Health-CAT: Development of a Mobile Robot for Assisting Caregivers

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Abstract: The demographic change is expected to challenge the healthcare sector which in many countries is already struggling today leading to, e.g., a shortage of staff. Since robot technology is playing a minor role in healthcare today, robotics is considered to be one mean to mitigate some of the challenges related to the demographic changes. This paper discusses hurdles for introducing robotics solutions in healthcare and describes the identification of a use case as well as the development of a robot prototype. End users have been involved throughout an iterative development process leading to a prototype that has been tested during normal operations.

1 INTRODUCTION

The demographic change is challenging many healthcare systems. Not only is the share of citizens in the working age declining but also the demand for healthcare services is increasing since the number of elderly citizens is growing and this population group has a higher prevalence for comorbidities. Already today a shortage of staff can be observed in the caregiving domain (Drennan and Ross, 2019) which only can be expected to worsen given both the general demographic development and, recently, the increase of the turnover intentions amongst nurses during the COVID-19 pandemic (Falatah, 2021).

Lately substantial progress has been achieved in the domain of robot technology in general, including related areas such as computer vision or artificial intelligence. However, unlike the industrial domain, robots are currently only playing a minor role in healthcare, apart from niche applications such as surgical robotics or pilot cases. Therefore robotics can be considered to present a not yet utilized potential mean for at least partially mitigating the demographic challenge (Bodenhagen et al., 2019).

The Health-CAT project[1] was initiated prior to the pandemic and focuses on identifying how robot technology that is largely already available can be exploited to support care givers and develops and tests a prototype of such a robot. Throughout the project there was a focus on the involvement of the end-users for identifying a use case that remains relevant in the light of the demographic change and generating an understanding of how a robot should be integrated into existing workflows.

2 BACKGROUND

Given the shortage of staff and an increasing demand for services, healthcare could be considered to be able to benefit from the implementation of robotic solutions. However, while the expenditures for healthcare in OECD countries amount to around 10 % of the GDP (OECD, 2014), it only plays a minor role in the application of robotics. The majority of applications outside the industrial domain are related to logistics where 10 times as many installations are reported compared to medical robotics (International Federation of Robotics, 2020).

A large variety of robots for applications within healthcare can be found in the literature (see, e.g., (Holland et al., 2021)), ranging from topics such as hygiene which got an increased focus during the covid-19 pandemic where, e.g., mobile robots have been equipped with UV-light emitting lamps for sanitizing surfaces, to handling of samples or social robots. While the development of robotic solutions for less structured environments can be challenging, mobile robots are for instance able to operate safely and largely autonomously in environments shared with humans which suggests that solutions for mobile robots should be feasible to achieve. However,

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[1] Health-Care Assisting Technology, https://healthcat.eu

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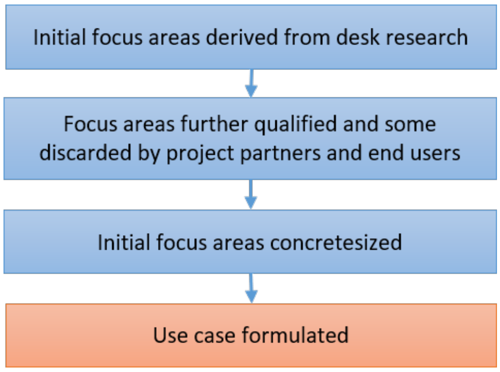

Figure 1: Steps taken to come from focus areas to use case formulation.

besides technical challenges, also various additional challenges such as a negative reputation of robots, workflows being altered, the fear of jobs to be taken over by robots or unclear liability are considered important to be addressed (Cresswell et al., 2018; Radic et al., 2019). In addition, ethical aspects related to the consequences, such as the potential reduction of human contact or the handling of privacy, of introducing robots are considered important for achieving acceptability (Stahl and Coeckelbergh, 2016).

