The SMOOTH Robot: Design for a Novel Modular Welfare Robot

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***Abstract*— The demographic change is expected to challenge many societies in the next few decades if todays' standards of services in e.g. elder care shall be maintained. Robots are considered to at least partially mitigate this challenge, however, robots are rarely applied in the welfare domain yet. This paper describes the development of a concept for a novel welfare robot based on participatory design process and by taking strengths and limitations of selected, commercially available robots into account. The resulting robot concept addresses three use cases in a care center and foresees multi-modal robot perception accommodating a proactive robot behavior for achieving smooth interactions with end-users.**

I. INTRODUCTION

Many societies are facing a demographic shift. In 2015 8.5% of the global population was aged 65 or above. This number is projected to increase to 17% by 2050 [5]. Inherited, an increase in multi-morbidity is expected which causes prolonged, complex and transverse patient care. This leaves an increased pressure on the healthcare system, both in an economical and staffing aspect, which threatens the coherent patient pathways [1].

The healthcare systems are experiencing various challenges such as high workloads and difficulties with recruiting new staff already today, making it unlikely that the existing structures can handle the challenges imposed by the demographic change without a substantial decrease of the provided services. Robots are suggested to have the potential to be a partial solution by supporting caregiving staff with selected tasks, however, robotic solutions are rarely found in this domain yet [10].

The SMOOTH project[1] aims at developing a robot that is able to address some of the needs induced by demographic change. In particular, it aims at supporting current staff at Danish elderly care facilities concerning the three use cases illustrated in fig. 1. To fulfill this goal *affordability, simplicity* and *acceptability* are considered to be essential aspects that needs to be taken into account during the development process.

This paper describes the process in which a design concept for a welfare robot for three use cases was developed. In section II we cover a detailed use case analysis based on an ethnographic study. In section III existing robotic solutions are discussed in the context of SMOOTH and in section IV requirements for welfare robots are identified. In section V, we create three design concepts for for the SMOOTH robot to solve the three use cases. The final design concept of the SMOOTH robot is provided in section VI.

II. DETAILED USE CASE ANALYSIS

Use case 1 (fig. 1a) is a logistic task in which the robot transports laundry and garbage at distances between 10 and 50 meters. Little interaction between staff, residents and the robot is expected. From a detailed analysis, we found that other smaller items are transported over the day. Use case 2 (fig. 1b) addresses the offering of drinks to elderly people, who often lack a feeling of thirst. The important aspect is motivating the elderly to drink. This involves human-robot dialog, and the technology developed can also be transferred to other contexts, such as receptions at conferences or celebrations. Use case 3 (fig. 1c) addresses the problem of elderly people often requiring guidance to reach a certain place such as the dining table. Also this can be transferred to, e.g. airports and hospitals. Use cases 2 and 3 pose a significant challenge with respect to the smoothness and appropriateness of human-robot interaction (HRI), a core idea of the SMOOTH project is to design "proactive" control, which takes expected actions of the humans into account (see section VI-C).

Development of the use cases was done in an iterative refinement, using context evaluation and taking ethical, anthropological, design and geronto-psychological considerations into account, as well as aspects of computational and economic feasibility. This was done to ensure: user acceptance, smooth integration of the robot into the workflow, and to align expectations between the different stakeholders.

The three potential use cases were identified based on focus group studies and idea generation led by Patient@home[2]; these potential use cases were then developed further in a participatory design approach through: An ethnographic observation, a focus group and co-design workshop, consortium and stakeholder meetings and a conference workshop

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[2]http://www.en.patientathome.dk

(a) Laundry and garbage handling

(b) Water delivery

(c) Guidance

Fig. 1: The three cases of the SMOOTH project (all illustrations made by the Danish Technological Institute)

1) Ethnographic Observation: To study current workflow, a 24-hour ethnographic observation was done in two units at Ølby elderly care center (ØECC). We found that the residents at ØECC receive highly individualized care due to the small units and the high number of personnel per resident (two on the early shift and late shift, one on the night shift, for 5-6 residents). The caregivers often walked between residents' rooms and the laundry and garbage room, automating laundry and garbage collecting would relieve caregivers and free them for social interaction with the residents. Drinks where mostly provided during mealtimes, different drinks are served in different and specific ways. There was little resident activity in the common areas, this could be facilitated by offering drinks between mealtimes in the common spaces. We observed that caregivers spend considerable amounts of time guiding residents on even short distances.

