Robot Games for Elderly

A Case-Based Approach

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Robot Games for Elderly
Ph.D. thesis

Preface and Acknowledgements

This PhD thesis has been initiated by Centre for Robot Technology at Danish Technological Institute and conducted in collaboration with Section of Automation and Control, Department of Electronic System and Department of Architecture, Design and Media Technology, Aalborg University under the Danish Industrial Ph.D. program. It is submitted as a collection of papers in partial fulfilment of the requirements for Doctor of Philosophy at the Section of Automation and Control, Department of Electronic Systems, Aalborg University, Denmark. The work has been done during the period March 2008 to March 2011 under the supervision of Head of Centre for Robot Technology Claus Risager, Professor at Aalborg University Thomas Bak and Associate Professor at Aalborg University Hans Jørgen Andersen.

First of all I would like to thank my wife for tolerating me these three long years. I would like to dedicate the thesis to her and my son who we dragged all over the world while writing the thesis.

I would especially like to thank Mikael Svenstrup for priceless technical help and fruitful discussions along the way. Also I would like to thank Ashwin Ram for letting me stay at Georgia Tech and to Santiago Ontañón for spending time on explaining me D2. Thanks to my colleagues at DTI who helped out - especially Dorte Malig, Lone Gaedt and Julie Christoffersen.

Thanks to all who participated in the different experiments especially Pall Hermonson, Rikke Jensen and Christina Leeson. Also thanks to all the other people who have supported me when writing the thesis, especially Torben and Kate.

Last but not least, thanks to my parents who bought my first computer back in the 80's. It finally paid off.

Abstract

The demographic structure of many developed countries forecasts an increase of elderly citizens and a decrease of young people to support them. An ageing population implies that the number of people with mental and/or physical disabilities will grow, and as a consequence, the elder care sector in a number of countries is under pressure. Development of new types of technology which can secure self-sustainability and life quality for elderly has been suggested as way to diminish some of the problems caused by an ageing society.

It has been shown that even a small amount of physical activity can improve a person's overall health, and this thesis investigates how games based on an autonomous, mobile robot platform, can be used to motivate elderly to move physically while playing. The focus of the investigation is on the development of games for an autonomous, mobile robot based on algorithms using spatio-temporal information about player behaviour - more specifically, I investigate three types of games each using a different control strategy. The first game is based on basic robot control which allows the robot to detect and follow a person. A field study in a rehabilitation centre and a nursing home shows how the robot operates autonomously in in a real-world scenario although the elderly use different assistive tools. The elderly express a low degree of rejection of playing with the robot and tend to treat it as a living creature, i.e. talking to it as if it was a young boy or a dog. The robot facilitates interaction, and the study suggests that robot based games potentially can be used for training balance and orientation. The second game consists in an adaptive game algorithm which gradually adjusts the game challenge to the mobility skills of the player based on spatio-temporal analysis. The game is a pursuit and evasion game and an evaluation in a rehabilitation center and nursing home shows how the game algorithm adjusts the difficulty of the game challenge to users with different levels of mobility. However, adaptation at the level of each individual revealed to be difficult for players showing non-standard behaviour. The last game allows multiple users to compete against the robot based on an AI system originally created for real-time strategic computer games. This game has been evaluated in simulation, and the outcome is a generic software framework which can be used for implementing strategic robot based games.