The Health-CAT project focuses on the development of a healthcare robot involving end users throughout the process to develop a use case that is both feasible but also relevant and where the integration of the robot into existing workflows has been a integrated part of the design process. Ethical challenges have been taken into account during the selection of the use case to minimize the risk for a later implementation of the robot to be inhibited by ethical aspects and potential negative publicity.

In the following the overall approach is outlined (section 3) followed by a needs analysis (section 4) that culminates in the formulation of a specific use case and a test of solution for this use case. Details of the technical development are provided in section 5.

3 METHOD

When developing and implementing new technology, it is essential to have an understanding of the end users and the context of the developed solution. It ensures that the solution will fulfil an actual need rather than, potentially driven by technology, formulating new applications for existing technologies. In addition, it ensures a preparation of possible challenges of the solution - for instance physical limitations, different levels of competencies among users or unwillingness to adopt new technology amongst others. Furthermore, involving end users of the technology at an early stage often pays off in the implementation process, because the users get a sense of ownership to the final solution.

Health-CAT focuses on the general needs of the healthcare sector and its users. We involved the users (staff at German and Danish hospitals and care centers) during every step in the development process to determine actual requirements for a robot prototype. The feedback of the users was utilized in the subsequent steps in the development process. Thereby we ensure to always meet the needs of the users. In the following (section 4 the needs analysis, starting with desk research and progressing via multiple mock-ups to the final prototype, which was performed in the Health-CAT project will be described.

4 NEEDS ANALYSIS

The overarching goal in the Health-CAT project is to investigate use cases in the healthcare sector where robot technology can create value and help mitigating the challenges related to the demographic change. We want to ensure that the quality of care does not decrease in our future healthcare system that is challenged by to the expected issues arising from the societal challenges described in section 1. A needs analysis was conducted based on broad involvement of patients and healthcare employees. The analysis consist of desk research, ethnographic observations, interviews and focus-group interviews. Initially desk research was conducted to find societal challenges that later was further investigated through observations and interviews at different healthcare institutions in Denmark and Germany. In total 20 interviews with patients and 62 interviews with employees at healthcare institutions ranging from nurses, caregivers, doctors, service- and kitchen staff was conducted. The needs analyses attempts to:

- Identify focus areas where healthcare professionals have a need to be relieved in their daily work.
- Evaluate, how these workflows can be supported by robot technology
- Map the barriers and challenges with implementation of robot technology.

Finally the needs analysis points towards several scenarios where robot technology could play a role.

In order to conduct a qualified identification of needs, it was crucial to gather input from many different types of employees in the healthcare sector so that the needs analysis will represent needs across different parts of the healthcare sector. The first step in the needs analysis was to identify existing potential problems within the healthcare sector in our case in Danish hospitals and German nursing homes, see figure 1 for an overview of our process. The context is analyzed at three levels macro, meso and micro. The macro and meso levels was studied by conducting literature search and expert interviews with e.g. union representatives. The output of researching these two levels was a list of 10 potential focus areas within Healthcare that could potentially be supported by robot technology:

1. Hygiene: poor cleaning
2. Poor oral hygiene: pneumonia
3. Malnutrition and lack of follow-up
4. Overweight and obesity
5. Transporting equipment and patients
6. Inappropriate medication
7. Rehabilitation
8. Documentation
9. Cultural diversity
10. Measuring health parameters

These areas are then qualified by the project partners as well as relevant hospital employees. After conducting interviews, it was possible to map common focus areas of potential interest, which was then agreed on by project partners, relevant stakeholders and users. This final qualification was conducted in a workshop, and resulted in a list where 6 of the initial focus areas got discarded and 4 was kept, these 4 focus areas was further discussed and detailed into 7 sub areas, see figure 2.

With these relevant focus areas identified, we further wanted to validate them by interacting with relevant employees and observing the work flow within the potential focus areas at both hospitals and care centers.