2) Focus Group and Co-Design Workshop: At ØECC, focus group interviews with the director and employees, a prototyping workshop involving residents and staff, and individual interviews with members of the staff were carried out to understand the staff's specific ideas, hopes, needs and fears. The interviews provided us with a quantification of the processes observed, for instance, how many residents need guidance to and from their rooms, and how often laundry is collected.

3) Consortium Meetings and Stakeholder Workshop: The use cases were subsequently discussed and detailed at various consortium meetings with invited stakeholders and associated partners, such as our ethical advisor. The stakeholders suggested that working climate, innovation, well-being, preventive measures, the quality of the care and quality of life should be valued as highly as economic aspects.

4) Conference Workshop: At the Robophilosophy 2018 Conference, a workshop was created to further discuss the use cases. Four invited guests with different backgrounds: ethics, design, geronto-psychiatry and HRI. Many useful considerations as to the concrete realization of the use cases and the robot prototypes were collected, for instance concerning the anthropomorphic design of the robot, which could appeal more to people with dementia, and the colors of the robot.

(a) Care-O-Bot 4

(b) Pepper

(c) MiR100

Fig. 2: Robotic solutions for the health care system

All of these considerations fed into the specification of the robot prototype.

III. Existing Technology in Context of SMOOTH

In this section, we present three robotic solutions (fig. 2) on the market that facilitates **service, personal assistance and logistics** required for the three use cases. They may serve as inspiration for our robot development we will discuss and analyze their strengths and limitation in the context of the SMOOTH project.

The Care-O-bot 4 [6] on fig. 2a is a **mobile service robot** with grasping ability. Due to the design of the robots spherical joints the work space of the Care-O-bot 4 is extended compared to earlier versions while enabling a 360-degree rotation of head and torso. The robot is modular such that it can be equipped with up to two arms, trays, a 'head' or just be used as a mobile base.

***Strengths**:* The novelty of the Care-O-bot 4 is its modularity, which makes it relevant to many scenarios while the height

and design of the robot facilitates human-robot-interaction. Therefore, this robot could be applicable for the guiding use case and perhaps also for the water serving use case.
***Limitation**:* The problem of grasping has been solved for controlled environments in the industry but still remain to be fully solved in less constrained environments, this limits the robot to only solve very specific serving tasks. Due to its design, the Care-O-bot 4 is not applicable for the logistic use case in SMOOTH. The price, depending on the modules chosen, is between 80.000 Euro and 130.000 Euro without the arms, and around 40.000 Euro per arm.

Pepper [8] on fig. 2b is a **personal assistant robot**. Pepper is designed as a day-to-day companion with the emphasized ability to perceive emotions. Pepper is designed to communicate with humans through his body movements and by voice. The pepper robot has different sensors such that it can recognize faces and speech, and move autonomously.
Strengths: The design of Pepper is appealing while also being mobile, which could facilitate the idea of the guiding use case in SMOOTH, here Pepper could function as a companion that welcomes and guides elderly while being entertaining and emotionally aware. The price of Pepper is around 20.000 Euro.
Limitations: The Pepper is not applicable for logistic or service tasks, which would limit the robots use in the SMOOTH project.