Synopsis

I mange lande foreskriver den demografiske udvikling, at der bliver flere ældre i forhold til unge, hvilket gør at plejesektoren kommer under pres pga. stigende økonomiske udgifter og faldende indtægter. Et andet problem er at der mangler hænder på området, da et stort antal af de ansatte er ved at nå pensionsalderen, samtidig med det er svært at rekruttere og fastholde nye medarbejdere. Udvikling og implementering af nye typer af teknologi til hjælp for ældre og handicappede (såkaldt velfærdsteknologi), er et bud på hvordan man kan løse nogle af problemerne i fremtiden. Således har en række kommuner i Danmark været aktive med at afprøve forskellige typer af nye teknologi, f.eks. robotstøvsugere. Da selv en smule motion kan forbedre helbredet signifikant, er formålet med denne afhandling at undersøge hvordan man kan udvikle spil til en autonom, mobil robot der kan benyttes til at motivere ældre til at bevæge sig mere. Det primære fokus for afhandlingen er den tekniske udvikling af spil-algoritmer til autonome, mobile robotter der kan benytte spatio-temporal information om spilleradfærd og jeg har undersøgt emnet via tre typer af spil. Det første spil er baseret på simpel robotkontrol, hvor robotten kan detektere og følge en person i et åbent miljø. Et feltstudie af spillet på et center for genoptræning og på et plejehjem, viser at robotten kan køre autonomt i et virkeligt plejemiljø selvom brugerne benytter forskellige hjælpemidler. Studiet viser en lav grad af afvisning af spillet blandt de ældre, og at de har tendens til at opføre sig overfor robotten som om det var et levende væsen ved f.eks. at tale til den som var det en lille dreng eller en hund. Studiet indikerer at robotbaserede spil potentielt kan bruges til at træne balanceevnen og evnen til at orientere sig et rum. Det andet spil er en implementering af en adaptiv spil-algoritme, der gradvist tilpasser sværhedsgraden til spillerens færdigheder. Dette spil er også evalueret på et center for genoptræning og på et plejehjem og evalueringen af spillet, viser hvordan robotten tilpasser sin bevægelsesadfærd til ældre med forskellige mobilitetsevner. Studiet viser dog at tilpasning på et individuelt niveau er vanskeligt for spillere der ikke udviser normativ spilleradfærd. Det sidste spil bygger på et AI-system, der oprindeligt er udviklet til PC realtids-strategispil. Dette spil er blevet evalueret via simulering, og et konkret udbytte er et generisk software framework, der i fremtiden kan benyttes til at implementere en række forskellige strategiske robotbaserede spil.

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1   Introduction

1.1   Motivation

Traditionally, the use of robots has been associated with the goal of creating economic growth by increased productivity. However, the last decade there has been an increasing interest in using robots outside production in e.g. private homes, for handicap assistance and in health- and elder care. In the latter case, the interest of using robots has been reinforced by the demographic development which in most developed countries shows an increasing number of elderly and a decreasing number of young people to take care of them. Between 1980 and 2005 there has been 23 million less EU-citizens under 14 years, which is predicted to cause a gap in the workforce all over Europe [44, 117]. With a growing number of elderly, it is expected there will be an increasing number of people with mental and/or physical disabilities and therefore more need for public services which will create a gap between tax income and expenses. One of the ways, which has been proposed to solve this problem, is to develop robots and other types of technology which can be used to extend the average time citizens will work actively in the society, while at the same time secure self-sustainability and life-quality for elderly citizens.

Figure 1.1: Training of elderly at a rehabilitation centre

Electronic games hold a significant promise for enhancing the lives of seniors, potentially improving their mental and physical well-being, enhancing their social connectedness, and generally offering an enjoyable way of spending time [122]. Games linked to physical activity seems especially promising, as it has been shown that mental and phys-

ical health can be improved through a small amount of physical exercises [285], [83]. Robot based games constitutes a distinct field of physical, electronic games, as the tangible nature of autonomous robots catalyses interaction [84] and offers an increased sense of social presence due to their capacity for touch and physical interaction [133].

Traditionally, training of elderly with mobility problems is performed by physiotherapists who instruct a number of people (5-10) at the same time. Training is often based on exercises where the participants sit on a chair and do different movements with their arms and legs while listening to music (Fig. 1.1). It is often difficult for the therapists to motivate the elderly to train hard and long enough, making it interesting to develop new tools for motivating elderly to be physical active. When this thesis was started in 2008, the use of robots in elder care was a new and very controversial topic in Denmark, making it an interesting subject to study. Although much research exists about the use of robots as rehabilitation devices for elderly, the concept of developing games based on mobile robots for elderly being the main focus of the thesis is still in its infancy.