4.1 Field Work

A field work protocol including an interview guide and an observation guide was created. The protocol defines who to interact with, how many, where, and how to document the interactions. The field work was conducted in a Danish hospital and in German care centers, we identified specific workflows, user needs, potentials and challenges, within the focus areas of interest. An observer's ability to observe can be influenced on whether the observer is in advance familiar with the observed workflows or not. The research team therefore included both a Healthcare professional and an engineer with a technical background conducting the field work. The field work process lasted 1.5 month in Germany and 2.5 month in Denmark with a total of 63 people from relevant roles being observed and interviewed. The intention was to interview both employees and patients in hospitals, as well as employees and residents in nursing homes. However, several of the patients in the geriatric department at the hospital suffer from cognitive impairment, which made it challenging to interview the patients. As a consequence only two patients was interviewed, see table 1 for more information about the field work.

The data received from the field work was further analyzed at a workshop and 5 focus areas was further detailed in the form of concrete robotic use cases:

- Cleaning of wheelchairs, toilet chairs, beds, nightstands
- Transportation of food
- Transportation of small equipment
- Transportation of large equipment
- Hand hygiene of patients and employees

4.2 Use Case Analysis

In the following the focus areas will be further introduced and potential use cases are outlined. In the conceptualization of the use cases ethical challenges in regard to introduction of robot technology was highly important and likewise was technical challenges, the solutions had to be technically feasible with today's technology while at the same time not cause any kind of "harm" to the employees. This could be altering their workflow excessively or creating technology that could end up being a liability.

Area: Cleaning of Wheelchairs, Toilet Chairs, Beds or Nightstands

During observations and interviews, it was clear that the health carers do not consider cleaning as their primary task. Furthermore, there is not allocated any space for cleaning and the consequence is cleaning of equipment takes place in the hallways or in bathrooms. Another consequence is bad work postures, as the employees do not have any tools available for easing the cleaning process. Therefore, the employees have to reach all parts of the equipment manually, including difficult accessible parts like wheels or the bottom of a nightstand and we observed that it was not cleaned properly due to several of the above issues.

Potential Use Case: Automated Washing Machine

Transport to Automated Washing Machine: The employees use different types of equipment as part of nursing tasks. Before or during use, the employee

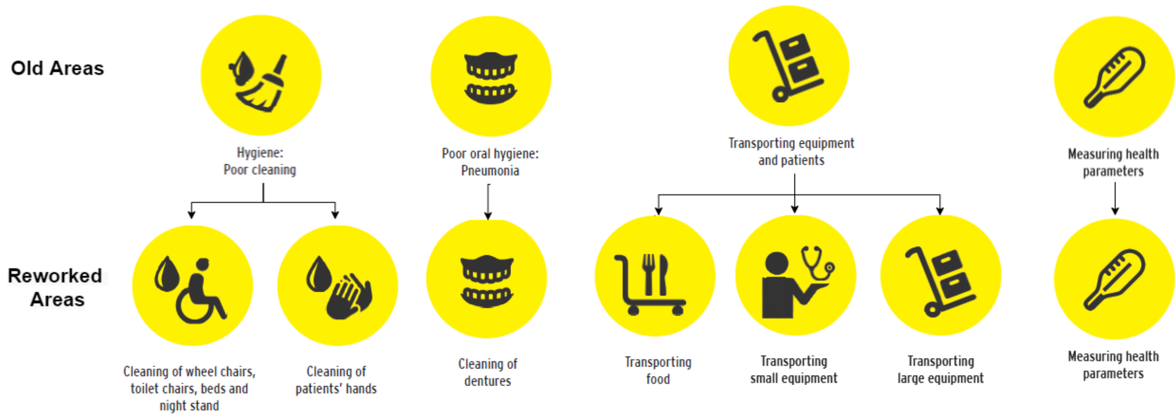

Figure 2: The 10 initial focus areas have been filtered to 4 (top row), excluding those that have been considered to be infeasible, and detailed further. This leads to 7 reworked focus areas (bottom row).

