Iterative Development of a Service Robot for Laundry Transport in Nursing Homes *

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Abstract. In the Agebots project, a multidisciplinary team investigated and tested the use of service robots in elderly care. Applications such as material transport, entertainment, companionship, reminder, information, and fitness exercises were studied. The project is being conducted in collaboration with a nursing home and a robotics manufacturer. In this paper, the task "laundry transport" is presented. With the goal of reducing nurses' walking distances and workload, four variants of a laundry transporter were designed and tested in a replicated and a real environment using a human-centered design approach (see Fig. 1). In addition, three possible human-robot communication interface designs were investigated with respect to the behavior of the transport robot.

Keywords: Human-Centered Robotics · Service Robotics · Social Human Robotic Interaction

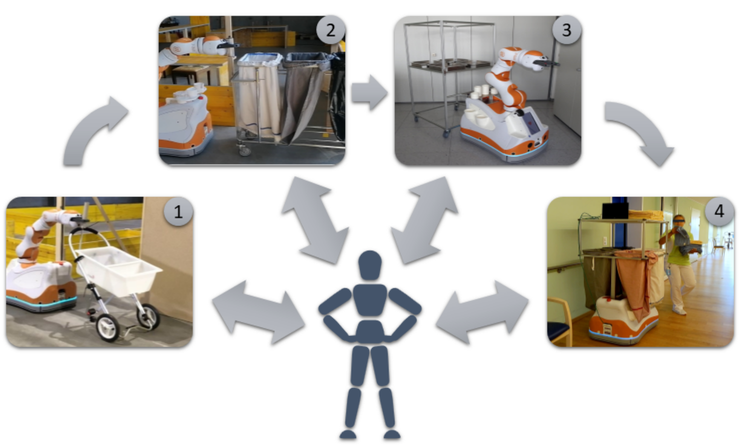

Fig. 1. (1)-(3): Three variants of the laundry trailer; (4): Top mounted laundry rack

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1 Introduction

Service robotics could be the solution to several challenges nursing homes are facing [18,30]. By 2050, over 27% of the Swiss population will be 65 and older. This will pose major challenges for nursing homes in particular [5,6]. A shortage of skilled workers is already evident. This situation will be exacerbated by the rising demand for nurses, which is expected to increase by 36% in Switzerland by 2030 [24,21].

The work presented here is part of the Agebots project. In general, the development of robot prototypes is driven by technology. Four different dimensions need to be considered for a successful use of service robots in elderly care: human [23,3], technology [22,25,16], business [1,10], and law [26,7]. A detailed description of the method used in this two-year research project is published in [14]. Table 1 gives an overview of the project phases with reference to the technology readiness levels (TRL). Prior to the laboratory test, a comprehensive test concept was developed based on the methods presented by Bartneck et al. [2], Heerink et al. [17], and Weiss et al. [31]. The concept describes the basic elements of the test setup: objectives, methods, cases, environment, infrastructure, organization, objects, types and plan. The challenges of stakeholders, such as nurses and the elderly, were identified through observations and interviews [9].

Parallel to the project, a quantitative survey was carried out in the German-speaking part of Switzerland with approximately 1500 nursing homes. 160 of the facilities surveyed completed the questionnaire in full. In the online survey, the applications identified in the project were visualized with short videos from laboratory tests. Subsequently, respondents had to answer various questions about these applications. Among other things, respondents were asked for each application whether they would find it beneficial if Lio were to take them over. Lio is the main robot system used in the Agebots project.

As can be seen from the results in Fig. 2, material transport is the most requested application. In this context, laundry transport was chosen because there is no interaction with elderly during the actual transport and there is a great potential for saving walking distances. The nursing staff supports the residents daily in their morning routine, changing the laundry in the bathroom on a regular basis. According to the nursing home management involved in the project, the nurses have to change the dirty laundry one room at a time. In between, they have to discard the dirty laundry, disinfect the trolley and load fresh laundry again. This results in a very inefficient routine for the nurse: get new laundry, walk to the resident's room, change the laundry, walk to the laundry drop off, dispose the dirty laundry, disinfect the trolley, and then start all over again by getting fresh laundry. For safety reasons, it is forbidden to leave a trolley unattended in the hallway (e.g. an elderly person could trip over the trolley). Taking a trolley with dirty laundry into another resident's room is also forbidden for hygienic reasons. As a result, the nurses have to spend a considerable amount of their working time walking. Here a service robot could come to help by surveying it's immediate neighborhood and ensuring that contact with dirty laundry and accidents are prohibited.

