“Hey, I’m walking here!”

An explorative study of spatial encounters between older adults and autonomous robots

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Abstract

This thesis is an explorative study of spatial encounters between older adults and autonomous robots. We have collected data from a wide range of contexts to explore the domain; using field studies, observations, focus groups, and interviews. Our primary empirical context has been an institution where older adults live independent in separate apartments, but with common areas for social activities. A robot platform based on the Robot Operating System framework has been used to observe how older adults react when encountering a robot.

We have found that the deployment of an autonomous robot is a pervasive alteration in the life of an older adult, and that it will require a substantial amount of facilitating tasks to be able to move autonomously. Thorough investigations and collaboration with participants for each particular context are required prior to deployment of the robot. A robot should communicate congruent information, utilizing multiple communication modalities.

We have seen that spatial conflicts can emerge from encounters between robots and older adults, and propose five design implications to mitigate these conflicts. The most important proposals are to identify possible problem areas, and develop navigation strategies that not only focuses on efficiency, but has an explicit focus on avoidance of such conflicts and challenges.

Keywords: *HRI, HRSI, motion planning, older adults, ROS, welfare technology*

Acknowledgement

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We would like to thank the members of the Multimodal Elderly Care Systems project for their support in data gathering, analysis, and interpretation.

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Magnus Søyland & Vegard Dønnem Søyseth
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Prologue

> *Come, old broomstick, you are needed,*
> *Take these rags and wrap them round you!*
> *Long my orders you have heeded,*
> *By my wishes now I've bound you.*
> *Have two legs and stand,*
> *And a head for you.*
> *Run, and in your hand*
> *Hold a bucket too.*

"Magic!" Personally, that is what we think of some particularly novel and exciting technologies the first time we experience them; when they create possibilities and experiences that were previously unimaginable. Of course, intellectually, we know that magic does not exist; at least not the kind the *Sorcerer's Apprentice* utilizes in the above excerpt from Johann Wolfgang von Goethe's *Der Zauberlehrling*. The poem is about the apprentice of a powerful sorcerer who is tired of fetching water by pail. The apprentice enchants a broom to do the job, thus giving himself the possibility to relax.

We consider the enchanted broom a fitting analogy for *robots*, the topic of this thesis. To us, robots are among the technologies most closely resembling magic, because of an appearance of sentient life due to autonomous motions. One of the motivations for acquiring a robot is to let it do a certain task, thus freeing oneself to pursue other endeavors; much the same reason why the Sorcerer's Apprentice enchants the broom. However, this thesis will show that the resulting consequences, in both reality and fiction, are much more complex and unpredictable.

Chapter 1

Introduction

> *"Science fiction writers foresee the inevitable, and although problems and catastrophes may be inevitable, solutions are not."*
>
> – Isaac Asimov

1.1 Motivation

The Norwegian society will in the coming years experience a dramatic increase in its population of older adults. In 2013, 13% of Norwegians were aged 67 or older. *Statistics Norway*[1] estimate that by 2030 this figure will have increased to 17%—and by 2050 even further to 20% [77]. In other countries, this increase has already occurred; Japan had in 2015 a population composition where 33% were of age 60 or older [105].

When we grow old, we wish to experience a meaningful everyday life, supported by a dignified care. We believe these wishes are shared by our current senior generation, and it is something we want all future generations to experience as well. However, as the population of senior citizens increases, there are concerns in how to enable care in ways that make these services feasible—both with respect to human and economic resources [77]. The main reason is that the demand for care services increases with the aging population [77]. The question is: how can society continue to provide care services while letting the older adults stay as independent as possible?

The introduction of robot technology might be one possible solution to this challenge [93]. However, deploying autonomous moving robots in the homes of older adults and in care facilities can potentially introduce its own

[1] The Norwegian statistics bureau

set of challenges. It is important to try to identify and consider these as a part of the design process before the robots are employed. By doing so, the cost will be reduced, and fewer problems will occur. One of the situations where challenges are most likely to occur is when a human and a robot encounter each other in physical space.

1.2 Objective

In this thesis, we will explore spatial encounters between older adults and robots. We will identify some of the unique challenges emerging from such encounters, and propose strategies for mitigating or removing them. These strategies will be compared and contrasted with current navigation approaches in the open source robotics community. The thesis will also investigate how seniors react to such encounters; how do they interpret the robot behavior?

The exploration has been done through prototyping, and by using qualitative methods of inquiry. We have conducted interviews, focus groups, and performed observations; both in controlled and natural contexts. Early in the process, we purchased a robotic platform called the *Autonomous Deep Learning Robot (ADLR)*. This robot has been used for two main purposes: First, we used it to learn about robots and the Robot Operating System (ROS). Second, we have used the prototype throughout the process as an artifact for eliciting opinions, and in observational sessions—where the robot and an older adult would encounter and pass each other. Thus it has served as a tool to mitigate the challenge of discrepancies between what informants say and do when researching interaction between humans and robots [9].

1.3 Context

This thesis is among the first master's theses written as a part of the ongoing Multi-sensor Elderly Care System (MECS) research project at the University of Oslo. The MECS project seeks to explore how robots can support older adults, with an emphasis on mobile robots. This involves a range of research fields including Human-robot Interaction (HRI), Human-robot Spatial Interaction (HRSI), and Artificial intelligence (AI). Further details about the MECS project can be found in Chapter 3. A goal for the MECS project is to study the usage of sensor technologies on or linked to mobile autonomous robotic platforms, rather than wearable sensors or static sensors placed in the home of older adults.

What are the implications of using autonomous robots when interacting with older adults? A premise of the project is to involve the senior citizens in the research actively. As they are the users, we see them as the experts on their everyday life; they are the key to understanding the needs that technology can complement and whether the technology works as intended. The autonomy level of the robot will impact how the user will interact with it. Imagine a robot in your home that cleans, does the laundry, takes out the trash, and other chores. What happens when it is dusting? Will it move things and put them back? In that case, what if you want to refurnish your home and the robot keeps putting the furniture back in its old place? What about if the robot starts vacuuming during a dinner with your family?

Even though the technology indicated in these examples may not currently be available; and they describe corner-cases of what autonomy represents; they illustrate the possible conflict between the autonomy of the robot and the user's situational control.

1.4 Background

There have been major advancements in development and research of robot technology over the past decades [27]. The application possibilities of robots have potential both in respect to entertainment and practical purposes [82]. However, the technological requirements for robots to take the step from labs and factories into more ordinary environments are considerable [27]. While robotics development traditionally has been business oriented, more robots are entering the consumer market.

In HRI and robotics, a vision is that the robots can provide a higher degree of efficiency or independence among users. The senior citizens represent one of the user groups where robots can have the largest applicability and impact. A piece of the puzzle in the implementation of robots in home environments is the ability to adapt—which includes the robot's movement pattern and behavior towards humans.

This research is placed in the field of HRI, and more specifically in the subfield called HRSI. The latter is an area of research that has garnered increasing attention during the past two decades, but there are still many challenges that must be solved to allow basic co-presence of humans and robots. Not to mention the multitudes of challenges that must be overcome to create robots with just a small fraction of the functions depicted in science fiction books and movies. We believe that robots will become almost ubiquitous in the future, and consequently consider this an important field of research. During our research of earlier studies, we have noted an absence of research dealing explicitly with spatial encounters between robots and older adults.

The fact that many robots will move around autonomously, will require other forms of interaction than stationary technologies. Since a robot will be moving around in a house or in public areas, there will be encounters between the robot and the user. The question is how the robot should behave in such encounters. In encounters between humans, there are many phenomena taking place. In the case of two people crossing paths on the street, the body language communicates the intention of such things as in what direction the person is heading; whether they are in a hurry; or if one is not paying attention to his or her surroundings. When someone bumps into each other, some politely apologize, and some do not. These interactions represent a form of social contract. What happens to these agreements when humans and robots move in the same physical space? The question has different dimensions. For instance, the physical shape and maneuverability of the robot impact the way it can communicate through gestures. Behavior such as motion patterns, speed, and acceleration is a subset of the human body language. Vehicles are an example of objects moving in the same space as us. Even though they are operated by humans, there are many inventions on the modern car that is designed for communicating with other drivers and pedestrians. For instance directional indicators, the horn, and tail lights.

1.5 Target population

The MECS project designate senior citizens living at home as the main target population. No age definition is specified by the project, so we had to decide this for ourselves. Statistics Norway designate those aged 67 and older to be part of the older population [61]. This is also the Norwegian retirement age and the officially stated minimum age for residents at Kampen Omsorg+, our primary source for empirical data.

However, the residents at Kampen Omsorg+ vary widely in age; currently, the oldest is 97 years old, and the youngest is 64 years old—a range spanning close to two generations. The average age of the residents is 82.

Joshi and Bratteteig discuss how there is a shared understanding within the research community that older adults must be considered a heterogeneous group with various challenges and abilities, and that their challenges and abilities are largely independent of age [42].

As such, we will not specify a strict biological age to define our target population. We will rather argue that all the residents at Kampen Omsorg+ are part of our target population, regardless of age. The residents have to be self-sustained while having some impairment to prevent them from living in their former home. Even though Kampen Omsorg+ is a facility, all the residents have their separate apartment and consider the place their *home*. These aspects all make them prime subjects for having a robot help them in their homes.

To denote the target population as "elderly people" can be considered derogatory. Therefore, to reference our target population, we will use the terms *older adults* and *senior citizens*; with their derivatives.

1.6 Research questions

The following three research questions have been the focus for our research. Each question is followed by a brief explanation.

> *How do older adults interpret the communication given by an autonomous navigating robot to convey its spatial objectives?*

Human beings are dependent on communication when moving in the same areas to prevent misunderstandings and conflicts. We will investigate how older adults interpret the communication given by an autonomous mobile robot. Will they use the communication to infer its spatial objectives, or will they interpret entirely different things? Furthermore, how can a robot best communicate its spatial objectives to older adults, and what consequences can arise from lack of communication? The term communication will encompass both verbal and nonverbal communication, although the main focus will be on the latter of the two.

> *In what ways can spatial conflicts emerge in encounters between an autonomous navigating robot and older adults?*

We will explicitly look for spatial conflicts occurring due to older adults and autonomous navigating robots moving in the same physical areas. By this we mean situations where the human and the robot limit each other's freedom of mobility in some way. We will do this for two reasons: First, such situations can be a particularly salient source of information. Second, we will propose ways to eliminate or mitigate the identified conflicts. Some of the identified challenges might not be unique for older adults.

> *How can the introduction of an autonomous navigating robot alter tasks and task distribution in the homes of older adults?*

Many domestic robots are advertised as doing a task that humans previously had to do, thereby claiming to remove the need for the human to do it altogether. We believe this to be an oversimplification; the introduction of an autonomous navigating robot in a private home will probably add some tasks, and alter others. We will thoroughly investigate the changes and discuss the consequences we identify.

1.7 Clarifications

1.7.1 Defining the robot

All the robots we have used for our investigations have a few things in common. The most accurate way to describe them would be as *autonomously navigating mobile robots*, but even this is somewhat ambiguous. Therefore we will define our meaning of the different terms, and introduce a briefer phrase that we will use throughout the thesis, for the sake of brevity.

When we use the term *autonomous*, we mean that the robots operate algorithmically in some way, not by way of teleoperation. Consequently, the operations of the robot will be somewhat unpredictable and arbitrary.

By the term *navigating*, we mean that the robot will be able to locate its spatial objectives; either by using a map or by using sensors to find them.

The term *mobile* will be used for robots that can spatially relocate themselves with the use of their own locomotive abilities. Thus, by our definition, a cell phone would not be considered mobile, since it requires someone else to move it.

We have chosen to abbreviate the term *autonomously navigating mobile robots* to simply *mobile robots*. The term mobile robots includes all the clarifications made in the previous paragraphs.

1.7.2 Privacy

Throughout the thesis, some of the informants will be referenced by name. None of these names are real; they are without exception pseudonyms meant to preserve the anonymity and privacy of our informants.

Additionally, we will discuss some institutions in the thesis, and these will also primarily be referenced to by pseudonyms. The exceptions are the official collaboration partners of the MECS project. We consider it unnatural to hide their identities. Thus we will refer to them by their actual names.

1.7.3 Anthropomorphism

Throughout our studies, we have seen that people have a propensity to anthropomorphize mobile robots. This was evident by the way our informants referred to the robots; giving them names and using animate pronouns. We have also seen examples of people talking directly to a robot, even though it was obvious that they expected no reply or reaction.

It is not very surprising that this phenomenon occurs, since entities that move randomly and autonomously usually are sentient beings. In some instances, we have seen that the manufacturers encourage this; e.g. by suggesting that the user should name the robot. We have ourselves experienced how easy it is to think of a robot as being sentient, even though we intellectually know it to be wrong.

To clearly distinguish between humans and robots we will in this thesis consistently refer to the latter as what they are, technological objects. Additionally, we will use disparate terminology when discussing humans and robots, e.g. the former has intentions, whereas the latter has objectives.

1.8 Thesis structure

The structure of the thesis is divided into the following chapters:

Chapter 2 – Theory presents prior research in HRI and HRSI. This includes related work, theories, and phenomena.

Chapter 3 – Case includes a description of the MECS project and the associated partner Kampen Omsorg+.

Chapter 4 – Methods introduces the approach of the study. Furthermore, the chapter includes a description of the techniques, how they were conducted, analysis, and the methodological and ethical challenges in the study.

Chapter 5 – Prototyping with the ADLR introduces the process of creating a prototype which was a central tool in multiple data gathering sessions. Additionally, the chapter includes a brief introduction to indoor navigation.

Chapter 6 – Findings presents the relevant empirical data gathered.

Chapter 7 – Discussion is a deduction of the empirical data and the theoretical framework. Furthermore, we put forward design implications based on the discussion.

Chapter 8 – Conclusion summarizes the thesis and suggests future work.

Chapter 2

Theory

> *"There's nothing like deduction. We've determined everything about our problem but the solution."*
>
> – Isaac Asimov, *I, Robot*

The topics of HRI and robotic motion planning are relatively new fields of research compared to many others, especially when it comes to robots operating in the same space as humans. Nevertheless, they have already become large and well-established research fields. In the following sections, we will present some of the former work that is significant for our research. First, a brief explanation of how the work was found will be presented. Second, we will discuss what a robot is and the research fields of HRI and HRSI as a theoretical background. In the last section, we will introduce some phenomenas related to older adults and robots.

2.1 Identifying related work

The MECS project has become an academic environment where we have received input from parties with different research backgrounds. We have benefited from this in regards of identifying related work and relevant theory for our study.

In addition, we have obtained papers and books through digital libraries. These were found by using keyword searches with Google Scholar search, keyword searches in journals and conferences, and by using the University of Oslo library.

2.2 Theoretical background

2.2.1 Robots

There is no clear definition as to what a robot is; what criteria must be met for us to call the artifact a robot, and not just a technological item? They come in all shapes and sizes, ranging from a fully artificial look to an almost human appearance. Some are mobile and move autonomously, some move with the help of a human operator, while others are not mobile at all. The following definition for a robot can be found in the Oxford English Dictionary:

> A machine capable of automatically carrying out a complex series of movements, esp. one which is programmable [79].

Even though this is a somewhat vague definition, it states some clear characteristics a robot should have. The notion that it should be able to perform automatically infers some degree of autonomy; while the statement of it being able to carry out a complex series of movements demands both a physical construct and mechanisms to allow motion. Mobility and appearance are notably absent from this definition. We find this absence interesting; both mobility and a humanoid appearance are among the main association's people get when they hear the word robot [78]. There are many things that one probably would not think about as robots that could fit into this definition. For instance, an airplane, since it can complete entire flights on autopilot.

In everyday speech, the term robot is used in a very broad sense. At the time of writing, *AV1* from the company *NoIsolation* [63] is frequently discussed and receives much media attention in the Norwegian society. *AV1* is a technological gadget that is remotely controlled by children with mid- to long-term absence from school. It lets them see and hear everything that happens in the classroom, and respond, thus decreasing their isolation. These devices are almost entirely being referred to as robots, even though they lack both autonomy and mobility.

Traditionally, robots have been used to automate manufacturing processes in factories. The car industry serves as a prime example; they have used robots in their manufacturing process for several years. However, robots are starting to spread into many different domains, and it is necessary to categorize them in some way. A literature review from 2015 studied the impact of new robotics in the following five application domains: the home, health care, traffic, the police, and the army. The authors state that new robotics do things like "[...]caring for the sick, driving a car, making love, and killing people." Thus, they argue that "New robotics, therefore, literally concerns automation from love to war" [82]. This thesis and the MECS project will concern health care robots that operate in the home of older adults. It will as such be a mix of the first two application domains, home and health care.

2.2.2 Human-Robot Spatial Interaction

We find it beneficial to sort the research conducted on moving robots into two fields of interest.

First, there is the technical research that is concerned with finding ways and algorithms to make the robot move in the most efficient way from A to B, while avoiding obstacles. These might utilize approaches such as Simultaneous Localization and Mapping (SLAM) and Adaptive Monte Carlo Localization (AMCL). In a 2012 review paper, researchers surveyed a total of 198 papers concerning robot motion planning [91]. Since such studies aim to find an optimal motion planning algorithm, they require an environment with unchanging variables. To achieve this, most of them simulate the robot moving, rather than having it move in the physical world.

The second field is the research that is more concerned with how the moving robot will affect people. They use physical robots and do tests with real people. This part of robotic research is called HRSI.

HRSI is a relatively new field of research. Through a literature review, Kruse et al. [47] found indications showing that the topic gained attention after 2000, and that interest is increasing. In the same paper, the researchers specify what they see as the goals of HRSI research, namely increasing *comfort*, *naturalness*, and *sociability*. They continue by defining their understanding of these terms:

- Comfort is the absence of annoyance and stress for humans in interaction with robots.
- Naturalness is the similarity between robots and humans in low-level behavior patterns.
- Sociability is the adherence to explicit high-level cultural conventions.

Butler and Agah [12] studied the psychological effect on humans during encounters with a robot. They argue that the psychological effect will greatly influence whether a human will accept a robot or not. In their study, they ran an experiment where a robot and a human would encounter each other, and the robot would display two separate behaviors: For the first behavior, the robot would approach the human, stop, turn to the right, and then make a wide turn to pass the human. For the second, it would approach and adjust its course to the right of the person, thus smoothly passing without stopping. The researchers found that the latter behavior was greatly preferred over the former. They argue that this might be because a smooth non-stopping behavior resembles human motion patterns [12].

During our literature review of previous HRSI studies, we have found few that directly concern spatial encounters between older adults and mobile robots. Many studies investigate either spatial encounters with robots, or older adults interacting with robots, but the two topics are seldom combined. The participants in studies of spatial encounters are often university staff and students, or random people recruited through convenience sampling [39, 41, 58, 94, 97, 101, 106]. Studies of interactions between older adults and robots tend to focus on other things than spatial encounters, such as acceptance [9, 55, 86], functionality [86], therapy [35, 72], or assisted walking [33, 75].

The one study we have discovered that directly addresses spatial encounters between robots and older adults is more focused on the feasibility and technological aspects. How the older adults react in the encounters is less emphasized [74]. Additionally, how people perceive a robot is highly dependent on the specific context and culture [102, 104].

We believe that spatial encounters between older adults and robots will present unique challenges. Thus, research in this phenomena is vital for successful deployment of autonomous navigating robots in the homes of older adults.

2.3 Phenomenons

2.3.1 Robot acceptance

In Human-Computer Interaction (HCI), models in acceptance of technology have played a role in understanding what human factors affects the use of technologies. The Technology Acceptance Model (TAM) was the original model which originated from Davis [14]. This approach of evaluating acceptance, in its most basic form, states that *perceived usefulness* and the *perceived ease of use* determine the behavioral intention to use a system

[37]. In more recent research, TAM has been extended to include *arousal and pleasure* to be associated with adoption intentions of Information Technology (IT) [48]. In HRI, the TAM model has been used in research of *acceptance of robots* as well [9, 55, 86]. In the more specific context of robots in health care and among the senior population, Beer et al. [7] describes the following set of variables:

- Robot functionality
- Robot social ability
- Robot form and appearance

In the following we will outline these themes by examining the *Robot Factors of Acceptance of Healthcare Robots* and the *Individual Factors in the Acceptance of Healthcare Robots* [9].

The robot factors

The appearance of a robot gives expectations regarding its functionality and abilities. For instance, a robot with a human-like face will cause people to expect that the robot can communicate by natural language or if the robot has an arm, people would expect it to be able to lift something [76]. The appearance of a robot is also related to the extent people anthropomorphize. A study on people's reactions to human-like looks—referred to as the *uncanny valley* by Mori [60]—found a coherence between the affinity towards a robot, and its appearance. Their findings suggested that a robot that looks very similar to, but not quite like a person, was the least favorable, as depicted in Figure 2.1 on the following page. An extended way of categorizing the appearance of the robot is by how *human*, *iconic* and *abstract* it looks [18].

A dimension that has ties both to the robot's functionality, as well as appearance, is the size of the robot [24]. Moreover, sometimes the context or usage of a robot will dictate its size.

The individual factors

There are a variety of factors influencing user's willingness to use mobile robots. In the following, we will outline the most apparent individual factors that affect people's attitudes towards the technology.

The demographics and the cultural differences are something that should be taken into account when implementing robots or doing research

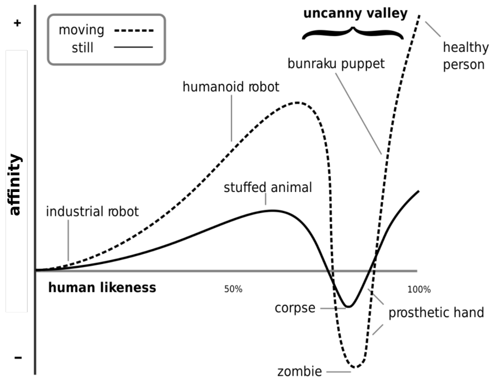

Figure 2.1: The uncanny valley. Reprinted from [60]

in HRI [9]. People's experiences with technology have implications on how they perceive new technology and robots. For instance, fiction and entertainment through the years is an external factor that can give both positive and negative perspectives on robots. Other media and political debate are no different [65, 78].

The differences in age and generations are also considered to impact people's attitude. For instance, the need for mobility aids among older adults is higher than among other parts of the population, because of mobility impairments [61, 68]. Another factor is that the experience with technology depends on age [16, 36]. More specifically, usage of robots and exposure and over time can alter people's acceptance [44]. Additionally, long-term studies of employment of robots, have shown that the operating issues influence the willingness to use the technology [15].

2.3.2 Anthropomorphism of robots

Anthropomorphism can be defined as "[...]the tendency to attribute human characteristics to inanimate objects, animals and others with a view to helping us rationalise their actions" [18, p. 180]. This tendency does not imply that the human is unaware of the inanimation of the object. Anthropomorphism will frequently occur when the robot is somewhat humanoid, and can affect the functionality we expect the robot to have.

A similar term is zoomorphic, the tendency to attribute animal characteristics to inanimate objects. This effect will also frequently occur in Human-Robot Interactions—not least since many robots are expressly designed to resemble animals—but it can also appear for more technical looking robots such as robotic vacuum cleaners and lawn mowers. People often give such robots names and talk directly to them [23, 89, 90].

One study has shown that anthropomorphism and zoomorphism can lead to unwanted behavior when children interact with robots. Brscić et al. [10] found that children sometimes will exhibit abusive behavior towards robots, thus delaying the robot. They propose and field test a strategy for avoiding such abuse, wherein the robot takes a detour to avoid the areas where abuse is most likely to occur. The test proves the efficacy of the strategy in their context; even though the robot takes a longer path, it uses shorter time because it avoids the delaying abuse [10]. We find the notion of creating algorithms that deliberately plan a suboptimal route intriguing. It shows how the context the robot operates in is of great importance.

2.3.3 Autonomy

Automation, or autonomy, specifies to which degree a system operates on its own, without human input. Sheridan, Verplank, and Brooks [85] suggests ten levels of automation in the decision support domain as presented in Table 2.1.

Table 2.1: Levels of automation by Sheridan, Verplank, and Brooks [85]

Automation level	Automation Description
1	The computer offers no assistance: human must take all decision and actions.
2	The computer offers a complete set of decision/action alternatives, or
3	narrows the selection down to a few, or
4	suggests one alternative, and
5	executes that suggestion if the human approves, or
6	allows the human a restricted time to veto before automatic execution, or
7	executes automatically, then necessarily informs humans, and
8	informs the human only if asked, or
9	informs the human only if it, the computer, decides to.
10	The computer decides everything and acts autonomously, ignoring the human.

An argument can be made that all robots should function somewhat autonomously. However, the level of automation influence the degree of control that is delegated by the user to the robot [82]. A robot requiring constant control by a human operator will not differ much from a remote controlled technological device. One of the primary benefits of robots is the fact that they can operate autonomously, thus relieving or replacing human workers. A challenge in autonomous systems is;

> "[...]designer errors can be a major source of operating problems" [3].

Moreover, an autonomous system can leave tasks to the human operator that the designers have not implemented or foreseen.

> "A 'black box' approach to full automation, in which the automation's decision making is completely transparent to the human, can be useful for redundant tasks that require no knowledge-based judgments such as autopilot systems. However, the subsequent lack of system understanding and loss of situational awareness that full automation can cause can lead to unanticipated effects for more complex tasks" [13].

Considering the mobile robot, there are numerous tasks that require decisions. Some decisions have to be made on a low-level, for instance; whether the servos are too hot, whether the battery is charged enough, and how to determine a path around the obstacles. On the high-level, the functionality of the mobile robot will in many cases require decisions. For instance, when a lawn mower, or a vacuum cleaning robot should start working. While automated decisions can reduce the need for human intervention and human error, it can cause new errors in the operation of the system [13].

2.3.4 Reality gap

A particular challenge in the field of robotics is often referred to as the *reality gap* [40]. The reality gap concerns the issue of transferring algorithms and controllers from a simulated environment to reality. Due to simplifications in the simulation, the result will likely be not as good in the real world than in simulation. Some papers have demonstrated strategies for "crossing" the reality gap [46, 107], but getting the robot to work in a real environment is only part of the problem. The issue becomes even greater when the robots also have to take into account the complexity and the unpredictable nature of humans.

2.3.5 Older adults and robotics

There is already a multitude of robots designed for the purpose of supporting independent living for older adults. A review paper from 2014 identified a total of 107 such robots in varying stages of development [5]. However, of these 107 robots, only six were commercially available; the rest were either in a concept- or development phase. Furthermore, none of the robots available for purchase were capable of supporting mobility-related activities, and in contrast to the ones under development, they only supported a single activity. The authors of the paper believe this to be no coincidence; they argue that when a robot is taken from prototype stage to mass production, single-functionality will be far easier to make robust and reliable [5].

