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# Mobile Robotic Rehabilitation Assistant for Walking and Orientation Training of Stroke Patients: A Report on Work in Progress

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***Abstract*—As report on work in progress, this paper describes the objectives and the current state of implementation of the ongoing research project ROREAS (Robotic Rehabilitation Assistant for Stroke Patients), which aims at developing a robotic rehabilitation assistant for walking and orientation exercising in self-training during clinical stroke follow-up care. This requires strongly user-centered, polite and attentive social navigation and interaction behaviors that can motivate the patients to start, continue, and regularly repeat their self-training. Against this background, the paper gives an overview of the constraints and requirements arising from the rehabilitation scenario and the operational environment, a heavily populated multi-level rehabilitation center, and presents the robot platform ROREAS which is currently used for developing the demonstrators (walking coach and orientation coach). Moreover, it gives an overview of the robot's functional system architecture and presents selected advanced navigation and HRI functionalities required for a personal robotic trainer that can successfully operate in such a challenging real-world environment, up to the results of ongoing functionality tests and upcoming user studies.**

## I. INTRODUCTION

About 2-5% of all health related costs in the western developed nations originate from stroke disease patterns. Due to demographic change, the rate of stroke occurrences is expected to increase, while at the same time family structures are changing and cohabitation of different generations, providing possibilities for informal care, is receding. In effect, demand for rehabilitative follow-up care for stroke patients is increasing. As motor and cognitive learning are not passive processes, patients recovering from a stroke must play an active role in the rehabilitation process if improvement is to occur [1]. Against this background, a new trend in rehabilitation care is promising vast medical as well as economic potential - the so-called self-training. This finding was the context and the motivation for the research project ROREAS [2] running from mid 2013 till the end of 2015, which aims at developing a robotic rehabilitation assistant for walking and orientation exercising in self-training during clinical stroke follow-up care. The robotic rehab assistant is to accompany inpatients during their walking and orientation exercises, practicing both mobility and spatial orientation skills. It shall also address the patients' insecurity and anxiety ("Am I able to do that", "Will I find my way back?") which are possible reasons for not performing or neglecting self-training. The assistant is also supposed to monitor the exercises and store clinical records for accounting and clearing with insurance funds, thus combining improved training capabilities for patients and organizational efficiency for the care or treatment facility.

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Fig. 1. Robotic walking coach based on a SCITOS A5 platform developed in the ShopBot project [3], [4], during a guided walking tour in our test site, a rehabilitation center in Bad Liebenstein (Germany).

The project requires consistent integration of robust autonomous navigation in populated public environments, advanced reliable human-robot-interaction (HRI), and intuitive assistive functions allowing customized individual exercise plans. Beside the user-centered development and implementation of the robotic training assistant, extensive user tests with the patients and a detailed analysis of the results shall quantify its medical effectiveness and reveal factors promoting or impeding the acceptance of its application. Following on from preceding own projects in socially assistive robotics [4] [5], the aim of the ROREAS project is (i) to complete the spectrum of robotic functionalities and services that are required for a robot-based assistant for walking and orientation training, but also for the training of such cognitive skills, like spatial exploration of the building or elevator usage and ii) to evaluate the usability, the usefulness, and the added value of

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the rehab assistant for the patients during their clinical stroke follow-up care.

Since this project is still ongoing work, this paper concentrates on the current state of implementation which already allows for a basic guiding and following service, and on the technical aspects of application-specific navigation and interaction skills. To this end, Sec. II at first discusses related work in the field of mobile rehabilitation robotics with a focus on walking and orientation training, then Sec. III gives an overview of the constraints and requirements arising from the rehabilitation scenario. Based on this, Sec. IV presents the robot platform ROREAS which is currently used for developing the demonstrators and is supposed to be substituted by a more application-tailored and smarter robot platform at the end of 2014. Then Sec. V gives an overview of the robot's functional system architecture, while Sec. VI and VII introduce selected HRI and navigation functionalities required for a robotic trainer operating in such a challenging real-world environment, like a rehab center. Finally, Sec. VIII briefly describes ongoing function tests and upcoming user studies, and Sec. IX gives a summary and outlook on future work.

## II. Related Work in Robot-based Rehabilitation

A comprehensive overview of applications of assistive rehabilitation robotics in health care and particularly in rehabilitation care is given in [1] and [6]. According to that, up to now the general approach in the field of assistive rehabilitation robotics has focused on orthoses – robotic solutions that physically interact with persons with motor deficits. This includes lower extremity devices such as the LOKOMAT and ALEX (Active Leg EXoskeleton) and upper extremity devices that measure and apply forces and torques to the patient's arm to assess or encourage specific motor task practice. Wade et al. [6] state, that the field of socially assistive robotics (SAR) is newer than assistive rehabilitation robotics, and that it differs in its methods. SAR is defined by them as "provision of assistance through social (not physical) interactions with robots. A SAR system uses noncontact feedback, coaching, and encouragement to guide a user during the performance of a task. SAR systems can demonstrate task goals, monitor the user, and provide augmented performance feedback" [6]. Although SAR has shown promise in a number of domains, including skill training, daily life assistance, and physical therapy, there is no robotic project known that aims in the same direction as ROREAS - the development of a mobile robotic walking and orientation trainer based on an autonomous robot with guiding and following skills.