Table 1. Agebots project phases

#	Project phase	Results	TRL
1	Understanding	144 challenges identified for nursing staff and the elderly.	1
2	Ideation	Generated 15 application fields with 170 ideas for nursing staff and 10 application fields with 88 ideas for the elderly.	2
3	Technology	Produced 7 robotic systems and conducted functional tests.	3
4	Lab Test 1	Conducted feasibility testing with non-users and initial legal analysis. Reduction of the 25 applications fields to 12.	4
5	Iteration 1	Development of applications and adaptation of the robotic systems based on the results of Lab Test I. Created a relational database for the analysis of the qualitative and quantitative data and populated it with insights.	
6	Lab Test 2	Conducted usability and acceptance tests with the nursing staff and the elderly of the nursing home in a replicated environment. Developed a business plan to open up new markets for the robot manufacturer.	5
7	Iteration 2	Development and adaptation of applications.	
8	Field Test 1	Examined the desirable, feasible, and economical application in the nursing home environment.	6
9	Iteration 3	Development and adaptation of applications.	
10	Field Test 2	Examining of the legally compliant, desirable, feasible, and economical application in the nursing home environment.	7
11	Marketing (planned)	Market launch and distribution of the service robot systems in German-speaking countries by the robot manufacturer.	8

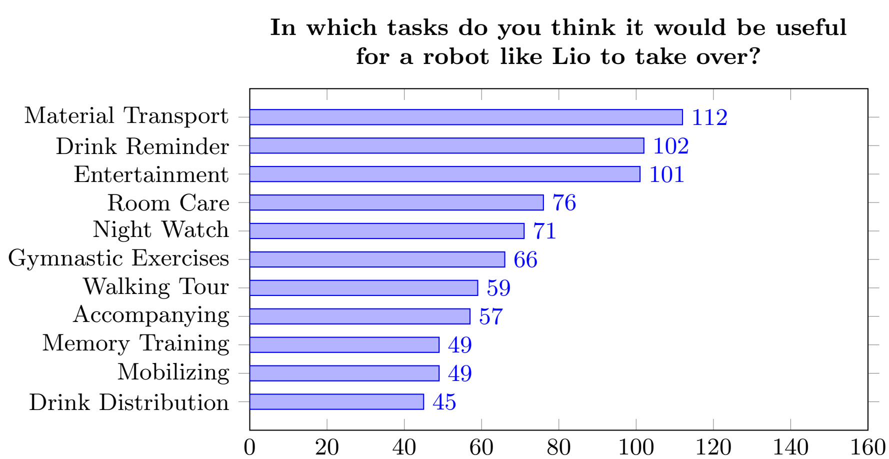


Fig. 2. Top 11 survey results, n = 160, multiple answers

2 Related Work

Past projects such as the STRANDS-project have focused on the feasibility and capability of mobile robots to endure usage for long periods of time without intervention [15,13]. With their goal of enabling a robot to achieve robust and intelligent behavior in human environments through adaptation to and exploitation of long-term experience, they have accomplished essential pioneering work in the field of healthcare robotics. Consistent with the findings of Hawes et al. [15] and Pineau et al. [28], the application studied must satisfy various requirements. I.e., Lio needs to position and orientate itself in space, map its environment, annotate locations and restricted areas, plan a path, navigate around temporary obstacles, communicate with caregivers and the elderly, and be easy to use. All these requirements are important prerequisites for the functionality of the presented task of laundry transport.

Together with Fraunhofer IPA, Graf et al. [12] developed an intelligent care cart based on MLR's CASERO 4 platform and tested it in two nursing homes in Mannheim. The intelligent care cart is operated by a nurse via a smartphone. Possible destinations are positions outside the resident's room, the storage (to replenish supplies) and the battery charging station. Thanks to the autonomous navigation of the intelligent care cart, the nursing staff no longer needs to walk to bring the intelligent cart to the desired destination. Nor do they have to walk to the storage to refill the cart. In contrast to the care cart, Lio is a multipurpose robot that allows to carry out multiple tasks.