2.3.6 Robot communication

All communication—both human and robotic—can be categorized either as *explicit* or *implicit*. Breazeal et al. define explicit communication as "deliberate where the sender has the goal of sharing specific information", and implicit communication as "conveying information that inherent in behavior, but which is not deliberately communicated" [8]. Conversely, Pereira et al. argue that: "[...]implicit communication occurs as a side-effect of robots' actions, or through the way they change the environment" [70]. We agree more with the first definition of implicit communication, since it focuses on intent, whereas the second focuses more on the source of the communication. When discussing explicit and implicit communication in this thesis, we will use the definitions provided by Breazeal et al. [8].

2.3.7 Nonverbal communication

Humans communicate by using both verbal and non-verbal communication. Verbal communication has a clear and intuitive definition, while non-verbal less so. The issue in defining nonverbal communication is in large part a question of intent. On one end of the scale, some argue that all non-verbal communication must be intended [20], thus excluding many behaviors that may communicate, though not intentionally. On the other side, some define nonverbal communication as all communication that carries information [103]; thereby including nearly everything.

Leathers and Eaves [52] groups nonverbal communication into three systems: *the Visual Communication System*, *the Auditory Communication System*, and *the Invisible Communication System*. In addition to these three, is the *Verbal Communication System*. The *Visual Communication System* is further subdivided into *Kinesic*, *Proxemic*, and *Artifactual* communication. The *Invisible Communication System* is divided into the *Tactile*, *Olfactory*, and *Chronemic* subsystems. The authors emphasize the importance of congruence between the systems; meaning that they all should communicate the same or complimentary information, otherwise it would be very hard to understand the communication [52, p. 12–13]. The model can be seen in Figure 2.2 on the following page.

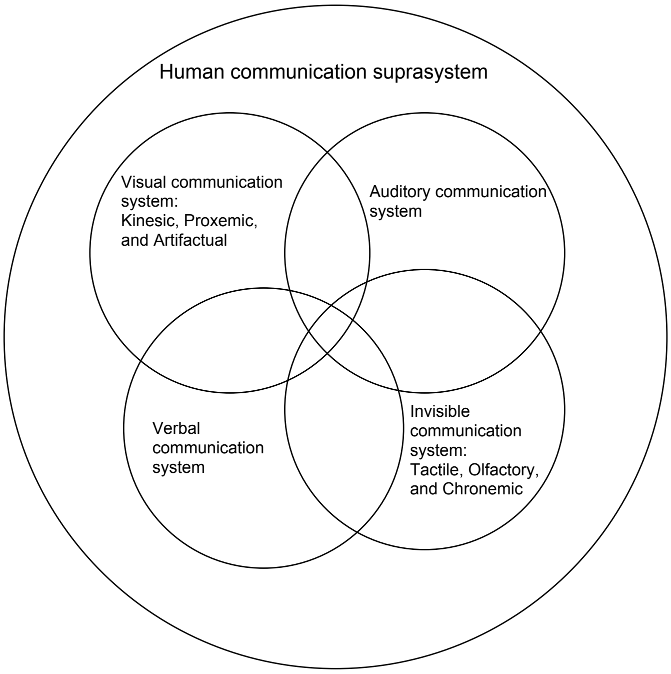

Figure 2.2: Human communication systems (adapted from [52, p. 12])

Which ones of these systems humans will use when communicating and interacting with robots depend on the robot, and can range from a single to all four. The one most important for this thesis is the *Visual Communication System*, therefore we will briefly define the subsystems it consists of, and how we believe they will relate to robotics.

Proxemic communication

The term *Proxemics* was coined by Hall [32]. He defined it as "the interrelated observations and theories of humans' use of space as a specialized elaboration of culture". He divided the interpersonal distances of man into four zones: intimate space, personal space, social space, and public space [32].

Several studies have shown that proxemics will be a major factor in interactions between humans and robots since it can affect whether the person gets comfortable, or uncomfortable [39, 64, 101]. This effect is not observed in interactions between humans and inanimate objects [38].

Kinesic communication

Kinesic communication comes from gestures and body movement; both part of the body, and the body as a whole. The equivalent colloquial term is "body language". All mobile robots will use this form of communication.

Artifactual communication

Artifactual communication stem from the way that a person looks, and what artifacts they choose to modify their appearance. Studies show that the appearance of a robot will create expectations about its functionality [76].

2.3.8 Redistribution of tasks

The introduction of a new technology to a context will often have an explicit goal of removing tasks or making them simpler. However, there is a consensus in the field of HCI that reality is more complex. New technologies will rather result in a redistribution of tasks; altering some, and adding others [26, 83, 99].

2.3.9 Predicting what others will do

It is impossible to be absolutely certain about what other people are going to do next; that would require an ability to read minds. However, we continually make predictions and inferences about our fellow humans, a requisite for functioning properly in modern society.

The neural sciences can inform us that these predictions are based on a multitude of prior knowledge and communication. Some of the sources we use are direct experience, observations, cultural information, movements, and other nonverbal communication. Despite the multiple sources of information, we frequently make errors; but in most cases these are easily resorted and of minor consequence. We learn from our mistakes and make better predictions in the future [25].

Chapter 3

Case

> *"I've come up with a set of rules that describe our reactions to technologies:*
> *1. Anything that is in the world when you're born is normal and ordinary and is just a natural part of the way the world works.*
> *2. Anything that's invented between when you're fifteen and thirty-five is new and exciting and revolutionary and you can probably get a career in it.*
> *3. Anything invented after you're thirty-five is against the natural order of things."*
>
> – Douglas Adams, *The Salmon of Doubt*

Being part of the Multimodal Elderly Care Systems research project and having a collaboration with Kampen Omsorg+ has shaped the thesis both in regards to the research questions, and the user involvement. In this chapter, the MECS project and Kampen Omsorg+ will be presented.

3.1 The Multimodal Elderly Care Systems research project

This work is among the first master's theses written as a part of the ongoing MECS project at the University of Oslo. The MECS project is an interdisciplinary collaboration between the research groups Design of Information Systems (DESIGN) and Robotics and Intelligent Systems (ROBIN) at the University's Department of Informatics. The project officially began in the early spring of 2016, but due to limited staffing, did not gain any real traction until late autumn 2016. It has funding until 2019.

The main goal of the project is to *create and evaluate multimodal mobile* *human supportive systems that can sense, learn and predict future events* [95]. These systems are intended to be used in the homes of older adults to increase their independence, security, and privacy. To achieve this, the project will strive to prove the feasibility of using mobile sensory platforms—in contrast to fixed and worn platforms. The interdisciplinary nature of the project is due to a recognition of the fact that such systems must be designed in close collaboration with the users to be successful. There is a shared understanding within the interaction design community that technologies designed without the inclusion of users will often fail. This is because the designers are likely not to understand the users' needs, motivations, and limitations sufficiently. The result will nearly always be that the system is considered too difficult to use, or provides too little functionality to be considered worthwhile. When the user group and the designers are far removed—as is the case with older adults—the possibility of failing to understand the needs and limitations become greater. Consequently, it is even more important to include users in the design process for this user group. There will be multiple stakeholders with interests in the project. These include, but are not limited to, older adults who actually get the robot in their home, relatives, and home care workers. The project staff realize that these groups probably will have differing needs; thus some conflict of interest is to be expected. The project will, therefore, need to make compromises between the different groups.

The project has established several external collaboration partners for various purposes in both the public and private sector.

- *Oslo Municipality, Kampen Omsorg+* will be the main facility for recruiting users to participate in design and evaluation activities. For more details about Kampen Omsorg+, see Section 3.3.
- *Xcenter AS* will provide novel sensor technology.
- *Novelda AS* will also provide novel sensor technology.
- *Giraff Technologies AB* makes a robot companion that could be used as a robotic platform.

To realize the goals, the project is organized in the following five Work Packages (WPs), also visualized in Figure 3.1 on the next page.

WP1: Multimodal Sensor Systems

This work package will deal with the sensing required by the project. One or more mobile multimodal sensor platforms will be established to be used

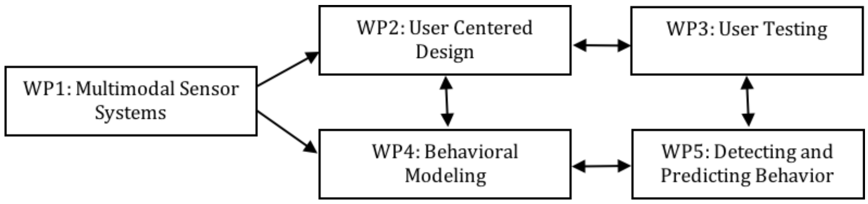

Figure 3.1: Work Package Model

in later WPs. The sensors that will be used are not decided but may include camera, microphone, force, proximity, ultra-wide band radar, and ultrasound sensor. The sensors will be mounted on the robot itself, not on the users.

WP2: User Centered Design

In this WP users will be included in exploration and experimentation regarding what kind of robots older adults will want to have and what they will accept into their homes. The participants will primarily be recruited from Kampen Omsorg+. There will be a focus on tailoring the interaction mechanism for the user group; to make it usable even for those who have neither knowledge nor interest in the technical solution. The WP will start by exploring whether a mobile robot can add to or replace existing technologies for safety and communication in the home. It will then continue by investigating whether such a robot can address new tasks such as medication, nutrition, or fluid balance. Privacy will also be of focus; will a mobile robot increase the sense of privacy for older adults compared to embedded "invisible" sensors? Lastly, the robot must be able to navigate in a typical home cluttered with furniture and other objects.

WP3: User Testing

In this WP, users will be recruited for long-term collaborative design purposes, and testing of prototypes in their homes. The participants will primarily be recruited from Kampen Omsorg+. Prototypes will be continually improved through several iterations, and by using modern prototyping techniques such as 3D-printing, CNC-milling, and laser cutting.

WP4: Behavior Modeling

The goal of this WP is to develop models of the human behavior for the given applications based on real user behavioral data. This model will be used to make the robot able to detect abnormal behavior and act accordingly.

WP5: Detecting and Predicting Behavior

In the last WP, there will be developed prediction models based on actual user data gathered in previous WPs. The tasks to be predicted can include both short- and long-term behavior changes. It will also be relevant to incorporate prediction of how a user moves relative to the robot companion as a part of the robot motion control.

3.2 Our contribution to the MECS project

The authors of this thesis are master's students in the DESIGN research group. We started working on our thesis at the outset of the project. Consequently, no previous work had been done, and there were several vacant Ph.D. and Post-Doctoral positions. During our work with the master's thesis, all the positions have been occupied, and the resulting team has proven to be a great asset.

Since we belong to the DESIGN research group, WP2 and WP3 are the two WPs that were most relevant for us to work with. Because no previous work had been done, it was natural to begin with WP2: User Centered Design. This WP had several different objectives that could be investigated, as specified in 3.1 on the preceding page. After some deliberation, we decided to explore spatial encounters between robots and older adults, since successfully managing such encounters is a prerequisite for the rest of the project. Robots that autonomously navigate in the homes of people is still a novel concept: some have acquired a lawn mower robot or a vacuum cleaning robot, but this is still not a widespread phenomenon. More advanced domestic robots are beginning to emerge from tech companies, such as the Asus Zenbo [1], but these are even more uncommon. Because of the low prevalence, many aspects of encounters between robots and humans are left largely unexplored. The focus on spatial encounters also allowed us to learn how robots can navigate autonomously; what technologies and algorithms are used?

There was no robot platform available in the project, and we decided that we needed one to be able to do testing with users. Thus, we spent some time investigating what kind of robot would be pertinent to the project. We decided on a robot called the ADLR. We spent a significant amount of time learning and configuring this robot, much more than we had anticipated would be required. Further details about the ADLR can be found in Chapter 5. The configuration work we did will hopefully be an asset for the remainder of the MECS project since both the robot and our knowledge easily can be reused.

3.3 Kampen Omsorg+

Kampen Omsorg+ is a facility run by The Church City Mission and the Municipality of Oslo. It consists of 91 separate apartments where the residents can live independently; alone, or as a couple. The service is targeted at senior citizens over the age of 67 [92] who due to a physical impairment are either unable to function properly in their former home, feel unsafe, or experience loneliness. However, the residents have to be able to function independently in the facilitated apartments, as well as be able to participate in activities and social gatherings. There are several common areas within the buildings where the residents can partake in such activities.

The apartments are unfurnished but include all utilities required for living independently, including a kitchen. A cafeteria is also available so that the residents can select whether they want to purchase their food there or make their own.

Kampen Omsorg+ is a relatively new facility; it was completed in 2013. Several smart house technologies are integrated into the buildings, and it has been used as an arena for testing new welfare technologies. Therefore, the DESIGN research group have collaborated with them on previous research projects.

There are currently 90 residents living at Kampen Omsorg+, of which 52 are female and 38 male. The average age is 84 for the females and 80 for the males. 5 of the residents use an electric wheelchair, 14 use regular wheelchairs, and 30 use walkers. The birth year of the females range from 1920 to 1947, while the range for the males are from 1920 to 1953[1].

[1]The information was provided by the managing director at Kampen Omsorg+ and was current as of 04/18/2017

Chapter 4

Methods

> *"People don't usually do research the way people who write books about research say people do research."*
>
> – Bachrach [2]

The main purpose of this chapter is to describe how the empirical data was gathered and analyzed. In this thesis, we have primarily used qualitative methods in our inquiries. The chapter starts by considering the paradigm and methodology of our research. Next, an introduction of the techniques is presented—before an outline of the activities is given. Finally, we present the methodological challenges we have encountered, and our ethical considerations.

4.1 Philosophical paradigm and methodology

Myers [62] argues that qualitative research can be classified in three paradigms; *positivist*, *interpretive*, and *critical*, based on the researchers' philosophical assumptions. The one that best corresponds to our values, and that we deemed most appropriate for this research is the interpretive paradigm. Researchers in this paradigm "[...]start out with the assumption that access to reality (given or socially constructed) is only through social constructions such as language, consciousness and shared meanings" [62]. This is opposed to positivistic research; where the belief is that reality can be described objectively and independent of the observer. We have performed our inquiries in Norway, as native Norwegians, and with our individual sets of knowledge. We believe that every past experience has the potential to influence how we interpret a given situation in some way. If two other people had performed the study, the focus and results would probably have been completely different.

The purpose of the research was to explore situations where humans and robots spatially interact, with the goal of discovering particularly interesting phenomena. Like Flyvbjerg [22] and Stake [87] argue, we believe that salient and sometimes generalizable knowledge can be inferred from a single case or situation.

We have studied a wide variety of contexts, some of which did not include our target population of older adults. The reason for this divergence is that there are very few—perhaps even none—arenas in the Norwegian society where one can observe naturally occurring interaction between older adults and autonomously navigating robots. This meant that the context for observing said phenomena would have to be constructed, and thus artificial. We chose to supplement with additional data and found other areas where robots and humans were interacting spatially. Despite the limitations that deviating from our target population brought, we argue that the insights garnered were more valuable due to our wide investigations. Stake [87] proposes that cases should be selected based on which gives the best opportunity to learn, and this has been our main approach.

Our work cannot be categorized as a single methodology such as ethnography, case study, or action research [62]. We have instead used methods from multiple methodologies, with the aim of gathering the most salient data. As such, we have used whichever method we deemed pertinent to each particular situation.

4.2 Methods of inquiry

Our primary methods have been prototyping, observation, and interview. As this was an explorative and interpretive study, we have focused on trying to understand the details of the human-robot interactions in the situations we have investigated. The previously mentioned methods are suitable for gaining such thorough understanding, opposed to for instance surveys, which usually gives a wider, but more superficial understanding. Geertz [28] introduced the notion of *thick description*; where the context surrounding human behavior is explained in sufficient detail to make the behavior understandable for an outsider. Our empirical data is probably insufficient to allow proper thick descriptions, but we have nevertheless tried to understand all observed behavior as accurate as possible.

All empirical data have originally been collected in Norwegian; consequently, all quotes from the data in this thesis have been translated by the authors. We have strived to perform the translations as verbatim as possible but cannot rule out that some subtleties have been lost in the translations.

4.2.1 Prototyping

Prototyping is an essential tool in interaction design. It allows the designer or researcher to quickly and inexpensively test their ideas and concepts with users. Prototypes range from low-fidelity to high-fidelity, referring to the degree of refinement: how closely does the prototype resemble a finished product in terms of e.g. material and functionality [80, p. 390–396].

We have used the ADLR as a prototype throughout the process, but only as a tool for eliciting information, not with the purpose of refining it. Lim, Stolterman, and Tenenberg [53] propose five filtering dimensions for prototypes: *appearance*, *data*, *functionality*, *interactivity*, and *spatial structure*. Our prototype was only supposed to test the functionality dimension; more specifically autonomous navigation and motion patterns. The other prototype dimensions of the ADLR are far removed from how we envision a completed robot.

4.2.2 Wizard of Oz

Wizard of Oz is a prototyping technique where the user interacts with what they believe to be a product or refined prototype, but in actuality, the prototype is manually controlled by a human operator [80, p. 395]. Through our prototyping, we were able to make the robot navigate autonomously while dynamically avoiding obstacles, but only in a clearly artificial manner, and somewhat arbitrarily. To simulate more natural and human-like behaviors, we employed the Wizard of Oz technique.

4.2.3 Observation

Observation is a key method for understanding the interaction between humans and technology. To rely solely on the user's accounts could give an incomplete description; they are seldom able to explain what they do in complete detail. Observations can be used to supplement the information elicited from surveys or interviews [80, p. 248].

Observations can be divided into two subgroups: direct observation and indirect observation. When doing direct observation, the researcher observes the subject performing a task directly—whereas indirect observation has the researcher record the events in some way without being present, usually some kind of automatic logging on a computer. We have used both in our research; observing persons interact with robots directly, but also using data logged on the robot for later review. We will emphasize that direct observation does not exclude the possibility of also recording the information. We have frequently used voice and video recording when performing direct observation. The recordings proved invaluable when performing analysis since both the written notes and our recollections proved to be inadequate and unreliable. In addition to what the participants said, we wanted to identify what they did in encounters with robots. Motion is inescapably linked to time, and humans are capable of performing highly complex motions in a very short time frame. Therefore it is implausible to record the minutiae of the movements with written notes, especially when the most interesting motions occur in the duration of only a few seconds. For this purpose, video recording is an effective medium for analyzing movement patterns and body language [57].

Observation can either be done in a controlled environment or a natural setting, both approaches having its strengths and limitations. The choice might not always be entirely up to the researcher; as previously mentioned we did not find any natural setting where we could observe interactions between older adults and robots. We therefore chose to perform the observations in a controlled environment. Conversely, when observing the Automated Guided Vehicles (AGVs) in the hospital, the observation was done in a natural context.

4.2.4 Interview

Interviews are often used in qualitative research for gathering empirical data, as is the case for our thesis. We have used a wide range of interview techniques, including "regular" interviews, focus groups, and in-situ interview.

Interviews vary in structure: On one side of the scale, they can be completely unstructured; with no prepared questions, only a general topic to guide the discussion. On the other end, they can be fully structured, with all the questions being predetermined. In addition, questions can either be open or closed. The former puts no limitations on the answer, while the latter requires the answer to be one of a set of predetermined ones [80, p. 228–229]. Structured interviews tend to have more closed questions than open, but this can vary.

All the interviews we have conducted have been semi-structured; with primarily predetermined open-ended questions, and a possibility to add both follow-up questions based on the interviewee's response; and entirely new questions. This structure gave us the opportunity to explore topics in great depth, but at the same time, we could guide the discussion when it would stray too far from our questions. Here lies both one of the biggest strengths and weaknesses of an interview: if properly directed, one can elicit data that would be hard to obtain through other methods; but conversely, failing to do so could lead to completely irrelevant information. Another potential deficiency is that interviews are prone to suffer from problems with recollection [50, p. 178–179].

To mitigate this deficiency, we have combined interviews with observations when possible. Another strategy we have employed extensively to elicit salient data is the use of artifacts such as physical robots, pictures of robots, and videos depicting different scenarios one might experience when encountering a robot. Some of the pictures and videos we used can be viewed in Appendix C.

4.3 Data gathering activities

We have performed several different activities for collecting empirical data to answer our research questions. In Table 4.1 an overview of the data collection is presented, and in the following sections the particulars of each activity is described.

Table 4.1: Data collection overview

Activity/Location	Techniques	Section
Older woman's house	Interview Observation	4.3.1
Vacuum cleaning robots in researchers' homes	Diary study	4.3.2
AGV at Oslo hospital	Observation In-situ interview	4.3.3
NordiCHI 2016	Workshop	4.3.4
Pilot in the University's common areas	Observation	4.3.5
Postdoctoral fellow's experience with lawn mower robot	Presentation Informal interview	4.3.6
Kampen Omsorg+	Project presentation Focus groups Observation	4.3.7

4.3.1 Introductory study at older woman's home

To learn more about how senior citizens experience having a robot in their home, the first thing we did was to perform an introductory study. We did this by visiting an 89-year-old woman in her home and conduct an interview with her. We will refer to the woman as Olivia. Olivia was a good fit for our research interests since she recently acquired a lawn mower robot, with the help of her children. At the time of the interview she had used the robot for a little under four months. The interview's central themes were her experience with the robot, general technical proficiency, and her attitude towards having robots in the home. After the interview, we observed the robot operating in her garden and asked additional questions based on our observations. The lawn mower robot is depicted in Figure 4.1.

4.3.2 Testing vacuum cleaning robots in the researchers' homes

During the period we were investigating robots and spatial encounters, both of the researchers acquired a vacuum cleaning robot for their apartments. The model designation of the robots was iRobot Roomba 980—the most advanced commercial vacuum cleaning robot available at the time. It can be seen in Figure 4.2. The purpose was to get a sense of the status quo of consumer-focused robot platforms, as well as experience how it felt to have a moving robot present in our everyday life. In addition, testing vacuum cleaning robots became a part of Iteration 0 in our prototyping (see Section 5.1.1 on page 54). We used the robots for a total of one month each, noting our experiences in a diary.

Figure 4.1: The Husqvarna lawn mower robot

Figure 4.2: The iRobot Roomba 980 vacuum cleaning robot

4.3.3 Automated Guided Vehicles at hospital

Even though spatial encounters between robots and humans are becoming increasingly common, they are still pretty rare in contemporary western society. While there are numerous examples of robots used in the industry, they will usually be found in their own separate and enclosed areas, and entering these areas is only possible for authorized personnel. In some instances the robot must be switched off before entering; failing to do so could lead to severe injury or death. Because of this, to locate an arena where encounters between humans and robots can be observed is challenging. Nevertheless, during our work with this thesis, we discovered an arena where such encounters happen; namely hospitals. Some hospitals have employed AGVs for several years. They do most of the heavy-lifting of transport tasks in the hospital and thus decrease the need for human porters. Moreover—most importantly for us—they operate in the same areas as the hospital staff and thereby create an arena for observing spatial encounters between robots and humans.

Some argue that AGVs and robots are not the same since the former is guided by some kind of control system and as such not strictly navigating autonomously [19]. They will usually follow a set route, consisting of e.g. magnets. This implies that an AGV will stop in its track if blocked, with no way to navigate around the obstacle. While this is true for many systems, the technology is rapidly advancing, and the differences are constantly blurring; some of the most modern AGV systems are in fact navigating autonomously. People not familiar with the field will probably use the term *robot* for both. We will use the terms interchangeably in this thesis.

One of the major hospitals in the vicinity of Oslo—we will use the pseudonym Oslo Hospital, or OH for short—has employed an AGV system consisting of 22 robots since 2008, and we were allowed to spend a day there, observing the robots and interviewing staff. Since the robots have been in service for several years, this setting would let us disregard the possibility of a novelty effect commonly caused by robots; the staff would regard them as commonplace. The AGVs can be seen in action in Figure 4.3.

We chose to use this hospital as an arena for learning about robots, even though the robots are industrial; not at all made for using at home; and the humans they interact with are not older adults, but medical staff in all ages. We found no scene in our vicinity where one could observe older adults and robots spatially interact in a natural setting. Since we were of the conviction that observing the AGVs would be an applicable supplement to our other studies, we chose to perform the observations despite differences in the target population.

The robots operate mostly in the basement of Oslo Hospital (OH) where there are no patients left unattended. The only time a patient can encounter a robot is when the robot takes an elevator up to one of the hospital departments. Even in these situations, the robot will venture no more

Figure 4.3: AGVs at the Oslo hospital

than a few meters from the elevator before leaving its goods in a dedicated delivery niche.

The data gathering session started with an observation of the robots in the basement. We wanted to be somewhat prepared for the upcoming interview and had therefore made arrangements to gain unattended access to the staff areas. We explored the area freely while observing and trying to understand multiple facets of the robots; how they navigated, what kind of sensors they used, what and how they communicated, ways to "trick" the robots, and most importantly interactions between the robots and humans. We performed observations for a total of one hour.

After the observations, we had an interview appointment with the managing operator of the robots. We will refer to him interchangeably by the pseudonym Tom and managing operator. We had planned for the interview to last approximately one hour and had prepared questions ranging from number of staff required to operate the robots, through technical aspects, and concluding with human-robot interactions. We were especially interested in situations where the humans and robots got in a "conflict" and breakdown situations. Since the interview was performed in situ—and the Tom had to operate the robots during the interview—there were multiple intermittent interruptions of varying length. In some of these, he only had to resolve small problems on the controlling computer, while others required manual intervention, and he had to leave the control room. In the latter instances, we would follow, and Tom would explain what he was doing. Sometimes, we would even try to help by giving suggestions. Figure 4.4 shows a screenshot from the controlling computer, where the blue lines represents where the AGVs navigated. The area depicted is the central intersection in the basement, where most of our observations took place.

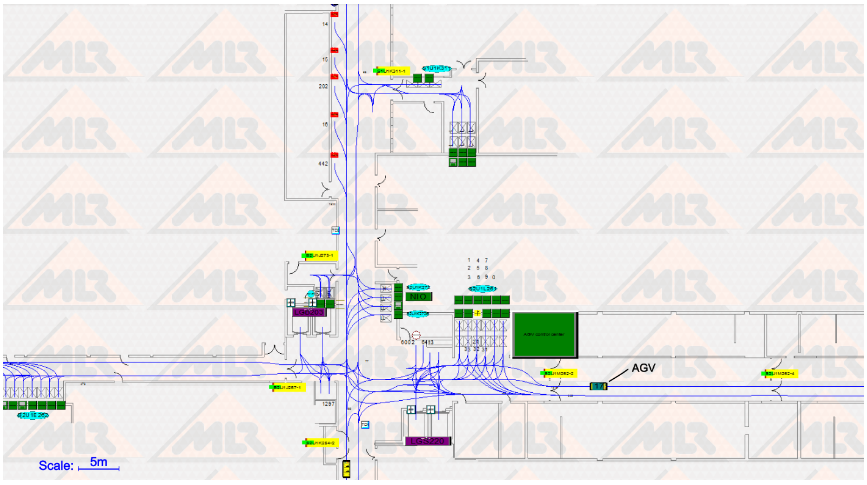

Figure 4.4: The AGV management system

While not planned, we consider these roaming interruptions to be entirely beneficial. They made the session share some similarities with the Contextual Inquiry method [43], rather than a "regular" interview, and we gained a deeper understanding than the latter probably would have given. The interruptions stretched the interview to approximately two hours. We recorded and transcribed the interview in its entirety.