Therefore, the so called *tour guide robots* are the only robotic systems which are at least of indirect relevance to ROREAS. Among them are such well known robots as Rhino, Minerva, and Sage, the exposition guide RoboX, or the robots Mona/Oskar at the Opel sales center at Berlin (see [7] for an overview). Usually, all these robots guide visitors to a set of exhibits while offering related information, and thus have at least a distant similarity to our walking guide function in ROREAS. Also relevant for ROREAS is the ShopBot project, where the first shopping guide robot suitable for everyday and long-term use was developed [3], [4]. In long-term field trials, nine of these shopping robots in three different home improvement stores in Germany successfully guided more than 8,600 customers to the locations of their goods of choice and traveled more than 2,200 kilometers. Of similar relevance is the Zuse-Guide project [8], where a robot-based mobile visitor information system with the capability for guiding the visitor to the points of interest (labs, offices, employees) in a multi-level university building is being developed. However, none of these systems was or is involved in challenging interaction and training tasks with disabled people as required in ROREAS. What is still lacking in all these applications of assistive robotics is a strongly user-centered, polite and attentive social navigation and interaction behavior as it is necessary for a rehabilitation assistant that can motivate patients to start, continue, and regularly repeat their self-training.

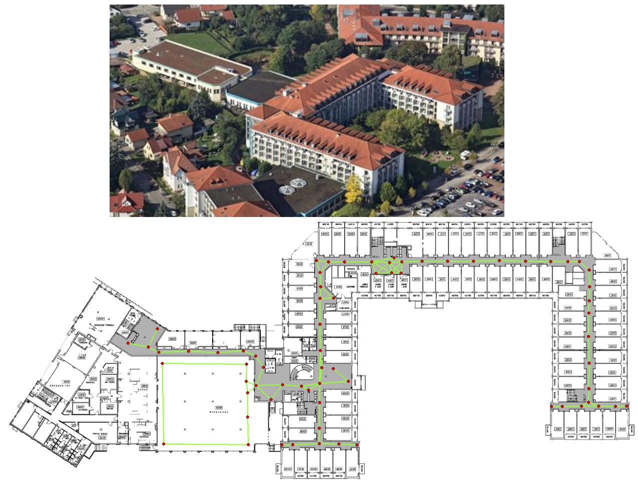

Fig. 2. View and floor plan of one floor of the multi-level rehabilitation center in Bad Liebenstein (Germany) used as test site in the ROREAS project.

## III. Challenges, Constraints and Requirements of the Clinical Rehab Scenario

In this section, the key insights we gained from (i) requirement specifications of the medical and physiotherapeutic experts in clinical stroke follow-up care, (ii) interviews with the stroke patients, and (iii) own experimental experiences achieved in former social robotic projects dealing with guiding functionalities are summarized. These requirements pose great challenges to the navigation, HRI, and training components of the robot training assistant. Our test site, the rehabilitation center in Bad Liebenstein, is a complex, multi-level environment (Fig. 2) and accommodates more than 400 patients. Particular challenges arise from the eight-floors architecture of the building so that the robot assistants must be able to navigate over different floor levels. Multi-floor navigation with incorporation of elevator usage is known from mobile transport systems [9], however, usually they are centrally controlled or using fixed pathways for navigation. Since our robots are supposed to navigate fully autonomously, they have to be able to control and use the elevators of the building, and to recognize the current floor they are operating on, requiring multi-level localization. Moreover, the operational environment is highly dynamic. Staff working in the patient's rooms and patients are moving in the corridors and in the public areas, many of them using walking aids (walkers, wheel-chairs) which makes the person detection very challenging. Often beds, supply and cleaning carts, or wheel-chairs are occupying the hallways, resulting in a quite crowded environment at some times. All this requires situation-aware and polite navigation behaviors. To fulfill these requirements, a broad spectrum of functionalities and capabilities has to be implemented for navigation, HRI, and assistive and training services.

Regarding the *Training services*, the following applications (use cases) were specified: (T1) guiding and observing the patient during walking training - practicing their mobility after stroke, (T2) following and observing the patients during the orientation training - practicing simple spatial orientation skills, (T3) accompanying the patients during training of more complex spatial exploration capabilities taking them the anxiety "not to find the way back", and (T4) accompanying and instructing the patients during the training of elevator usage practicing operating skills as prerequisite for doing T1 to T3 in the whole building.

For autonomous *multi-floor navigation and situation assessment* the requirements include: (N1) to build a detailed navigation map of all levels of the rehab center while the robot is manually driven around during the installation phase of the robot, (N2) to robustly self-localize within the center at all levels, (N3) to drive to any given destination in the center, (N4) to reliably avoid collisions with all possible static and dynamic obstacles in the corridors and public spaces, (N5) to politely pass standing or walking people guaranteeing a socially acceptable navigation, (N6) to predict and evaluate forthcoming critical deadlock situations and react proactively and politely, e.g. by waiting in front of a bottleneck and leaving an oncoming person passing by, or by active searching for an undisturbing waiting position in front of the bottlenecks, and (N7) to autonomously drive and dock to the charging stations in the center.

Besides these challenging aspects of real-world navigation and situation assessment, an intuitive and robust patient-robot interaction plays an important role in our scenario, as the patients have to be interested and motivated in repeated using their robotic training assistant during their self-training. Therefore, for *Interaction between robot and patient*, the following requirements were defined as mandatory: (I1) to reliably detect and keep track of moving, standing, or sitting persons in the local surroundings of the robot even under hard conditions, for example if patients using walking aids or sitting in wheelchairs, (I2) to autonomously orient towards the user or drive in a position facing the user as prerequisite for GUI-based interaction, (I3) to robustly re-identify the current user if s/he was lost from view or occluded by other persons or obstacles, (I4) to follow the user in adequate distance during orientation and exploration training, (I5) to guide the user during walking training through the center, (I6) to express simple robotic emotions by using its facial capabilities and body language, and (I7) to realize an intuitively understandable multi-modal (GUI, touch, speech synthesis) dialog for getting and staying in contact with the patients.