1.2   Hypothesis

The basic idea of the thesis is to improve the health of elderly by motivating them to do physical activity by playing a game with a mobile robot. The commercial aspect of the project is to create a robot game which potentially can be used as rehabilitation tool in the elder care sector.

The thesis is technology centered and investigates how algorithms based on **spatio-temporal** information about the physical behaviour of a player can be used for a mobile robot to choose navigation actions in a game scenario.

The hypothesis of the thesis is:

> **Hypothesis:** Motivating elderly to move physically can be facilitated by mobile robot games based on algorithms using spatio-temporal input about player behaviour

Based on this hypothesis, I want to answer the following research questions:

- How to implement game algorithms on an mobile robot which can interpret the physical spatio-temporal behaviour of the interacting person while operating autonomously in a daily life environment?

- How can a robot learn about the user's game skills from interaction experience, and how should the robot adapt its navigation behaviour to the skills of the user throughout the game?

- How do elderly receive the implemented robot based games, how are their play patterns, and what is the potential use of the robot games in elder care?

- How to implement robot games for promotion of physical activity in elder care in the future?
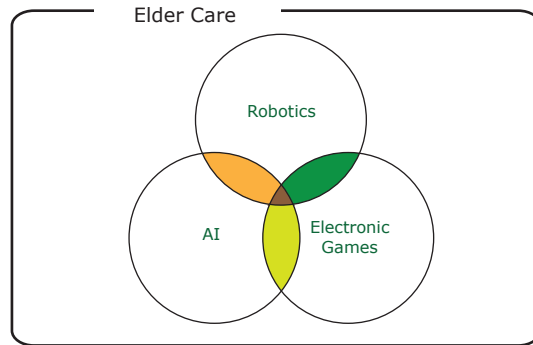
Figure 1.2: The thesis is in the intersection of Robotics, Artificial Intelligence (AI) and Electronic Games put in the context of Elder Care.

To answer the questions, I use theory and methods from different scientific areas including **Robotics**, **Artificial Intelligence (AI)** and **Electronic Games**[1] (See Fig. 1.2). Much research has been conducted in all of these areas, but the use of **mobile robot games** in the context of **Elder Care** is not extensively investigated.

1.3 How to read this thesis

This thesis is technology centered and has been initiated by **Centre for Robot Technology at Danish Technological Institute (DTI)** and has been made in collaboration with **Aalborg University (AAU)** under the **Danish Industrial PhD Program**. The goal of the Industrial PhD Program is to strengthen research and development in Danish business communities *by educating scientists with an insight into the commercial aspects of research and development and by developing personal networks in which knowledge between companies and universities can be disseminated.* The PhD-program lasts for three years, out of which one year is spent on participation in courses and dissemination activities. The program includes requirements with respect to public-private cooperation and half the time is spent at a private company and half the time at the university (detailed information can be seen in Appendix J). In order to fulfil the requirements, the thesis has a strong focus on dissemination of results and on integration with related innovation projects and applications at Centre for Robot Technology at DTI.

> **How to read this thesis:** This is a technology centered Industrial-PhD which besides academic research focuses on dissemination, applicability and integration with activities at Center for Robot Technology at DTI.

The thesis has been partly funded by the Danish Ministry of Science and partly funded by DTI. During the thesis, half a year was spent at **Georgia Tech (GaTech)** in Atlanta,

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1 In this thesis, electronic games are broadly defined as games based on PCs, video consoles and other electronic devices. A game is defined as an interactive, goal-oriented activity in which players can interfere with each other [59].

US and the project was made in collaboration with the national project **IntelliCare** lead by **University of Southern Denmark (SDU)**.

1.4   Scope

The primary focus of the thesis is on the technical development of applicable, autonomous robot based games for elderly, i.e. how to create game algorithms for a mobile robot which can operate autonomously in an **open-ended environment**. The research is based on a mobile robot platform with an expressive face, but the expressive face is not a central part of the thesis.