Table 1: Field work information.

Country	Germany	Denmark
Location of Observation	Tabea, nursing home and UKSH, hospital	SHS Aabenraa, hospital
Ward	Orthopedics and Trauma Surgery	Geriatric
# of employee observations	14	28
# of employee interviews	14	27
# of interviews with patients or residents	19	2

calls a robot to place itself right outside the patient's room. When the employee is done using the equipment, the employee places the equipment on the robot, and the robot transports the equipment to the automated washing machine. After cleaning, a robot transports the equipment back to the designated equipment space.

The equipment cleaning: The robot automatically places the equipment on a conveyor belt. The belt will transport the equipment into the automated washing machine, where it is automatically cleaned and dried.

Area: Transportation of Food

Transportation of food is a time consuming task due to registration of intake, ordering and serving of food and it requires a lot of walking. In the morning the kitchen staff have to prepare and transport food to all wards at the same time which creates a crowded kitchen area. At noon and in the evening the food is transported to the ward by the kitchen staff and the health carers helps the patients eat. The health carers and the kitchen staff do not coordinate their tasks so the patients' meals is sometimes stranded in the hallway for a while before the health carers have time to serve food to patients. Furthermore, the registration of patients' food intake is often a challenging tasks since it is time consuming and meals are brought to the patient by one employee and picked up by another.

Use Case: Food Transport and Registration

Transportation of Food: Health carers order meals and kitchen staff loads a robot (with a combined heating- and cooling cabinet) with trays of meals for a specific ward. The robot registers food for the each patient or resident and drives to the specific ward. The health carers pick up and serve trays for patients or residents one by one.

Registration of food: When the patients or residents are finished eating, the health carers pick up the trays and load the robot. The robot registers food intake (calories) for each patient or resident and uploads data automatically (e.g. in Cosmic or Dankost) and returns to the kitchen.

Area: Transportation of Small Equipment

As part of care-giving, the health carers need small equipment, such as venflons, bandages etc. The health carers have to leave the patients, walk to the storage, pick up small equipment, walk back to the patient and continue their original task. If equipment is damaged the procedure is repeated. The health carers cannot bring spare equipment, due to a policy to minimize waste. Collection of small equipment is an issue since it is a time consuming task that requires walking up to 10 km a day. Patients and residents often experience the situation as both time consuming and confusing since the staff interrupts their routine.

If small equipment has been brought along to a patient room without being used, it has to be discarded due to risk of infection. One specific observation that illuminates this issue was patch being fetched which took up to 5 minutes.

Potential Use Case: Mobile Dispenser

Each ward has a number of robots with a dispenser mounted that is filled with small equipment, specific to the ward's requests. The refilling of all robots is done by e.g. a service assistant in the basement. After refilling, the robots drive to the ward and wait in allocated spaces in the hallway. When equipment is needed, the health carers visit the robot or call it to the room via. a call system installed on the ward. When the robot is low on inventory, it automatically calls a another robot to replace it. The empty robot drives to the storage, where it will be refilled and cleaned by a service assistant.

Area: Transportation of Large Equipment

When equipment is needed for a nursing task, the health carers start searching in hallways before looking in the allocated space since equipment is often not positioned at the allocated space. In German nursing homes, we observed that health carers interrupt their colleagues just to locate equipment. Once the equipment is located, and if not in use, the health carers transport the equipment manually. Due to lack of time, equipment is often left without proper cleaning, which mean the next person have to clean it before using it.

Potential Use Case: Equipment Caddy

When large equipment is needed, the healthcarers call a robot via. a tablet, to bring required item to the desired area. The healthcarers can also locate equipment on the tablet, and pick it up and manually. If equipment is already in use, it will display a waiting list. After use, equipment is loaded on the robot. The robot transports the equipment to the next user or to allocated free space. Thereby healthcarers can continue there routines and be more efficient.