The SMOOTH-Robot is a mobile, modular, and interactive service robot developed by Krüger et al. [19]. One of their use cases was the collection of laundry and garbage bins. During development, they considered four aspects to achieve high acceptance of the robot: technical complexity, degree of anthropomorphism, wide range of applicability and affordability. A key message of the study on anthropomorphism is that it is important not to raise expectations that the state of the art cannot meet. Therefore, a robotic appearance is preferable to a human-like appearance. Further it is emphasized that socially aware navigation is important when a robot is used in a space occupied by humans. Another issue is the safety and cognitive prerequisites needed for successful human-robot interaction (HRI). Human interaction is multimodal, incremental, and highly dynamic. Humans communicate through body orientation, speed, gaze, mimic, gesture and speech, often using multiple channels simultaneously. Consideration of these principles in HRI leads to extreme complexity. Therefore, according to the authors, it is unlikely that this problem can be solved within the next decade.

Langedijk et al. [20] identified various challenges in testing two service robots in the wild. Thereof, the technical challenges are of particular interest for our research questions. A realistic twin of the actual working environment should be replicated in the laboratory. Narrow aisles or grouped chairs are typical challenges for robots. Another technical challenge that may occur in the preparation phase is a poor network connection.In addition, the robot must have sufficient error handling capabilities to cope with unexpected changes in the environment.

3 Development, Experimentation and Tests

In general, an agile product development approach [4,29] using rapid prototyping [27,11] and 3D printing was selected. This allowed for a flexible and human-centered design. An overview of the development process can be seen in Fig. 3.

3.1 Verification of the Suitability for Reducing Walking Distances

As described in the introduction, nurses spend a substantial amount of their time walking during their shift. The number of steps taken by several nurses during a week was recorded with a pedometer. It was shown that a nurse covers an average of 9000-12000 steps during a shift (8 hours). It was also measured that 100 steps take about 50 seconds. This results in a walking time of 80 to 100 minutes per shift.

To check the suitability of a laundry transporter to shorten walking distances, a simulation was conducted during the project phases 1 to 3 (see Tab. 1 and Fig. 3). A nurse was chosen to do his or her daily work during the early shift. A researcher then took on the role of the robot, manually pushing a material trolley around with bags for dirty laundry and trash, as well as fresh laundry. Both the nurse and the researcher wore a step counter. Without the human simulated robot, a step count of 1315 steps was registered for the nurse. With the simulated robot, the nurse's step count was reduced to 583 steps, while the simulated robot made 646 steps. Thus, having a robot that takes the laundry items to where they are needed on the command of the nursing staff can save over 50% of walking distances. This neglects human adaptability, which leads to nurses using the reduced walking distance for other tasks. Therefore, the walking distance will probably not decrease that much in reality.

3.2 Agile Development of a Laundry Transporter

After the first simulation of the laundry task, it was evaluated whether Lio could be used to support the task. To be able to check the feasibility quickly, easily, and inexpensively, a bicycle trailer (variant 1) was bought during the project phase 4 (see Tab. 1). Using the simplest of means, a coupling was fitted to the trailer so that Lio can grab, release and pull the trailer (see Fig. 1: (1) and Fig. 3: (1)). This function was tested in a replicated environment with a nurse.

Since the lab test 1 showed good results in terms of feasibility and the nursing staff gave positive feedback, an improved trailer (variant 2) was designed and built during the project phase 5 (see Tab. 1). This was done to incorporate more space and to sturdy the construction and coupling. For this purpose, a metal frame with four caster wheels was developed, to which three different material bags can be attached (see Fig. 1: (2) and Fig. 3: (2)).