> **Scope:** The focus of the thesis is on the development of applicable, mobile robot based games operating autonomously in a open-ended, real-world environment with elderly users.

The target users are elderly citizens attending institutions handled by the public elder care sector in Denmark, more specifically rehabilitation centres and nursing homes. As the goal of the thesis is to motivate users to move physically, it is required that the elderly are capable of moving around with or without the use of assistive tools. Users who are bedbound, suffers from severe dementia or other cognitive problems have not been included. In Denmark, you are only assigned a nursing home facility if you are not capable of living in your own home, whereas users of rehabilitation centres are considered self-sustainable. In general, we assume that people attending a rehabilitation centre have less cognitive and physical problems than people who live in a nursing home.

There are a number of elements related to the investigation of robot based games for elderly which would be relevant to investigate, but due to restricted time and resources have been considered out of scope:

- Although the physical design of the robot affects the way elderly and health care personal think of a robot [35], it is deliberative not considered a central part of the research presented in this thesis. The thesis includes explorative and qualitative reflections about the user's reactions to games based on the used robot platform, but in-depth user studies related to physiological effects of the physical design and the expressive face are considered out of scope.

- Although highly relevant to investigate, quantitative measurements of the physiological benefits of robot based games are considered out of scope. Reflections about how robot games potentially can benefit the users' health are based on literature studies, user and expert testimonials.

- Reflections about elderly's acceptance of game is made, but quantitative or qualitative measurements of game enjoyment is considered out of scope.

- It is considered out of scope to include detailed quantitative data about the users medical history. However, I do collect user information regarding age, gender and the use of assistive tools.

- I do not consider any legislation which potentially could prohibit robots being applied for games in elder care. I also abstract from practical problems related to e.g. usability of operating the robot in training situations.

- As this is an Industrial PhD aiming at educating scientists with an insight into the commercial aspects of the research, the thesis relates to non-academic perspectives of applying robots in elder care.

1.5   Method

The development method of the PhD has been an **iterative development strategy** (See Fig. 1.3), in which the various parts of the system are developed and evaluated as they are completed [295]. The basic idea of the method is to incrementally develop, implement and evaluate the parts through repeated cycles and the philosophy is that learning comes from both the development and use of the system. At each iteration, modifications are made and new functional capabilities are added, and user comments and expert testimonials have been used in the process. This allows taking advantage of what was learned during the development and to be able backtrack to a former iteration.
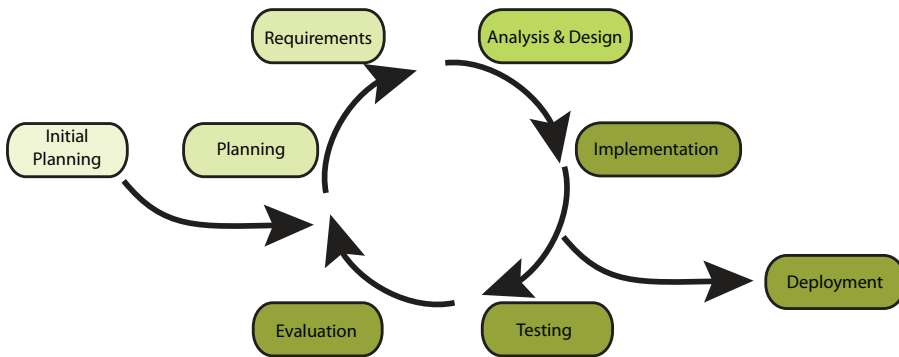
Figure 1.3: A model of the iterative development strategy [295].

The iterative strategy is in contrast to the **Waterfall model**, in which results are delivered all at once, and only at the very end of the project [295].

The approach has lead to the development of three different games, each using a different robot control strategy; **Basic Control (BC)**, **Case-Based Reasoning (CBR)** and **Case-Based Planning (CBP)**. The characteristic of each game implementation and the corresponding control strategy can be seen in Table 1.1.