Area: Hand Hygiene of Patients and Employees

As part of the morning routine in hospitals in both Germany and Denmark, the patients get a cloth or a wet tissue. It is up to the patients to assess what to clean. From our observations, most patients forget to clean their hands thoroughly. During the day there was little or no focus on cleaning of patient's hands, neither before meals and after toilet use. In nursing homes, the residents are responsible for their own hand hygiene, but at the geriatric ward the healthcarers had to ensure proper hand hygiene of weak patients. The healthcarers disinfect their own hands between each patient visit to avoid the spread of infections, however, it is also important to clean hands thoroughly with water and soap. We observed that the healthcarers tend to disinfect their hands instead of washing, as this is faster.

Potential Use Case: Mobile Hand Disinfection

A mobile robot drives into the patients' rooms and offers disinfection of hands. The patients place their hands in robot and disinfection is sprayed directly on patients' hands. An important feature of the robot is that it motivates/nudge the patients to disinfect hands.

These 5 early use cases were introduced to a focus group in a Danish hospital and a German nursing home. The group of Healthcare professionals qualified and ranked the use cases with regard to importance. Based on the inputs from the focus group, two use cases were chosen. Use case 1 dispensing of small equipment and use case 2 tracking of large equipment. Use case 2 is a non robotic use case consisting of a Bluetooth tracking system placed on all large equipment in order for healthcarers to track it. In the following only use case 1 will be focused on.

Use Case 1 Flow: Mobile Robot Dispensing Small Equipment

The goal of the use case is to support the care staff by giving them a storage room on wheels, that is always where it's needed with needed equipment. All the necessary equipment are sterile and/or clean, until they are pulled from the dispenser. The flow of the use case is outlined below:

1. The robot is filled with the required items in the central storage.
2. The robot drives to its designated department and positions itself centrally in the corridor.
3. The robot can be called to the entrance of a patient room using call buttons installed in each room.
4. When the robot arrives the nurse is informed and the necessary items from the robot can be taken.

In the following section, a description of the tests process of the Health-CAT robot is given.

4.3 The Test Process

Three rounds of tests in the geriatric ward at SHS Aabenraa have been conducted. The testing consisted of two, one-day long mock-up tests and final test with the developed prototype that spanned a full week. The goal is to verify in the clinical setting that the robot complies with the use case and to document the effects of its use. With each test a new iteration of the robot has been developed, incorporating findings of the earlier tests and progressing from a simple mock-up to an actuated robot. We started with something very simple and then in each test iteration, we added more technical details. Thereby We avoided the

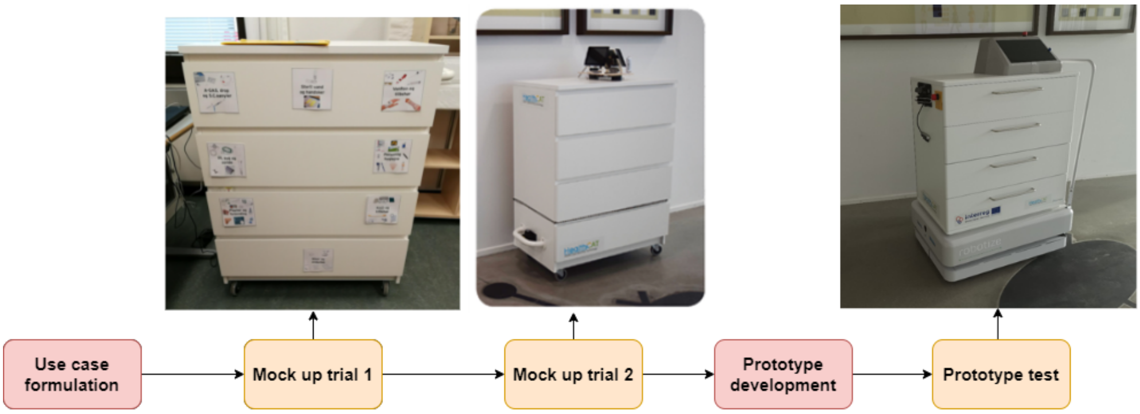

Figure 3: Timeline of the development and test cycles in Health-CAT with three different prototypes: a passiv mockup (left), a mockup with relevant sensor capabilities and user interfaces (center), and the final, actuated prototype.