For the realization of these functionalities, the technology of the robot platform requires high performance computational units for the execution of all interaction, navigation and service algorithms often running in parallel, intuitive interfaces adequate for disabled people, and multiple sensor systems to analyze to robot's environment. Moreover, the system design

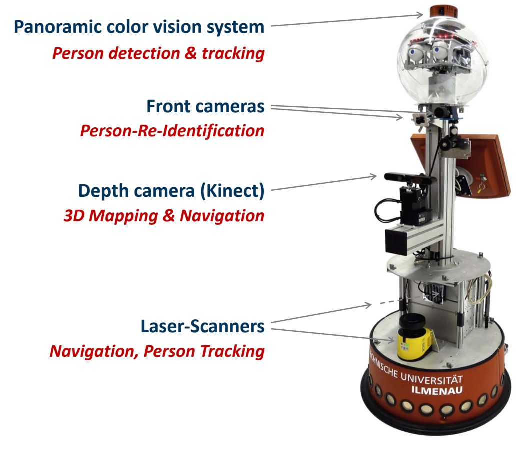


Fig. 3. Experimental platform ROREAS I with its main equipment for environment perception, navigation, and HRI.

had to consider that the robot typically needs to move in an narrow and populated clinical environment. As a consequence, numerous requirements to the design, the technical realization, and the sensor equipment of the robot platform were derived which have directly influenced the design process and the functionality of the robot assistant. In addition to the functionalities and a pleasant design, we have considered later production and operating costs and the longevity of system components during the development process. This led to the technical implementation described in the following sections.

## IV. Experimental Platform Roreas I

The robot platform used currently in the ROREAS project for developing the algorithmic fundamentals of a robotic training coach is based on a SCITOS [saitoz] A5 shown in Fig. 3, which was developed in the ShopBot project [3], [4]. Its size is optimized for a friendly appearance and an ergonomic operation. The drive system of the robot is a differential drive with a castor on the rear which gives the robot a good maneuverability and stability in spite of its height of 1.5 meters and weight of 75 kg, and allows a max. driving speed of up to 1.4 m/s. For navigation and collision avoidance, user perception and environment monitoring, the robot is equipped with multiple sensors, namely two laser range finders, a Kinect depth camera, a panoramic color vision system mounted on the top of the head, as well as two high-resolution front cameras. For interaction with the patients, ROREAS is equipped with an integrated touch display, a sound system, and a 6 DOF RoboHead. The touch screen is the central communication interface to the robot. The head with several degrees of freedom gives the robot a smart appearance, which is very helpful for a successful interaction and exercising. The hierarchical energy-saving concept in conjunction with the energy-saving units enables a long run-time of about 8 hours until it needs a break for recharging. Easily connected to its self-charging station, it can be recharged by the integrated charging system in about 6 hours. For the final implementation of the demonstrators and user tests to be done in the second half of the project, a smaller and smarter platform is currently being developed as a solution more tailored to the user group of stroke patients with a focus on joy of use and positive user experience but also on later production and operational costs.

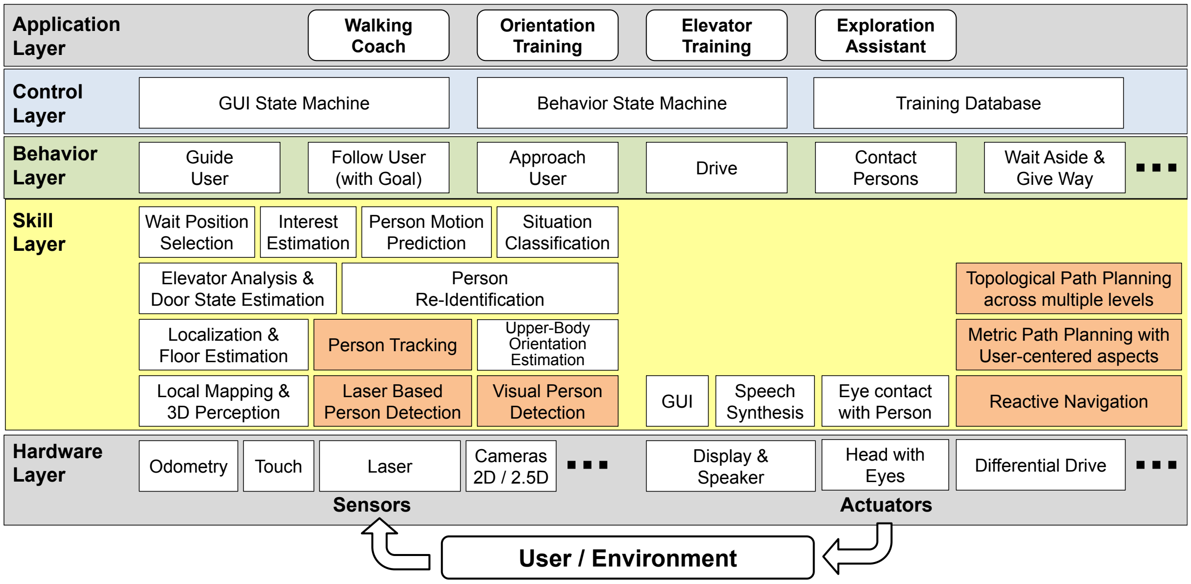


Fig. 4. Multi-layered functional system architecture of the ROREAS training assistant: the *Hardware Layer*, the *Skill Layer* with navigation and HRI-specific methods and skills, the *Behavior Layer*, the *Control Layer* orchestrating the behaviors, and the *Application Layer* implementing the specified applications for post-stroke self-training. Only the reddishly highlighted modules will be covered in this paper as they are of particular relevance for a user- and bystander-aware navigation of the robot training assistant.