The MiR100 [7] (fig. 2c) is a **mobile logistic robot** used for the automation of internal logistic tasks. The MiR100 applied both in industry and in the healthcare domain for logistic tasks, but also utilized as mobile base for other robots such as the UV Disinfection Robot described in [12]. Other mobile robot solutions like TUG [11] are also applied for logistic tasks in the healthcare system.
Strengths: The MiR100 can solve many types of logistic task with a payload of 100 kg. It is designed such that customized modules can be mounted on top. Thereby, the robot can be utilized for various applications sharing the same base platform and navigation system. The price of this robot is between 20.000 Euro and 30.000 Euro.
Limitations: The design is not optimal for the interaction with humans due to both its low height of 352 mm and lack of relevant sensors and bulky design. This would generally limit its relevance for SMOOTH since seamless human-robot-interaction is an integral element.

The robots outlined above represent available solutions to some of the identified use cases. However, none of them can be generalized to all three use cases without becoming economically infeasible. It follows from this that a modular design which allows for the robot to solve multiple tasks is desirable. In the following we will, based on the strengths and weaknesses of the above robots, derive design criteria for an actual welfare robot.

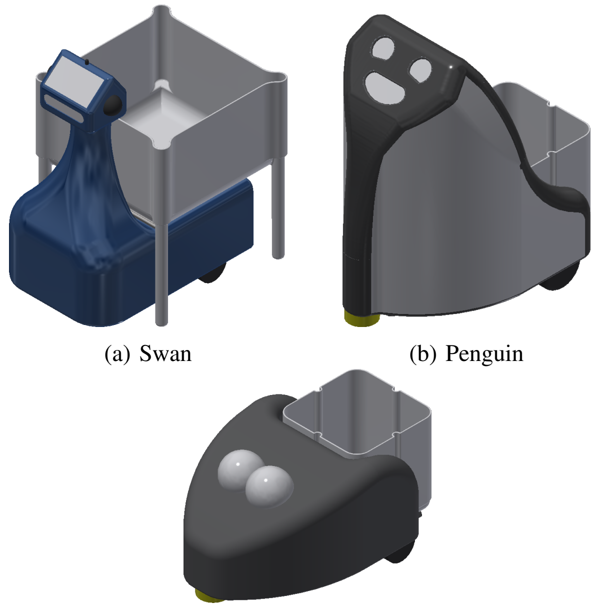
IV. Requirements for Welfare Robots

In industry, robots have been accepted and adopted into the daily work environment for more than a century. This was enabled by having a controlled environment where humans and robots are separated by fences. Today, collaborative robots and humans share the environment rather than being separated, enabling collaboration on tasks. Such collaboration is essential in welfare robotics for handling less structured environments. Welfare robots are required to navigate and manipulate changing environments, while communicating with the user. One of our primary goals when developing welfare robots is enabling the robot to operate alongside humans – e.g. the caretakers and residents at elderly care facilities.

To create this collaboration, we face technical constraints. In contrast to industrial robotics, grasping and manipulation is much more complex in general scenarios. In elderly care institutions and at hospitals the environment changes frequently and objects are different. Todays welfare robots that grasp physical objects are still only research projects. To create a technically feasible welfare robot that can be implemented and accepted at hospitals and care facilities we believe that we for now are required to avoid having manipulators in the form of robotic arms and instead use less dexterous devices to manipulate in the environment.

To facilitate the acceptance of a welfare robot by the staff, patients, and residents in hospitals and elderly care facilities it is required to design the appearance and behavior of the robots in an appropriate way to ensure the dignity of the humans interacting with the robot. The robot should also be aware of the expectations and capabilities of the residents and patients. Human interaction is successful because we are able to predict each other's reactions and actions. We believe it is essential that a welfare robot have the same ability, as much as possible. Therefore, it is important that it can read body language and understand a complex scene of interactions. Essentially the human perception of a welfare robot is shaped by its behaviors and physical design. In our view, it is crucial that welfare robots are able to anticipate human actions and proactively act on these, to arrive at smooth and hereby acceptable behaviors.