robot getting a negative reputation early and the workflow being altered drastically before we knew that we could technically solve the actual use case. The hospital staff reported, that the existing robot technology deployed there often also was a nuisance. The way it behaved was often unclear and we wanted to ensure the opposite in Health-CAT. Therefore we recorded data about the environment to be fed into the vision and navigation system. The hospital employees also reported fear of losing their jobs to robots. We included them after each test iteration. This made the users feel ownership of the robot since they were part of the development process and we could continuously explain and show them that this robot was a tool for them and not a replacement. On figure 3 a timeline of the overall test process in Health-CAT can be seen. In the following, a general description of the test process is listed.

4.3.1 Mock-up 1 and 2

The first two mock-up tests were designed as non robotic and was situated at the geriatric ward at SHS Aabenraa. A nurse was pushing a drawer on wheels and together they functioned as the robot, see figure 3. In mock-up test 1 we did some very basic and early testing, we installed Bluetooth buttons in half of the patient rooms at the ward. These buttons was connected to a similar Bluetooth button outside the room that was visually on the hallway, when the button inside the patient room was pushed, the button outside lighted up with green light, and the nurse acting as the robots actuators pushed the mock-up to the specific room. The testing was done during the morning round, afternoon round and during the night shift. The flow of the mock-up test basically follow the earlier described use case; when a nurse enters a patient room, the installed button was clicked and the button outside the patient room lighted green, resembling that the robot was notified that this specific room needed equipment. The nurse controlling the ”robot” would then drag the drawer to the specific room that lighted green. This early mock-up test was primarily conducted to get a general understanding of how this robot solution could be build and how it potentially would affect the workflow. Interviews with the staff involved in the mock-test was conducted and data from this was feed into the following testing.

Mock-up test 2 is an extension of the first test, see figure 3. We performed the test on the full ward including every patient room. We automated more features in the process such as the calling system. We added a feedback mechanism on the button so the nurses could see that the robot is on its way and that the robot has arrived outside the patient room. We added visual feedback (LED strip around the robot) that indicates the internal state of the robot, blue when it drives and green when it can be accessed by a nurse. We added later a laser scanner and a camera hub on top of the robot so we could gain data about the real environment to use for improving and developing our navigation system. Again, interviews with the staff involved in the mock-test was conducted and data from this was feed into development of the prototype.

4.3.2 Prototype Test

The final test was also performed at the geriatric ward at SHS Aabenraa. The Robot prototype shown on figure 4 was tested for 1 week during every shift of the day. In this test we focused on measuring and observing the general work processes and compare it to data collected during our field work. Some of the core findings are listed below:

- **Change in Nurse Walking Distance:** One of the core findings was that the nurses took way less steps during a work day working with the robot vs not having the robot.

- **Change in Used Time Picking up Equipment:** There was a large time save in picking up equipment and they spend less time locating equipment.
- **The General Flow of Their Work with a Robot:** Several nurses reported an increase of empowerment and that the environment was less hectic in general since the robot was always at the right place at the right time. The risk of spreading infections was considered reduced using the robot.
- **Change in Disturbances from Other Employees:** The nurses were disturbed less by each other and therefore more time was spend with the patients.
- **Use of Freed up Time:** We measured that the nurses spend more time in the patient rooms.