After the interview with the managing operator, we performed short interviews with five OH medical employees in the basement. Recruitment was done simply by asking them whether they could spare a few minutes to answer some questions about the robots. We did these interviews because we wanted to get some empirical data about the medical staff's opinions and knowledge about the robots. The interviews lasted approximately five minutes each, and we only took written notes, not voice recordings.

4.3.4 Workshop on autonomous vehicles

NordiCHI is a conference held every second year. It serves as an important forum for HCI in the Nordic countries [66]. In 2016, during our work on this thesis, the conference was held in Gothenburg, Sweden. As a part of the conference, several workshops were scheduled, one of which had the topic of autonomous vechicles. We find this topic very intriguing, and although there are several obvious differences between autonomous vehicles and domestic robots, there are some similarities as well: Both are autonomous to some degree, both move spatially, and both are self-propelled. Autonomous vehicles can be though of as a type of robot; they certainly satisfy all the criteria given in the quoted textbook definition in Section 2.2.1 on page 12. In collaboration with our supervisor, we decided to attend the workshop. The workshop was named *Living room on the move - Autonomous Vehicles and Social Experiences* [71].

The workshop we attended lasted from 9 AM to 5 PM. It commenced with an introduction from the organizers, followed by a presentation about Volvo Cars' "Drive Me" project, given by the company's head of autonomous vehicles initiative. The "Drive Me" project is a research and development project where residents in Gothenburg, Sweden will utilize autonomous cars on public roads during their daily commute [100].

After the presentation, we were split into three groups to explore three different subtopics about autonomous vehicles as follows:

Theme A: The autonomous car's social experiences with other road users/places/etc.: how the car autonomously interact with other road users such as pedestrians and other drivers.

Theme B: Social experiences inside the car: how to support social experiences with others (both present and non-present in the car).

Theme C: Social experience with the car: the social aspects of the interaction between car and user(s).

Both authors of this thesis participated in the group exploring theme A since this was considered the theme most relevant to our research interests. The workshop concluded with the three groups presenting their results and answering questions from the other workshop participants.

During the workshop, we were given a demonstration of a prototype used for testing communication between pedestrians and autonomous vehicles. The premise of the prototype was that when pedestrians interact with cars that are driven by a person, both parties use various forms of non-verbal communication to communicate. In this way, they can give a mutual confirmation that they have noticed each other, and they can communicate intent. In autonomous vehicles this communication will be non-reliable or missing altogether; the driver could be reading a paper, sleeping, or be otherwise occupied. The researchers that had made the prototype therefore wanted to come up with an adequate substitution to this communication.

Their solution was a large LED-strip on top of the car. When the car was driving autonomously, the strip would dynamically change to communicate what the car would do next: In regular operation, the strip would be narrow; when a pedestrian was recognized, the LED-strip would broaden as the car applied the brakes, and eventually stopped. When the pedestrian was gone, the strip would narrow to show that the car soon would start driving forward. This can be seen in Figure 4.5.

Figure 4.5: AVIP prototype explanation. Top left: Autonomous driving mode. Top right: Yielding. Bottom left: Resting. Bottom right: Starting. Reprinted from [49]

We were subjected to the car with knowledge of how the LED-strip worked, both in autonomous driving mode and in manual mode. In addition, we were informed that due to traffic regulations, a person would be sitting in the driver seat—the left seat—ready to take control over the car if necessary, when it was driving autonomously. He would however not do anything unless a dangerous situation occurred. During the experiment we verified the statement; the driver always kept his hands away from the steering wheel. Several participants in the group decided to test the autonomous car by suddenly stepping in front of it, and looked impressed by its behavior. The authors of this thesis were certainly impressed, to the point that we were skeptical whether this could be an actual autonomous car. After the experiment our skepticism proved to be justified; the car was not autonomous at all. It utilized Wizard of Oz to test the applicability of the LED-strip: In Sweden they drive on the right side of the road, so most cars therefore have the steering wheel on the left side. However, the car used in the experiment had the real steering wheel on the right side, and had cleverly hidden the real driver by dressing him with fabric from the seat. On the left hand side it had a fake steering wheel to trick people into believing the car to be autonomous. The interior of the car can be seen in Figure 4.6.

Figure 4.6: AVIP prototype interior. Fake steering wheel on the left, real steering wheel on the right. Reprinted from [49]

This prototype had been used to methodically test whether people will trust an autonomous car with such a LED-strip more than one without. The tests indicated that communication between pedestrians and the autonomous vehicle improved with the LED-strip. Details of the research done with this prototype can be found in [31, 49, 56].

4.3.5 Pilot observations in the University's common areas

We performed a pilot observation with the ADLR robot at the University's common areas to garner initial insights into spatial interactions between robots and humans. Even though an average student is very different from our target population of older adults, we believed that some findings could be relevant, and help us prepare for our main empirical activities.

We performed the observation around 1 PM since this is the time with most people in the common areas. It was performed on two consecutive days, each observation lasting approximately two hours. The observation was conducted as follows: One researcher would remotely control the robot, utilizing both mapping and a camera to control it. The setup can be seen in Figure 4.7 on the next page, but to preserve privacy, no participants are shown. The researcher would navigate it in the midst of students moving to and from their lectures. A second researcher was inconspicuously placed in the vicinity of the robot and took notes of what he observed. After the first hour, we switched from manually controlling the robot to autonomous navigation, while one researcher was still observing. The second day was done in the same way, the only difference was that the researchers interchanged roles and the observation

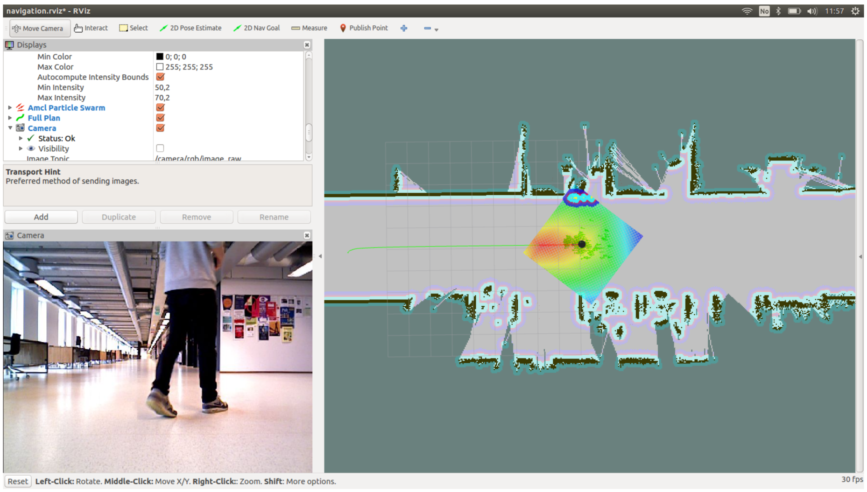

Figure 4.7: Setup for pilot observations in the common areas

was performed in a slightly different area.

4.3.6 Presentation by postdoctoral fellow on personal experiences with a lawn mower robot

One of the postdoctoral fellows in our research group had for some time used a lawn mower robot for mowing her lawn. We will use the pseudonym Sophie to refer to her. Sophie had utilized the robot a total of three summer seasons. During work on our thesis, she held a presentation about her experiences with this robot. We decided such a personal account would be a useful supplement to our studies, and therefore attended the presentation.

Directly following the presentation, we engaged in informal discussions with Sophie to obtain more elaborate information on the topics we found most interesting. She gave us her consent to use the experiences in our thesis, and we had several more informal interviews and discussions in the following months. Sophie presented a paper about her experiences at an open seminar called *Sociomateriality: Exchanges on theory and empirical issues* in the spring of 2017 [98].

4.3.7 MECS project presentation at Kampen Omsorg+

Since Kampen Omsorg+ was an official collaboration partner for the MECS project—and thus an important source of empirical data—the project leader and several researchers, including the authors of this thesis, held a presentation of the project for the residents and staff. Approximately 25 residents and five members of staff were in attendance. The presentation began with some general information about the project from the project lead, followed by the Ph.D. and master's students presenting their particular research interests. We then took questions from the audience, and answered to the best of our abilities. In the end, we invited those that found the topic intriguing and wanted to contribute, to sign up for possible participation by giving their contact information on a list. We emphasized that there was no commitment in signing up; they could at any point choose whether they wanted to participate in an activity or not. A total of 16 residents and one member of staff signed up, and these were our main recruitment group for the subsequent activities.

4.3.8 Focus group at Kampen Omsorg+

To learn more about older adults' knowledge and impressions of robots, we had two focus groups at Kampen Omsorg+. They were held simultaneously and with the same program, focusing on the same two themes: The first was about appearance and functionality, and how they affect each other. The second theme was about how a robot moves around humans. The authors of this thesis were the main facilitators for their respective group and were supported by an additional researcher from the MECS project in each group. Recruitment was done by sending invitations to all residents who had previously expressed their interest, and on bulletin boards with the help of facility staff. Everyone who wanted to attend was able to do so, meaning the participants were self-selected. One of the focus groups had seven participants; the other had six. We took voice-recordings and transcribed the sessions in their entirety. The focus groups had a duration of approximately 1.5 hours.

The focus groups commenced with a round of brief presentations of the facilitators and participants; we each stated our name, age, and background. To prime the participants for the following discussion, this was succeeded by a short discussion about *smart-house-technologies* such as automatic lighting, blinds, heating, and doors.

To begin our main discussion, we asked them about their previous experience with robots. We firmly suspected that to elicit significant thoughts and opinions about robots from the residents, artifacts would be crucial. Consequently, we continued the session by showing pictures of some robots, varying greatly in both appearance and functionality. The slides we used can be viewed in Appendix C. Most of the robots were intended for home use, and almost all of them were available for purchase. We asked the seniors opinions about the robots, and whether they would

Figure 4.8: Focus group at Kampen Omsorg+

want any of them.

For the next part of the focus group, we continued to the theme of how a robot moves. As depicted in Figure 4.8, we began by showing them an open ended video where a human and a robot moves towards each other in a narrow hallway. The video was meant to stimulate them into thinking what they would prefer the robot to do and initiate a discussion. When the discussion simmered down, we continued with several more videos depicting different solutions to how the situation could be solved. The videos were presented in a specific order: In the first one the robot moved completely out of the way, but for each video after, it yielded less than the previous. This culminated in a video where the robot would not yield at all; it would simply stop when detecting an obstacle, imitating the behavior of an AGV. Since there was not enough space for the person to move around it, he had to back out of the hallway. These videos and the order they were presented served two purposes: We wanted to show the seniors that there are several ways a robot can yield, many of which may be acceptable behaviors for humans. The second purpose was to be a little provoking by showing incidents where the human had to yield for the robot. We hoped this small provocation would help elicit stronger opinions and thoughts. To make things more concrete, we concluded this part with asking the senior citizens whether their homes were suited for having a robot moving about, or if they could think of some immediate challenges.

During the focus groups, the subject of functionality requirements was a recurring theme, but none of the participants mentioned an increased sense of safety as a possible function. Since this is one of the main topics of the MECS project, we decided to ask specifically whether this was a desirable functionality. We also inquired whether such functionality could be sufficient in a robot, or if it would need to have some additional uses.

In the end we had a general discussion about robots and technologies, before ending the session with a brief evaluation.

4.3.9 Observation sessions with residents and robots

We wanted to understand how seniors interact spatially with robots, and to achieve this, we conducted an observation at Kampen Omsorg+. Ideally, we wished to observe naturally occurring interactions, but this was deemed infeasible due to privacy, ethical, and practical concerns. Therefore, we conducted the observation in a controlled environment, with the implication that participants were fully aware they were part of an observation. The observation sessions were arranged during the facility's *Activity week*, as one of the available activities. Therefore, all residents had an option to join. In addition, we specifically invited residents that had partaken in our earlier activities, by sending them personal invitations.

Figure 4.9: Observation at Kampen Omsorg+

Since the observation was part of the facility's *Activity week*, it was important that the older adults would gain some benefit from participation. We assumed the observation itself would not be very exciting for the participants, and therefore decided to complement it with a showcase of new technologies. The showcase consisted of a 3D-printer, a NAO robot, and a Virtual Reality headset. The showcase was located in one room, while the observations were done in the adjacent room. The authors of this thesis ran the observations, while additional researchers demonstrated and explained the technologies of the showcase. With this setup, the showcase area served as a pool of participants for the observations.

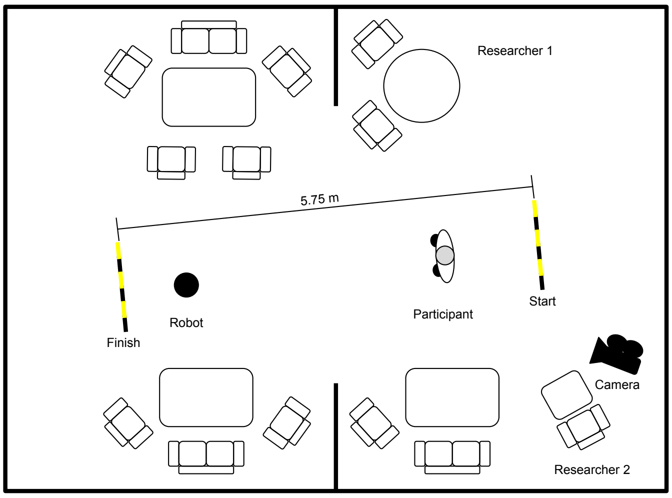

Figure 4.10: The setup of the observation at Kampen Omsorg+

The showcase gathered many residents, and we commenced the observations as planned. Unfortunately, after some time the seniors lost interest in the technologies displayed, and the available pool of participants declined. Because of this, we had to actively recruit participants towards the end of the day. We performed the observation with five people during the first day.

We decided to do observations one more day. Since the residents now had seen the technologies in the showcase, we decided to drop it, and move to a different room where recruitment would be easier. We performed the observation with three additional participants the second day, thus reaching a total of eigth participants.

The setup of the observation is visualized in Figure 4.9 and Figure 4.10. We used the same measures for the distance of travel the second day. Additionally, we tried to distribute furniture, camera angle, and positioning of the researchers as similar as possible.

Each observation session began with one of the researchers reading the following information to the participant in Norwegian:

> "You will now participate in an experiment. We will be testing the robot, not you. The experiment will have you walking through a hallway and encountering a robot heading in the

opposite direction. In this scenario, the robot is carrying medicines, and as such has an important task. We will conduct a total of three such encounters. We want you to behave in the most natural way when meeting the robot."

We observed each participant three separate times, with the robot behaving slightly different each time. Both sound and video were recorded. The three behaviors were as follows:

B1. Manually controlled yielding robot (Wizard of Oz)

One of the researchers controlled the robot. It would start going straight forward, but when approximately three meters from the participant, it would turn slightly to its right, imitating human behavior. Thus, the participant would be able to pass the robot by going straight or yielding to their right. The robot would continue to the other end of the room.

B2. Manually controlled stopping robot (Wizard of Oz)

One of the researchers controlled the robot. It would start going straight forward, but when approximately two meters from the participant, it would stop. It would not continue unless there was no obstacle in front of it. The robot would continue to the other end of the room, if possible.

B3. Autonomously navigating robot

The robot would navigate autonomously using AMCL. One of the researchers gave it the starting position of the participant as the goal. It would then try to navigate there while avoiding obstacles. The robot would thus move in a somewhat arbitrary fashion. Sometimes it would reach the target, other times it would not. It would always start by moving straight forward until it discovered the participant as an obstacle.

The three behaviors will be referred to as *B1*, *B2* and *B3* in the forthcoming chapters. The participants will be referred to as *P1* through *P8*.

After each observation run, we asked the participants to explain what they thought the robot did during the encounter, what the participant him or herself did, and why they chose to do so. We then applied some of the questions from the *Godspeed Questionnaire* [4] by asking the participant to rate the robot on a scale from 1 to 5 for the following bipolar adjective pairs:

- Dislike - Like
- Unkind - Kind
- Unpleasant - Pleasant
- Incompetent - Competent
- Unreliable - Reliable
- Unintelligent - Intelligent

We also asked the participants to rate their emotional state during the encounter on a scale from 1 to 5 where 1 meant *anxious* and 5 meant *relaxed*.

We originally planned for the behaviors displayed by the robot to come in a random order for each participant, since randomization of treatments is a methodological advantage. When we started to do the observation, we realized this was infeasible, since the amount of configuration and resetting between each run already was substantial. We therefore started doing it in the order specified above. With this sequence, the participant would be presented with what we consider to be the most *humanlike* behavior first, followed by more robotic behaviors. We presupposed the older adults would react most agreeable to the former, and as such, it would serve as a benchmark for the Likert scales. With the second participant, we changed the order slightly, starting with B3, followed by B1 and then B2. We did this to decrease the amount of configuration required during an observation, and in turn, decrease the overall time of an observation session. However, since the robot was operating autonomously in B3, this run was the most unpredictable. We realized that to present the participant with the unpredictable behavior first, was unfortunate. It would make it hard to answer our questions, and the results would be more arbitrary, since there would be nothing to serve as a benchmark for the participants. Therefore, we decided to return to our original ordering of behaviors. This meant that P2 was presented with a different order of behaviors than the other participants.

After the three runs of the observation session, we had some general questions for the participants. For the first five participants, one of the researchers facilitating the showcase administered these. There was no voice recording from these interviews, only written notes. For the three participants on the second day, the concluding interviews were held by the authors of this thesis, and the voice from the interviews was recorded.

Information about the participants in the observation can be seen in Table 4.2. The median age among the participants was 84.5 and the mean was 84.6 with a standard deviation of 6.5.

Table 4.2: Information about the observation participants

#	Sex	Age	Mobility aid
1	Female	93	Walker
2	Female	85	Walker
3	Female	90	None
4	Female	79	Walker
5	Male	91	Cane
6	Male	74	Standing walker
7	Male	81	Wheelchair
8	Female	84	Electric wheelchair

4.3.10 Observation in common areas

We conducted an observation in the cafeteria and reception area at Kampen Omsorg+. One researcher controlled the ADLR-robot manually, while the other observed interactions between the robot and the residents. Both the observer and the controller were located in immediate vicinity of the robot; there was no point in operating it from a more remote location since the residents already knew that we were the ones controlling it. However, since the controlling was performed on a laptop, it was not obvious that we controlled it manually, not merely monitoring it while it navigated autonomously. We did not ask the residents about this, but from our observations, it is plausible that they believed the latter to be true. The observation lasted approximately 1.5 hours.

4.4 Analysis

The empirical data we collected through our research activities have primarily been qualitative; in the form of voice recordings or written notes. We have transcribed all voice recordings, and have fleshed out our written notes shortly after concluding the activity.

To analyze the data, we have used coding techniques from the *Grounded Theory* methodology [29], but without constructing a theory from the data. We started with open coding, identifying interesting phenomena in the data. We then grouped the phenomena into concepts and eventually created categories encompassing several concepts [50, p. 248]. Since our thesis is about the spatial encounters and interactions between humans and robots, this was our main focus in the analysis. Nevertheless, we also identified phenomena not directly pertaining to this topic, for two reasons: First, some phenomena could superficially seem unrelated to spatial interaction, but on further analysis could have implications not initially discovered. Second, we wanted to be thorough and not exclude the possibility of expanding our research questions should a sufficiently salient concept emerge from the data.

To increase the reliability of our analysis as *subjective* coders, we have also used more *objective* coders in some instances [50, p. 299]. The coders were three Ph.D. students and an associate professor, all affiliated with the MECS research project. By having them help with the analysis, we achieved both increased validity and reliability. Validity because they had more experience and knowledge about analysis; reliability since they were more removed from the data. There were no large discrepancies between the coding done by the other coders and us, but they did help us discover some insights we had not seen.

4.5 Methodological challenges

4.5.1 Finding appropriate contexts for study

One of the biggest challenges of this study has been to find arenas where we could observe spatial encounters between older adults and robots. In fact, it has been a challenge even to find arenas where humans of any age encounter robots, due to the low proliferation of robots outside of laboratories and workplaces. This challenge is the reason why we choose to perform an exploratory study. Instead of researching a single case or context, we found it necessary to perform wider investigations.

Another challenge related to the low proliferation of robots and the fact that it is a relatively new technology, is the novelty effect [88]. When people are exposed to technologies that they are unfamiliar with, they tend to be more interested in the technology just because it is new. As time passes, the effect wears off and the interest diminishes. This means that to investigate how a person truly regards a robot, they would have to use it over a long span of time, requiring a longitudinal study. None of our activities are longitudinal, but we argue that the novelty effect has little influence on our data, since we do not focus on how the older adults regard the robot. In fact, the ADLR robot was partly chosen because it is anonymous and has no apparent functionality.

Nevertheless, we also decided to observe robots in a context where the novelty effect had long passed since the robots had been operating for several years. This context was the AGV robots at OH.

4.5.2 Recruitment of participants

Another challenge was that of recruiting participants for our activities. Having Kampen Omsorg+ as an official partner in the project has been a great resource in this regard. Both as a source of recruitment, and through the assistance we have received from staff members. During our presentation of the MECS project at Kampen Omsorg+, we were met with a somewhat hostile question; one of the residents asked whether the plan was to replace human health care professionals with robots. Before we were able to respond, one of the staff members answered that an increase in the use of welfare technologies such as robotics are all but inevitable. She continued by saying that the best course of action is to influence the direction of the development, instead of trying to fight it. It was incredibly helpful for us that she answered this difficult question since the message had much more substance coming from a familiar person than from us as outsiders. She concluded with the following remark:

> "It is okay not wanting to participate [in the study]. However, no one is allowed to think that you have nothing to contribute."

Since she knew the residents, she also knew some of their attitudes. In the data gathering sessions, we encountered similar challenges. For instance, one of the participants said; "We do not know anything about this. So why do you need us?"

All the residents that took part in our study were recruited through self-selection, thus resulting in a non-random sample. We presented the project and invited anyone wishing to contribute to participate. Consequently, the data is susceptible to self-selection bias. It is, for instance, likely that our participants were overly enthusiastic about technology compared to the average resident at Kampen Omsorg+. We were told by both staff and residents that usually the same small group of people would participate in activities such as ours, while most of them would not. This further indicates that our participants shared some of the same character traits.

However, we argue that the nature of our study makes this bias less consequential. As it is an explorative study, our goal was never to generalize our findings to the entire target population. We rather sought to discover salient incidents and situations that should be investigated further.

4.5.3 Prior assumptions and attitudes towards robots

The topic of robot functionality was prominent among the older adults. This became a challenge since the robots we used to elicit opinions and in observations had no apparent utility. They were either primarily used as a toy, or as a platform for prototyping. Some of the older adults attitude's towards these robots was unfavorable. This put us as researchers in a dilemma because we did not want to influence their attitudes towards robots. We tried to emphasize that the functionality in the robots we used was of little importance, since we primarily were interested in the spatial encounters. In interviews and informal discussions, we answered questions concerning the topic by asking them what features they would like in a robot, and by presenting scenarios. As mentioned in the previous section, we were also met with some hostility towards robots. This might be because of a fear of *social isolation*, which can affect the way people perceive robots [84].

Robots are artifacts that can appeal to people's emotions. The influence of media such as fiction and political debate may have given the participants a preconceived attitude to this type of technology. Since the robots depicted in fiction are much more advanced than real ones, this could give unrealistic expectations [9].

4.5.4 Prototyping with a robot

We have performed extensive prototyping with the ADLR, detailed in Chapter 5. Some of this work has been about trying to make it navigate autonomously. To achieve this has been a challenge, and have given us an insight about how hard it can be to program a robot. We have seen two reasons why this is so challenging: First, to test a new configuration requires the robot to navigate physically, and this takes a considerable amount of time and is near impossible to automate. Second, due to small variations in the environment, the robot might behave differently in two tests even though the configuration is identical. For instance, we repeatedly observed that the robot would behave slightly differently in sunlight than it would in artificial lights. We also experienced that the robot had problems recognizing glass surfaces; one of the predominant surfaces used for walls in the building housing the Department of Informatics (IFI).

These two challenges in combination make it a time-consuming task to with any certainty determine the consequences of a change in programming of the robot.

4.6 Ethical considerations

4.6.1 Working with older adults

Researching interaction between senior citizens and robots introduces a unique set of ethical considerations [84]. The staff at Kampen Omsorg+ were helpful in recruiting participants who had sufficient cognitive abilities to participate—measured in terms of being able to understand and sign the informed consent form.

4.6.2 Informed consent

All our research activities were preceded by a short session where we gave information and received explicit informed consent from those who wished to participate. Anyone who abstained—before, during, or after the activity—were excluded from the research; and any previously recorded data about them were deleted. We recorded voice for most of our interviews. Additionally, some of the observations included video recordings. We used a consent form (see Appendix A), which informed about the goal of the study, data storage, contact information, and included explicit checkmarks for the data that were to be recorded.

Storage of data

Some of the data included identifiable information about the participants. To ensure legality and respect for the participants' information, we stored all identifiable data on secure servers [96]. As part of the MECS project, we applied for and received an approval to perform our study from the Norwegian Centre for Research Data (NSD), shown in Appendix B.

4.6.3 Physical hazards

In the observation at Kampen Omsorg+, we considered the possible hazard caused by a mobile robot. There was always the risk that one of the participants could trip over the robot, resulting in a fall. We assessed the probability for this to occur to be small, and since one or more researchers always were present when the robot moved, the consequence was mitigated. Additionally, we established contact with staff members to make sure that if something were to happen, we could easily call for immediate assistance.

Chapter 5

Prototyping with the ADLR

> *"We are stuck with technology when what we really want is just stuff that works."*
>
> – Douglas Adams, *The Salmon of Doubt*

The Autonomous Deep Learning Robot (ADLR) is a robot platform, designed for prototyping, educational, and research purposes. The combination of its default, out of the box hardware and open source software, gives opportunities for customization to a wide range of contexts. In this chapter we will present the prototyping process and our final implementation of the prototype.

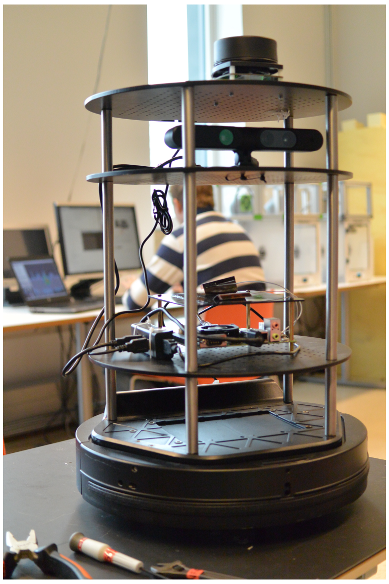

Figure 5.1: Working on the Autonomous Deep Learning Robot (ADLR) prototype.