Interactions with robots in the laboratory, do often not provide insights into the aspects of human-robot interaction that emerge in the less structured real-world social settings in which they are meant to function. It is therefore necessary to evaluate human-robot interactions as socio-culturally constituted activities outside the laboratory, or "'in the wild'" [121]. In this thesis, the implemented games have been evaluated in four different types of scenarios, namely **Simulation**, **Lab**, **Real World** and **In Situ**. For each scenario,

Game	Game description	Control strategy
1	Compete about getting and maintaining the attention of the robot	Basic Control (BC) which allows the robot to detect persons in a open-ended environment as a self-contained system.
2	Single player game with the goal of getting and handing back a ball to a moving robot	Case-Based Reasoning (CBR) which allows the robot to learn from behaviour patterns of interacting persons.
3	Strategic multi player game with the goal of competing against the robot about first visiting a number of locations without getting tagged	Case-Based Planning (CBP) which allows complex strategic control of the robot in a game scenario.

Table 1.1: Relation between the control strategy and characteristics of the implemented game.

the games have been evaluated using qualitative and quantitative approaches (Table 1.2). In this thesis, quantitative research include qualitative interviews, focus group interviews, observation and expert testimonials. The quantitative methods, which have been included, are spatio-temporal measurements based on indoor localisation equipment, visual laser scanner input and time measurements. The relation between scenario and type of evaluation can be seen in Table 1.2.

Type	Characteristic	User	Evaluation
Simulation	Experiments conducted in computer simulation without implementation on the physical robot.	User behaviour is simulated based on computer models.	Evaluation is based on analysis of simulated data
Lab	Experiments using the physical robot conducted in the robotics lab at AAU.	The user is any random person, including the conductor of the experiment.	Quantitative measurements based on localization equipment and laser scanner input
Real World	Experiment using the robot system, where it has been set loose in an open-ended environment.	The users are randomly selected from a random population.	Quantitative measurements based on laser scanner input and qualitative data based on interviews and observations.
In Situ	Real-world experiments conducted in a daily life situation, e.g. in a nursing home or rehabilitation centre.	Users are real potential users of the robot application	Quantitative measurements based on laser scanner input and qualitative interviews, observations and expert reviews.

Table 1.2: Characteristic of each evaluation scenario.

Throughout the thesis, the robot platform has been the **Robotino platform** from AAU,

which was originally developed in a Master's Thesis from 2007 [142]. It is stated that being over-ambitious is one of the robot community's biggest problems for achieving commercial success, and therefore it has been an overall design strategy to keep the application as simple as possible relaying on relative mature technology and few sensor components. The robot platform was given as a part of the PhD project, and has not been modified through the thesis except that the clothes has been changed. The advantage of this approach is that is has been possible to develop robot games which are robust enough to be evaluated using in situ experiments. The drawback is that the limited capabilities of the robot platform puts a constraint on which kind of games are possible to create. In a development process, the relation between complexity and robustness is often a trade-off, and in this thesis the emphasis has been on creating robustness.

As mentioned, the conducted research relies on theories and methods from three different areas:

- Robotics. Knowledge about the use of robots for elderly and theory within the field of mobile robotics, e.g. robot navigation using potential fields and robot vision based on laser scanner images and sensor fusion.

- AI. Knowledge about paradigms in artificial intelligence for robotics, and learning algorithms based on case-based reasoning and case-based planning.

- Electronic games. Knowledge about **Game AI** and to a limited extend psychological theories related to the creation of games namely the **Theory of Flow** and the **Theory of Mind**.

These areas are all well investigated in different forms, but the combination of using autonomous, mobile robots to create games and apply in-situ in elder care is not extensively investigated.

1.6 Contributions

The scientific contributions answering the research questions mentioned in Section 1.2 are summarized in Chapter 7 and can be seen in detail in the appended publications. The main scientific contributions of the thesis are:

- Knowledge about the implementation of games for elderly using an autonomous, mobile robot operating in daily life environments which can learn from and adapt to the spatio-temporal behaviour of the player.

