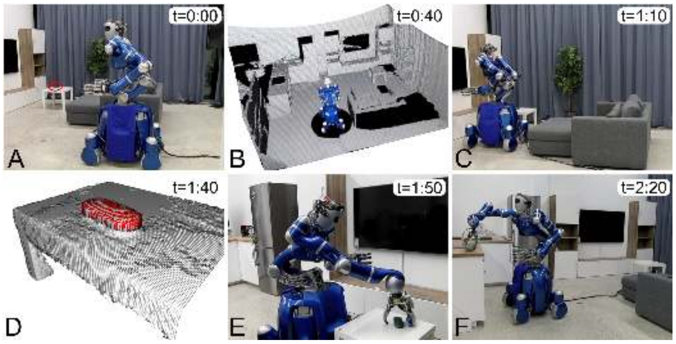

Fig. 11. Personal Assistant: Retrieving a lost spectacle case. A: creating a 3D model and searching for the spectacle case (marked in red), B: resulting 3D model of the environment, C: planning collision-free motion and approaching the case, D: recognized pose of the spectacle case used for grasping, E: grasping the spectacle case in a confined environment, F: placing the spectacle case on the kitchen counter. Execution time for this task is 2:20min.

C. *Telepresence Support*

Haptic teleoperation can serve as an alternative solution for tasks that cannot be achieved autonomously, or in case of emergency situations. In the EDAN use case, one task that has been identified during the interviews was changing the position of the blanket at night, for instance, when the person feels too warm or cold. Potential users of the system reported that they sometimes feel uncomfortable waking the caregivers in order to adjust the blanket by a few centimeters. On the other hand, to safely and robustly handle a blanket in autonomous mode is currently beyond the state of the art in robotics. However, haptic teleoperation offers a practical solution for such a case.

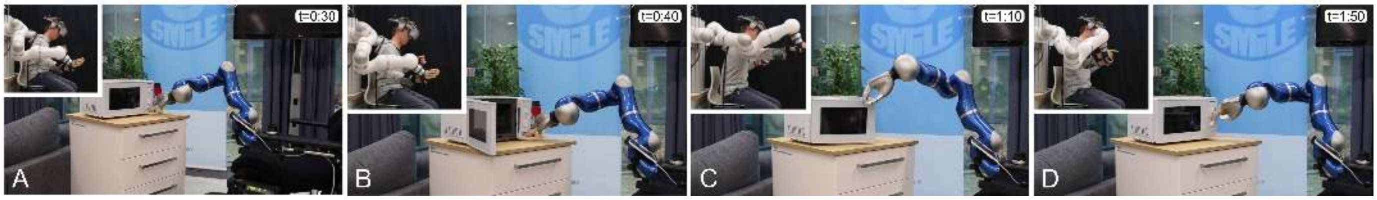

Fig. 12. Telepresence support: operating a microwave. A-B: opening the microwave by pressing a button, C: closing the door of the microwave, D: setting the timer on the microwave. The whole sequence of opening and closing the microwave and setting the timer takes about 2:00min.

Moreover, direct teleoperation can also be used if a task has not yet been implemented on the system, for example, when the user has purchased a new kitchen appliance not yet known to the robot.

Using direct teleoperation of EDAN, we have demonstrated the scenario of operating a microwave, as depicted in Fig. 12. The teleoperator opens the microwave by pushing the respective button (Fig. 12 A-B). Afterwards, the user might place an object inside the microwave, e.g. by using the manual control mode (not shown). Upon request, the teleoperator again takes over control, in order to close the door and setup the timer on the microwave (Fig. 12 C-D). While at first it might sound impractical to have a teleoperator available for such tasks, we envision that the data used from these teleoperation activities can actually be applied to learn skills to handle new objects such as the microwave in this example. In other words, the productivity and efficiency of the autonomous operation is going to increase in the future, as the robot learns more tasks which have been initially executed in teleoperation mode.

Besides serving as a fall-back solution to tasks that cannot be handled autonomously, telepresence and haptic teleoperation can be of great benefit in emergency situations. A potential use case could be a scenario in which the tele-healthcare assistant, who is a medically trained professional, does administer an injection to a person in need. Obviously, before applying that in reality in the future, there is need for clarification regarding medical and ethical issues. However, since this task would not be performed autonomously by a robot, it is a suitable example to demonstrate the technological capabilities of the ecosystem.