5.1 The prototyping process

When we started the thesis work, we wanted to use a robot as a tool for exploring the research questions. Our initial goal was to have a prototype which we could deploy in the home of one or more residents at Kampen Omsorg+, and use diaries for gathering data. A requirement for the robot was *that it could navigate from one point to another, without using random strategies and the need for human intervention* and *that it was appropriate for indoor use*. Iteration 0–3 describes the prototyping process:

5.1.1 Iteration 0: Deciding on a robot platform

We decided that we would be unable to design, produce, and test a robot in the short timeframe of a master's thesis. Universities and companies have used a multitude of years to get to where they are today. Thus, we concluded that we had to buy or borrow a robot that we could use as a tool for our data collection. We tried and explored different robots, before deciding which one we would use. This exploration also served as a means for us to learn about the current state of the robotic field.

Acquiring a robot platform that had the sufficient abilities in navigation, the level of configuration, and was within the price range was the first step. We started by exploring the possibilities of using vacuum robots. We found that most vacuum robots used random strategies for movement—meaning that they moved in a straight line until they hit an obstacle, before they redirected. The more advanced ones like the Roomba 980, had more systematic strategies. However, the customization possibilities were low. Vacuum robots were the most relevant among consumer oriented robots. Nevertheless, we did not find any vacuum robots that was applicable for exploring the phenomena of autonomous navigating robots because of their limitations in customization.

Due to our requirement of being able to configure the robot, we realized that we needed a robot with open source software. We noticed that much of the research environment in HRI and robotics used ROS in prototyping. We found it beneficial to use a robot that used this operating system for two reasons. First, everything was open source in a Linux environment—which made us able to program in Python and Bash which were familiar programming languages to the authors, and having a large community of developers using it. Second, ROS comes with tools for navigational purposes; e.g. SLAM, AMCL, and ROS visualization (Rviz). Using a ROS based operating system narrowed the selection to three robots i.e. NAO, Pepper, and ADLR / Turtlebot 2. Even though there are other possibilities, we found that these platforms were some of the most used platforms—thus making it easier to get documentation and feedback from the community. In the following we will describe our considerations of the three robots.

Figure 5.2: The NAO robot

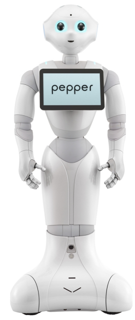

Figure 5.3: The Pepper robot

NAO

NAO is a small humanoid robot made by the company Aldebaran, shown in Figure 5.2. It has two legs and two arms; therefore it looks and moves much like a human, but at just 58 cm height, it is much smaller than human adults. There are multiple servomotors controlling all its limbs, and it can respond to voice commands. It uses lights to express its "emotions". We were able to borrow one of these since a former Ph.D. student had acquired one during his work at IFI. It was quite easy to get started with the robot. We were impressed with the range and accuracy of motions the robot could do, but less so with the speech recognition. Today's state of the art digital assistants such as Siri, Google assistant, and Alexa, have made major advancements in understanding natural language and context. In contrast, the speech recognition on the NAO was old technology where you have to say predefined phrases clear and without hesitation. Even so, the commands were not recognized most of the time. This, in combination with the fact that the NAO cannot navigate an environment autonomously, made us decide that it would not be suitable for our project.

Pepper

Pepper is similarly to NAO a humanoid robot made by Aldebaran. It can be seen in Figure 5.3. Pepper is the successor of the NAO and in addition to better technology, there are some big changes. The most apparent one is size. With a height of 120 cm it dwarfes the NAO. The second difference is that it comes without legs and instead uses a wheeled base to move around.

The third change is that it has a touch-screen in front, which is used in two-way interactions with users.

Pepper is a costly robot, and the University of Oslo did not posess one during our work with the thesis. We were, however, able to test one out in a local shop where it is used to supply customers with information, in addition to being an entertainment gadget. During our interactions, we discovered that the speech recognition was greatly enhanced compared to the NAO, and the robot now seemed more "alive". We will mention one particularly interesting situation. At one point Pepper suddenly complimented the checkered shirt of the person interacting with it. This solicited an audible exclamation of surprise and impression from the person in question. We believe that such functionality will most effectively simulate intelligence.

Since the Pepper robot was used in a shop, the functionality and possible interactions were quite limited. Thus, it was hard to determine whether such a robot could be usable in our study. This uncertainty, combined with the fact that the purchase of such a robot probably would take a considerable amount of time, compelled us to continue our investigations.

In this thesis, the main objective is studying movement patterns. We had concerns that the NAO and Pepper robots would draw away the participants' attention from the robots' objective. The more advanced the robot looks, the more people tend to expect functionality such as natural language [9, 76]. Since both NAO and Pepper are refined humanoid robots, we saw expectations of the robot as a risk. Another factor was the tendency people have to anthropomorphize robots. Since these robots have a very similar anatomy to humans, we did not know how the older adults would react [60].

Autonomous Deep Learning Robot (ADLR) / Turtlebot 2

One of the most widely used open source robots is the Turtlebot 2. This is an open source robotic platform with ROS-support, thereby offering autonomous navigation with SLAM and AMCL. There are multiple suppliers of this robot, some of them offering slightly different configurations. The exact configuration is of little importance, since they all consist of the same mobile base, and all the other components are supported in ROS. Furthermore, we decided that this would be a suitable robot for both our investigations, and for the MECS project.

The robot is relatively cheap, so we were able to purchase one immediately. We chose a supplier based on a combination of price and availability, and therefore ended up with a robot called Autonomous Deep Learning Robot (ADLR), with the exact same software as the Turtlebot 2.

5.1.2 Iteration 1: Exploring opportunities

The ADLR came in a kit of components. The computer was preinstalled with ROS and drivers for the kit's components. The setup was mostly plug and play, except connectivity to the external workstation. However, there was a process to get familiarized with the tools enabling autonomous navigation. We used the website *Learn TurtleBot and ROS* [51] as our main source for learning ROS. In this stage, we tested SLAM's *gmapping* in a combination of 3D depth camera and odometry.

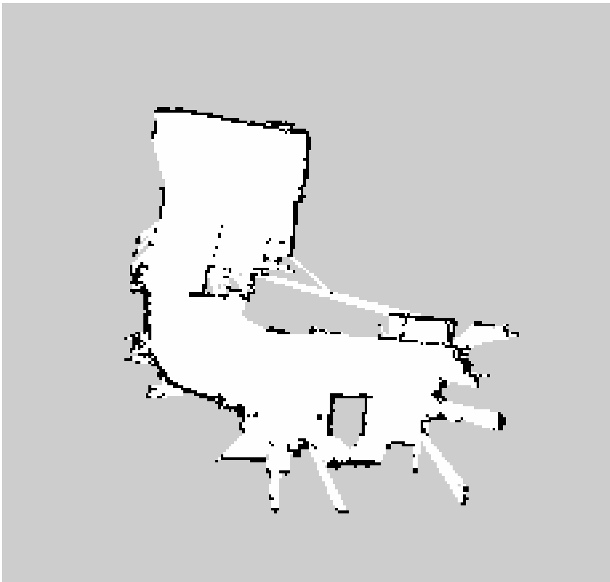

Figure 5.4: Map generated with gmapping and 3D depth camera

In Figure 5.4, one of the maps we generated is presented. At this stage, we tested the robot only in lab environments. However, we emulated different environments by altering obstacles, such as chairs and tables. A challenge with these maps was a lack of precision. For instance, perpendicular walls were not perpendicular in the maps. In addition, the 3D depth camera gave a faulty projection of cluttered areas—which added errors in recognition of mapped areas.

5.1.3 Iteration 2: Equipping sensors

To increase the precision we investigated two factors; the sensors and the mapping approach. First, we examined different alternatives to the 3D camera sensor. We concluded that using a Light Detection and Ranging (LIDAR) sensor would improve the precision, range, angle and speed of mapping. However, after implementing the new hardware, we had trouble using the gmapping software due to challenges with the interface between hardware and software. We decided on using *Hector Mapping* which was compatible. The downside was that this mapping algorithm did not have loop closing, but the advantage was that the precision was higher.

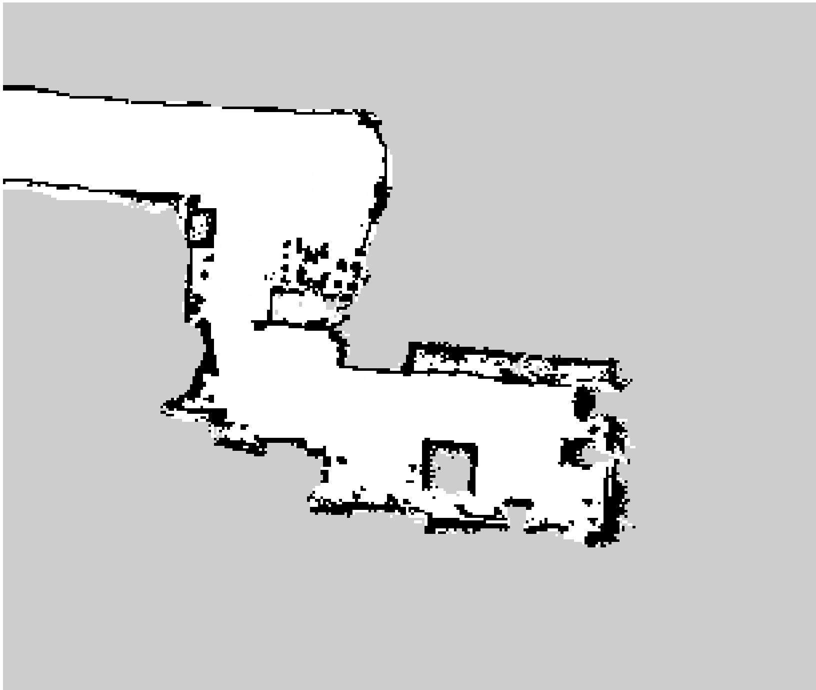

Figure 5.5: Map generated with hectormapping and LIDAR

5.1.4 Iteration 3: Adaptation to natural environments

In Iteration 1 and 2, the ADLR was only tested in laboratory environments. To test the robot in more similar environments to home environments, we deployed the robot in one of the researchers home. The goal was to evaluate whether the ADLR managed more chaotic environments. We realized that the labs were more spacious than a home environment. For instance, the width of doors and between obstacles such as furniture, caused the robot to fail in navigating between two points. We adjusted the configuration of the buffer zones in the local costmap by increasing the threshold for stopping. This alteration made navigation in cluttered areas possible.

The increase of the threshold for stopping certainly would influence the interaction in encounters between humans and the robot. We conducted a pilot study to evaluate the research approach and the configuration of the robot—both in means of safety and navigational capabilities among humans (see Section 4.3.5 on page 40).

Through the prototyping process we found that the prototype was not robust enough for deployment without one or more researchers present—due to accumulated errors over time and more importantly; the hazard risk of crashing into the robot. However, the prototype was able to navigate autonomously indoors and we could teleoperate the robot from a workstation.

5.2 The final implementations and configuration of ADLR

5.2.1 Hardware setup

ADLR consists of various components to enable basic operations. These are the main components:

1. Yujin Kobuki
2. Nvidia Tegra K1
3. Bluetooth speaker
4. Asus Xtion Pro 3D Depth Camera
5. Robo Peak RPLidar 360° Laser Scanner A1

The Kobuki platform is a mobile base designed for prototyping. It is set up with two servos, one for each wheel, which makes it possible to turn the base co-circular to the the center of the robot. Additionally, it includes different safety features such as cliff sensor, wheel drop sensor, and bumper sensor. These sensors stop the platform from damaging itself and hurting people. The Kobuki base also has a one-axis gyroscope to orientate the direction of the base. The infrared sensor which is in both the mobile base and the docking station, allows the base to dock automatically. All of these sensors, motors, and controller units, running on a C++ environment, makes it possible to communicate with external hardware. In addition, it has different connectors for power supply such as 3.5 and 12 volt direct current, that feeds of the internal battery which has an operating expectancy of three hours before requiring recharging.

The motherboard is the brain of the platform, and it is important that it has enough power to process camera feed and calculations concerning navigation. The ADLR is equipped with a Nvidia Tegra K1 board. Its Central Processing Unit (CPU) has the capacity of running up to 2.2GHz and different ports such as USB, JACK, and HDMI for connectivity. For wireless connectivity it has a built-in Wi-Fi solution.

For interpretation of 3D environments, ADLR has two different types of sensors. The first sensor is the Asus Xtion Pro camera, which is equipped with three different cameras. One of them is a normal camera that transmits a feed similar to a conventional web camera, and the other two is able to see depth, through merging the different images together and the usage of the offset and angle parameters between them. The second sensor is a LIDAR sensor named RPLidar A1. This sensor is continually rotating in a 360° motion and sending a laser beam—enabling it to calculate the distance between itself and surrounding objects.

5.2.2 Software setup

There is no definitive approach in how to develop autonomously navigating robots [91]. Our software implementation utilizes three main dimensions. First, the robot requires a representation of the real world i.e. a map. Second, it needs to locate its position on the map. Third, a strategy for finding a path from the current position to the objective.

The robot was delivered with the required software installed on the Nvidia Tegra K1. In addition to the robot, we were required to have a PC with Ubuntu 14.04.4 LTS and ROS installed. This would be used as a ROS-workstation, where we could configure, teleoperate and monitor the robot.

After the workstation was installed and configured, we started testing some default functionality on the robot, like remotely controlling it through teleoperation over Wi-Fi— which was a key feature for doing Wizard of Oz.

Mapping

SLAM enables the robot to map the environment it is in and estimate its position in that environment. Using this framework, our workflow of setting up the robot was first to get a representable map by manually controlling the robot and create a map based on input from the sensors. Our implementation used Hector Mapping [45] to generate the global costmap. Additionally, it generated a .pgm file and a .yaml file which holds key attributes of the map—as shown in Figure 5.6.

Figure 5.6 shows an example of the generated .yaml file. Line 1 to 6 automatically gets generated by running the AMCL mapping module. This

```
image: /home/ubuntu/maps/rplidar_robin.pgm
resolution: 0.050000
origin: [-25.624998, -25.624998, 0.000000]
negate: 0
occupied_thresh: 0.65
free_thresh: 0.196
b0: {x: -5.10, y: 5.21, d: 90}
b1: {x: -1.14, y: 0.271, d: 0}
b2: {x: -2.56, y: -9.35, d: 0}
init_pos: {x: -5.12, y: 6.36, d: 90}
p0: {x: -1.11, y: 4.73, d: 290}
p1: {x: -0.186, y: 2.55, d: 270}
p2: {x: 12.4, y: -0.998, d: 270}
p3: {x: 12.4, y: -2.83, d: 180}
```

Figure 5.6: ROBIN laboratory .yaml file

includes a pointer to the .pgm file, and information about the map, like where the origin is, and the scale. The points b[0–2], initpos, and p[0–3] are different references to grid positions in the map. These are points chosen by us, which later are accessible for the robot to navigate to.

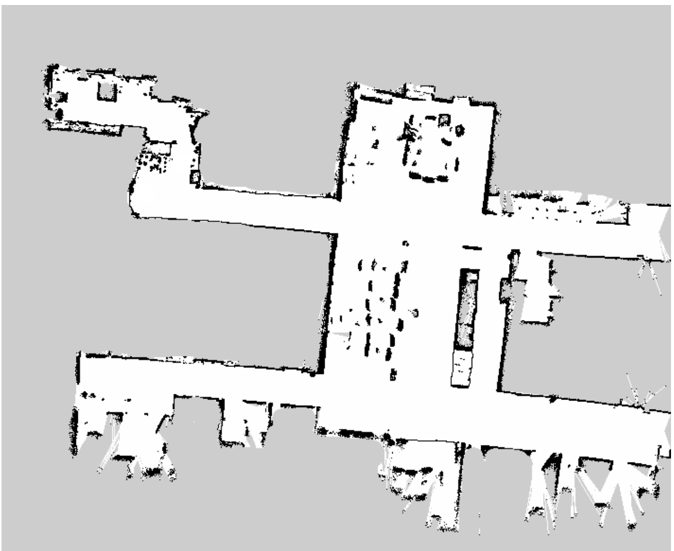

Figure 5.7: Map of ROBIN

The image that is outputted in Rviz, as shown in Figure 5.7, is what ADLR uses as reference to find the paths. The gray areas represent unknown territory, the black represent walls and the white parts represent areas where it is possible for the ADLR to navigate. This shows one of the critical issues with the design of the logic in a mapping process; because it

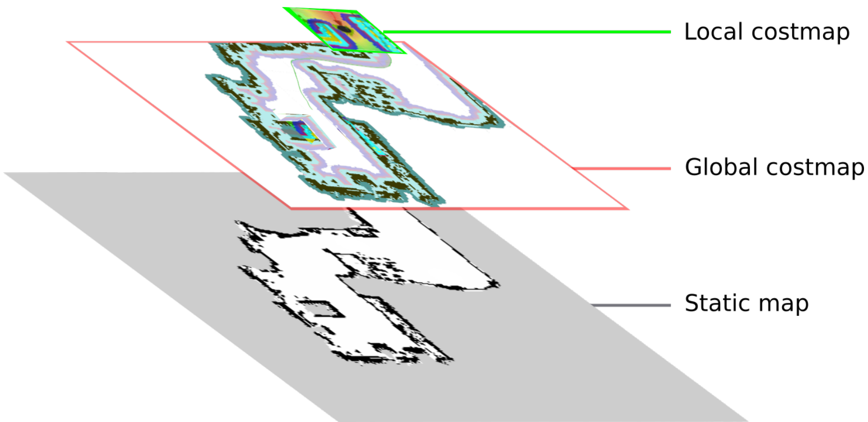

Figure 5.8: Local and global costmap

relays on static objects in the environment not getting dramatically altered after the mapping.

Autonomous navigation

Our final prototype of the ADLR uses AMCL for navigation. For pathfinding, it uses Dijkstra's algorithm to find the shortest travel distance between the nodes [17]. When the AMCL runs, it uses the .pgm file, as well as real time input from the RPLidar. It accomplishes this by utilizing two different layers of obstacles, as shown in Figure 5.8, namely the local costmap and the global costmap. An Rviz visualization of all the layers combined, is depicted in Figure 5.9.

In Figure 5.9, the ADLR is displayed as the black circle in the middle. The square around it with a color gradient from red to green represents the robots' real time field of view. Within the square, there is a gradient from yellow to purple in different shapes. These forms represent the obstacles ADLR can detect. Simultaneously, it uses the shape of the objects around it as reference to position itself in the map. The green line from the robot to the top of the map is the planned path. If the robot finds obstacles within the real-time obstacle square—the robot tries to find an alternative path. If the robot for some reason cannot detect an object with the LIDAR, it will crash into it. However, the bumper sensor will catch it if it lies on the ground invisible to the LIDAR.

All of the attributes mentioned above are possible to alter in various configuration files on the robot. For instance, the minimal distance from an obstacle and the range of the real-time obstacle detection in the local costmap. For our use-cases, we have adjusted the route algorithm to allow navigation through spaces no wider than the diameter of the robot. This is

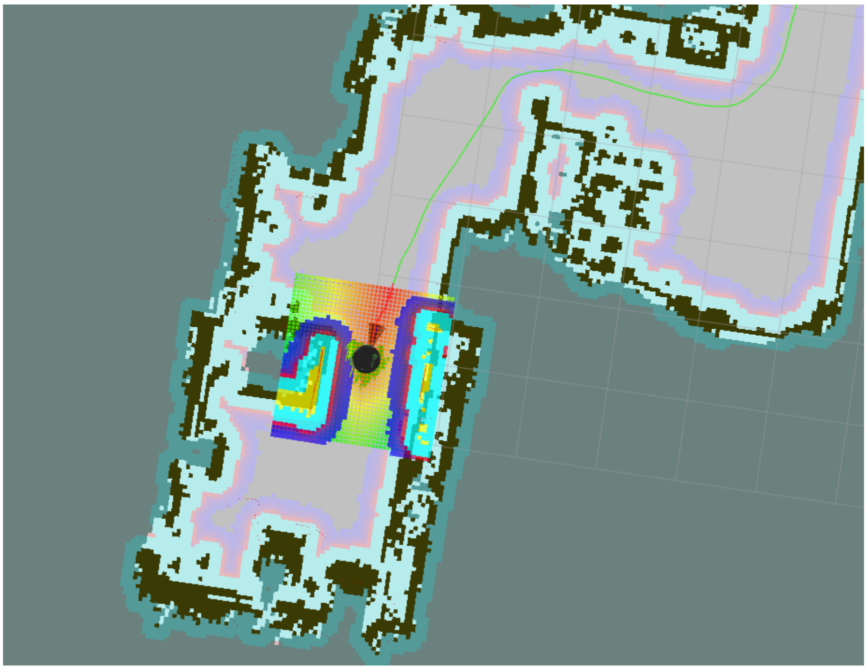

Figure 5.9: Autonomous navigation

due to being able to navigate in a home environment which is less spacious than a lab environment. The other adjustment worth mentioning is the size of the global costmap. This can be set to a bigger size than at the current configuration. This layer can also be temporally stored so the robot can plan based on what it saw when it previously navigated through an area. The downside with this is that if it gets an instruction to navigate from one point to another and it has seen an obstacle, even if it is not there anymore, it will fail to even initialize the instruction. For that reason we have limited the robot to only see one meter for real time obstacles.

Recovery mode

When the robot moves autonomously, the main flow is so that it moves according to the planned route towards the target. Nevertheless, the robot takes into account changes in the environment. For example, a chair can be moved or a person can get in the way of the scheduled route. If it is possible to find an alternative path in these cases—the robot will alter the path in real-time. There are challenges that may arise that make it unable to find alternative routes. This will typically occur when obstacles are too close, the planned path turns out to be completely blocked, or the robot is physically stuck.

It is in these cases the robot enters *recovery mode*. This mode is divided

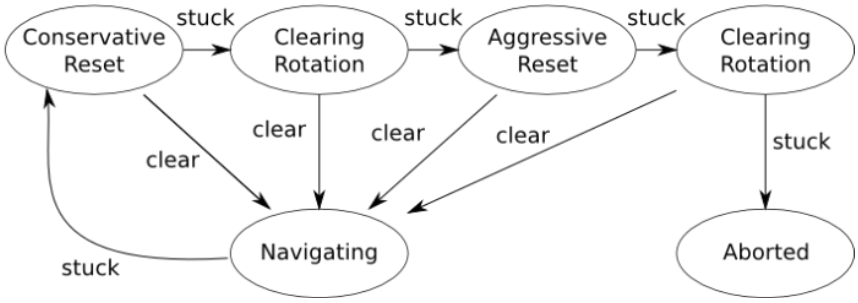

Figure 5.10: Recovery mode work flow. From [81]

into two main phases—namely *conservative reset* and *aggressive reset*. The reason for an escalation in behavior is the assumption that the detected obstacles are real. Therefore, the robot begins with a conservative reset as seen in Figure 5.10. In this phase, it tries to find a way to the objective by clearing the closest obstacles in the map. If this does not work it initiates *aggressive reset*. In this phase, it tries to remove the barriers from the map before it tries again. The reason that it rotates between and after the two types of reset is; (1) enable the sensors to re-scan the environment and (2) if the robot is physically stuck, rotating motion behaviour will in many cases help to get unstuck.

Chapter 6

Findings

> *"The most exciting phrase to hear in science, the one that heralds new discoveries, is not 'Eureka!' but 'That's funny...'"*
>
> – Isaac Asimov

This chapter presents the empirical data collected in the study. It is divided into the following three themes: (1) Interpretation of robot communication, (2) challenges in spatial encounters, and (3) facilitation for robot autonomy.

6.1 Interpretation of robot communication

6.1.1 Interpretation of AGVs

The AGVs at the hospital used sounds and light to communicate with people. When a person obstructed an AGV, it stopped and said with a male voice "Automated transport. Please move." This particular type of AGV had two orange lights in the front and two similar in the back, as depicted in Figure 6.1. These lights were used in different ways to communicate its objectives to people. When the robots were turning in a cross-section, they blinked the lights on their left or right side, according to which direction they were going in; in the same manner as cars and other vehicles. When the robot was moving straight along its path, the four lights were blinking simultaneously. There were two additional lights in the front, one red and one green, which was used by the AGV-operators.

When the AGVs required use of an elevator, the elevator got reserved. Due to the size of the AGV, the elevator could only fit the AGV, whether it had cargo or not. When an elevator got reserved, the display outside the elevator—which normally indicated the floor the elevator was in—changed to "Reserved AGV", as depicted in Figure 6.2. There was also

Figure 6.1: The AGVs used at the hospital

Figure 6.2: An AGV using an elevator

audio feedback to the people inside the elevator that they had to leave the elevator. The voice message in the elevator was "The elevator is reserved for automatic transport. Please use another elevator", said with a female voice.

In the hallways of the hospital, there were different kinds of warning signs about the AGVs. The culvert and the basement were some of the most trafficked places by AGVs. In these areas, the AGVs and people had their lanes separated by markings on the floor, as can be seen in Figure 6.3. These areas were quite similar to how cars and pedestrians have lanes and sidewalks. The AGVs stuck to its lane except when turning in intersections; the path that they moved in were so precise that there were rubber marks and small indentations on the floor due to wear and tear from the wheels. The walking people, however, were only sticking to their designated lane when they saw fit. We observed numerous people that crossed the markings between the lanes. These "transgressions" occurred e.g. when people were overtaking each other; when one person or more were transporting large objects such as beds; or when there were too many people walking side-by-side.

Figure 6.3: Lane division marking on the floor between the AGVs and people

The AGVs had multiple places for storing, delivering, and collecting cargo. These were small niches, all distinctly categorized by one of the three functions above. The storage niches were a kind of buffer; the robots would place cargo in these niches whenever the intended delivery niche was occupied, or unreachable. Then the cargo could be collected and delivered at a later time without creating congestion in the system. The niches that the AGV used for collecting cargo had guiding rails near the floor to ensure that medical staff would place the carts correctly. The delivery and storage niches had no such rails since there was no need; the robots would set the carts in exactly the same position every time. The placement of the niches was next to the elevators; outside clinical and logistics departments; and in buffer areas. These areas had signs stating that no objects should be placed there, shown in Figure 6.4 and Figure 6.5. Nevertheless, according to the managing operator of the AGVs, the hospital staff displaced things that obstructed these areas on a daily basis—thus violating the signs.