During the project phase 6 (see Tab. 1), the trailer variant 2 was subsequently tested in the replicated environment. Lio had enough power to pull this new, heavier trailer. Gripping and releasing the newly developed coupling also worked

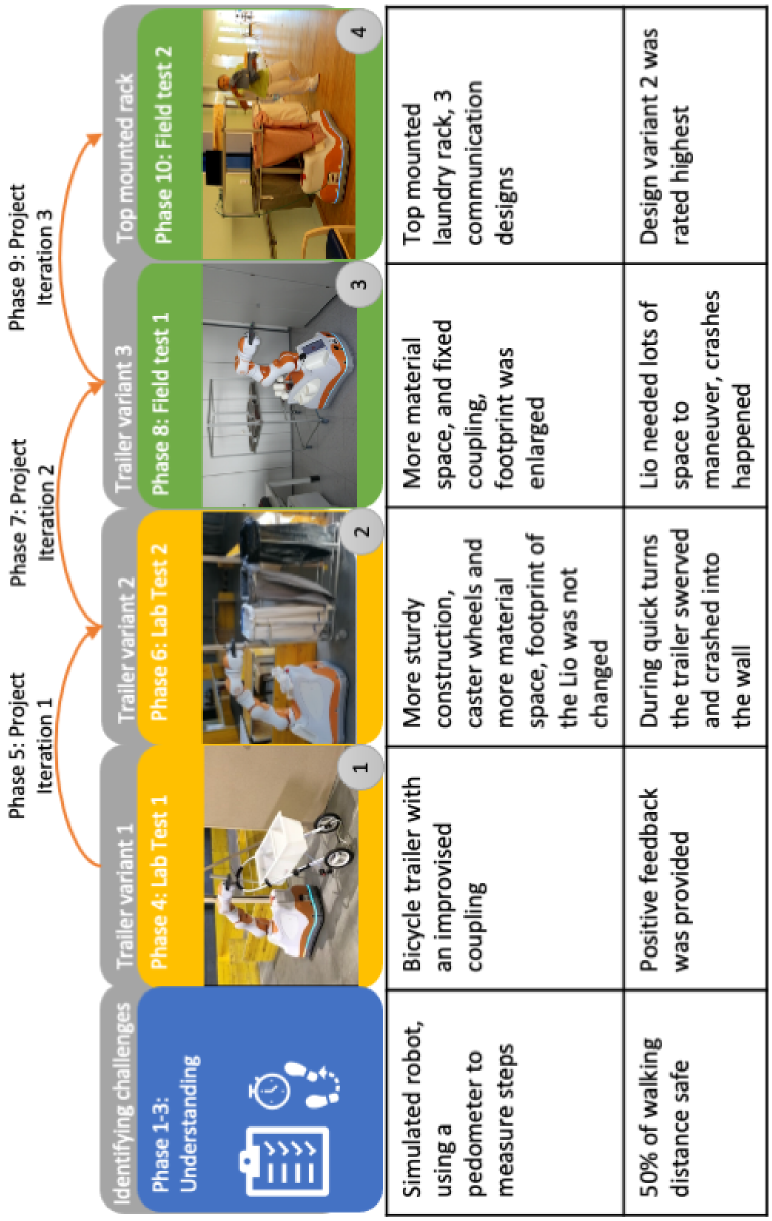
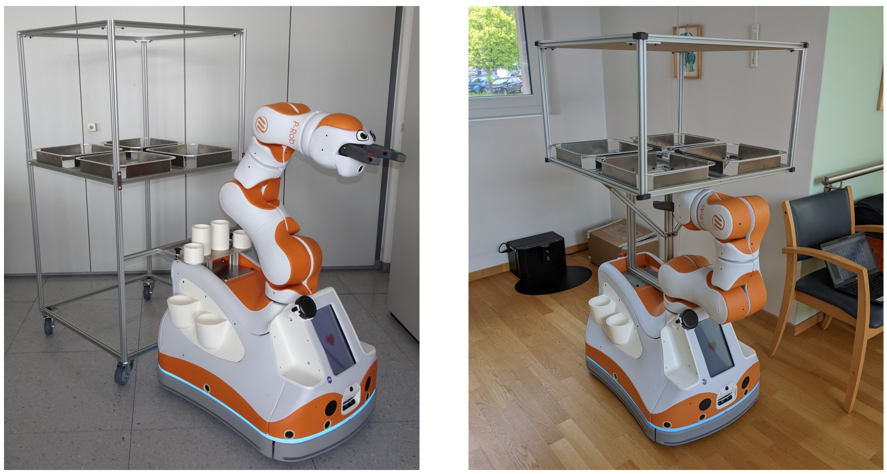


Fig. 3. Development process overview

very well. However, only the footprint of Lio and not that of the attached trailer was considered when planning the path. During quick turns the trailer swerved and crashed violently into the walls. But even if Lio had known about the trailer, it would have had no way to prevent the trailer from swaying due to the roller bearing coupling. After these tests, it was clear that a completely different design was needed.