- Knowledge about the elderly's acceptance and use of the implemented games using the platform and reflections about the potential benefit in rehabilitation.

- Implementation of generic software framework for strategic robot games by interlinking an AI system for computer games and a robot control environment.

The contributions of the conducted research as published in the appended papers can be seen in Table 1.3. As this is an Industrial PhD, it is required that the research is relevant for applicability in elder care and to emphasize dissemination.

Table 1.4 shows the relation between the publication, the applied control strategy and the evaluation scenario.

Research objective	Paper	Contribution
What is the state-of-art for applied robots in elder care in Denmark?	Paper A: Practical evaluation of robots for elderly in Denmark - an overview [108]	Analysis of results from robot projects conducted in Danish elder care.
How does the robot platform operate in an daily life environment and how do people react to it?	Video 1: The SantaBot Experiment [266]	Shows how the robot operates autonomously in a shopping mall and people's different reaction to it
How do elderly play a game based on a mobile robot, and how can it potentially benefit rehabilitation?	Paper B: Robot Based Games For Elderly - A Qualitative Field Study [110]	Elderly has a high degree of acceptance of robot games and tend to treat the robot as a living agent. Games can potentially be used for training the postural control.
How to estimate motion patterns from laser range scanner measurements.	Paper C: Pose Estimation and Adaptive Robot Behaviour from Human-Robot Interaction [251]	A new Kalman filter based method for pose estimation of persons.
How to adapt robot navigation based on run-time motion pattern analysis of a person	Paper D: Adaptive Human aware Navigation based on Motion Pattern Analysis [111]	A robot navigation system based on a potential field, and a method based on Case-Based Reasoning for learning from run-time motion pattern analysis
How to implement an adaptive robot pursuit evasion game based on run-time motion pattern analysis	Paper E: An Adaptive Robot Game [265]	A game algorithm estimating the mobility skills of a person in order to adjust the game challenge.
How do elderly play the adaptive pursuit and evasion game?	Video 2: Robot Games for Elderly [107]	Illustrates the variety of play styles when playing the pursuit and evasion game
How does the algorithm adapt the game challenge to the mobility skills of the user?	Paper F: An Adaptive Robot Game for Elderly - A Field Study [109]	Shows that the game algorithm adequately adapts the game challenge to player's skills but fails when players show non-standard behaviour
How to create a game where multiple players can compete against a mobile robot	Paper G: A Software Framework For Multi Player Robot Games [264]	Shows how an AI system developed for real-time strategy computer games can be applied to create robot based game.

Table 1.3: The relation between the research objective, the publication and the contribution.

Game	Control Strategy	Simulation	Lab	Real World	In Situ
1	BC				Paper B, Video 1
2	CBR	Paper C, E	Paper C, D, E	Paper C, D	Paper F, Video 2
3	CBP	Paper G			

Table 1.4: The relation between the game, the publication(s), the applied control strategy and the evaluation scenario

1.7 Structure of thesis

This thesis is written as a collection of papers, and has been divided into two main parts. The first part includes the introduction, relevant theory and conclusion while the second part contains a collection of the most important publications. The first part contains the following chapter:

- Chapter 1: An introductory part (this one) which explain the motivation and structure for the thesis

- Chapter 2: Gives an overview of scientific and economic motivation for the thesis.

- Chapter 3: Describes the state of art for robot based games.

- Chapter 4: Describes the state of art for artificial intelligence and robotics.

- Chapter 5: Describes the state of art for academic and commercial game AI .

- Chapter 6: Describes techniques and methods which have been applied in the thesis, but left out of the appended publications.

- Chapter 7: Summarizes the main scientific contributions of the thesis, discusses the results and describes to academic and industrial communities.