Figure 6.4: Warning sign in delivery niche

Figure 6.5: Sign within a delivery niche

Notable events during the observation

In the following we will describe the most notable events concerning spatial interaction between people and the robots that we observed:

Incident 1

Two staff members had a discussion a couple of meters from one of the intersections. They were facing each other, and they were apparently engaged in the conversation. Their alignment was in such a way that they were slightly angled towards the intersection. One of the staff members was positioned in the lane of the AGV. This caused him to stand with his back to an AGV closing in. The AGV was only a couple of meters away from them when the staff member that was blocking the path moved slightly towards the lane reserved for humans. He did this without turning his head towards the AGV. The AGV was able to pass without stopping. The staff members gave no discernible sign that they had noticed it, other than the small movement.

Incident 2

A woman with a stroller was closing in on an intersection. She was walking quite close to the wall on her left-hand side, which caused her not to have a full overview of what was coming from the other directions in the intersection. Just as the stroller had passed the end of the wall by approximately half a meter, an AGV came from the woman's left. The AGV stopped a couple of meters from the stroller. The woman got a little startled before she backed up, away from the path of the AGV. She waited until the AGV had passed before she continued walking.

Incident 3

A person came from the elevator towards an intersection. She was looking down at her cellphone as she was walking, and seemed quite focused on it. As she was entering the intersection, an AGV came towards her from her right-hand side. When the AGV was about two meters from her, it suddenly stopped. This clearly startled her, since she jumped up for a second before she continued to walk in the same direction.

Interviews with medical staff

We conducted five interviews with members of the medical staff about the AGVs. They all seemed to have a sense of what the robots were doing; all of the participants knew that they were transporting things. On the question of whether they felt it was irritating that the AGVs were occupying space in hallways and that they had to move away from the robot, they all stated that they did not consider it a problem. However, one of the participants pointed out that there had been accidents with these robots. He mentioned an example of a physician that had broken a leg. Another interviewee said it could be frustrating when the AGVs occupied the elevators. He pointed out that it was merely an inconvenience—not a problem—since he knew that the elevator could be occupied by an AGV at any time. He emphasized that AGVs reserving elevators could result in him being late to a meeting, but that patients were not affected. Another participant emphasized that the hallways were spacious enough to accommodate both people and robots.

6.1.2 Interpretation of ADLR

In this section, we will present the data related to what the participants did during the observation on Kampen Omsorg+. In the following sections, we will present a table for each encounter strategy and summarize the actions of the participants.

Robot behavior B1: Manually controlled yielding, Table 6.1

During manual yielding, one participant paused in front of the robot whereas the rest kept moving. However, P3 stumbled a bit as she was paying attention to the robot and not the direction of the goal. Half of the participants did not decelerate at all while passing the robot (i.e. P2, P5, P7, and P8). Some of the participants greeted the robot in some manner. For instance, P5 waved to the robot and P4 said "How clever you are!" as they passed it. During this sequence of the observations, the robot did not bump into any of the participants. All the participants passed the robot successfully on the right-hand side.

Table 6.1: Robot behaviour B1: Manual yielding

Participant	Description
1	P1 is about 1 meter from the robot when she stops. P1 states: "What am I supposed to do now? Walk past it?". As soon as she stopped, the robot moved on her left side.
2	P2 and the robot started by moving straight towards each other. After P2 has moved a third of the distance, she starts turning slightly to her right. The robot does the same, and there is symmetric yielding between the two.
3	P3 watches the robot carefully, as it is passing by. As her attention is on what the robot is doing, she stumbles a bit when the robot is on her left side. She quickly recovers and turns her attention to the goal. When she reaches the target, she says "It didn't do much."
4	P4 and the robot move straight towards each other. When the participant reaches a third of her distance, the robot starts yielding to the participant's left side. When P4 has reached around half of the distance, she slightly adjusts her speed down to prepare for changing her direction. The robot continues in the same yielding direction, which enables the participant to accelerate and proceed in a straight direction for the finish line.
5	P5 and the robot pass each other to the right of one another. As they cross paths, the participant waves to the robot.
6	P6 and the robot start moving towards each other. After the robot has traveled approximately one meter, it starts to yield to its right. P6 also starts to yield to his right, but since the corridor is narrow, he bumps slightly into the robot when they go past each other. Both continue to the opposite side of the room.
7	P7 starts changing his direction slightly after 1 m from the start line. P7 keeps moving at the same pace the whole time as he passes the robot on his right-hand side. They cross each other at half of the distance to the goal.
8	The robot starts yielding after moving 1 meter. P8 also starts yielding after moving 1 meter. They pass each other on the right-hand side, with less than 50 cm of space between them.

Robot behavior B2: Stopping manual control, Table 6.2

All of the participants stopped in front of the robot in some manner, except P3 and P4. These two participants decelerated while they were adjusting their course. The rest of the participants stopped in front of the robot.

However, how they stopped varied; P1, P3, and P5 barely stopped before they decided on a new route. Whereas P8, was not able to finish (more about this incident in Section 6.2.2). The placement of the robot was consistently in the middle of the room during this run. All the participants, except P8, was able to pass the robot on their right-hand side.

Table 6.2: Robot behaviour B2: Manual stopping

Participant	Description
1	When the robot stops, P1 reacts by slowing down her pace. Her direction is straight towards the robot. It seems like she waits to see what the robot is doing before she decides to pass the robot on her right-hand side.
2	When the robot stops, P2 seems to get a little startled as she stops with her foot in mid air. She watches it for less than a second before she continues around the robot on her right-hand side.
3	P3 and the robot head straight towards each other. P3 had covered about 0.5 of the distance before the robot stopped. With an instant fluctuation in pace without stopping, P3 turned slightly to her right to pass the robot.
4	P4 slows down her pace for one second, until she is about 20 cm from the robot. She redirects her wheeler without stopping, and continues to pass the robot on her right-hand side
5	P5 walks one step towards the robot, before he stops for half a second to adjust his direction and passes the robot on his right-hand side.
6	P6 and robot moves towards each other. When they are approximately two meters away from each other the robot stops without turning. P6 passes the robot on his right side. The robot continues once P6 is not in front of it.
7	P7 and robot moves towards each other. When they are approximately two meters away from each other, the robot stops without turning. P7 passes the robot on his right side, but just barely avoids to bump into it since the room for passing is very narrow. The robot continues once P7 has passed.
8	When P8 covered half of the distance, the robot stops moving. P8 tries to pass the robot on her right-hand side, but when she is next to the robot, she stops. The distance between the obstacles is too small to enable passing. After 10 seconds she tries to back up. When she is backing up, the robot keeps moving forward the same distance as she is backing up. She then says ”Is it going to crash with me?” P8 tries to back up a second time. This time she tries to turn at the same time, but the robot keeps moving forward in the opposite direction. P8 gives up, due to lack of space.

Robot behavior B3: Dynamic navigation, Table 6.3

The behavior of the robot in autonomous mode was not as consistent in path choices as to using the Wizard of Oz approaches. The robot entered recovery mode in all the runs, except in P3s and P5s case. P3 stated “It was certainly not intelligent now.” P5 compared it to meeting a person on the street, where that person is taking a closer look. P7 bumped into the robot while it was in recovery mode. The robot was located right in the middle of two obstacles, thus making narrow passages on both sides. P7 still just managed to pass through the passage on his right side. P8, who also was a wheelchair user, was able to pass the robot with a few centimeters of clearance on her left and right side. However, in her case, the robot stopped where there were fewer obstacles than in P7s case. All the participants were able to finish the runs. The robot on the other hand only finished during P3, P4, and P5. When it did not finish, it was due to the robot not being able to find alternative routes around the participants. Of the runs where it did manage to finish, the robot entered recovery mode in P4s run. She expressed that she was confused by this behavior, even though it helped the robot to achieve its goal.

Table 6.3: Robot behaviour B3: Dynamical navigation

Participant	Description
1	P1 stops about 10 cm from the robot. At this point, the robot starts turning around in circles. P1 responds with "Whats happening now?[. . .]Maybe I should just pass it." She starts moving towards her left side, but immediately changes her mind and passes the robot on her right, despite that there is more space on her left side.
2	The robot turns and stops in the left hand direction of P2. Her reaction is to stop in front of the robot where she waits a bit before deciding on where to pass the robot. The robot is still in recovery mode and starts turning around in circles.The gap between the robot and the furniture on the right hand side of the participant is too small for her to pass the robot with a wheeler. She stands still for 13 seconds before she decides to pass the robot on her left hand side.
3	When the participant is between 0.5 and 0.75 of the distance, she encounters the robot. Without any of them stopping, P3 starts adjusting her direction to pass the robot to her right. The robot starts moving at a slightly lower pace and does some adjustments to its direction. It keeps adjusting direction while it is moving slowly forward for 6 seconds, before it starts moving in a normal pace to its goal. The participant says "It was certainly not intelligent now."
4	The robot does not stop until it is about 30 cm from P4. The participant starts redirecting her wheeler while the robot is static. She starts moving to her left of the robot. At the same time, the robot starts the recovery behavior. It starts turning clockwise, in the same position as it stopped. The participant says "What are you doing now? Are you just going to move around in a circle?" The robot is still in recovery mode as P4 has reached the finish line. She turns in its direction to watch it.
5	P5 starts yielding after 0.75 of the distance without slowing down his pace. P5 turned to the right to pass the robot. When P5 reached the finish line, he says "It was a bit like when you meet someone and think 'there is something familiar about you; have I seen you before?'"
6	P6 stands straight in front of the robot when he is about 0.75 of the way to the finish line. He stops and watches the robot for about 2 seconds, before he redirects his wheeler to the right-hand side. When he starts passing the robot, it starts turning clockwise. P6 states as he is crossing the finishing line: "I can't remember if it did anything differently now than the last time."
7	P7 starts adjusting his direction when he is 0.33 of the way. The robot stops in the middle of the path when P7 is about 0.5. Without stopping, P7 continues to adjust his direction and passes the robot on his right-hand side. The gap between the robot and an obstacle in the path of the participant is so close that the wheelchair touches them both as he passes. He also raises his arm to make sure he does not hit any obstacle.
8	P8 starts yielding after 0.33 of the distance. Simultaneously the robot stops, and P8 aims for the gap between the robot and the chair on her right-hand side. The robot enters recovery mode and starts spinning slightly as P8 slows down her pace. She keeps an even speed while passing the robot, even though it is only a couple of cm on each side of the wheelchair.

6.1.3 Robot communication modalities

Table 6.4 lists the communication modalities the robots we have investigated employ to communicate with humans. Speech refers to verbal sounds; either recorded or generated through text-to-speech. Explicit sounds are all other sounds made with a speaker or a buzzer. Implicit sounds are the sounds that are a result of motor movement or similar in the robot. Light are LEDs or other light sources that are used on the robot for communication purposes. Screen refers to the robot having any kind of screen where it presents textual or graphic information. Gestures are movements that the robot makes with its arms, legs or other extremities. Of the robots we investigated only NAO and Pepper had such extremities; consequently, only they employed this modality. Motion pattern refers to the way the robot convey communication through its movements. The motion pattern encompasses the direction the robot moves, the speed, how it accelerates, and all other aspects related to its movement.

There are only two modalities that are employed by all the robots: implicit sounds and motion patterns. Both of these come as a result of the movement of the robots. Implicit sounds could, in theory, be removed by having the motors operate at an inaudible speed. However, in practice, such a low speed will make most robots useless. Motion patterns are unavoidable in all autonomous navigating robots; where there is motion there will also have to be a motion pattern.

Table 6.4: Robot communication modalities

	NAO	Pepper	Vacuum Robot	Lawn mower robot	AGV	ADLR
Speech	X	X			X	
Explicit sounds	X	X	X		X	
Implicit sounds	X	X	X	X	X	X
Light	X	X	X		X	X
Screen		X		X		
Gestures	X	X				
Motion pattern	X	X	X	X	X	X

6.2 Conflicts in spatial encounters

One of the main findings we have discovered throughout our research concerns situations where a robot and a human in some way limit each other's mobility. In the most extreme case, the limitation can become complete; resulting in neither the human nor the robot being able to move. We encountered two such extreme incidents during our research, one at

Oslo Hospital, and one at Kampen Omsorg+.

6.2.1 Case 1: Oslo Hospital

During preparation for the interview at the hospital, we discovered a news article concerning people getting trapped by AGVs in hospital elevators. The article discussed a different hospital in Norway [67] than the one we would visit, but the robots were almost identical. We found this incident very intriguing, and therefore did two tests and asked Tom, the managing operator about it during our observations and interview at the hospital.

The first test was done before the interview: during our roaming observations, one of the researchers stepped into an elevator that was reserved by an AGV. It continued to move into the elevator, but quickly discovered the researcher, and stopped. After a short period, it started to reverse out of the elevator, contrary to our understanding. We were pleasantly surprised and hoped this meant that the problem had been recognized and resolved.

In the interview, we inquired the managing operator about both the problem and our experiences from the first test. He confirmed that this was a big problem, and responded with surprise when we said that the AGV reversed; he believed it would just stop. He asked how far into the elevator the AGV had moved, and speculated that the reversing might be because it had not gotten far enough into the elevator. He also said that these kind of situations were of high priority since a human might be stuck. One of the AGV operators would quickly respond when such an incident occurred, which was possible since one operator would always monitor the control computer during AGV operating hours.

During the interview, we did a new test along with the managing operator. Both he and one of the researchers stepped into a reserved elevator, but this time they stood all the way to the back, allowing the AGV to move further. Again the AGV recognized the persons as obstacles and stopped. We waited for two minutes to see whether it would reverse, but it did not. Since the researcher and the managing operator had no mobility impairment, they were not trapped in the elevator and simply stepped out past the AGV. To our surprise, the AGV did not automatically continue after the humans had moved. Tom tried a few different things in the control system—including instructing the AGV that all was clear, and "rebooting" the elevator—but to no avail. During his attempts at resolving the error, we observed further adverse consequences: The stalled AGV blocked other AGVs from passing, which resulted in 5 out of 22 also being stalled and creating a "gridlock" just five minutes after we began the test. Since this was done in a crucial intersection—and no AGV could pass the stalled ones—it was evident that all the AGVs would eventually have stopped, had the situation not been resolved.

The operator eventually had to connect a tethered remote control device to the AGV and manually move it out of the way. He then had to specify its location in the control system before it was able to continue its duties. When the problematic AGV was removed the "gridlock" quickly dissipated.

We observed the interaction between AGVs, elevator, and human working as follows: When an AGV is required to take the elevator, it will reserve it so that no one else can use it. The elevator will inform humans of its occupied status through both voice statements and info displays. However, there are no physical constraints preventing humans from entering a reserved elevator ahead of the AGV. Nor are there any sensors in the elevator that will discover the human and communicate the situation to the AGV. The AGV measures 1.975 x 608 x 351,5 mm [30], and weights approximately 500 kg according to Tom. These figures are without any load, and will increase substantially when it is transporting cargo. This all results in the following sequence of events being possible as visualized in 6.6:

1. An AGV is required to use an elevator.
2. The AGV reserves an elevator.
3. The elevator starts to move toward the AGV while informing humans of its reserved status.
4. The elevator arrives at the same floor as the AGV.
5. The AGV begins to move into the elevator.
6. A person with some kind of mobility aid due to a mobility impairment fails to notice both the information given by the elevator and the objective of the AGV.
7. The person moves into the elevator.
8. The AGV also begins to move into the elevator, but detects the person as an obstacle, and stops before it is completely inside.

9. The programming of the AGV does not allow it to retreat out of the elevator, and due to the mobility impairment of the person—combined with the size of the AGV—the person is unable to go past it and exit the elevator.

10. A standstill has occurred; the AGV, the person, and the elevator are all stuck; and none of them are able to resolve the situation.

The described incident is damaging in two main respects: First, the person is stuck, and unless someone discovers him or her, it could escalate to a dangerous situation. Even if the situation gets resolved before it becomes perilous, this is clearly an undesirable situation both for the hospital and the person that gets trapped. Second, the elevator and the AGV as a resource are unavailable, and the assignment of the AGV will not be completed.

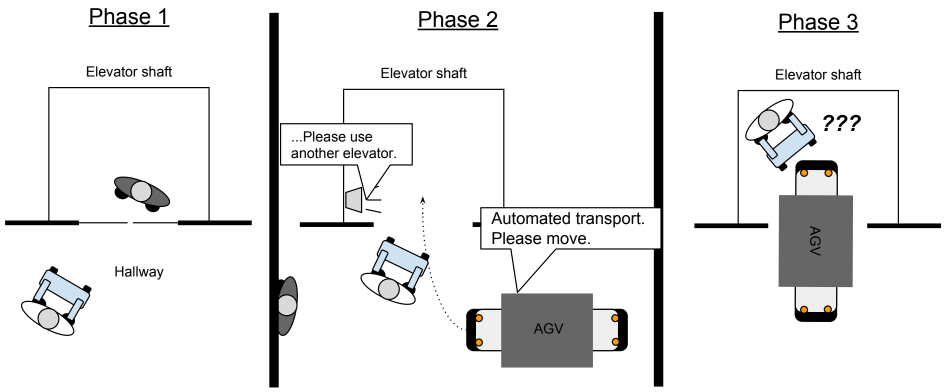

Figure 6.6: Phases of standstill situation with AGV

In the interview, we learned of a mechanism that could be used for preventing such situations: the AGVs had a stop button on the front that would stall them temporarily. The managing operator said some of the porters would use this button when e.g. coming out of an elevator, to prevent the AGV from getting in the way. The stop button then had to be released by physically rotating it for the AGV to continue, and the managing operator expressed grievance with the fact that the porters sometimes would forget this—since this meant that one of the operators would have to walk to the AGV and do it himself.

We did not observe someone getting stuck in an elevator during our observations, but combining results from our tests with accounts given by the managing operator, we consider this a substantial problem.

6.2.2 Case 2: Kampen Omsorg+

The second occasion where we observed an extreme case of mobility limitation, was during our observations at Kampen Omsorg+. It occurred only one time: in the B2 run for P8. In B2, the ADLR was controlled manually by one of the researchers, and the behavior was that it would move straight forward until encountering an obstacle. It would then stop, and not continue unless the obstacle moved. It would never turn to any side. P8 used an electric wheelchair as a mobility aid, with a corresponding large footprint.

The observation run started with both the subject and the robot moving straight towards each other. When the robot was approximately two meters from the subject, it stopped. Due to the footprint of the electric wheelchair, the P8 could not go past the robot without crashing into it; and consequently, she stopped as well. She expressed confusion as to how she should proceed both through verbal and nonverbal communication. P8 and the robot had reached a standstill where none could continue unless the former reversed to let the robot pass.

After approximately ten seconds, the P8 backed up slightly. The robot immediately responded with moving a little forward, in an attempt to indicate that this was the only way to get out of the standstill. Despite this clue, the participant quickly stopped, and a standstill was once again reached. The researchers gave some hints that she might have to reverse further—being very careful not to give too much information—but the participant did not seem to understand the clues. After approximately one minute the researchers decided to end the observation run despite neither the robot nor the participant having reached their goal.

Immediately following the observation, we invited P8 to describe her understanding of the situation resulting in the following exchange:

> Participant: "I didn't have enough room to go past it, and he wouldn't move. I thought that when I came near, he would steer around."
> Researcher: "Did you dislike this approach compared to the previous one?"
> Participant: "Yes, I do believe he should have yielded, when he saw that I didn't have enough room. I found him a bit stubborn. It wasn't particularly polite either, just standing there."
> Researcher: "Did you find the robot unintelligent based on its actions?"
> Participant: "Yes. If it were a human, I would have called it selfish."

> Researcher: "Do you think the strategy of the robot simply stopping is a good one?"
> Participant: "Yes, but if it is to function properly it should move aside to allow me past."
> Researcher: "Did you find the robot behavior to be irresponsible, or responsible?"
> Participant: "Yes, it could be irresponsible. Perchance I absolutely had to get through."

Even though she found the behavior irresponsible, when asked, she responded that she felt calm throughout. After completing all three observation runs with the participant, we conducted a debriefing interview concerning the entire session, and the participant elaborated about the described incident. She said she felt somewhat helpless in the situation because she could not talk to it and tell it to move. She said she felt it would have helped if this was possible, and continued by saying that it should move backward or to the side if she had asked it to do so. We asked whether she thought the robot should have said anything. She responded that it should have told her to reverse in the situation and that she would have been willing to comply. Conversely, she concluded by stating that ideally, the robot should be the one to yield since it was the one in the wrong location.

6.2.3 Attitudes towards motion patterns

In addition to the empirical data gathered through observations, we discussed different movement patterns in encounters between humans and robots during our focus groups at Kampen Omsorg+. As detailed in Section 4.3.8, we showed videos of increasingly provoking robot behaviors to stimulate the discussion. After showing the video where the human had to yield for the robot, the participants int the first focus group had the following discussion:

> Participant 1: "That is how it is going to work in reality."
> Participant 2: "Indeed."
> Participant 1: "That's what I think at least. If a robot is heading against you, you will yield."
> Participant 3: "But where do you get the signal?"
> Participant 2: "I don't need a signal"
> Participant 3: "You don't know whether the robot is here. Maybe you haven't seen it."

Participant 2: "Well, if you can't see it. But if you'll encounter a robot, you'll step aside won't you?"
Participant 3: "If you can see you would."
Participant 2: "Yeah, if you can see."

The second focus group had the following discussion about the same theme:

Participant 1: "Who has to back up? Well, it's not always easy to back up while using a wheeler."
Participant 2 and 3: "No"
Participant 2: "No, I didn't like that"
Participant 1: "No, I would not have that one. It [the robot] would have to yield."
Researcher: "The robot should yield?"
Participant 1: "Yes."
[*Several participants express agreement*]
Participant 1: "Or stop completely next to the wall."

The focus groups also discussed the participants' attitudes towards practical challenges in adoption of robots in home environments.

Researcher: "Could you have a robot which moved around in your apartment now?"
Participant 1 and 3: "Yes."
Participant 4: "No. It's too cramped, so I couldn't."
Participant 1: "If it was able to avoid bumping into things all the time. We've got a lot of furniture. So if it was able to move around."
Participant 5: "It wouldn't be a problem if that were the case."
Participant 4: "Moving like we move. That would've worked."
Participant 1: "Yes, indeed."
Participant 2: "But then we couldn't have carpets."
Participant 1: "Yes, we must have carpets."
Participant 2: "No, we cannot then[have carpets]."
Participant 4: "We must get really great robots."
Participant 1: "He[the robot] must be able to deal with carpets too."
Participant 4: "He[the robot] must deal with carpets, we have plenty of those."
Participant 4: "Understood."

6.3 New and altered tasks due to autonomous robots

In this section, we will describe some of the new tasks and alterations of existing tasks brought about by robots. Some of these have we observed directly; other have we been told about during interviews. Our main focus will be the vacuum cleaning robot, the lawn mower robot, and the AGVs at OH. We chose these three since they all have well-defined functionality; they perform a job otherwise done by humans.

6.3.1 Vacuum cleaning robot

The vacuum cleaning robots did not require much prior to deployment. The docking station had to be placed and connected; then the robot could be started immediately. However, we quickly discovered that it could damage itself or other objects when the floor was littered. Cables, in particular, seemed to constitute a problem. Therefore we had to tidy some to be confident the robot would operate properly. We wanted the robot to vacuum every weekday when we were not home. The process of achieving this, was as follows:

1. Download the app for the vacuum cleaning robot on a phone.
2. Instruct the vacuum cleaning robot to set up a hotspot Wi-Fi network.
3. Connect the phone to the hotspot.
4. Connect the vacuum cleaning robot to the Wi-Fi network.

Additionally, we generally had to keep our home tidier; items had to be removed from the floor prior to the robot operating, lest it would quickly run into problems. Pieces of clothing were especially critical to remove, since the robot would get stuck, and might damage itself or the garment. To achieve an optimal cleaning result, chairs had to be put on top of tables or moved so that the robot could clean everywhere.

Despite the tasks mentioned, the robot would sometimes get stuck, and require us to move it. Even with all these minor adaptions, the robot did not reach every nook and cranny. Everything above floor level—such as sofas or tables—were naturally unreachable. This meant that a regular vacuum cleaner had to be used once in a while, so the task of manual vacuum cleaning was not completely eliminated.

After testing the robots for a month, we were unable to state with any certainty whether we in total had spent more or less time on the task of vacuum cleaning after deployment of the robot.

6.3.2 Lawn mower robot

The lawn mower robots required some moderately extensive tasks to be performed before they could be used. A "virtual fence" in the form of a metallic cable had to be embedded in the ground around the entire perimeter, as well as a leading cable to the charging station. The charging station had to be appropriately situated, and connected to power. Any area of the garden that the robot should avoid had to be delimited or encircled with the "virtual fence." The robot also had to be configured for when it should operate. Olivia—the older woman we interviewed early in the process—said these tasks had been accomplished in approximately twelve hours over two separate days; with considerable help from her family. The postdoctoral fellow, Sophie, said that she and her husband had done these tasks during one Sunday. Both parties reported that further alterations to the garden had been done after the initial ones as they became more familiar with the strengths and limitations of the robot. One example of this was removing a two ton rock that proved problematic. Olivia's son told us that they had been offered to buy a support program; 30,000 NOK for initial installation plus three years of operations and maintenance. Sophie had been quoted a price of 2,000 NOK for just the installation. They had both declined these offers, and done the job themselves or with help from family.

The lawn mower robots required an uncluttered garden, hence continuous tidying was needed. Sophie told us, from her experience with the robot, some of the items it did not handle well included tools, garden hoses, toys, towels, and apples. An example of a problematic situation can be seen in Figure 6.7 on the next page, and new routines for storing tools can be seen in Figure 6.8 on the following page. Sophie had an apple tree and said that she had to check for, and possibly remove fallen apples under it every morning while it was bearing fruit. She also told us she had to get rid of a trampoline, since the robot otherwise would break itself on the trampolines metallic support structure. Another problem for the robot was steeply sloped areas of the garden. These were inaccessible for the robot, and Sophie had for some time after deploying the robot cut these areas manually. On more than one occasion this had resulted in cutting the perimeter cable the robot required, which then with some difficulty had to be spliced together. This nuisance had eventually made her stop mowing these areas altogether. She also said that the robot periodically would stop and require manual intervention, primarily due to steep slopes or wet grass. Olivia reported far fewer problems; she said the robot had gotten stuck only one time.

Figure 6.7: Problematic garden hose. From [98]

Figure 6.8: Tools stored where the robot cannot reach. From [98]

In addition to the tasks described in the two preceding paragraphs, Sophie told us about some more extensive alterations. She and her husband had removed a stump from the garden that proved problematic for the robot. After the stump had been removed, they had sown new grass where it was previously located, and to allow this new grass to grow; it had to be encircled with the "virtual fence". In addition, she had considered removing the apple tree, since she frequently had to remove apples underneath it. Furthermore, the garden had some stone steps from one part to another, which was problematic in two ways: first, the robot could not cut the grass right next to the steps; and second, it could not move past them to the other part of the garden without assistance. She consequently contemplated removing the stone steps as well. Neither Olivia nor her family had done any such extensive alterations, but she told us about a neighbor who was in the process of redesigning his entire garden to better facilitate for the robot.