## V. Functional System Architecture

Similar to the former software architectures used for the shopping robots [4] or the Zuse guide [8], the robotics related methods and skills have been abstracted from the applications itself resulting in a flexible, layered system architecture (Fig. 4). In this architecture, the bottommost *Hardware Layer* encloses the hardware (sensors and actuators) and the operating system. The low-level sensor information is processed in the next higher level, the *Skill Layer*, which covers the whole spectrum of required robotic-specific navigation and HRI skills that are executed in the *Hardware Layer*. Speech synthesis and the GUI are also placed in this layer and provide their services to the higher application levels.

Above the skills there are diverse modules representing the *Behavior Layer* which make use of the HRI and navigation skills in the layer below. Here, for example, a ”Guide user” behavior is realized, other behaviors are ”Approach user”, ”Follow user”, or ”Wait aside” which are necessary for direct interaction as well as a polite human-aware navigation. These behaviors are exclusive units each representing an individual control loop for accomplishing the different navigation and interaction functions of the robot. To do so, the currently active behavior activates, deactivates, and parametrizes a set of skills. This regards notably the navigation objectives, which are described more detailed below. Furthermore, the *Behavior layer* operates as an interface for the *Control Layer* where two finite state machines, the *GUI-* and the *Behavior State Machine*, and the *Training Database* are implemented representing the application and the behavior control which make use of the basic features provided by the HRI and navigation skills and are orchestrating the behaviors. Based on the *Training Database* and closely coupled to the Graphical User Interface (GUI) and the Speech Synthesis, the *GUI State Machine* is responsible for the patient-specific training process taking into account personalized therapy plans and the already achieved progress in self-training. The *Behavior State Machine* comprises a set of states where each state is associated with one of the behaviors in the *Behavior Layer*. Transitions between the states are triggered by navigation events, person tracking events, GUI interaction, or via the administration remote interface. The highest layer, the *Application Layer*, implements the specified applications, the ”Walking coach” and the ”Orientation training” as the currently most important training functionalities, and leaves room for further applications, as for example the ”Exploration assistant” or the ”Elevator training”.

The robot’s basic functionalities for user tracking, navigation and interaction are implemented using MIRA [10], a middle-ware developed for robotic applications, providing a framework suited to the requirements of distributed real-time software. For an introduction to MIRA and comparison to the popular robotics software framework ROS [11], see [12].

## VI. HRI Functionalities for a Robotic Trainer

*Multi-modal user detection and tracking:* In order to guarantee a successful walking and orientation training of the stroke patients, the robot at any time needs to know the exact position of its current training partner and of other people (staff, patients, visitors) in its vicinity. For this purpose, we utilize the probabilistic multi-hypotheses people detection and tracking system (Fig. 4, left) developed in our lab in other HRI projects over the last eight years from [13] to [14]. This system is able to track walking people and people in standing or sitting poses. It is based on a 7D Kalman filter that tracks the position, velocity, and upper body orientation of the respective persons assuming an uncertain random acceleration. The tracker processes the detections of different, asynchronous observation modules – namely a 2D laser-based leg detector, a face detector, a motion detector, and an upper-body shape

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detector. The leg detector in its initial version is based on the boosted classifier approach of [15]. The face detection system utilizes the well-known face detector of Viola & Jones [16]. The motion detection cue is only active when the robot is standing still and utilizes a fast and simple image difference approach [13]. Finally, we apply an upper body shape detector based on Histograms of Oriented Gradients (HOG) [17]. A detailed description of the person detector and tracker and the tracking results of comparing evaluation studies on different data sets with increasing difficulty is given in [14].
However, to develop really autonomous training robots that robustly support the patients during their self-training over a longer time-span, we still need to enhance the reliability of the person detection and tracking algorithms. The face and upper body detection are not robust enough to detect people in sitting postures or given occlusion. Using the FPDW detector (Fastest Pedestrian Detector in the West) [18] in the combined tracker could help to raise up-right posture performance. Real-time implementations of part-based detection concepts, like partHOG [19] that handle occlusion and multiple postures, can improve tracking performance as well. Therefore, a major challenge for the next phase of the project lies in the development of real-time capable methods for detecting people in different critical poses, like sitting in wheelchairs or walking bent forwards on walkers. As next step, we will also integrate video-based person re-identification [20] in order to improve the performance of the person tracker and to guarantee an uninterrupted training with the same person during the training session.

*Detection of persons with walking aids:* The skill for laser-based person detection (Fig. 4, left bottom) is well suited for detecting pairs of legs as indicator for the presence of people in the vicinity of the robot. However, in a rehabilitation center we have to deal with stroke patients who often need walking aids. These tools occlude or touch the legs of the patients. Therefore, we advanced our aforementioned approach by introducing generic distance-invariant laser-scan features [21]. These features are unspecific to the objects to be detected, and the features' extraction area is not dependent on any segmentation algorithm. A jump distance-based segmentation of the range scan is just applied to identify origin points for feature extraction. The dimensions of the extraction area are based on the proportion of the objects to be detected. The extracted distance-invariant laser-scan features are then utilized to train classifiers for detecting people without walking aids, people with walkers, people in wheelchairs, and people with crutches. Using this approach for people detection, we achieved an $F_1$ score [22] of 0.99 for people with and without walking aids, and 86% of detections are classified correctly regarding their walking aid. For comparison, using state-of-the-art features presented in [15] on the same data results in an $F_1$ score of 0.86 and 57% correct discrimination of walking aids. The proposed detection algorithm takes around 2.5% of the resources of a single 2.8 GHz CPU core to process $270^o$ laser range data at an update rate of 10 Hz. Further details of this application-driven improvement can be found in [21].