(a) Trailer variant 3 (b) Top mounted laundry rack

Fig. 4. Laundry transporters developed in project phases 7 and 9

In project phase 7 (see Tab. 1), a new trailer (variant 3) was designed with four squarely arranged bag hangers and a removable fresh laundry tray, offering even more space and featuring a fixed coupling to counteract swaying (see Fig. 1: (3), Fig. 3: (3) and Fig. 4a). To deal with the path planning issue, the footprint of the robot was increased in ROS by the additional area of the trailer to allow the path planner to account for the trailer and avoid collisions. Also the local cost map had to be enlarged, because otherwise the back end of the robot was almost at the edge of the local cost map and thus the path planner had only little time to react to obstacles.

During project phase 8 (see Tab. 1), a feasibility test was conducted for trailer variant 3. Lio can navigate between obstacles with the enlarged footprint and local cost map. However, the path planner occasionally provides poor solutions, especially when it has to reverse the direction of travel. Also, the trailer is very fast when turning, as Lio rotates around its front axis, and the target position and orientation are not always approached accurately. Even worse, Lio sometimes collides with the environment. This could be because the wheels of the trailer partially block the view of the laser scanners, so that Lio can no longer perceive the surroundings properly.

Due to the described navigation difficulties a shift away from the laundry trailer to a top mounted laundry rack (see Fig. 1: (4), Fig. 3: (4) and Fig. 4b) is made in project phase 9 (see Tab. 1). Other solutions like adapting Lio and rewriting the planner were discussed and deemed out of scope for this project. The top mounted laundry rack only slightly increases Lio's footprint, making it much easier to navigate than with the trailer. It can be used as an add-on for Lio or it can be further developed into a stand-alone solution. It is important to note that due to the radical design change, the prototype is at a TRL of 4-5, which is below the TRL targeted at this stage of the project.

3.3 Evaluation of Three Human-Robot Communication Interfaces

In addition to the aforementioned technical developments, the communication interface design was also discussed and improved during the project. For this purpose, the required communication between the robot and the nurse was clarified in several design meetings with the stakeholders. Three possible human-robot communication interface designs were evaluated for practicality and usefulness in project phase 10 (see Tab. 1) using the top mounted laundry rack:

- **Design 1 - Initially defined sequence of targets:** At the beginning of 1, the nurse defines a sequence with all the targets to be approached. The robot is then prompted with a command to move independently to the next target in the sequence.
- **Design 2 - Flexible sequence of targets:** The robot receives the target as a command, which it then moves to independently.
- **Design 3 - Follow Me:** The robot follows the nurse. A start and stop command activates or deactivates the Follow-Me behavior. The nurse must be in the robot's field of view.

The targets in the designs 1 and 2 correspond to the room numbers of the residents or the nursing wards. For each target, a stopping point is defined in the corridor where Lio can stay for a longer period of time. In design 3, the robot simply stops at the position where it received the stop command.

The three designs were tested in the nursing home involved in this project. Two scientists accompanied a nurse during laundry distribution on three consecutive days for three hours. Due to the immense time and financial effort, only one nurse was accompanied. The Wizard of Oz principle [8] was used in the experiment, with one scientist taking over the communication and navigation of the robot. The other scientist was responsible for observations and annotations.

At the beginning of each test, the laundry rack was filled with fresh laundry and the nurse was informed by the researchers about the particular design. During the test, the wizard interacted with the nurse according to the predefined flowchart of the design. He positioned himself behind the robot and spoke its parts of the dialogue. Over the course of the three days, the rooms and the nurse's path varied. The amount of laundry changed also varied. At the end of the laundry distribution, the transport robot accompanied the nurse to the laundry drop-off.

The nurse completed five questionnaires at different times. Before and after the overall experiment, one questionnaire was completed with specific questions about laundry distribution and another with questions based on the Technology Usage Inventory. After each experiment, a questionnaire with specific questions and a System Usability Scale was completed.