For the healthcare system to truly adopt and accept welfare robots we believe four things are key in the development process of these:
Affordability**:** As all governmental institutes operates on limited budgets, it is important that welfare robots are not overly expensive. It is often hard to determine how much value a welfare robot will create, so the decision whether or not to buy it will often be based purely on price instead of created value. To ensure an affordable price, the robots need a simple design and mechanics of limited complexity.
Modularity**:** A strong business case can be facilitated through a modular design. This enables the robot to solve different tasks, allowing it to serve multiple purposes and thereby creating value. Such tasks could include logistics, aid in communication, guidance, service, and serving.
Simplicity**:** Installing a robot at a facility should not overly disrupt workflow, to avoid irritation and negativity towards the robot before it is even put to use. Likewise, the daily use of the robot should be as uncomplicated as possible



(a) Swan (b) Penguin

(c) Mouse

Fig. 3: Three different initial design suggestions.

for the users – i.e users should not be interrupted in their daily work to service the robot in any way. The interaction between the robot and humans using it should be simple and intuitive. This should be facilitated through a user-oriented design process when creating both the design of the robot and the graphical user interface.

***Acceptability*:** While ease of use has a big role, the physical attributes of the robot also plays a role in whether users accept it into their workflow. It is important that the robots design allows it to convey its intentions as well as its internal state, while in no way facilitating misuse of the robot.

V. SMOOTH WELFARE ROBOT

Three initial robotic design concepts have been discussed for solving the three use cases in the SMOOTH project: The Swan, the Mouse and the Penguin. Each design was discussed with respect to the requirements defined above.

The requirement of **affordability** has been facilitated trough a economic distribution of sensors, in particular the most expensive safety laser scanner. **Modularity** is solved by all three designs by having interchangeable attachments, which can be chosen depending on the current use case. **Simplicity** of interaction has been partially solved in all designs through a richness of sensorial modalities. However, the limited height of the Mouse makes interaction difficult. To increase **acceptability** we purposefully chose a design with minimal anthropomorphic features (as suggested in [4]).

A. Designs

All three initial designs are build on the same three-wheeled mobile platform. The platform features two actuated wheels, and a single caster wheel, allowing the robot turn around the axis between its driven wheels. The platform uses a single safety laser scanner in the front. This means that

TABLE I: Table of scores (from 1 to 3) based on the designs capability to solve each goal of the SMOOTH project.

	Swan	Mouse	Penguin
Affordability	2	3	2
Modularity	2	3	3
Simplicity	3	1	3
Acceptability	2	1	3
Total	9	8	**11**

the robot is designed to drive forward, and is only in certain conditions allowed to drive backwards. For this cheaper 3D vision sensors will be used to avoid collisions. The designs differ in the way they handle the modular attachments, as well as the sensor kit and user interface on top of the mobile platform.