## VII. Navigation Skills for a Robotic Trainer

In addition to a reliable and intuitive human-robot interaction, robust and human-aware navigation is a fundamental requirement for an autonomous robotic rehabilitation assistant.

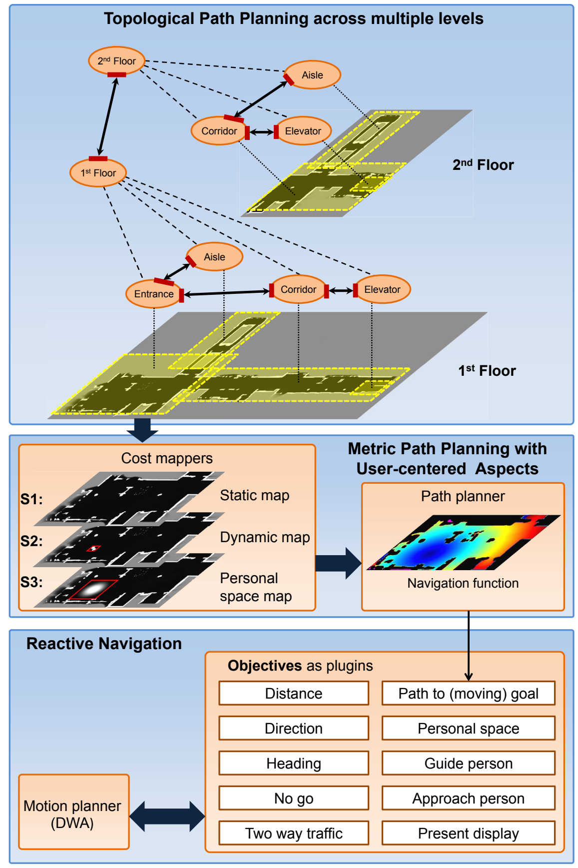



Fig. 5. Detailed view of the navigation components shown in Fig. 4 right. The topological path planner (strategic layer) and the metrical path planner (tactical layer) inject global knowledge into the reactive navigation layer via the *Path to (moving) goal - objective*.

Important navigation skills (see Fig. 4) are self-localization, path planning, and motion control with collision avoidance. However, within the scope of this paper only those skills dealing with path planing and human-aware motion control are covered. The core components of this part of the navigation architecture can be classified in a reactive, a tactical (based on metric path planning), and a strategic (activation of the objectives by the behaviors plus topological path planning) level located within the *Skill Layer* (see Fig. 4, right). These components are shown more detailed in Fig. 5. On the reactive level, the motion planner and the objectives determine velocity commands for the robot's motor controllers according to the current task, which is set by the current behavior localized in the *Behavior Layer*. Therefore, the navigational tasks are decomposed into objectives. Each objective is a separate software plugin specialized for a certain sub-task, as for example following a path or a person, approach the user, or respect the personal space. This allows us to add new objectives easily, when new tasks and behaviors become necessary without changing existing parts of the navigator. The output of the objectives is then used by the *Motion Planner* (Fig. 5, left bottom) to generate motion commands that are then sent to the robot's motor controllers. At the moment, we use the Dynamic Window Approach (DWA) [23] as motion planner. For evaluation of the velocity commands within the dynamic window, the objectives require additional information from

| Objectives | Activating Behaviors | Description |
|---|---|---|
| Distance | enabled by default | avoids collisions by calculating distance between robot and obstacles on the predicted trajectory |
| Direction | Guide, Follow, Drive, Approach, Wait Aside | reinforces movement commands that move the robot into specified preferred direction |
| Heading | Drive, Wait Aside | tries to achieve the specified orientation and alignment at the target position |
| No Go | enabled by default | avoids areas, the robot is not allowed to enter (specified in a No-Go map). |
| Two way traffic | enabled by default | prefers to drive on the right side in narrow passages |
| **Person centered objectives** | | |
| Path | Guide, Follow, Drive, Approach, Wait Aside, Give Way | plans paths to a (possibly dynamic) target pose; tries to follow the planned navigation function |
| Personal Space | enabled by default | respects the personal space of moving and standing persons on reactive level |
| Guide | Guide | reduces the robot's velocity to keep constant distance to guided person |
| Approach | Approach | steers robot into interaction distance and orientation relatively to user |
| Present Display | enabled by default | turns robot's display towards user |

Fig. 6. Subset of the already implemented navigator objectives used in the DWA-based motion planning

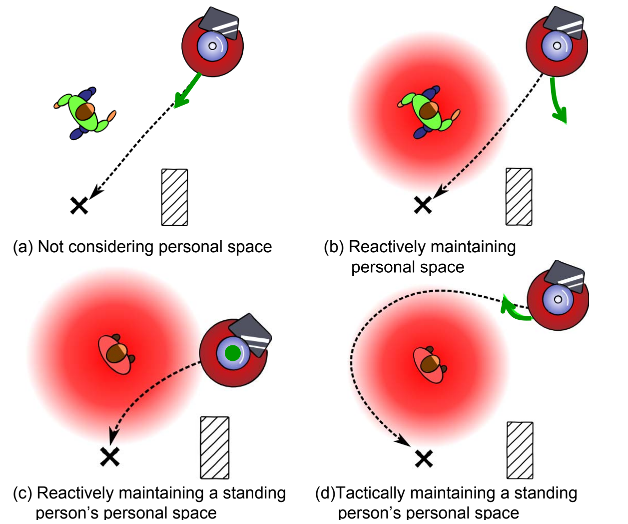



Fig. 7. Effects of reactive and tactical person avoidance. The planned path is marked by dashed lines and the resulting robot motion by green arrows.