After each experiment, the nurse was interviewed by a scientist. The interview focused on the subject's personal feelings about working with the transport robot. A video of the interviews was recorded and a transcript was made.

The results of the tests showed that the nurse used and utilized the transport robot for laundry distribution. According to the questionnaires, the nurse was curious and open to working with the robot. The nurse also believed that there is potential for service and transport robots in the care sector, both before and after the experiments. During the interview, the nurse said that she appreciated the fact that the use of the transport robot reduced her walking distances. She also liked that the robot waited outside the room and did not drive in.

The nurse ranked the three designs in the following order: 1) design 2 - flexible sequence of targets, 2) design 1 - initially defined sequence of targets, 3) existing workflow with the trolley 4) design 3 - follow Me. This rating is further supported by the evaluation of the System Usability Scale. Designs 1 and 2 achieved a very good rating of 87.5 points, while design 3 only achieved 77.5 points.

In the interview, the nurse indicated that she preferred design 2 over the others because of its greater flexibility. On the other hand, however, she noted that the order of the rooms is usually known and therefore it might be easier to determine the order at the beginning of the nursing round.

When interviewed about the third application, the nurse mentioned that the robot moved too slowly and that, compared to the other applications, she had to concentrate more on the robot in order not to get out of its field of vision. To do this, she had to adjust her walking speed to match that of the robot. Another problem that both the researcher and the nurse observed was that the robot stopped and waited at critical points, such as near a door or in the middle of the hallway, creating a safety issue. These were the nurse's main reasons for rating the third design even lower than the current situation.

According to the nurse, the robot was easy to use and she rated it overall as a support in daily work. It does not need to be disinfected between rooms, nor does it need to be carried when performing another activity, e.g., accompanying an elderly.

4 Discussion, Conclusion and Outlook

According to the quantitative study conducted, material transport is the most common application requested by nursing homes. Over the course of ten project phases, three different variants of a laundry trailer as well as a top mounted laundry rack were iteratively developed, manufactured, and tested in a replicated and a real environment. In addition, three possible human-robot communication interface designs were investigated with respect to the behavior of the transport robot.

It is shown that the employment of service robots for laundry transport is suitable for reducing the walking distances of the nurses. Savings of over 50% of walking distances were recorded. These savings relieve the nurses and allow them to pursue more important tasks.

Lio's wide range of applicability, coupled with the technical complexity of the task, is a problem that is not easy to solve. In particular, many problems were found with the navigation of the robot, which increased with its size. These results are consistent with those of the SMOOTH robot project [19] and support their emphasis on implementing human aware navigation.

The replicated test environment as it was described by Langedijk et al. [20] proved extremely useful in the early phases of the project. It allowed for quick iterations, the involvement of all stakeholders, and simplified the identification of challenges. During the COVID-19 pandemic, the replicated environment was also of great value as it allowed to proceed with some tests at a time when they would not even have been conceivable in a nursing home.

Although a reduction in walking distances by using a service robot has be demonstrated, this use should also be questioned from an economic point of view. As described, hygienic and safety reasons prohibit the nurse from simply leaving the cart in the hallway or taking it to another room. Using a simple lock or a hermetically sealable bag could therefore be just as effective and much cheaper than using a transport robot. However, adding additional functionality to the transport robot might again favor the robot over these simple approaches. But due to the described navigation problems, a dedicated robot, such as the intelligent care cart [12], could be superior to a multi-purpose robot, simply because a dedicated robot can usually be built smaller and is therefore more maneuverable.

During the investigation of the three possible human-robot communication interface designs, it appeared that the nurse focused on the wizard when communicating. An influence on the result cannot be excluded, and therefore the rating of the nurse should be taken with caution.

Although interface design 1 was considered the best solution due to its high flexibility and autonomous movement of the robot between positions, design 2 received a high rating as well. In particular, the simplicity of being able to define the targets in advance was appreciated in design 2. A hybrid solution with a predefined sequence of targets that can be changed as needed during runtime could therefore be an even better solution.

Due to the complexity of the laundry task, more time should be invested to understand the required human-robot interaction strategies. An important aspect of transportation in an environment as unstructured and active as a nursing home hallway is the fallibility and adaptability of a robot's path planning. This requires a small and easy to maneuver platform, which at the same time provides enough space to transport the laundry.

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