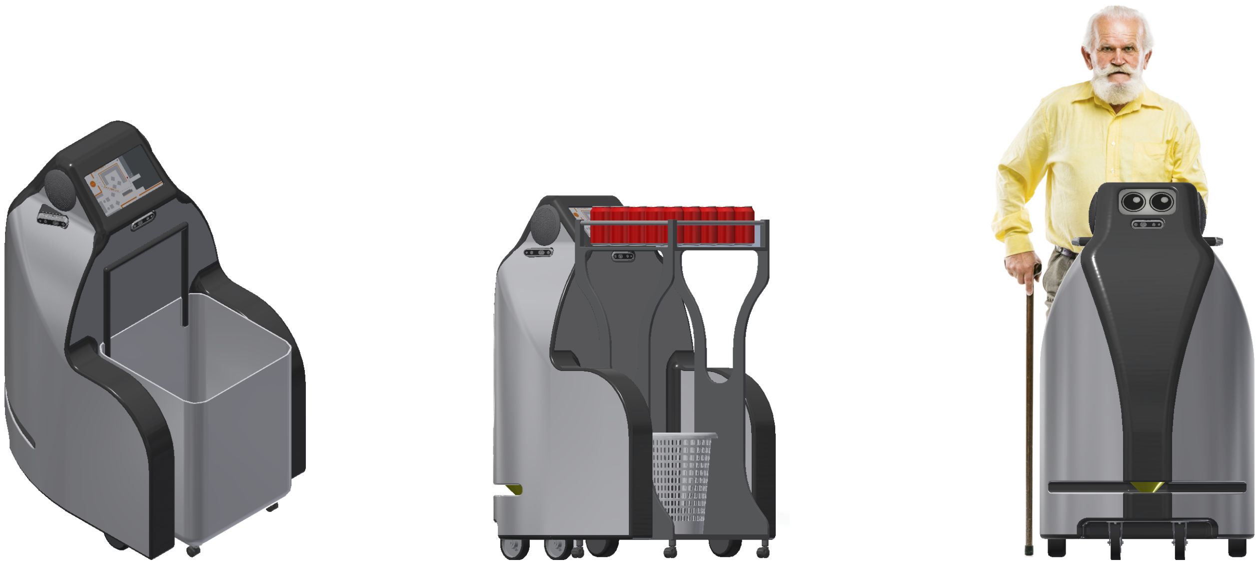
The Swan: The design (fig. 3a), uses a liftable platform to carry the attachments, which have legs to facilitate that the robot can drive underneath them. The design includes a elongated neck with a sensor head on top, which is the primary user interface (UI). It contains touch screens and vision sensors in the front and back, speakers on both sides, and a microphone on top. The Swan addresses the logistical use case well, except that the legged design of the attachments might limit the field of view (FoV) of the safety laser. Furthermore, the protruding platform might be inviting for people to sit on.

The Mouse: The design (fig. 3c) is a small logistic robot, that solves the problem of modularity by having attachments with wheels, which it can drag around. While the design does feature speakers and a microphone, it does not have the same type of UI as the Swan. This, combined with the low height, makes it less than ideal for social interaction, as well as making it unsuitable for the guidance use case. The low height also complicates the vision system of the robot. The small footprint makes the robot very affordable, while easing safety constraints of taller robots with a higher mass, however, people might easily stumble over the robot.

The Penguin: This design (fig. 3b) was created to fuse the positive aspects of the Swan and the Mouse, while avoiding their limitations. It uses the same attachment system as the mouse, to avoid having the attachments block the safety scanners FoV. It has a tall body with a UI at the top, similar to the Swan. The height of the robot makes the design suitable for social interaction, while also allowing for control using a touch screen within standing reach.

B. Selection Process

The final design was chosen based on how well the designs solve the goals of the SMOOTH project. Table I shows the scores of the different designs for each goal. In the goal of modularity, all designs scores fairly well. However, since the legged design of the Swan attachments limits the safety lasers FoV, it is scored a bit lower than the Mouse and Penguin. The affordability is also quite good for all robots, due to the use of a single safety laser. However, because of the small footprint of the Mouse, it is scored



(a) (b) (c)

Fig. 4: Visualization of the final design. (a) and (b) show different modules for the logistic and drink serving use cases and (c) illustrates the robot being applied to the guidance use case (stock image from Colourbox).

higher than the Swan and Penguin. The acceptability of the mouse is scored the lowest, since the low profile makes it unsuitable for interacting with end-users in general and for the guidance use case in particular. The Swan is scored lower than the Penguin, because its protruding platform might lead to potentially dangerous situations, i.e. if anyone sits on it. The Mouse is also scored the lowest in interaction, again because of the limited height.

The Penguin ended up with the highest score (see in table I), and it was therefore chosen as the final design.

VI. The Penguin

Figure 4 shows a refined version of the Penguin design. The refinement contains both changes to the mobile platform and the UI hub. The changes to the mobile platform was done because of stability concerns. The original three wheel design had the caster wheel placed behind the safety scanner. However, a mock-up showed that this wheel placement led to instability when the wheel was turned to either side. This is remedied by adding a second caster wheel while moving the safety laser up, such that the wheels can be placed beneath it. The three wheel design was decided upon because there will always be three points of contact, regardless of the roughness of the surface. To get the same stability from a four wheeled design, a spring or dampening system will have to be devised. To make sure that the full 270° FoV of the safety laser is unobstructed in the new placement, a groove has been added to either side of it (see fig. 4b).