5 ROBOT PROTOTYPE

The robotic system consists of two major parts – a robot prototype and a call system – which both consists of various subcomponents. The prototype consists of a mobile base, a cabinet, a GUI head, and a handle for manual movement of the robot in emergency situations (see fig. 4). The base has two actuated differential drive wheels in the middle of the base, and two safety lasers in opposite corners. The cabinet is made by Standard Systemer[2] and is approved for clinical use. The two narrow sides of the cabinet (front and back of the robot) each has a RealSense D415[3] RGB-D sensor, which are used for detecting people in the hospital hallways. The GUI head has a screen which is used to show the control interface for the robot. It also contains processing units for sensor processing and robot control. The handle is attached to the brake system and disengages the brakes when pulled, which allows for manual movement of the robot. The robotic prototype is based on ROS (Quigley et al., 2009) and uses the ROS navigation stack (Marder-Eppstein et al., 2010) for navigating the hallways of the hospital.

The call system consists of WiFi enabled buttons which are placed in each patient room. Once a button is pressed it transmits a unique ID to the robot through the MQTT messaging protocol, and the room corresponding to that ID is placed in a queue. An RGB LED on the button provides feedback to the user: blue if that room is first in line and yellow otherwise.

When the queue is not empty, a navigation goal in front of the door to the patient room at the top of the queue is sent to the navigation stack. While navigating to the room the robot detects and tracks people in the hallway (Juel et al., 2020), and the tracked people are used as input to a social navigation behavior (Haarslev et al., 2021). The tracker is based on the CenterNet (Zhou et al., 2019) human pose estimation network and the Deep SORT (Wojke et al., 2017) object tracker. The system works by feeding images from the two cameras to the human pose estimator, which estimates bounding boxes and joint locations for each person in the view. The joints are projected to 3D, and the torso center and facing direction of each person is estimated using the 3D shoulder joints. The pose is transformed to the map frame using localization data from the navigation stack. The transformation to the map frame serves two purposes: it unifies the detection frames from the two cameras, and it eliminates the problem of egomotion when tracking.

Figure 4: Final prototype that has been evaluated.

The transformed detections are used as input to a modified Deep SORT algorithm. Deep SORT tracks objects based on deep appearance features found by inputting images of each detected person to a Siamese CNN trained with triplet loss (Schroff et al., 2015). It incorporates a Kalman filter , which predicts the motion of the tracked people. A cost matrix is created using the distance between the deep appearance features of the tracks and the new detections. The cost matrix is gated by setting costs to infinity for detection/track pairs where the detection is too far away from the predicted position of the track. Association is done by solving the cost matrix using the Hungarian algorithm. The Deep SORT algorithm is modified by changing the state space of the Kalman filter from image coordinates to 3D map frame coordinates.

The tracked people are input to a social navigation method, which is integrated with the ROS navigation stack. The method works by creating costs representing social spaces (Lindner and Eschenbach, 2011) at estimated collision points between the robot and the

[2] https://standardsystem.dk/

[3] https://www.intelrealsense.com/depth-camera-d415/

tracked people. The collision points are estimated using the tracked motion of the people, and the motion of the robot. By projecting costs to future positions of the people the robot preemptively avoids entering the personal space of the people, resulting in a socially acceptable navigation behavior.

6 CONCLUSIONS

We have described the process of developing a robot to solve a use case within healthcare. The goal of the Health-CAT project is to ensure that the quality of care does not decrease despite the healthcare system being challenged due to the expected issues arising from the societal challenges. This process is based on a needs analysis using literature search and ethnographic studies to identify relevant focus areas. From these needs, seven use cases were formulated with ethical and technical challenges, concerning the implementation and introduction of robot technology, as a focus point. We ended up choosing one use case, the transportation of small equipment, where the robotic system consists of two major parts - a mobile robot prototype and a call system enabled staff to call the robot to any patient room.

This robot concept was tested in three iterations. The first two iterations were highly focused on identifying the requirements, issues, and benefits of the robot. The last test involved the actual robot prototype in a one-week-long integration of it at the hospital ward. The Health-CAT robot showed that the daily work life for nurses improved. They walked less, which decreased the physical stress, and experienced an increase of the time spent with the patients. Furthermore, nurses reported an increase in perceived empowerment and that their work environment was less hectic in general.

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