In the chosen scenario depicted in Fig. 13, a wearable device or alternatively the robotic assistant detects the state of emergency of a person in need. The robot autonomously contacts an emergency medical service that is able to analyze the situation instantly. If necessary, the service can advice the robot or a tele-healthcare assistant, respectively, to administer medication through an auto-injector to the person in need as a transitional action until a medical doctor has arrived on site.

When demonstrating this scenario on Justin, a mixture of remote control through the intuitive tablet GUI and direct teleoperation with force feedback through HUG was used. The task to be performed was to get a replicated glucose auto-injector from a drawer and administer it to a person on the sofa. The system knows the location of the injector and proposes to the tele-healthcare assistant in the tablet GUI to move the robot to the specific location. Via supervised control, the teleoperator commands the robot to open the drawer, pick up the injector, and close the drawer in a sequential manner, similar to the scenario in Section IV-B. This first part of the task is depicted in Fig. 13 A-D.

After retrieving the auto-injector, the teleoperator takes over direct control authority of the robot via HUG. He moves Justin from the kitchen to the sofa and places the injector onto the patient's arm, a task in which the haptic feedback plays an important role. With his left arm the teleoperator can then press a button on the injector device to administer the injection (see Fig. 13 E-G). In this demonstration, no real glucose injector was used but an imitation, which paints a dot on the patient's arm when the button is pressed successfully. In the last picture of the photo series you can see how the teleoperator places the injector onto the kitchen counter.

V. CONCLUSIONS AND FUTURE WORK

THE use of assistive robots to support caregivers and those in need of care is an aspired goal in robotics research. Care is based on the interpersonal relation and communication of a human caregiver and the person in need. Work in care robotics involves a large number of primary (users/patients; clinicians; care givers); secondary (engineers; environmental service workers; health administrators); and tertiary stakeholders (policy makers; insurers, advocacy groups) [2]. It is our aim to respect this large variety of stakeholders and to involve them into the eventual development as far as possible.

People in different life situations demand individual levels of support and thus individual solutions. Furthermore, providing support for this vulnerable part of society demands high requirements on safety, reliability and functionality of assistive technologies. The human individual has to be kept in the center throughout, and robotic solutions must be designed accordingly. Robotic systems like Justin and EDAN will support patients and caregivers and relieve them from repetitive and exhausting tasks that do include no or few social interactions, one day. Using the time, availability, and energy gained by this support, better care quality can be delivered. We certainly do not aim to replace human care-givers. A more complex and in-depth discussion of the ethical compliance of robotic systems in the caregiving is vital for bringing robotic assistants into application, but it is beyond the scope of this paper.

To contribute towards the technical solution, we presented a holistic ecosystem which includes various robots and concepts to meet the individual requirements of people in need of care. In the current state of implementation, the ecosystem employs robots such as the humanoid Justin, the wheelchair-based assistant EDAN, and the haptic teleoperation device HUG. While Justin can serve as a helping hand in households or support the elderly in retirement homes, EDAN is designed to support people with severe disabilities. Within the ecosystem,