We asked Sophie whether she in total spent more or less time now than she did prior to acquiring the robot on the task of mowing the lawn. She answered that she honestly could not say for sure, but believed it was roughly the same amount.

Before acquiring the robot, Olivia had utilized a service provided by the municipality where she paid a fee to get the lawn mowed. However, she said it was somewhat unreliable when they would come, and that over time, a robot was more cost effective. As such, her main incentive for getting a robot was monetary, not efficiency.

Both Sophie and Olivia said that they were very satisfied with the result of the robot.

6.3.3 The AGVs at Oslo Hospital

The AGVs in OH required both building structure and infrastructure to accommodate them. They followed magnetic markers embedded in the floor throughout their operating areas, and utilized strategically placed charging stations—as can be seen in Figure 6.9. These infrastructure requirements were part of the planning and building process when the hospital was constructed. However, Tom, the managing operator, told us that a few existing buildings were reused and the infrastructure the robots required thus had to be implemented in them as well. He said "they had to deal with what was here, such as old buildings where you didn't have the advantages that you get with new buildings."

Figure 6.9: AGV charging area (green artifacts on the left)

Figure 6.10: Makeshift warning sign

Tom further said that two to three technicians from the manufacturer of the AGVs initially worked full-time on implementation and configuration for two to three years. After that, they considered the system to be stable enough that they could leave.

In addition to Tom, two additional full-time employees had operation of the AGVs as their main task, though the group also performed some additional transporting tasks. Tom told us that during operations of the robots there would always be one or more persons monitoring the system. We observed the necessity of this while interviewing him; he would periodically perform small tasks in the control system to keep the robots operating smoothly. He said that the constant monitoring originally had not been planned when the robots were acquired and deployed. He elaborated by stating the assumption had been that the robots could operate almost entirely without supervision and that an operator only would have to check it once in a while. He said they soon realized this assumption to be flawed: "If you leave the screen for 10 to 20 minutes, there is a standstill somewhere." He explained that the single standstill quickly would result in a cascading failure that eventually would stop the system altogether. This was because the AGVs could not get past each other.

The stalling could be because of technical problems in the AGVs themselves, but more often—Tom estimated in 90% of the instances—it was due to "human error". The medical staff would leave all sorts of objects in the path or the delivery niches of the robot. Since the robots had no way to go around, all objects became an insurmountable obstacle. The only solution was for one of the AGV operators to find and remove the object. We observed that to mitigate this problem, there were signs throughout the hospital informing people about the robots, and not to leave anything in their path. Some of these signs looked very professional and refined, e.g. the one in Figure 6.5 on page 68; while others had a makeshift look, such as the one in Figure 6.10.

Tom said that the amount of tasks required for smooth operation of the AGVs varied both on a day-to-day basis and during the day. He said that in the morning and the afternoon—when large groups of employees were arriving or leaving—there would often be more problems and standstills. In addition to the tasks of the AGV operational team, Tom explained how other staff at the hospital had to order transportation tasks. He said this was primarily done by the logistical departments and porters, not the medical staff.

The AGV operators performed basic maintenance themselves, but more substantial maintenance had to be performed by technicians from the manufacturer of the AGVs. Some technicians were scheduled to come to perform this a couple of weeks after we conducted the interview. We asked whether they also would do any configuration changes to the robot, but Tom answered that all large changes were very costly. Especially ones that could be considered as added functionality.

The executives at the hospital required monthly reports to assess the efficiency of the AGVs. These reports were generated by Tom, adding to his workload.

Towards the end of the interview, we asked Tom about the future plans for the robots. He said they had been in operation for approximately nine years, and that they had a total operating time of 10 to 12 years; maybe 15 with proper maintenance. He said some of the parts for the robot were no longer produced. Therefore the current AGVs would have to be replaced at some time, but there was no specific plan. Tom did not know whether the existing infrastructure and software could be used with the new robots.

Tom had no precise number for how many full-time equivalents the AGVs constituted, but estimated between 15 and 25 based on 400 to 500 transport assignments performed every day of operation. He also said that the work they performed could be considered tedious. The latter aspect was substantiated by one of the medical employees we interviewed. He said that some of the tasks the AGVs performed not only could be considered tedious, but also unsavory; such as transportation of biological waste.

During our observations, we noticed some areas where the hallways were not sufficiently wide to allow for separation between the lanes of the AGVs and humans. In these areas, the robots could potentially come in conflict with doors, as can be seen in Figure 6.11. This door is right next to the path of the AGVs, and the door opens outward into the hallway. This means that the door will be impossible to open when an AGV goes past it. According to Tom, this was not a big problem. We can only speculate whether there was a good reason why the door did not open the other way, into the room—or whether this was an example of oversight in the planning.

Figure 6.11: Conflicting door with the path of the AGV

Chapter 7

Discussion

> *"I am certain there is too much certainty in the world."*
>
> – Michael Crichton

The themes of this study are divided into three parts: (1) An investigation of how the older adults interpret an autonomous mobile robot's communication in encounters. Related to this topic, we explored how the AGVs and ADLR communicated its spatial objectives. (2) Identification of some of the conflicts in spatial encounters with autonomous mobile robots. (3) Some of the implications of introducing robots in the home environment.

In this chapter, we will discuss these themes sequentially, in light of their respective research question. Each topic is laid out in respect of the empirical findings and the related work. The chapter concludes with a discussion about the functionality of robots, a topic that is relevant for all three research questions.

7.1 Interpretation of robot communication

> Research question 1:
> *How do older adults interpret the communication given by an autonomous navigating robot to convey its spatial objectives?*

7.1.1 Conveying and interpreting spatial objectives

Chapter 6 showed some of the communication modalities that are employed for a robot to communicate with humans. It can use speech, sounds, lights, gestures, present information on a screen, and communicate through motion patterns. Most of this communication is explicit; the robot is deliberately sharing specific pieces of information [8]. Some of the modalities are in fact inherently explicit, e.g. speech and lights. Explicit communication is no guarantee that the communication will be understandable and unambiguous, but it will most often be logical—or at least consistent—after some training with the robot. We observed this during our observations of AGVs at OH; the robots used their lights and sound for communication in an entirely consistent matter that could be learned in a couple of minutes.

We have explored four types of robots in depth in this thesis. These are the vacuum cleaning robot; the lawn mower robot; the AGVs; and the ADLR. These four robots have no movable extremities, and consequently no way to communicate by gestures. However, we have seen that these four robots communicate through their *motion pattern*. We argue that this will be true for all mobile robots per definition, since motion inherently will communicate something. Furthermore, this communication will occur and be interpreted by humans whether it is explicit or implicit [8].

The motion pattern as a communication modality for a robot can be easy to overlook. However, the notion that it will constitute some of the communication that a robot conveys should not come as a surprise. It is a well-established fact that a large part of human communication comes not from what we say, but from the multitude of non-verbal communication we convey [11, 52, 59]. One part of this is the motion pattern, which primarily communicates our intentions of movement. In Chapter 2 we saw that movement of the entire body is part of the kinesic subsystem in the visual communication system. We saw that the visual communication system also includes proxemic commmunication, which comes as a result of motion. Humans communicate both explicitly and implicitly through our motion patterns. To illustrate this, we will use the situation of exiting and entering a subway train. It is recognized that the most efficient way to do this is that passengers should be allowed to disembark before the boarding occurs. Some boarding passengers consciously and deliberately place themselves well to the side of the doors, thus explicitly communicating that they will yield for the disembarking passengers. Conversely, other passengers stand in front of the doors, effectively blocking the disembarking passengers. They often appear surprised when they realize that the people on the train expect to exit before they can enter. This surprise indicates that their communication was implicit.

When humans move about, we constantly gather sensory inputs from our surroundings and interpret them. This information is employed in several ways, but one of the most prominent ones is to avoid spatial conflicts with humans and vehicles; otherwise known as crashing into one another. We try to understand the intention of others, but can never be 100% confident that our conclusions are correct; the communication could be unintentional, or we might have misinterpreted it. It becomes a numbers game where we constantly evaluate the probability and consequence of making an error, to determine the total risk: If the consequence is low, we accept greater uncertainty, and vice versa; if the consequence is severe, we demand higher certainty. To exemplify the former, one could think about simply walking down the street. We try to determine our fellow pedestrians' intentions by interpreting things like their speed, heading, and gait. However, the consequence of miscalculation is nothing more than awkwardly bumping into someone. Therefore, the demands of certainty are low. Conversely, when we decide whether to cross a pedestrian crossing in the street or not, the consequences of misinterpreting the signals are dire. This results in using more time to achieve a greater certainty; we exploit all sources of information available to us to increase our assurance that we will not be run over by a car.

As presented in Section 4.3.4 the topic of communication between pedestrians and drivers have been explored by Lagström and Lundgren. They argue that one of the most important modes of communications is eye contact between driver and pedestrian, and propose a substitute for this that can be used in autonomous vehicles. The prototype is an array of LEDs on the top of the vehicle that communicate whether it has seen a pedestrian, and consequently is about to brake [49]. In the workshop we attended about the topic, the prototype was discussed extensively. While everyone agreed such a substitution would be beneficial, we also addressed the fact that people extensively use pedestrian crossings in the dark when no eye contact is possible. The conclusion to the discussion was that the main communication in the dark is motion pattern. By analyzing speed, acceleration and heading of a vehicle, the pedestrian can be reasonably sure of the driver's intention. Nevertheless, we would also argue that the combined certainty one might achieve by combining both eye contact and motion pattern during the daytime, gives an increased sense of safety compared to in darkness.

The discussion from the workshop shows that every mode of communication is significant and can add certainty to the communicated intention between drivers and pedestrians. The eye contact can be considered as an agreement between the actors. We argue that such metaphorical handshakes are relevant in encounters between mobile robots and humans as well, since they can help give a mutual understanding of the situation.

7.1.2 Interpretations of the recovery mode

Many robots have sensors that only operate in a limited arc, the implication being that to acquire complete situational awareness, the robot has to turn 360° around its own axis. We refer to this as the *recovery mode* (see Section 5.2.2). This behavior will frequently occur when the robot has to make a new plan for reaching its target.

In our testing at Kampen Omsorg+, we observed that every small movement of the robot was interpreted. The ADLR entered recovery mode when it was navigating autonomously six out of eight times. We were surprised how much the participants would construe of the motions, especially since much of it was strictly coincidental and implicit. When the robot went into recovery mode and tried to find a different route to its goal—it would start turning in an effort to update its spatial localization, surrounding obstacles, and find a new path. We anticipated this behavior would make the participants understand that the robot was in the process of recalculating its plan for motion. However, this was not the case as the participants expressed vastly differing interpretations in their understanding of what the robot was doing. Some notable quotations among the participants clearly illustrate this. For instance, P3 stated "It [the robot] was certainly not intelligent now", assigning unintelligence to the particular behavior. P5, on the other hand, said he felt the robot was taking a closer look at him, to determine whether it knew him or not. Referring to what he believed the robot was "thinking" he said: "It was a bit like when you meet someone and think 'there is something familiar about you; have I seen you before?'". This notion of asserting humanlike behavior to the robot implies that he believes it to have a high level of intelligence. Conversely, P4 expressed a strong reaction of uncertainty towards the behavior, since she did not understand what it was doing. She stated "What are you [the robot] doing now?" and "Is it sick?."

The differing interpretations among the participants are likely partly caused by the robot behaving somewhat differently in each observation run. This was unavoidable since it was navigating autonomously; dynamically avoiding obstacles. The essentials of the behavior were identical; it would move forward until encountering the participant, then it would try to find a new route to its spatial objective. However, exactly where it would encounter the participant, and how far the robot and the participant would be then, was out of our control.

While it is not ideal for a robot to be in a recovery mode where it has no plan for reaching its spatial objective, it is still better that the users recognize this state should it occur, than being unaware of it. Our findings clearly indicate that the current motion pattern of the ADLR in itself is insufficient for communicating its spatial objectives.

7.1.3 Implications

While the motion pattern of a robot is an import mode of communication for all users, we argue that it will be even more important for the seniors of the population, since they often have impaired hearing or other sensory impairments. These impairments could make it harder for them to perceive some of the other modes of communication.

Through our findings and the preceding discussion, we argue that a robot's motion pattern is important for it to communicate its spatial objectives to humans. Since motion pattern is a part of the communication of all mobile robots, we strongly recommend designers and programmers of robots to put explicit thought into how their robots move, and what this communicates. The alternative is to let the communication remain implicit, resulting in a much larger possibility of misinterpretation and confusion. However we have also seen that the optimal way to communicate clearly is by utilizing different modalities that communicate congruent information.

At the same time, we recognize the significant challenge in making robotic movement patterns clear and unambiguous; when this evidently is problematic even in spatial interactions between humans—despite our multitude of sensory abilities—it will be excessively more difficult to achieve when humans and robots interact in spatial encounters.

7.2 Conflicts in spatial encounters

> Research question 2:
> *In what ways can spatial conflicts emerge in encounters between an autonomous navigating robot and older adults?*

In Chapter 6 we presented two extreme cases where a human and a robot limit each other's mobility: The first was getting trapped by an AGV in an elevator in OH. The second was a resident at Kampen Omsorg+ being unable to pass the ADLR. To discuss this phenomenon, we will borrow a term from Computer Science and programming; namely *deadlock*[1]. We will define what we mean by the term in the following paragraph.

[1] A condition or situation in which it is impossible to proceed or act; a complete standstill [69]

The first situation is a bona fide deadlock; the human and the robot are literally unable to solve the stalemate without intervention from a third-party. The second situation is not strictly speaking a deadlock situation, since the person could solve the situation by backing up or otherwise yield for the robot. However, we will refer to both situations as deadlocks in the following discussion.

Both situations could be solved by the robot withdrawing—but that would require it to already include programming for doing so—otherwise we consider it a third-party intervention. Moreover, if such functionality exists in the robot, it could possibly avoid the deadlock situation altogether.

We have chosen to use these two incidents and the concept of deadlocks to clarify our discussion. However, we recognize that this is no binary phenomenon where there either is a deadlock, or there is not. It is rather a whole spectrum; on one end both robot and human have full freedom of movement, on the other end we have a full deadlock. In between, there are an infinite number of variances.

P8 could have gotten out of the standstill by reversing and giving the robot way, even though she did not do so during the observation. It is likely that had she encountered the robot alone she would eventually have backed up. Therefore, this particular incident is less severe than the one at the hospital. However, if for some reason the older adult is unable to reverse in such an incident, the result will once again be that neither robot nor person can move in any way.

Such an incident only occurred with one of the eight participants, as previously stated. However, it will likely happen whenever there is insufficient room for passing. Seven of our eight participants used a mobility aid, as specified in Table 4.2. Such aids will greatly increase the space required to get past the robot relative to people with no mobility impairment; the robot we used is small enough that they would be able to simply step over it. P8 used the aid with the biggest footprint, and because of this such a situation only happened with her. We observed that all the participants who used a mobility aid required a substantial amount of room to pass the robot. Even P3, who did not use a mobility aid, required a somewhat large area to go past it. Since older adults often have reduced mobility compared to younger people, these situations are likely to occur more frequently for the former group. As such, these situations can constitute a problem for older adults.

In the following, we will use the terms *yielding* and *stopping* frequently. Yielding and stopping usually refer to the same action; when driving a car, one yield for other vehicles and pedestrians by stopping or reducing speed. From our observations, we argue that yielding and stopping should not be considered the same when it comes to domestic robots. We will illustrate this with a short scenario: Imagine relaxing in your garden on a lovely summer afternoon. Suddenly, your robotic lawn mower approaches the chair you are sitting in. It continues until it bumps into the chair, then stops. Nothing more happens; the robot stands still right next to the chair, and it becomes obvious that it will not continue unless you move. After a few minutes, you decide to do so; picking up your chair and moving to another place in the garden. The robot lawn mower immediately continues. However, after a few minutes, the exact same thing happens; the lawn mower bumps into your chair and stops. You realize that this will happen regardless of where in the garden you move, so you decide to relocate yourself to the patio.

Would you characterize the behavior exhibited by the robot in this scenario as *yielding*? We certainly would not, and see this as an illustration of why yielding and stopping should not be considered the same action in the context of domestic robots. Our understanding of yielding and stopping correspond to the B1 and B2 behaviors detailed in Section 4.3.9 that we used during the observations at Kampen Omsorg+.

Deadlocks caused by mobile robots represent a potentially critical issue in regards to safety and utility. In our findings, we discovered deadlock situations in the hospital and at Kampen Omsorg+. In this section, we will discuss why the phenomena occur by reviewing the triggers of the deadlock situations and the relation between the robot and the humans. Secondly, we will propose models and strategies that could prevent such situations.

7.2.1 Triggers of deadlocks

In the observation at OH and on Kampen Omsorg+, we saw that various variables can lead to deadlocks. In the following, we will discuss these by the following categorization:

- Human-robot communication
- The actors' maneuverability
- Level of autonomy and sophistication in obstacle avoidance on the robotic platform

Human-robot communication

The ADLR robot did not have any explicit communication modalities to communicate its intention to the user [8]. However, when we observed the participants' interaction with the ADLR on Kampen Omsorg+, we saw that they were able to complete their tasks in all the runs without any deadlocks, except in one single case. The incident occurred during the B2 run, when the robot was manually controlled to stop upon encountering an obstacle, never yield. Even though the robot was manually controlled, we will discuss the situation as if it was operating autonomously.

In the hospital, we saw that the AGVs had explicit communication modalities, e.g. voice, warning lights, and sounds. Despite this, the deadlock situations occurred. From our experience, the behaviors of the ADLR in B2 and the AGV are quite similar. Their strategy is to stop if an obstacle is in the path of their objective and wait for the obstacle to disappear. If it disappears, the mobile robot continues towards its objective until it reaches its destination or detects a new obstacle in its path.

In the case of the deadlock at Kampen Omsorg+, we saw that P8 tried to navigate around the robot when it stopped. Moreover, that all the other participants were able to complete their runs during the B2 behavior suggests that they knew what to do. However, when the deadlock occurred, P8 was not able to get out of the situation. As she backed up, the ADLR immediately followed forward towards her, as a consequence of the current behavior. This behavior made it more difficult for the participant to resolve the deadlock. The robot's persistence to keep moving forward as long as it did not detect any obstacles could be regarded as an operating issue [3] that was self-reinforced. When the situation occurred, the participant tried to back up to see whether the robot would eventually go around her. Since it did not do so, she was unable to complete the task, and the researchers stopped the observation run. In this case, the mobile robot implicitly communicated [8] that it would not yield, by repeating the motion pattern of moving straight when the participant backed up. In the same way, the robot also implicitly communicated that P8 would have to pass it on one of the sides. However, because of the lack of space between the robot and the surrounding obstacles—combined with the large footprint of the electric wheelchair—this was impossible. The robot did not communicate what action the participant needed to do to get out of the situation; it used no other communication modality apart from its motion pattern. The motion pattern consist mainly of kinesic communication, but also some proxemic communication. The distance between the participant and the mobile robot was less than 0.5 m—which indicates that the robot was within the intimite space or the personal space of P8 [32]. The uncertainty that we observed, and that the participant reported, may partly have been caused by the close proximity of the robot.

It is interesting that P8 reported she felt helpless in the situation because she had no way to communicate with the robot. As discussed in the previous section, metaphorical handshakes through two-way communication is a prerequisite for successfully moving around other people. It is therefore natural that the absence of this possibility leads to uncertainty. It is also interesting that P8 reported she would have moved out of the way of the robot if it had asked her to do so. This indicates that the communication from the robot through its motion pattern was insufficient, but that she would have complied had the message been sufficiently clear by using additional modalities, such as voice.

The AGVs in the hospital had primarily explicit communication strategies. They used voice and lights to communicate their presence and to indicate the direction they were headed. There were also various types of signs and markings on the floor warning people about the hazard of the AGVs as well as information about where to place carts. In addition, we saw that they used their motion pattern to communicate; for instance, the way an AGV would slow down before an intersection communicated a plan of motion. Since the same plan was communicated by the directional lights on the robot, a congruence of communication was achieved, and humans could be more certain where the robot would move next. The wear marks on the floor gave predictability in the sense that people could see where the AGVs had moved most. However, this was no guarantee that the robot would keep away from where there were no visible marks; it might just be that the robots visited such areas less frequently. In the deadlock situations in the hospital, the AGV and the elevator explicitly instructed that people needed to yield for the robot. The lights flashed at a high interval, as the robot slowly entered the elevator. Despite the signals from both the robot and the elevator, deadlocks frequently occurred according to the managing director. Neither the AGV nor the elevator recognized the deadlock incidents; consequently, the person(s) involved were not in any way informed how they should handle the situation. We argue that this implies that the designers of the AGV left an error that led to operation issues, or that the designers left the problem to the human operators [3].

The actors' maneuverability

Sensory, psychological and physical disabilities are three of the afflictions that affect the way a person can detect and avoid obstacles while on the move [6]. Such challenges create restrictions in the maneuverability of individuals. In the observations on Kampen Omsorg+, we saw a difference in the ease of completing the observation runs. Both of the participants using wheelchairs either bumped into the robot or ended in a deadlock during one of their three runs. P7 slightly bumped into the robot in the B3 run. However, he completed the task without stopping his wheelchair. P8 was not able to complete the task in B2 due to lack of space, but she did make it in the B3 run. None of the participants except P7 and P8 touched upon the robot, or ended in deadlock situations. However, we did see a difference between these participants as well. Our findings indicate that the participants using walkers experienced challenges during the B3 run. All these participants stopped in front of the robot in some manner. P1 tried to pass the robot on her left-hand side, but suddenly changed her mind and found a path on her right-hand side. P4 was the only one that passed the robot on her left-hand side, and she only did it during the B3 run. These two instances were the only runs where participants tried or decided to pass the robot on the left-hand side. This observation suggests that there is a preference in passing the robot on the right hand-side. P8 stated:

> "I anticipated the robot to go on the left side, so it would pass me on the correct side.[. . .]I had to move against the direction of travel."

However, the way we conducted the observation can suggest that we influenced the participants by the order of the robot behavior. In the B1 run, the robot navigated very close to the obstacles on the left-hand side of the participant, leaving only the option to pass on the right-hand side. As this was the first run in all except P2s case, it can suggest that it created a precedence in which side to pass the robot.

Furthermore, we saw that the size of the mobility aids, the robot, and the space between the obstacles in the surrounding environment, are significant factors in the occurrence of deadlock situations [9]. Two participants, namely P3 and P5, stood out in this regard; P3 used no mobility aid, and P5 used only a walking cane. Although they had similar reactions in some of the runs such as stopping during B2 and B3; they redirected faster and more seamlessly than the participants using mobility aids. In addition to the restrictions caused by the size of the mobility aids, we also saw a difference between the limitations in maneuverability when using walkers and wheelchairs. Tom, the informant in the hospital, said the deadlocks was mostly an issue among users of mobility aids such as walkers or wheelchairs, and among people transporting large equipment like hospital beds and strollers. An additional element is the ability to perceive what the robot is doing and act on this information. The incident where the woman was startled by the AGV in the hospital shows that lack of attention can cause misunderstandings. This particular person was using her phone while she was walking across the intersection.

Level of automation and sophistication in obstacle avoidance on the robotic platform

In this thesis, we have studied a variety of robots, with different navigational strategies. A question is how the robot's level of automation relates to the challenges in spatial navigation. In this section we will use Sheridan, Verplank, and Brooks definition on the *level of automation* to estimate the robot's level of automation according to Table 2.1 [85]. Furthermore, we will discuss the significance of the latter in light of challenges in spatial encounters between humans and mobile robots.

The AGVs decided when to retrieve and deliver trolleys completely autonomously. However, the operators needed to manage them in the sense that they were started, stopped, reset, and monitored. Additionally, the occurrences of various failures were quite frequent. These failures required diverse interventions from the human operators, such as acknowledging warning messages in the control system, or manually controlling the AGV in the hallways with a tethered remote. The AGV actively informed the operator when it had a problem and suggested to either proceed or stop. Based on this information, we argue that from the perspective of the AGV operators, the robots are on automation level 5.

Conversely, everyone apart from the operators—including staff and patients—had far fewer ways to interact with the AGVs. The information they received was mainly warning messages when they were blocking the AGVs path, or when elevators were reserved for the robots.

We observed two ways non-operators could impose control over the robots: First, they could block an AGV's path, thus preventing it from completing its objective. Second, they could press the stop button on the robot. We argue that neither of these interactions alters the autonomy level of the robot. The first action will only stop the robot temporarily;

the human must eventually move, and the robot can then continue to its objective. The second action will stop it more permanently, but only because the robot is effectively switched off. We argue that this has nothing to do with the automation level; all technological artifacts are possible to turn off, regardless of automation level. Based on this, we place the AGVs at automation level 10 from the perspective of "regular" people.

The ADLR robot is mainly a prototyping platform. However, the robot was able to move autonomously to specific points by using different strategies. Given the scenario that was presented to the participants in the observation on Kampen Omsorg+ (see Section 4.3.9), the ADLR had a high level of automation. The participants had no role in the decision in the robot's path or destination—neither did the robot explicitly communicate its spatial objective, thus, ignoring the human. However, the robot had to consider all obstacles when it was moving. In this sense, the robot's decisions could be manipulated from the participants. Although the robot would have to recalculate the path, the objective would still be the same, characterizing the robot by the highest level of automation—level 10.

Neither the B1 or B3 runs ended in deadlock situations. In the case of B3, we learned through the prototyping process that there are no guarantees of deadlocks not occurring. The way SLAM worked when the robot was navigating from one point to another, was through constant monitoring of obstacles in the planned path. When the sensors detected an obstacle, it attempted to find a new path around it. In addition, when a barrier appeared suddenly or close to the robot, the strategy was to stop, before it tried to find a new path. If the robot was unable to find a path to its spatial objective, it would simply stop exactly where it was. A central issue is that there is nothing in the algorithm that prevents the robot from stopping in a bottleneck. Another dimension is that the ADLR prototype uses Dijkstra's algorithm [17] to find the shortest way possible to the objective. The consequence is that the mobile robot can plan paths around obstacles on both sides, which could introduce an issue if the robot should be consistent on the side it sticks to while moving in a direction.

One of the similarities in all of the behaviors we observed at Kampen Omsorg+, is that there were no strategies for recovering from a situation where a human entirely occupied the path of the ADLR's objective. Even though B1 represent a *utopian* ability to avoid obstacles, an obstacle that is impossible to pass would force the robot to stop.

7.2.2 The priority relation

A condition for movement is that something is moving relative to something else. This is an irreflexive relation, implying that something cannot move relative to itself. Encounters is an extension of this relation in the sense that movement is a requirement for encounters to occur. Moreover, encounters have the additional property of being symmetric. For instance, let A and B be humans. If A encounters B, then B encounters A. If we consider encounters as a *negotiation* between the actors crossing each others path, at least one of the actors need to yield for the counterparty. In this section, we will discuss the encounters in respect to the priority relation—who or what yields for whom?