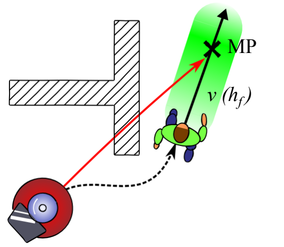
other modules of the *Skill Layer*, such as person hypotheses from the person tracker (see Fig. 4, left). Therefore, the objectives can access this information directly from these modules. To rate the possible motion commands, most objectives use short-term predictions of the robot's clothoid-shaped motion trajectories. To evaluate the approaching to a goal position, the *Path objective* evaluates the predicted robot positions based on a global navigation function. This navigation function is calculated at the tactical level by the *Metric path planning* (Fig. 5, middle) using E* [24].

To allow path planning across multiple floors and to decrease the computing effort for path planning on metrical maps, a topological path planner is used at the strategic level (see Fig. 5, top). As already applied in [8], we use here a hybrid, hierarchical topological map for path planning, which allows us to model the elevators as transitions between the different floors. On the coarsest level of this graph-based map, each node represents a single floor of the building. Each node is further subdivided into sub-nodes that represent the aisles of each floor, etc. On the finest level, the leaf nodes contain metric occupancy maps. The path planning starts on the coarsest level using a general Dijkstra algorithm and is iteratively refined up to the metric occupancy maps, where we finally apply the computationally more expensive E* path planning algorithm. This hierarchical approach combines fast path planning on a topological map and the ability of dynamic re-planning that is supported by the E* algorithm. Application-related aspects of all three navigation levels are described subsequently.

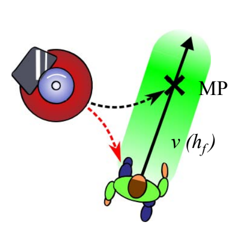
*User-centered aspects of reactive navigation:* When the robot is applied as a "Walking Coach", the "Guide User" behavior is particularly relevant. Guiding a user basically means, that the robot drives to a predefined destination and therewith shows the user the way to the destination as well. Accordingly, the generated task activates the *Path objective* to drive to the target position, the *Distance objective* to prevent collisions, the *Direction objective* to make sure the robot drives forward towards the target, and so on. The table in Fig. 6 illustrates how many objectives are involved when a user is guided. However, for the comfort of the guided user, it is important that the robot adapts its speed to the current velocity of the guided user. Otherwise the user would feel hindered or put under pressure. Therefore, the *Guide objective* constantly tries to maintain a certain distance between user and robot and slows down the robot, if the user does not follow fast enough.

While the robot performs a user-centered behavior, like guiding, the robot also should not interact with persons randomly passing by. Instead, the robot should signal its busy state and politely pass a standing or moving person (bystander). If humans do not want to interact with each other, the spatial configuration between them signals the intention of each person. Those spatial behavior patterns are quite complex and are profoundly investigated by psychologists. One aspect of spatial configurations and their meaning is described in the theory of the personal space, created by Hall [26]. In our work, we use the spatial configuration (or distance) which signals "non-interaction". We utilize a simple mathematical model of the personal space and combine this model with predicted motions of the observed bystanders. With this knowledge, a non-intrusive path towards the current goal, that does not violate the personal space of the bystanders is determined. This is realized by the *Personal Space objective* which aims to maintain this distance towards bystanders. The costs for violation of each personal space are approximated by a Gaussian (Fig. 7). To assess the violation of the bystanders' personal space for each possible velocity command $\mathbf{v}$, the maximum violation over time $\Delta t_T$ and over the positions of all bystanders $\mathbf{h}_i \in H$ is calculated.

$$\text{cost}_{\text{PS}}(\mathbf{v}) = \max_{\Delta t_1,\dots,\Delta t_T} \max_{\mathbf{h}_i \in H} \left(\text{cost}_{\text{PS}}(\mathbf{h}_i, \Delta t, \mathbf{v})\right)$$




(a) Tactical (black) and reactive (red) pursueing a person




(b) Lagging behind (red) and interception (black) trajectories

Fig. 8. Schematic depiction of the navigation function in the temporary target area, which is the origin of the local planning algorithm. By planning towards the current position of the person only, the robot would continuously lag behind the robot (red trajectory in b). However, using our planning-based approach, the temporary goal area (green) based on the user's motion prediction allows an interception behavior (black) at the meeting point $MP$.

For calculation of the costs, which represent the violation of a bystander's personal space $\text{cost}_{\text{PS}}(\mathbf{h}_i, \Delta t, \mathbf{v})$, the robot's own movement and the movement of the person are predicted. For more details about the comparison between a linear and a learning-based prediction of the human motion in the robot's vicinity see [25]. Fig. 7b shows the influence of the reactive *Personal space objective*.

*User-centered aspects of path planning:* However, if the robot only respected the personal space at the reactive level, and a person stood still, the tactical navigation function might conflict with the reactive *Personal Space* objective, and then the robot would stand still as well (Fig. 7c). This is not a problem when the person enters the space which was cleared by the robot and moves away. However, for standing persons, the personal space already has to be considered during path planning at the tactical level (see Fig. 5, middle). Therefore, we add the Gaussian costs which represent the violation of the personal space into the cost map which is the basis for the metric planning algorithm. The manipulation of the cost function by individual modules is visualized in Fig. 5 as well. The cost mapping modules are arranged in a cascade, where at each stage the cost map of the previous stage is manipulated. To reduce the calculation effort for cost map manipulation in the stages and for application of the E* re-planning, the modified regions (called dirty regions) are passed from stage to stage and extended accordingly. S1 holds the static occupancy grid map including no-go regions, in S2 dynamic obstacles are added, and at S3 the personal space costs around standing persons are added. Fig. 7d shows the effect of taking a standing person's personal space into consideration on a tactical level. Note, that the reactive *Personal space objective* does not become superfluous, when the personal space is already respected during path planning, because for moving persons or persons which are suddenly tracked close to the robot, the tactical avoidance is too delayed.