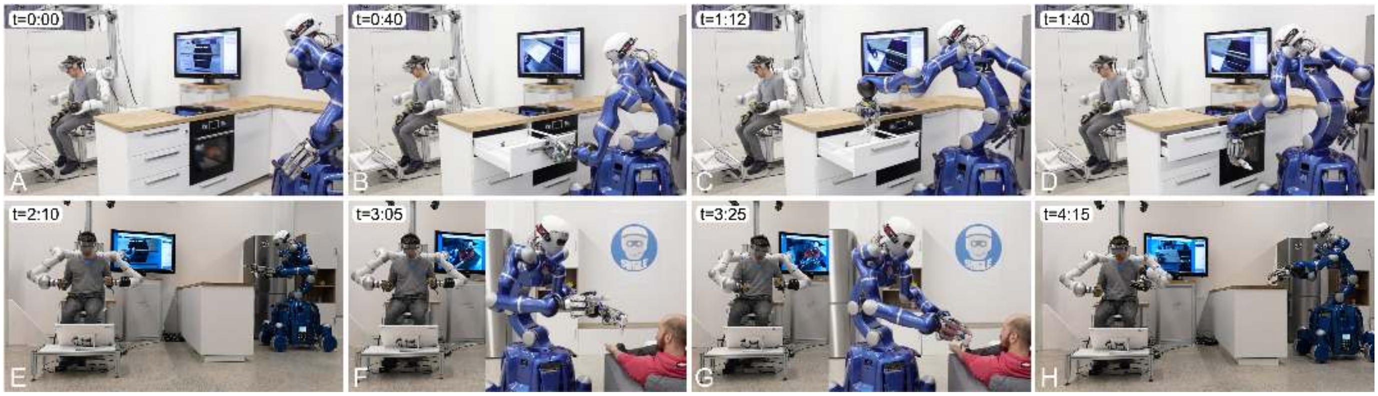

Fig. 13. Telepresence support: Administer medication in a medical emergency. A-D: picking up the auto-injector command via the tablet interface, E: switching to haptic teleoperation, F: moving to the patient, G: administer medication, H: placing medication on kitchen counter. Execution of the task takes 4:15min.

different control modes and user interfaces are available, which allow for a tailor-made application for the user. These range from an intuitive and simple voice command, which triggers fully autonomous operation, to overcoming one's own physical limitations by using a direct control interface to command a robotic manipulator. The ecosystem presents a concept to combine all these approaches in a holistic way, thereby providing a solution for the individual, including all stakeholders: caretakers, caregivers and relatives.

The ecosystem is complemented with a trained teleoperator, who can take control over the robots whenever necessary. This additional interface is a key aspect of the ecosystem as it mitigates the risk of system failure, even without permanent fully autonomous behavior. Additionally, a teleoperator with medical or nursing background can help the user in emergency situations. In exemplary scenarios derived from the needs of the envisioned users we have shown how the various parts of our proposed ecosystem could provide support in practice. It is now important to evaluate these findings in a real-life environment together with those in need of support. As shown in the previous chapters, the current status of our development already allows for a wide range of applications in the context of healthcare. However, further developments and improvements of some technologies are foreseen, which will enhance the ecosystem and its interaction and thus promote the operation in a real environment. In particular, we are currently working on making the different levels of autonomy available across all systems and user interfaces. We envision, that users of the EDAN system can benefit from fully autonomous robot behavior, especially, when they are temporarily not sitting in EDAN's wheelchair. Here, they may make use of the EMG- or joystick-based interface to activate tasks in supervised autonomy mode. Having all autonomy levels available across all systems allows the users to freely decide which mode to use in a particular situation.

As a result, a smooth transition between the interaction modalities or autonomy levels between the different robot systems has to be further developed. On the one hand this requires to create a unified action representation from which task execution at various levels of autonomy can be derived. On the other hand, when switching between the autonomy levels, or from and to telepresence, a state estimation is needed to continuously evaluate the actions being performed, in order to seamlessly switch back to autonomous operation afterwards [34]. Additionally, we will investigate how our shared-control approaches can be applied to provide assistance to the teleoperator in order to increase efficiency of the haptic teleoperation in the scenario of medical assistance, and to better support the teleoperator by automatically coordinating redundant DOF in terms of multi-tasking [35].

An important step in the development process is handling of new and unknown objects. So far the autonomous capabilities of Justin and EDAN are limited to known objects, which are available in the common object database. Two goals are pursued to overcome this limitation. One is to identify classes to which objects belong and derive information for interaction and manipulation based on the respective class. The other goal is to use task executions performed via haptic teleoperation in order to learn new shared-control skills. This learning-by-demonstration approach could also be used based on tasks performed with the direct control mode in EDAN. Having the means to create new manipulation skills without the need of a robotic expert would empower the users to increase the capabilities of the systems according to their needs.

Besides handling of unknown objects, dealing with an unknown environment also needs to be improved. By exploiting semantic knowledge from the scenes, the mapping capability can be improved to provide a higher level of autonomy. In addition, the integration of dynamic map changes should further be developed to ensure robust navigation and localization. This will enable the robot to move around faster and more independently in a dynamically changing environment.

The future goal for our ecosystem is to evaluate it in a real-life environment, such as a retirement home. A close collaboration with all stakeholders will allow us to advance the development in the needed direction. A participatory research of the necessary robot capabilities will help to evaluate the existing functionalities of the system and allow to identify additional robotic features needed by the people concerned. Such iterative development steps will enable us to bring the ecosystem out of the laboratory and towards application in real life. Ultimately, the ecosystem may allow to make efficient use of robotic assistants in care-giving already in the near future by increasing reliability in the operation of autonomous robots.

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