One view of the AGV at the hospital is that it represents a lower priority because it always waits for the counterparty e.g. a human. In another perspective, the humans represent the actor that has to move away from the path of the robot. In respect to the latter point of view, one could argue that the priorities are opposite. For instance, think of a situation where an AGV encounters a wheelchair user. In this situation, the AGV would stop and ask the person to step aside. However, this would not solve the issue as the wheelchair user is the one who needs to decide on a strategy to pass the robot. The way the AGV interacts with the human in this instance is the robot behavior [9]. A question is whether people find the robot's behavior acceptable.

The staff members in the hospital gave the impression that the AGVs were not occupying the hallways unnecessarily. Some of them mentioned that they found it irritating to wait for an AGV when it reserved an elevator, but they emphasized their understanding of why the elevator was reserved. During one of the focus groups, one of the participants stated; "That is how it is going to work in reality" after viewing a human yielding for the robot (see Section 6.2.3). However, in the second focus group, several participants collectively stated that the robot should yield. Additionally, most of the participants in the observation indicated that they preferred B1 over B2; that is, active yielding over just stopping.

When the AGVs used the elevator, we saw that the AGVs had the highest priority. The individuals in the elevator were forced to use another elevator, take the stairs, or wait for the robot. If they failed to notice that the elevator was reserved, they would risk getting into a deadlock situation. In our findings, the deadlock situations occurred in situations where the robot was holding the higher priority. In OH, the reason for assigning the highest priority to the AGV was to make sure that it could execute its objective. If the AGVs had to wait for people to be finished with the elevator, the robots might never reach their destination. A different solution could be to give the AGVs special privileges to specific lifts. This could make such situations less likely to occur, and could perhaps decrease the need for human operators. On the other hand, implementing this in a real scenario would restrict the efficiency of the AGVs because it could become a bottleneck in the delivery chain. Furthermore, it could become less efficient for the humans, as they would have fewer elevators. The dynamics of the AGV would be restricted, as they could not pick-up and deliver in as many places.

The conflicting findings regarding the priority relation show that it is unclear whom or what should yield. However, in the perspective of *robot acceptance*—understanding the robot's functionality is an important factor [7]; if a person does not recognize or appreciate the utility of a robot, she is less likely to willingly give it priority. For the participants at Kampen Omsorg+, we got the impression that there was more confusion regarding what the robot could do than at the hospital.

We believe the question of whether humans or robots should have precedence when they share the same physical space is an important one. This is not a major concern now, when robots in domestic and public domains are few and far between, but will become increasingly important as the proliferation of robots increases. Our conflicting empirical data show that there is no clear answer; the question must be considered in each specific context.

7.2.3 Design implications

In the following we will describe our deduced design implications. We will emphasize that the proposals we describe have not been developed or tested, they are merely concepts.

Bottleneck avoidance

To prevent deadlocks, one of the biggest issues are the bottleneck areas. What typically identifies these passages is that they have less width than the robot's width and the human's width combined. Moreover, if the person operates a wheelchair or walker, this should also be included in the calculation. Our suggestion is to implement an algorithm that identifies these areas, as a static extension to the map. The aim is to enable the robot to distinguish areas that are more problematic.

An illustration of how a robot plans the shortest path is presented in Figure 7.1. How an implementation of bottleneck avoidance potentially could work, is shown in Figure 7.2. In the latter case, the shortest way is between two obstacles standing quite close to each other. The area between the obstacles is not wide enough for both a human and a robot. Thus, there is a higher probability of conflicts or deadlock situations in Figure 7.1. However, the path of the robot with the bottleneck avoidance implemented results in a longer travel distance.

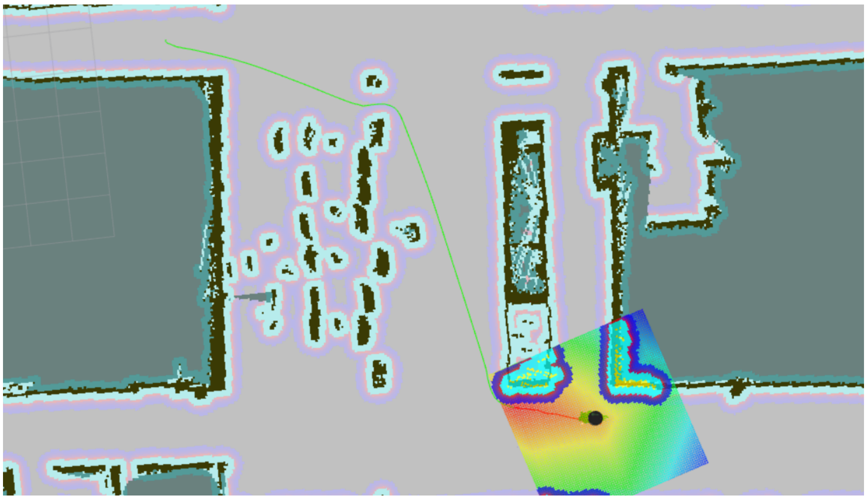

Figure 7.1: Robot navigation without *bottleneck avoidance*

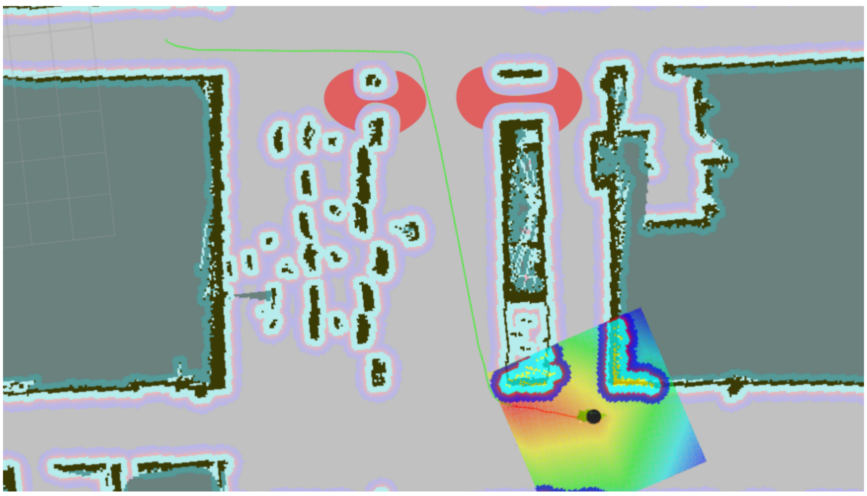

Figure 7.2: Robot navigation with *bottleneck avoidance*

A practical implementation would also require the robot to benefit from the bottleneck areas in pathfinding. The utilization can be implemented by putting a higher cost on these areas; thus it would make the robot find paths outside the bottleneck whenever possible. However, when the robot has no choice, it will use these areas. This approach will only serve to reduce the likelihood of conflicting encounters in bottleneck areas, not remove the occurrence of them altogether. However, these areas could be employed as part of the *recovery behavior*. If the robot decides that it can not achieve its objective through following the path, i.e. the robot stops, then it has the possibility of backtracking the path until it is outside of the bottleneck area.

The avoidance of bottleneck areas could be taken one step further; the robots could try to avoid areas where it is most likely to encounter humans. Since humans frequently move from A to B by choosing the shortest path, this would mean that the robot would have to take a suboptimal route, thus decreasing the efficiency of movement. Such a route could minimize the spatial conflicts and resulting time delays. This approach has similarities with the strategy of avoiding areas where a robot is likely to receive abuse from children by taking a detour [10]. As presented in Chapter 2, this particular study found that the overall time the robot used to move from A to B actually decreased due to avoidance of abuse.

The approach of avoiding the paths most trafficked by humans can be compared to the servants quarters that were common in many large houses from the late 17th century until the early 20th. Similar to a servant, the robot would try to prioritize moving in areas where the likelihood of meeting humans are as small as possible.

The consistency in pathfinding

By default, SLAM uses Dijkstra's algorithm [17] for finding the shortest path to the objective. This algorithm is very consistent in path planning, although it might not be obvious for humans what route it decides on—especially if the robot does not convey its spatial objective. The robots spatial objective and what obstacles the robot detects are the determining factors for deciding on a path. During the prototyping and the observations on Kampen Omsorg+, we saw that the robot cut turns as much as possible. From a theoretical point of view, cutting corners is a result of finding the shortest way in a weighted graph. However, this introduces a conflict if the robot should stick to a specific lane. As P8 mentioned in the observation on Kampen Omsorg+: "[. . .]the robot headed in the wrong lane".

Consistency in which side the robot is navigating could be beneficial. It introduces *predictability* in the movements of the robot, which in turn can be a measure for preventing deadlock situations. Similar to this approach, the AGVs at OH consistently navigated on one side. However, in Incident 2 and Incident 3 in Section 6.1.1, we saw that the employees at OH were startled by the behavior of the AGVs. Additionally, Tom informed us that there had been incidents where humans and AGVs collided. This shows that consistency in holding specific lanes will not remove the possibility of humans crashing into the robot.

Distinguishing obstacles

In the focus group, several participants signalized that the robot should be the one that yields for humans (see Section 6.2.3). Classification of different obstacles can enable the robot to handle obstacles in a more sophisticated manner. If a robot can differentiate between humans and objects it could provide a basis for deciding when to yield. In Figure 7.3, a illustration of human detection is presented. On the lower left side, the detected humans are marked with red squares. Moreover, in the map, the humans are distinguished from other obstacles by the red circle.

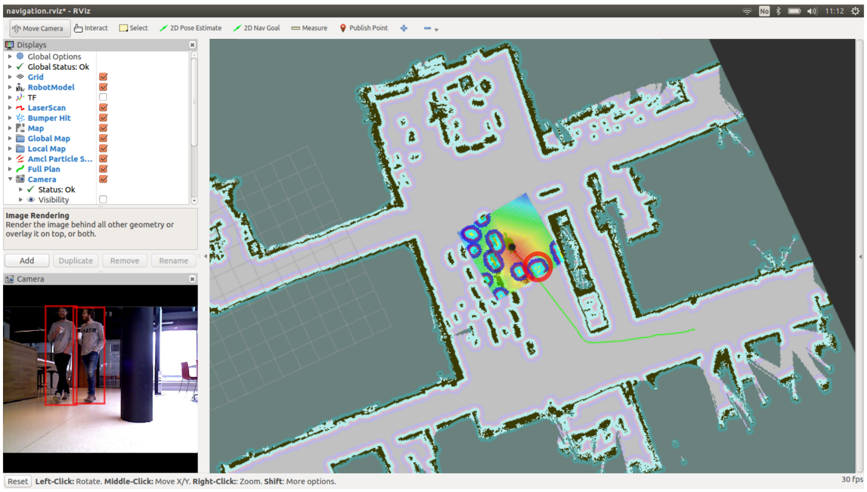

Figure 7.3: Robot navigation with human detection

However, what the robot should do in these situations is not clear. One strategy that was discussed during the focus group, was to predict where the humans are going and avoid that particular path. Another implementation could be to move to the nearest obstacle and stay there as long as a human is detected within a specific range. Both of these strategies would rely on a prediction of where the humans are heading—which may be faulty. The workflow would consist of a series of complex decisions: First, the robot would need to detect the human(s). Second, it would need to calculate the direction and speed of the person to estimate which areas to avoid. Third, a decision in how to yield and when to stop yielding has to be estimated. This workflow is a challenge in the real-time execution of such behaviors. The chain of decisions and the execution on the robot's behalf have to be accomplished within a limited time frame. The time frame, in this case, is between the robot detecting a person and the person passing the robot.

Taking advantage of external sensory capabilities

The deadlock situation with the AGV in the hospital only used the proximity sensor on the robot to identify obstacles in the elevator. The sequence in the deadlock situation (see Section 6.2.1) shows that if a person remained in the elevator while the AGV was entering, the sensors detected the issue when it was too late. Additional sensors in the elevator could increase the robots' confidence in detection of obstacles. For instance, measuring the weight of the elevator or adding a 3D depth camera would allow the AGV to wait at a longer distance from the elevator and not enter when humans are inside.

Avoidance of distant obstacles in path planning

The environments outside of the artificial environments such as factories and laboratories are *chaotic* environments. One of the issues of these environments is the changes that occur in the configuration of people and things over time. Alterations in the real environment which does not occur in the robot's model may cause the robot to miscalculate paths and its position.

By default, SLAM uses two maps to compensate for the issue of altering environments. These are called the global and local costmap. The global costmap is the premade static map. The local costmap is the map of the emerging obstacles the robot's sensors detect and the buffer zone of the obstacles (see Section 5.2.2). When the robot moves, the local costmap overlays the global costmap. This strategy gives the possibility to store obstacles the robot has detected at an earlier stage. However, we experienced that the ADLR did not differentiate between static and mobile obstacles. This caused the path planner to fail during trivial environment changes. For instance, if a person blocked a door and the robot detected it, the path planner would have trouble finding the path to that room when it was in a distant location.

In our configuration of the ADLR, we decreased the radius of the local costmap only to include the range the sensors could detect. This enabled the robot to stop for occurring obstacles without tracking distant obstacles.

However, this strategy is suboptimal because the robot's path calculation will not be able to account for obstacles that are detected earlier.

There are challenges with both the approach of storing and ignoring the distant obstacles in the robot's map. A method that is utilizing stored information about distant obstacles, have to distinguish between static objects and humans. A suggestion is to implement a probabilistic analysis of whether the obstacles are still there. For instance, if the robot detects an obstacle that is not present in its global costmap, it stores the information but awaits using it in the local costmap until it has passed the same obstacle multiple times. The level of certainty increases for each time. How certain it needs to be is hard to say. In addition to how many times an obstacle is detected, the time interval between the detections affects the reliability of the information.

7.2.4 Summary

This section is mainly concerned with what we refer to as deadlock situations. The reason for illuminating this issue is due to the hazard and the operational issue the phenomena represents. Introducing technology that causes the user to get stuck—could potentially endanger the one using it—especially in the case of older adults. Furthermore, the operational issue it represents affects the willingness to use the artifact.

We have discussed what we have seen as the triggers of deadlock situations by considering the communication between humans and robots, the actors' maneuverability, and the level of autonomy and sophistication of software in the robot. To acquire insight to the deadlock situation, we have discussed the relation between maneuverability and the likeliness of yielding. There is no definite answer to who or what should yield for whom. The answer is rather that it depends on the context. Notably, in the case of the AGVs and the ADLR respectively, we have seen that the deadlock situation occurred when the robot had higher priority than humans, with a high level of automation. Whether this would be the case for other robots is not certain. We argue that it is related to what considerations the designers of the software in the robot has taken.

Based on the findings we suggest the following five design implications.

- Bottleneck avoidance
- Consistency in pathfinding
- Distinguishing obstacles

- Taking advantage of external sensory capabilities
- Avoidance of distant obstacles in path planning

These implications include strategies to prevent the robot from encountering deadlock situations. Additionally, in *Bottleneck avoidance* we discuss a strategy that could be beneficial in recovery mode—unless the robot is physically stuck.

7.3 Facilitation for robot autonomy

> Research question 3:
> *How can the introduction of an autonomous navigating robot alter tasks and task distribution in the homes of older adults?*

Section 6.3 showed that all the robots we have investigated both altered existing tasks and added new ones for them to operate properly. We also saw that the tasks varied widely; from small alterations to the operational environment, through continuous tidying tasks, to substantial infrastructure modifications. To accommodate the forthcoming discussion, we will refer to all such tasks as *facilitation*. Furthermore, we will group all facilitation into three self-defined categories, *pre-facilitation*, *peri-facilitation*, and *post-facilitation*.

7.3.1 Pre-facilitation

Pre-facilitation is the facilitation required prior to deployment of the robot. Our empirical data show that users expect some facilitation will be needed. This requirement is sometimes advertised—therefore the user will often know about the tasks required. The discussion in the focus group at Kampen Omsorg+ about whether a robot can handle carpet shows both an understanding that some change will be necessary, but also a reluctance to implement significant changes.

The vacuum cleaning robots that the researchers deployed in their homes required less than 30 minutes of work to set up. Power cords had to be removed from the floor so the robot would not get tangled in them, and the docking station had to be placed (see Section 6.2.3). For the robotic lawn mowers, we consider the task of embedding the cable constituting a "virtual fence" as pre-facilitation. The lawn mower robots thus required substantially more such facilitation than the vacuum cleaning robots.

The pre-facilitation for the AGVs was quite extensive since both infrastructure and building structure had to accommodate them. We argue that this was made possible since the facilitation was done as a part of planning and building the hospital. To implement the same infrastructure in an existing hospital would probably be very expensive, and perhaps not cost-effective.

7.3.2 Peri-facilitation

Peri-facilitation is the facilitation required continuously during deployment of the robot. We have discovered that some of the tasks required might come as a surprise for the user, because they are somewhat unexpected, and not easy to anticipate in advance.

We have seen that all three robots required an uncluttered operating area, and consequently, continuous tidying is part of the peri-facilitation for all the robots.

It is clear that both the vacuum cleaning and the lawn mowing robot eliminate some tasks, but add others, as is the case with most technologies (see Section 2.3.8). During the time of testing the vacuum robots we no longer had to spend approximately half an hour every week to vacuum; instead, we spent a few minutes almost every day to facilitate for the robot. It is interesting to note that both the vacuum cleaning robot and the lawn mowing robot gave no definite efficiency increase. These results show that one of the main incentives for getting a domestic robot—spending less time on the task—might be flawed. In theory, the increased efficiency may be substantial, but in real life, the equation is more complex.

Another incentive for acquiring a robot is the result. With the vacuum cleaning robot, this was undeniably better; far less dust gathered on the floor compared to using a regular vacuum cleaner, since the robot vacuumed more frequently. The result with the lawn mowing robot was somewhat unclear. The majority of the lawn will be better since the grass is mowed more often, although some parts might not be cut at all, due to the robot not being able to access them. Whether this is a better or worse result depends entirely on the preferences of the user.

Peri-facilitation for the AGVs in the hospital was on a whole other scale than that of the vacuum and the lawn mowing robots. Three full-time employees operated them as their main task, working in shifts so that one of them always would be present to monitor the robots. After studying robots navigating autonomously in the same areas as humans, this did not come as a surprise for us. There is an almost infinite number of small complexities and variables that in sum will result in unpredictable breakdown situations. The aspect that we find more interesting, is the fact that Tom said constant monitoring had not been initially planned. This speaks to a discrepancy between the assumed capabilities of robots, and the actual ones. However, one would think that the company producing the AGVs could clarify such faulty assumptions. We can only speculate why this did not happen. One possible reason is that there could be misunderstandings in the communication between the hospital and the AGV manufacturer. A second is that OH could be one of the first locations where such a system was implemented, such that even the manufacturer had unrealistic expectations.

The periodic maintenance performed by technicians from the manufacturer that delivered the AGVs should also be considered as peri-facilitation.

Even though the AGVs required a substantial amount of peri-facilitation, they seemingly gave a net positive amount of work. Tom, the managing operator, said they provided the same work as 15 to 25 full-time employees, based on between 400 to 500 assignments every day. Even when one subtracts the three full-time employees operating them, this equation shows a net positive from the view of the hospital administration. The positive contribution of the AGVs was compounded since they can carry heavier loads than a human porter, do not mind that the work is tedious, and have no reservations against unsavory assignments.

However, this equation could be somewhat flawed. Tom mentioned that some other employees had to use a system for ordering the AGVs services. We have not investigated how much time this task took, but it is likely that it in total would be a substantial amount. Such facilitation should also be included in the equation, and it is likely that the AGVs generated even more facilitation that neither Tom nor we thought about.

7.3.3 Post-facilitation

Post-facilitation is the larger alterations one might do—or wish to do—after having deployed the robot for some time. These are very hard to predict since they require a thorough understanding of how the robot works, and many are caused by small details that one only recognizes through experience.

During our test of the vacuum cleaning robots, we experienced an inclination towards some of this post-facilitation. One of the researchers observed that the legs on his TV-table were too low to allow the robot to clean under it, while the other noticed it could not clean under his sofa. Since we only had the robots for a limited time, no changes were made. We would probably not have purchased a new TV-table and sofa even if we had the robot permanent. However, it could have influenced us to buy those things earlier than we would otherwise, and at that time, we definitely would have taken the robot requirements into consideration.

Sophie had already done some post-facilitation and contemplated doing more. She had removed a stump from the garden, had contemplated removing her apple tree, and considered removing some stone steps. We did not observe any such post facilitation in the garden of Olivia, but the plans of her neighbor to redesigning his entire garden to facilitate for the robot is a prime example of post-facilitation.

In the hospital, we did not observe any such post-facilitation, but we will not exclude the possibility of such alterations having been done at an earlier time. However, we will argue that the inevitable replacement of the robots—and the infrastructure changes that may come because of it—is post-facilitation. We find it somewhat imprudent that according to Tom, there was no plan for the replacement of the AGVs. For instance, he mentioned that it was getting harder to get spare parts, as the manufacturer did not produce the particular AGV model anymore. Tom added that some of the spare parts had to be custom made—thus increasing the price. Furthermore, Tom said that there were no formalized strategies in co-operation between the hospitals that used AGVs—which could be beneficial in the sense that they could utilize each others experiences. This illuminates the benefit of *proactive* processes rather than *reactive*. Particularly when the resources needed for gathering information about others experiences are available.

The findings of facilitation for robot autonomy provides evidence that the facilitation required for the investigated robots was extensive. Furthermore, much of said facilitation was hard to know about before acquisition of the robot and therefore came as a surprise for the users. The findings are based on empirical data from investigations on only three different robots. However, both current literature and our knowledge of robotics suggest that this holds true for most contemporary robots—especially the ones intended for domestic use. The unforeseen facilitation is a part of the *reality gap* inherent in robotics; things that work perfectly in a simulation or a lab will most likely be more problematic when exposed to the real world and its complexity.

During work on our thesis, a news article was released, with a statement from the Norwegian Directorate of Health where they warn against domestic robots [54]. They make the argument that such robots perform manual chores which we previously had to do ourselves; thus leading to increased inactivity and deteriorating health. The article contains no reference to studies that can substantiate this claim. Superficially, the argument is valid: (1) A woman regularly vacuums her home, necessitating movement; (2) the woman purchases a vacuum robot; (3) the robot vacuums the woman's home; (4) the woman becomes less active.

However, as our discussion shows, this portrayal of the chain of events is an oversimplification—it fails to take into account various nuances that also might be of relevance: Does the increased tidying that must be done counteract for the decrease in activity? Can the robot affect the mental health of the woman? What does she do with the added free time? These are just a few examples of factors that might change the situation, but they do show the necessity of making more thorough assessments of what changes come from a new technology.

Such oversimplified statements from governmental agencies—lacking any corroborating evidence—can be damaging. Since the information originates from a recognized authority, people are likely to regard it as highly credible, maybe more than what is prudent.

7.3.4 Costs and benefits of a robot

When the time spent on facilitating for a particular robot is accumulated, and compared to time spent on the task the robot is supposed to replace, we found that the result is unclear. It might require more time, less time, or approximately the same. Since increased efficiency by spending less time on a task is arguably one of the main incentives for acquiring a robot, we consider this realization particularly interesting. One question in particular arise; *would the user have acquired the robot if he knew this ahead of time?*

To answer this question one could try to determine whether the robot constitutes a net benefit for the user. However, this question is near impossible to answer, and the answer will be different in every context. The first problem with answering the question is that comparing the time spent is far from straightforward. If we use a vacuum cleaning robot as an example, one could relatively easy record and add together all the periods of time spent on regular vacuum cleaning. However, after the vacuum cleaning robot is in place, the equation becomes less clear. Instead of spending distinctive, relatively large time periods, the work shifts into doing various short tasks that are more or less related to the act of vacuum cleaning; e.g. programming the robot on a mobile app, removing a sock from the floor, and moving a chair. Some of these tasks exclusively facilitate for the robot, such as the task of programming it, while others have multiple purposes. Removing a sock from the floor not only makes it easier for the robot to vacuum, but it also makes the home more tidy and pleasant. To further add to the complexity, these small tasks only constitute the peri-facilitation; for the calculation to be complete the pre- and post-facilitation must be considered as well.

Even if there was some way to calculate these figures definitely, it makes little sense to compare them directly to one another to find whether there is a net benefit of the robot. This leads to the second problem with answering the question; the tasks required are completely different before and after. The user might have a preference for the new kind of tasks that the robot introduces, depending on his interests. Also, he might prefer multiple short tasks over one long, even when the total time amounts to the same.

The third problem that makes the answer to the question unclear is that time is not the only incentive for acquiring a robot; the result is equally, or perhaps, more important.

These problems will in combination make the answer to the question posed a few paragraphs ago next to impossible to predict—it might even be hard for a user to answer himself.

The obvious way to make sure a robot represents a net benefit for a user is to eliminate the facilitation tasks required altogether—not only peri-facilitation but pre- and post-facilitation as well. The "ideal" scenario would be to acquire a robot, place it in its operating area, and start it. The robot would then do its job without requiring the user to facilitate and with perfect results—which resembles level 9 or 10 in the level of automation in Table 2.1 [85]. This scenario closely resembles how robots frequently are depicted in science-fiction literature and films. However, this is a utopian scenario; the state of technology in contemporary society does not allow us to make robots this advanced. Nevertheless, the state-of-art of technology is continuously expanding, with new possibilities emerging. We argue that this progress should be employed to remove as much as possible of the facilitation tasks required for robot autonomy.

Since discarding with the facilitation tasks altogether is currently not possible, we propose the next best thing; make sure the users are well acquainted with the necessary facilitation prior to the acquisition of a robot. By doing this, the decision to get a robot will be more informed, and there will be less chance of adverse surprises and disappointment. However, to fully inform users about the facilitation required is implausible; many of the tasks are unpredictable—by definition hard to foresee—and dependent on the context. Still, this should not be used as an excuse for not informing;

it is beneficial that the users know facilitation will be required, even if the particular tasks are uncertain.

Thus far we have discussed facilitation for robots predominantly as a negative aspect. That might not always be the case. For instance, if the deployment of a robot results in the habit of keeping one's home tidier, this is a positive outcome. The facilitation has ceased being a set of tasks and rather become a change of practice.

7.3.5 Cognitive dissonance and Material Agency

We have shown that a robot might not only require small changes and facilitation, it might also induce the user to implement more pervasive changes to their homes or environment to help the robot. Most of such changes will probably be aligned with the person's other interests, but the findings indicate that some might not. Sophie reported she had contemplated removing an apple tree also said she did so solely because of the robot lawn mower, not because she inherently wished to remove it. These situations, where a user contemplates or enacts changes because of a robot that she otherwise would not, are unfortunate. At best, the change would be considered neutral had the robot been removed from the equation, but it could also be deemed negative.