Another behavior which greatly depends on the metrical path planning is "Follow user". The red trajectory in Fig. 8 shows, how pure reactive user following would conflict with the *Distance objective*, which prevents collisions. That's why, the "Follow user" behavior employs the *Path objective*, whereas the predicted position of the user is used as temporary goal. Therefore, the *Path objective* has to handle dynamic goal positions. This means, the navigation function is repeatedly recalculated, when the person position changes. Double buffering of the navigation function is applied in order to use one buffer by the *Path objective*, while the E* algorithm uses the other buffer during path planning to the updated person position. To compensate the computation time of the navigation function and the time for robot motion, the goal area of the E* algorithm is initialized considering the person's velocity. Basically, the goal covers the area the person might enter within the prediction horizon $\Delta t$. Within this area the navigation function is already initialized, whereas the estimated meeting position $MP$, where the robot might reach the person, is initialized with zero costs. From this point, the costs increase linearly with the Euclidean distance. This way, a simple interception behavior (Fig. 8) can be realized.

## VIII. Function Tests and User Studies

*Function tests:* As described in Section III, we defined a number of system requirements and success criteria with respect to the navigation and HRI capabilities of the robot coach to assess the technical performance of the different subsystems and the training assistant as a whole before user studies can take place. With respect to the *navigation functionality*, the defined use cases (N1), (N3)-(N5) and (N7) have already been completed successfully from qualitative point of view, only use cases (N2) and (N6) are still ongoing issues that still need to be finalized until the upcoming user studies. A detailed quantitative analysis of the navigation capabilities regarding localization and positioning errors, velocity profiles and smoothness of the movement trajectories, distances to obstacles and bystanders, timely recognition of forthcoming deadlock situations, etc. is still pending, but in preparation. In comparison to the already relatively advanced navigation functions, most of the required *HRI functionality* I1 to I7 (see Section III) is currently still work in progress. While a few of these functions could be finalized successfully from qualitative point of view (e.g. (I2), (I4), and (I5)), (I1) and (I3) still need to be improved and made more robust before function tests in the rehab center can be executed. (I6) and (I7) are still open as they are to be tackled not until the final robot platform with a new design and more application-tailored patient-robot interfaces will be available. Therefore, quantitative function tests are still pending, but are scheduled for the end of 2014.

*User studies:* Within the ROREAS project the user studies have been divided into two phases with different focuses, in order to adequately implement technical and user-specific requirements. In the first phase, the *usability* of the developed training applications is evaluated formatively using the following indicators: effectiveness, efficiency and satisfaction, but also learnability, robustness and safety, which are very important criteria in assessing the usability of a mobile robotic coach. In that way, we get precise feedback for each functionality. Revised robot functions can be evaluated in an iterative loop. When these functions work appropriately, they are integrated into the training applications (T1) to (T4) defined in Section III, which are then evaluated summatively using the criteria usability, joy of use, and utility. Because it is essential that the robot adapts to the patients' needs and the therapeutic requirements, medical and psychological experts are involved in all phases of the evaluation process which is challenging in two respects: firstly, there is tremendous diversity concerning the cognitive, sensory, and motor deficits of the patients as well as concerning experience with and attitude to technology among them. Furthermore, recruiting stroke patients is quite difficult because of their motivation and health restraints. As the robot used so far is a provisional prototype, various technical issues occurred while testing, making it difficult to reproduce exactly the same conditions for each run. Thus, a qualitative research design has been chosen. Data is going to be collected by participative observation, and participants (patients and medical experts observing their self-training with the robot) are asked to think aloud (if possible) while using the robot. Subsequent to the video-taped user trials, semi-structured interviews are conducted. Theses studies are scheduled for the beginning of 2015 as combined studies of further technical functionalities and training services.

## IX. Conclusions and Outlook

This paper describes recent progress in developing a robotic rehabilitation assistant for walking and orientation exercising in self-training during clinical stroke follow-up care. Building on former work in robot navigation and human-machine interaction, new approaches specifically aimed at robust and polite user-centered navigation and human-robot interaction in dynamic and populated clinical environments are presented. The forthcoming second half of the ROREAS-project has a relatively demanding overall project schedule. As next steps, we will continue with implementing, pre-testing, improving, and formatively evaluating all the required robot navigation and interaction skills and behaviors (see Fig. 4) and integrate them into the defined training demonstrators ("Walking coach" and "Orientation trainer"). Then both demonstrators will be evaluated separately (formatively). In the last project phase in 2015, both demonstrators will be integrated into a final version of a robotic rehabilitation assistant and summatively evaluated with field tests (one week per patient). Then we are going to see how well the robot's behaviors and offered training services fit into the self-training concept and can foster the physical and mental wellbeing of the stroke patients. We are aware, that any claims of real benefits of robotic assistance can only be substantiated by controlled comparative studies directly comparing robot-based assistive services to relevant conventional approaches [1]. The ROREAS project hopes to make a significant contribution by gathering information about the performance of assistive technology in real life and in daily clinical practice.