The changes to the UI hub includes placement of four vision sensors (explained in section VI-B) as well as added detail to the screens. Figure 4c shows animated eyes on the front display, while fig. 4a shows a map on the back display, which is visible during the guidance use case.

(a) Frontal view (b) Back view

Fig. 5: Detailed Visualization of sensor unit, the 'head' of the robot.

A. *Use cases*

Figures 4a and 4b shows possible attachments for the laundry and drink use cases. The bin can contain 75 liters, making it well suited for carrying laundry or garbage. It has a handle and wheels, which makes it easy to push it around when it is not attached to the robot. The rolling serving tray is one possible attachment for the drink use case. One could also imagine a water fountain attachment with added cup holder.

B. *Sensor head*

Figure 5 show the innards of the sensor head. The head features two tablet displays, four 3D vision sensors, two speakerphones for dialog, and two microphones for sound localization. For the displays two tablets were chosen (7” in the front and 10” in the back) as they generally are designed to be as compact as possible, while containing all hardware for processing the UI. The front screen will show animated eyes, and not be used for interaction to avoid the discomfort of poking something in the ”eyes”. The back screen will facilitate the main way of instructing the robot non-verbally.

It might use a dock, to allow authorized people to control the robot remotely.

The vision sensors are placed with one in the front, back, and on either side. The ones on the sides are tilted slightly backwards (see fig. 5a), because of the limited FoV of the sensors. This is done to cover everything behind the robot, since it relies on the vision sensors when going backwards. Also, during the guidance use case people will be behind or two the side of the robot, making the area to the front left and right less critical to be visible.

C. Proactive control

The control scheme of the SMOOTH robot combines two main components: 1) Multi-sensory integration for adaptively combing different sensor types (e.g., vision, sound, laser range) and 2) proactive control for autonomous learning to anticipate human behaviors and to perform proactive responses. This approach will result in predictable and comprehensive actions of the robot with natural human-robot interaction.

Human-human interaction is smooth and multi-modal, involving the processing of information from visual, auditory and tactile senses. Smooth movements influence a robot's apparent animacy, unpleasantness and likability [2]. Multiple sensory modalities offer redundancy in information, which can subsequently reduce overall movement errors.

Conventional model-based robot controllers require a priori models of the environment. Adaptive sensor-driven controllers on the other hand directly link perception to action. They can deal with unpredictable events better than controllers based on the sense-plan-act paradigm [3]. Multi-modal sensor-based control can be beneficial for smooth, naturalistic robot. The SMOOTH robot utilizes a crossmodal learning-based sensor-driven controller for fusing sensor information irrespective of modality. The fused information is directly mapped to motor commands as a weighted sum of sensory cues. The weights are learned online on a moment-by-moment basis [9]. This ensures that the robot executes smooth movements. Exploiting temporal correlations between sensor modalities also allows the model to realize proactive control by generating movements that predict the signal a given sensor will generate. This can help to determine intention in human-robot interaction.

VII. Conclusion and Future Work

Based on participatory design process and on properties of commercially available robots that have been developed for different use cases but that are applied or at least applicable in the welfare domain, the design of a novel welfare robot has been derived. In order to facilitate the development of an applicable welfare robot that can mitigate some of the challenges of the demographic change, the criteria of affordability, modularity, simplicity and acceptability have been used to guide the development. To facilitate a seamless interaction between the robot and its end-users a multi-modal sensor unit, including devices for providing feedback to the user, is integrated. Multi-modal sensor-based control is foreseen to generate proactive robot behaviors.

The next steps in the development process includes, besides the development of the individual modules, the construction of a functional prototype allowing for a test in both lab environments and at an actual care center. This will allow for evaluation change to the workflow which a robotic solution will induce.

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