It is prudent not to exaggerate the problem. The user can never be forced to perform any such changes by the robot; it will always be hers or his decision, based on an overall assessment of the situation. Nevertheless, all technologies that introduce a conflict of interest inherent in a person can be unfortunate. Such conflicts can result in a *cognitive dissonance* [21] where the user ends up with two contradicting ideas; on the one side wanting to facilitate for the robot, but on the other being reluctant to the change since it would remove a desirable attribute. Cognitive dissonance can lead to a feeling of psychological discomfort, and motivation to reduce the mental stress.

Contemporary technologies are irrefutable not sentient; they are not self-aware and do not have any will of their own. However, some authors argue that technology can become an actor asserting change itself [34], through *Material Agency* [73].

Robots operate best in homogenous and uniform environments; the ideal lawn for a mowing robot would be a flat rectangle with no trees or obstructions of any kind. Such an environment has lower complexity than real home environments. For the same reason, robots generally perform better in a lab setting than in a home context. This prepossession runs contrary to the preferences of many humans; we celebrate diversity and strive to distinguish ourselves from others. We argue that this large disparity can make the *Material Agency* of a robot substantial. If robots successfully influence their users to implement changes that facilitate for the robot, this could over time result in a less diverse environment. *Is this something we should allow robots to do?*

7.3.6 Design implications

The findings show that the tasks required or enacted vary immensely; from picking up a sock from the floor to remodeling an entire garden. We categorized the facilitation into three groups. Of these three groups, we argue that peri-facilitation will be the one of most importance for older adults. The other two types of facilitation are limited in time and can, therefore, be done by others than the seniors themselves. The findings show an example of this; the older woman we interviewed about her lawn mower robot had extensive help from her relatives for doing the required pre-facilitation. However, since the peri-facilitation by definition is continuous, the user will be more or less left to her own devices: She lacked the aptitude and knowledge to operate the robot herself, and therefore depended on it operating according to the programmed schedule. Besides, we observed at Kampen Omsorg+ that many of the residents had some mobility impairment, which also could make it hard to perform the continuous tasks that the peri-facilitation constitutes.

These findings indicate that for a robot to be deployed in the home of older adults successfully, it should require little to none peri-facilitation. This will probably make the pre-facilitation more extensive, but that is a necessary compromise. Nevertheless, successful deployment and integration are also dependent on the seniors accepting the changes caused by the pre-facilitation. Discussions in the focus groups indicate that some changes will be accepted, while others will not. However, it is important to note that no actual observations were performed to test which changes seniors will accept and which they will reject. Therefore the opinions they gave during the focus groups should not be given prominence. Extensive observations must be performed to gain any degree of certainty.

7.4 The functionality of robots

Robot functionality cannot be linked to any single one of our research questions; it is an all-encompassing topic that has relevance for all three of them. Unless the robot has sufficient functionality so that the older adults perceive it as useful and relevant, movement and navigation are irrelevant. This became evident by the fact that the most frequent question the older adults have asked through our research is "What can it do?", referring to one of the robots we showcase. To discuss the reason for the frequency of this topic—and to consider what functionality older adults expect from a robot—we will refer to functionality as two types: primary-functionality and secondary-functionality.

Primary-functionality is the actual utility of the robot for a user; what task can it perform, or which service can it provide to the user. Some examples of primary-functionality include vacuuming, cleaning, transporting, mowing the lawn, and monitoring health status.

Secondary-functionality is the supporting functionality of the robot; this is required for the robot to be able to perform its primary-functionality. Secondary-functionality includes navigation, movement of extremities, movement of the robot itself, and algorithms for utilizing various sensor data. Some of the secondary-functionality can be very advanced, and thus exceedingly difficult to perfect; e.g. creating a robot that can navigate and move through the world as well as a human or an animal can. This complexity makes the creators and programmers of the robot acutely aware of the functionality. However, unless the robot also has some primary-functionality, it has no usefulness for a user, and they might not consider the robot to be relevant or of value to them.

Superficially, these groups are distinct and clear; but they become less so when we introduce the argument that the groups depend on the perspective of the user. To illustrate this, we will consider the ADLR-robot used throughout the thesis work. In Table 7.1 and 7.2 the functionality has been categorized from the perspective of a researcher and a resident at Kampen Omsorg+, respectively. These tables show that the robot provides ample primary-functionality for a researcher, but none for an end-user.

Table 7.1: ADLR-functionality from researchers perspective

Primary-functionality	Secondary-functionality
Learn about ROS	Navigate autonomously
Elicit opinions from others about the robot	Dock with charging station automatically
Perform observations with the robot	

Table 7.2: ADLR-functionality from users perspective

Primary-functionality	Micro-functionality
None	Navigate autonomously

The differing ways researchers and robots perceive functionality became evident during observation sessions at Kampen Omsorg+. As explained in Section 4.3.9 one of the observation runs had one researcher manually controlling the robot to dynamically yield to the right for the participant—much as a human would do. As researchers, we realize the complexity in managing to get a robot to do the same thing autonomously. To mention a few, it would have to differentiate between humans and obstacles, as well as be able to precisely determine the distance, speed, and direction of the human. However, even though the participants believed the robot to be navigating autonomously, they were not impressed; one participant said that from her perspective "It[the robot] did nothing." Several others expressed similar views.

Conversely, in the run where the robot would simply stop upon encountering an obstacle—a far easier feat to accomplish from our perspective—many of the participants said that they perceived the robot to be more active; or to have more functionality.

We believe this difference in perception from separate point of views to be the crux of the reason as to why we were frequently asked about the functionality of the robot: It has apparent primary-functionality for us, but for the user, it has none. We consider the constant recurrence of this question important in two regards: it is indicative towards older adults demanding clear and useful functionality from a robot; and secondly, it became a methodological challenge throughout our studies. The former aspect will be discussed in the following paragraphs, while the methodological challenge is discussed in Section 4.5.

The first point was corroborated by our focus groups, interviews, and informal discussions at Kampen Omsorg+. The participants and interviewees put great emphasis on the robot needing to be useful for them. A multitude of desirable functionality was proposed and discussed by the senior citizens, including cleaning, vacuuming, tidying, and serving coffee. One participant amusingly suggested that a robot could be used as a companion in bed.

Some of the robots we showcased were only meant for entertainment, such as the NAO robot. The participants response to these varied. Some appreciated the robots and expressed a wish to own one, while others pronounced "It is only a toy!" with disdain. Even though the robots elicited varying opinions among the residents, the attitude of the majority were one of skepticism. This further indicates the importance of clear and unambiguous primary-functionality in a robot for the older adults to accept it.

One possible primary-functionality was notably absent from the discussion in the focus group, namely that of a robot providing an increased sense of safety. Since this is a focus area of the MECS-project, we explicitly introduced the topic. Once introduced, the participants clearly stated that the feeling of safety was one of the main concerns in their lives. One participant said that: "No, I believe that it would be enough[functionality] if it could provide a sense of safety." Several other participants were in agreement with this statement. The participants said that a major problem at Kampen Omsorg+ was that residents would fall over and be unable to get up on their own. We asked whether providing increased sense of safety would be sufficient functionality from a robot, or if it should be able to do other things as well. The consensus in the group was that this would indeed be enough.

However, it would be imprudent to take this answer at face value. It is widely recognized that users have a tendency to say one ting, but do something else, for various reasons. The assertion would have to be tested to be able to determine its correctness, something we have not been able to do since the proposed health monitoring robot is currently just a concept, not a physical prototype. Conducting tests of prototypes is important in the entire domain of Interaction Design, but we argue that it is even more so in the domain of HRI. Since a robot represents a pervasive change to the user's environment, and we have seen that much of the facilitating tasks that are required are hard or impossible to predict ahead of deployment, testing is essential.

Chapter 8

Conclusion

"To summarize the summary of the summary: people are a problem."
– Douglas Adams, *The Restaurant at the End of the Universe*

This final chapter summarizes our main insights and implications from the discussion, before we propose future work based on our thesis.

8.1 Main insights and implications

In this thesis we have conducted an explorative study on how older adults and autonomously navigating robots interact in spatial encounters. During our work, we have seen a variety of pertinent aspects influencing the encounters. We chose to investigate the following themes; (1) interpretation of robot communication, (2) the conflicts in spatial interaction, and (3) the facilitation of robots.

The three themes in our thesis are connected since they all concern spatial interaction and encounters between older adults and robots. However, they are also more intimately linked. The communication and interpretation between a human and a robot can significantly influence the likelihood of conflict situations or other challenges in spatial encounters. The communication can also affect the facilitation that will be required since clear communication can decrease the occurrences of mishaps. Facilitation is linked to conflict situations since increased facilitation for the robot can alter the probability of such situations.

The older adults who partook in our empirical activities had various reactions towards robots. They were a heterogenous group with disparate backgrounds, interests, opinions, and age. We have seen the importance of close collaboration with the actual users: Our design implications have not materialized by mental agility; but emerged from specific challenges, situations, and interactions.

8.1.1 Robot communication

Robots can potentially employ a multitude of communication modalities to communicate with humans. We argue that one must strive for this communication to be congruent; the different modalities should communicate the same or similar information. Successfully doing so will make the diverse sources of information complement each other, thus increasing the possibility that the human interprets it correctly. Conversely, incongruent information can result in ambiguity and misinterpretation.

Multiple modalities and congruent commmunication are important for older adults. Many of them have one or more impaired senses, thus multiple modalites can be essential for them to perceive the communication.

How can we achieve congruence between the communication modalities? We propose that one must endeavor to make the robot communication explicit rather than implicit. Our empirical data has shown that mobile robots emanate communication through their motion pattern and that this communication will be interpreted whether it is explicit or implicit. Furthermore, the data has shown that the communication given by the motion pattern often is implicit; the motion pattern of the ADLR was completely implicit. We believe a greater focus on a robot's motion pattern and what it communicates will go a long way to make robot communication more congruent and unambiguous.

8.1.2 Robot navigation

The algorithms that govern the way a robot navigates are mainly employed to optimize the route; how can the robot most efficiently move from point A to point B? They do take into account obstacles—both fixed and moving—but humans are frequently regarded as just another obstacle. By focusing on optimization, the risk of spatial conflicts between robots and humans increase, since humans also tend to take the most efficient route from point A to B.

We have seen that such spatial conflicts can become severe if the area in which they occur is narrow. We have observed some extreme cases where a robot and a human are unable to move because of each other. We have denoted such situations as *deadlocks*. This is more likely to happen with older adults since they often require a larger area to move; due to mobility aids or mobility impairments. We argue that robots should be able to identify areas where conflicts are likely to happen so that they can avoid them or take extra precautions in them, such as reversing out when encountering a human. For the latter to be possible, the robot must be able to distinguish between humans and obstacles.

To take the argument one step further, we propose the possibility of intentionally making the robot navigate in a suboptimal way, to prioritize humans by avoiding the paths most frequented. We do not state this as a solution, but merely argue that the question should be carefully considered.

8.1.3 Robot facilitation

It can be easy to think of robots as a technology that has the potential of eliminating tasks. We have seen that this is not the case; akin to other technologies they rather cause a redistribution of tasks— adding, altering, and removing. We have proposed to name all the tasks required for a robot to operate autonomously as facilitation. Furthermore, we have introduced a framework for categorizing the facilitation—partly temporal, but even more based on the purpose of the facilitation. We use the three categories *pre-facilitation*, *peri-facilitation*, and *post-facilitation*. Pre-facilitation is the facilitation required prior to deployment of the robot. Peri-facilitation is the facilitation required continuously during deployment of the robot. Post-facilitation is the larger alterations one might do—or wish to do—after having deployed the robot for some time.

Our results show that the sum of the facilitation for the robots we have investigated is extensive, largely because of the autonomous movement in space. They further indicate that it is difficult to predict whether a domestic robot will be considered a net benefit to an end user, as this will depend on both the specific user and the context. The only one who can answer the question is the user him or herself, and only after having used the robot for some time.

We have identified that the most crucial facilitation for an older adult to be able to use a robot is that of peri-facilitation. The tasks that belong to this category must be done continuously; thus they are the hardest for an older adult to get any help in doing. The other types of tasks are done in specific intervals of time, and therefore it is easy to receive help or get someone else to do the task altogether.

Lastly, we have seen that autonomous robots can influence people to do or want to do changes to the environment for the sole purpose of better facilitating for the robot. Some of these changes could go directly against the inherent inclinations of the person, meaning they would never even consider them if the robot was removed. We do not state that this is necessarily damaging; formerly introduced technologies has shaped much of our environment. We merely supplicate that the question should be considered explicitly.

8.2 Future work

The work in this Master's thesis has opened for several possibilities for future work. More knowledge concerning spatial interaction is needed to be able to utilize robots in domestic contexts among older adults and other citizens.

The ability for a robot to move autonomously with specific objectives, is a condition for many areas of use. Safety monitoring, security monitoring, and transport serve as examples of some applications robots can contribute in the future. Our findings suggest that there are different strategies in pathfinding. Furthermore, the interpretation of a robot's movements and challenges in spatial encounters depend on the context. The design implications discussed in Chapter 7 are not explored in our prototype. Researching one or more of these implications would contribute to the understanding in HRI and HRSI.

The user's control depends on the level of automation in the robot. Researching this phenomenon, using various forms of user involvement through implicit and explicit communication of the robot's decisions—would contribute in understanding what humans expect, thus enforcing acceptance of robots and how humans can solve tasks along with robots.

Research of mobile robots in lab environments is a very important first step. However, without deploying robots in the actual environments and contexts where they are supposed to perform tasks, it is impossible to know whether they will work, especially among humans. Moreover, there is a need for long-term studies of mobile robots. Many of the challenges in spatial interactions are corner cases, which may not occur in controlled experiments and observations. Expanding the time scope will reveal many of these challenges.

Epilogue

Come, old broomstick, you are needed,
Take these rags and wrap them round you!
Long my orders you have heeded,
By my wishes now I've bound you.
Have two legs and stand,
And a head for you.
Run, and in your hand
Hold a bucket too.

We begin the end, as the beginning began; with the third stanza in Johann Wolfgang von Goethe's poem *The Sorcerer's Apprentice*—or as it is called in the original language of German; *Der Zauberlehrling*. We explained how we sometimes think of novel technologies in general—and robots in particular—as a kind of magic. The poem is from 1797, a fact that incites an interesting thought: Had we been able to travel backwards in time and show Goethe the technologies that people take for granted today, he would most likely have believed it to be actual magic.

However, he might also have responded with dread, as the poem is a tale of caution. It begins harmoniously as previously stated: The Sorcerer's Apprentice is tired of fetching water by pail, so he enchants a broom to do the job for him. The problem is that he does so using magic in which he is not yet fully trained. In the beginning everything is fine; the broom fetches water while the apprentice can relax and monitor its progress. However, when the basin is full and the apprentice tries to make the broom stop, he discovers that he has forgotten the stop word, and from thence the situation quickly deteriorates:

Brood of hell, you're not a mortal!
Shall the entire house go under?
Over threshold over portal
Streams of water rush and thunder.

Broom accurst and mean,
Who will have his will,
Stick that you have been,
Once again stand still!

The apprentice's attempts to stop the broom are unsuccessful. He becomes desperate, takes an ax and chops the broom into pieces. Alas, this only serves to make the situation exponentially worse; every piece turns into a new broom, and the water continues rising at a rampant rate. When the situation is at its most dire—just before the apprentice drowns—the Sorcerer comes and immediately solves the crisis.

The reason why we have chosen to feature *Der Zauberlehrling* so prominently in our thesis, is how we came to know it. We first became acquainted with this poem when a male resident at Kampen Omsorg+ spontaneously recited two of its lines during one of our focus groups:

Die ich rief, die Geister,
Werd ich nun nicht los.

He explained that the lines roughly translates to: *The spirits that I called, I can't get rid of*—and gave a brief summary of what the poem is about. Furthermore, he told us his interpretation of the text, and that he found the poem an apt metaphor for the dangers robotics can pose—being a technology that we do not fully understand.

We wholeheartedly agree with his assessment; especially since in the real world, there is no all-powerful sorcerer who can relieve us from our plights. Hence we see it fitting to let his concluding remark be the final words of our thesis:

"Remember the stop word!"

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Appendices

Appendix A

Consent form

Samtykkeerklæring om deltakelse i forskningsprosjektet: Multimodal Elderly Care System (MECS)

Bakgrunn og formål

MECS er et pågående forskningsprosjekt ved Universitetet i Oslo, Institutt for Informatikk. Prosjektets formål er å undersøke bruk av informasjons- og kommunikasjonsteknologier (IKT) i sammenheng med helseteknologi og robotteknologi. I dette ligger det å forstå brukernes behov gjennom brukersentrert design, utvikle effektiv sansing av hvordan mennesker oppfører seg og deres helsesituasjon, og utvikle læringsmetoder for å forutse uønskede hendelser. Prosjektet vil på denne måten demonstrere mulighetene for modellering og prediksjon for økt sikkerhet og personvern til hjemmehjelp for eldre.

Målgruppen for studien er eldre mennesker som bor hjemme eller på institusjon tilsvarende eldrehjem. Du er forespurt om å delta i studien fordi du passer i denne beskrivelsen.

Hva innebærer deltakelse i studien?

Vi ønsker å snakke med deg om teknologi og roboter. Vi kommer til å ta lydopptak og notater av det du forteller. Hvis du tillater det vil vi gjerne også ta noen bilder.

Deltakelse i studien vil *på ingen måte* påvirke ditt nåværende behandlingstilbud.

Hva skjer med informasjonen om deg?

Alle personopplysninger vil bli behandlet konfidensielt. De vil lagres på egne krypterte servere som kun brukes til forskning ved Universitetet i Oslo. Opplysningene vil kun være tilgjengelig for utpekte medlemmer av prosjektgruppen som har et aktuelt behov. Konfidensialitet opprettholdes ved at vi bruker en egen liste der deltakernummer kobles med navn og andre personopplysninger.

Du vil ikke på noen måte kunne gjenkjennes i materiale som publiseres fra studien.

Prosjektet skal etter planen avsluttes 31.12.2020. Alle personopplysninger vil da anonymiseres. Alle opptak vil slettes, uavhengig av om de inneholder personopplysninger eller ikke.

Frivillig deltakelse

Det er frivillig å delta i studien, og du kan når som helst trekke ditt samtykke uten å oppgi noen grunn. Dersom du trekker deg, vil alle opplysninger om deg bli slettet.

Dersom du har spørsmål til studien, ta kontakt med førsteamanuensis Jo Herstad ved UiO, tlf. 228 40 051.

Studien er meldt til Personvernombudet for forskning, NSD – Norsk senter for forskningsdata AS.

Samtykke til deltakelse i studien

Jeg har mottatt og forstått informasjon om studien, og er villig til å delta (Ja) _____

Jeg gir tillatelse til å bli fotografert (Ja) _____

Jeg gir tillatelse til lydopptak av samtale (Ja) _____

Jeg gir i tillegg tillatelse til at bilder blir brukt i dokumenter, presentasjoner og demonstrasjoner fra prosjektet. Slikt materiell vil være allment tilgjengelig utover prosjektperioden (Ja) _____

Deltakerens fulle navn: ____

____________________ ____

Sted, dato Signatur av representant for MECS prosjektet

Appendix B

NSD approval letter

Jo Herstad
Institutt for informatikk Universitetet i Oslo
Postboks 1080 Blindern
0316 OSLO

Vår dato: 21.11.2016 Vår ref: 50689 / 3 / STM Deres dato: Deres ref:

TILBAKEMELDING PÅ MELDING OM BEHANDLING AV PERSONOPPLYSNINGER

Vi viser til melding om behandling av personopplysninger, mottatt 21.10.2016. Meldingen gjelder prosjektet:

50689	*MECS: Multi-sensor Elderly Care Robot Systems*
Behandlingsansvarlig	*Universitetet i Oslo, ved institusjonens øverste leder*
Daglig ansvarlig	*Jo Herstad*

Personvernombudet har vurdert prosjektet, og finner at behandlingen av personopplysninger vil være regulert av § 7-27 i personopplysningsforskriften. Personvernombudet tilrår at prosjektet gjennomføres.

Personvernombudets tilråding forutsetter at prosjektet gjennomføres i tråd med opplysningene gitt i meldeskjemaet, korrespondanse med ombudet, ombudets kommentarer samt personopplysningsloven og helseregisterloven med forskrifter. Behandlingen av personopplysninger kan settes i gang.

Det gjøres oppmerksom på at det skal gis ny melding dersom behandlingen endres i forhold til de opplysninger som ligger til grunn for personvernombudets vurdering. Endringsmeldinger gis via et eget skjema, http://www.nsd.uib.no/personvern/meldeplikt/skjema.html. Det skal også gis melding etter tre år dersom prosjektet fortsatt pågår. Meldinger skal skje skriftlig til ombudet.

Personvernombudet har lagt ut opplysninger om prosjektet i en offentlig database, http://pvo.nsd.no/prosjekt.

Personvernombudet vil ved prosjektets avslutning, 31.12.2020, rette en henvendelse angående status for behandlingen av personopplysninger.

Vennlig hilsen

Kjersti Haugstvedt

Siri Tenden Myklebust

Kontaktperson: Siri Tenden Myklebust tlf: 55 58 22 68
Vedlegg: Prosjektvurdering

Dokumentet er elektronisk produsert og godkjent ved NSDs rutiner for elektronisk godkjenning.

Personvernombudet for forskning

Prosjektvurdering - Kommentar

Prosjektnr: 50689

FORMÅL

Prosjektleder sin beskrivelse: "The goal of MECS is to create and evaluate multimodal mobile human supportive systems that are able to sense, learn and predict future events. By using complementary sensor technology and machine learning analysis and modeling techniques, we will target the development of novel monitoring and robot systems to be applied in home care applications. Further, we will optimize their usability through participatory design, involving users in actual use contexts."

UTVALG

Utvalget består av oppegående eldre mennesker som bo hjemme, deres pårørende, assistenter og helsepersonell. Deltakerne rekrutteres gjennom Kampen Omsorg+, Oslo kommune og andre brukerorganisasjoner. Interesserte bes om å ta kontakt med prosjektleder om de ønsker å delta.

Dersom det skal gjennomføres intervjuer med pårørende/assistenter/helsepersonell ber vi om at intervjuguider og informasjonsskriv ettersendes til personvernombudet@nsd.no.

INFORMASJON OG SAMTYKKE

Utvalget informeres skriftlig om prosjektet og samtykker til deltakelse. Informasjonsskrivet til de eldre er godt utformet.

METODER

Datamaterialet samles inn gjennom intervjuer og observasjon. I tillegg er det krysset av for at det skal registreres personopplysninger via papirbasert- og elektronisk spørreskjema og blogg/sosiale medier/internett. Når det gjelder den elektroniske spørreundersøkelsen og innsamling gjennom blogg/sosiale medier/internett, fremgår det av prosjektmeldingen at dette ikke er utarbeidet enda. Vi har derfor ikke vurdert disse delene av prosjektet. Når og om det blir aktuelt å gjennomføre datainnsamling gjennom ovennevnte metoder, ber vi om at prosjektleder sender utfyllende informasjon, samt spørreskjema, til personvernombudet@nsd.no.

SENSITIVE PERSONOPPLYSNINGER

Det behandles sensitive personopplysninger om helseforhold.

INFORMASJONSSIKKERHET

Personvernombudet legger til grunn at alle data og personopplysninger behandles i tråd med Universitetet i Oslo sine retningslinjer for innsamling og videre behandling av forskningsdata og personopplysninger.

PROSJEKTSLUTT OG ANONYMISERING

Forventet prosjektslutt er 31.12.2020. Ifølge prosjektmeldingen skal innsamlede opplysninger da anonymiseres. Anonymisering innebærer å bearbeide datamaterialet slik at ingen enkeltpersoner kan gjenkjennes. Det gjøres

ved å:
- slette direkte personopplysninger (som navn/koblingsnøkkel)
- slette/omskrive indirekte personopplysninger (identifiserende sammenstilling av bakgrunnsopplysninger som f.eks. bosted/arbeidssted, alder og kjønn)
- slette digitale lyd-/bilde- og videoopptak

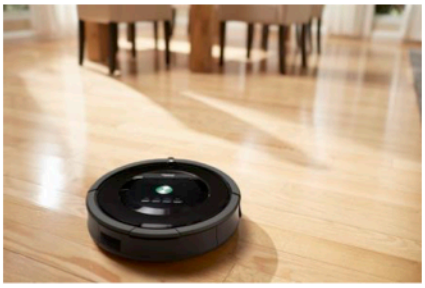
Appendix C

Focus group slides

In the focus group at Kampen Omsorg+, we used pictures and videos as a tool. In the following the slides from the activity is laid out. The first twelve slides were pictures and text and the last six slides was video. The videos can be viewed here: https://vimeo.com/album/4561922.

Eksempler på roboter for hjemmet

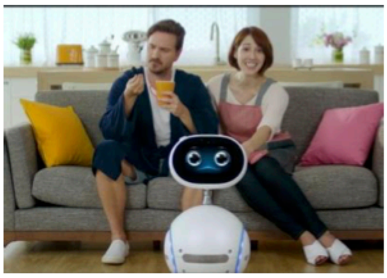
Robot A



Robot B

Robot C

Robot D



Robot E

Robot F

Robot G

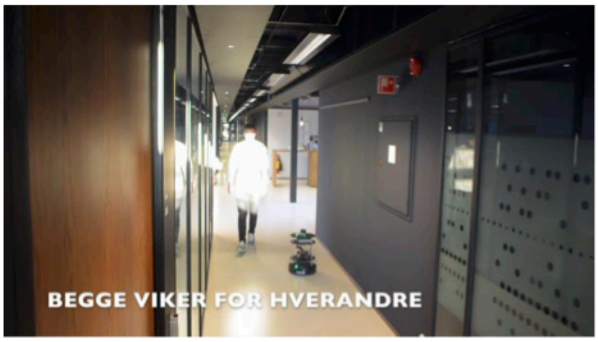
Robot H

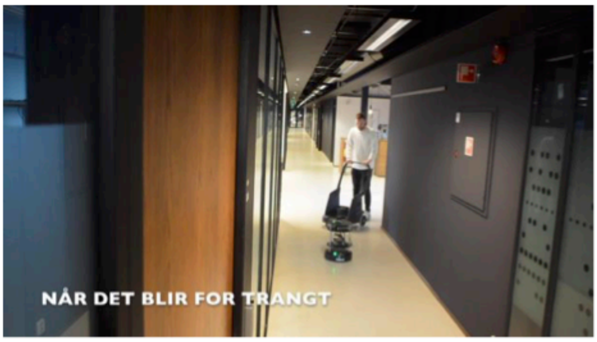
Robot I

Eksempler på møter mellom mennesker og roboter


HVA BURDE SKJE NÅR MENNESKET OG
ROBOTEN MØTES?

ROBOTEN VIKER

ROBOTEN STANSER OG MENNESKET VIKER

BEGGE VIKER FOR HVERANDRE

MENNESKET VIKER

NÅR DET BLIR FOR TRANGT