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## References

[1] A.O. Andrade, A.A. Pereira, St. Walter, R. Almeida, R. Loureiro, D. Compagna, P.J. Kyberd, "Bridging the gap between robotic technology and health care", Biomedical Signal Processing and Control, 10, 65–78, 2014

[2] ROREAS project website: www.roreas.org

[3] H.-M. Gross, H.-J. Boehme, C. Schroeter, S. Mueller, A. Koenig, Ch. Martin, M. Merten, A. Bley, "ShopBot: Progress in Developing an Interactive Mobile Shopping Assistant for Everyday Use", in *Proc. IEEE-SMC 2008*, 3471–78.

[4] H.-M. Gross, H.-J. Boehme, C. Schroeter, S. Mueller, A. Koenig, E. Einhorn, Ch. Martin, M. Merten, A. Bley, "TOOMAS: Interactive Shopping Guide Robots in Everyday Use - Final Implementation and Experiences from Long-term Field Trials", *Proc. IROS 2009*, 2005–12.

[5] H.-M. Gross, Ch. Schroeter, S. Mueller, M. Volkhardt, E. Einhorn, A. Bley, T. Langner, M. Merten, C. Huijnen, H. van den Heuvel, A. van Berlo, "Further Progress towards a Home Robot Companion for People with Mild Cognitive Impairment", *Proc. IEEE-SMC 2012*, 637–44.

[6] E. Wade, A. Parnandi, R. Mead, M. Mataric, "Socially Assistive Robotics for Guiding Motor Task Practice", *Journal of Behavioral Robotics*, 218–27, 2011

[7] B. Jensen, N. Tomatis, L. Mayor, A. Drygajlo, R. Siegwart. "Robots meet Humans - Interaction in public Spaces", *IEEE Trans. Industr. Electronics* 52, 1530–46, 2005

[8] R. Stricker, St. Mueller, E. Einhorn, Ch. Schroeter, M. Volkhardt, K. Debes, H.-M. Gross, "Konrad and Suse, Two Robots Guiding Visitors in a University Building", in *Proc. Autonomous Mobile Systems 2012*, Informatik aktuell, 49–58, Springer 2012

[9] N. Tschichold-Guerman, S.J. Vestli, and G. Schweitzer, "The service robot mops: First operating experiences", Robotics and Autonomous Systems, 34, 165–173, 2001.

[10] MIRA project website: www.mira-project.org

[11] M. Quigley, B. Gerkey, K. Conley, J. Faust, T. Foote, J. Leibs, E. Berger, R. Wheeler, A. Ng, "ROS: an open-source Robot Operating System," in *ICRA Workshop on Open Source Software*, Kobe, 2009

[12] E. Einhorn, R. Stricker, H.-M. Gross, T. Langner, Ch. Martin, "MIRA - Middleware for Robotic Applications," *Proc. IROS 2012*, 2591–98.

[13] Chr. Martin, E. Schaffernicht, A. Scheidig, H.-M. Gross, "Sensor Fusion using a Probabilistic Aggregation Scheme for People Detection and Tracking", *Robotics and Autonomous Systems*, 54, 721–728, 2006.

[14] M. Volkhardt, Ch. Weinrich, and H.-M. Gross, "People Tracking on a Mobile Companion Robot", in *Proc. IEEE-SMC 2013*, 4354–59.

[15] K.O. Arras, O.M. Mozos and W. Burgard, "Using Boosted Features for the Detection of People in 2D Range Data", in *Proc. ICRA 2007*, 3402–07.

[16] P. Viola, M. Jones. "Rapid Object Detection using a Boosted Cascade of Simple Features", in *Proc. CVPR 2001*, 511–518

[17] Ch. Weinrich, Ch. Vollmer and H.-M. Gross, "Estimation of Human Upper Body Orientation for Mobile Robotics using an SVM Decision Tree on Monocular Images." in: *Proc. IROS 2012*, 2147-52.

[18] P. Dollar, S. Belongie, and P. Perona, "The Fastest Pedestrian Detector in the West", in *Proc. BMVC 2010*, 68.1–68.11.

[19] P. F. Felzenszwalb, R. B. Girshick, and D. McAllester, "Cascade object detection with deformable part models", in *Proc. CVPR 2010*, 2241–48.

[20] M. Eisenbach, A. Kolarow, K. Schenk, K. Debes, H.-M. Gross, "View Invariant Appearance-based Person Reidentification Using Fast Online Feature Selection and Score Level Fusion", *Proc. AVSS 2012*, 184-90.

[21] Ch. Weinrich, T. Wengefeld, C. Schroeter and H.-M. Gross, "People Detection and Distinction of their Walking Aids in 2D Laser Range Data based on Generic Distance-Invariant Features" to appear: *Proc. RO-MAN 2014*.

[22] D.M.W. Powers, "Evaluation: From Precision, Recall and F-Measure to ROC, Informedness, Markedness & Correlation" *Journal of Machine Learning Technologies*, 2, 37–63, 2011

[23] D. Fox, W. Burgard, S. Thrun, "The dynamic window approach to collision avoidance", in *IEEE Robotics & Automation Magaz.*, 23–33, 1997

[24] R. Philippsen and R. Siegwart. "An Interpolated Dynamic Navigation Function", in *Proc. ICRA 2005*, 3782–89.

[25] Ch. Weinrich, M. Volkhardt, E. Einhorn and H.-M. Gross, "Prediction of Human Avoidance Behavior by Lifelong Learning for Socially Compliant Robot Navigation" in: *Proc. ICRA 2013*, 376–381.

[26] E.T. Hall, "The hidden dimension", Doubleday, NY, 1966