- Chapter 8: Concludes the work and describes the future directions of robot based games

- Appendix I: Abbreviations and definitions

- Appendix J: Outlines the structure of the Industrial Ph.D. program and the involved partners in the project.

- Appendix K: Description of the dissemination effort of the thesis.

- Appendix L: Overview of assistive robots

- Appendix M: Overview of commercial computer games

- Appendix N: Overview of the D2 system

- Appendix O: Description of the implementation of the multi-player game

The second part of the thesis contains the following publications:

Paper A: Practical evaluation of robots for elderly in Denmark - an overview [108]
A short abstract which summarizes robot projects in Danish elder care. Within the field of HRI, much research has been conducted on robots interacting with elderly and also a number of commercial products have been introduced to the market. Since 2006, a number of projects have been launched in Denmark in order to evaluate robot technology in practice in elder care, and this paper gives an brief overview of a selected number of projects and outlines the characteristics and results.

Video 1: The SantaBot Experiment [266] Video which illustrates an experiment, where a robot platform was set at large in a public transit space. The experiment was done to see how people reacted to an autonomous robot in their natural everyday environment and to get experience with operating a robot in the real world. The results are documented in detail in [250].

Paper B: Robot Based Games for Elderly - A Qualitative Field Study [110] This paper presents a study on how a robot game can be used as a physical activity for elderly. The study is based on two in situ experiments in a nursing home and in a rehabilitation centre for elderly with mobility problems. The goal of the study was to observe the elderly's acceptance of the game, observe how the robot adapts to players with different mobility problems and secondly obtain knowledge about their game play patterns and get ideas about future improvements of the game.

Paper C: Pose Estimation and Adaptive Robot Behaviour from Human-Robot Interaction [251] This paper, introduces a new Kalman filter based method for pose estimation of persons using simple measurements from a laser range scanner. Being able to estimate both position and orientation of persons can be used for robots to be able to navigate in a daily life environment, The paper introduces a navigation algorithm, which is more thoroughly described in Paper D and the method is evaluated in a lab experiment.

Paper D: Adaptive Human aware Navigation based on Motion Pattern Analysis [111] Describes an adaptive system for mobile robot navigation based on run-time motion pattern analysis compared to stored experience in a database. Using a potential field centered around the interacting person, the robot positions itself at the most appropriate place relative to the person and the interaction status. The system is based on the Pose Estimation described in Paper C, and leads to robot game which is described in paper E.

Paper E: An Adaptive Robot Game [265] In this paper, the framework presented in paper C and D is further developed into a robot pursuit evasion game intended to motivate elderly persons to do a regular amount of physical exercise. The game algorithm estimates the skill of person in order to adjust the game challenge. In this paper, the system is validated in simulation but real world studies have been evaluated in Video 2 and Paper F.

Video 2: Robot Games for Elderly [107] This video is based on the study described in Paper E, and shows different examples of how elderly play with the robot and illustrates the variety of play styles.

Paper F: An Adaptive Robot Games for Elderly - A Field Study [109] This paper describes the results from a field study of the adaptive robot game introduced in Paper E conducted in a nursing home and a rehabilitation centre for elderly with mobility problems. The study shows that the game algorithm adequately adapts the game challenge to player's skills but fails when players show non-standard behaviour.

Paper G: A Software Framework For Multi Player Robot Games [264] This paper describes a generic software framework which can be used to create games where multiple players can play against a mobile robot. The paper shows how an AI system (D2) developed for real-time strategy computer games can be successfully applied in a robotics context using the robot control framework Player/Stage. D2 is based on case-based planning which learns from demonstration. Using the proposed framework, the paper shows how a robot learns a strategy based on an implementation of a game.

2   Robot Games for Elderly

Elder care in Denmark is a public responsibility being under pressure because the number of elderly increases in relation to the number of young people. Similar tendencies are not only a problem in Denmark, but in a number of western countries - especially Japan followed by Italy and Spain [319]. As a consequence, a number of commercial and scientific robot platforms have been developed in order to find technical solutions which can secure self sustainability and improve life quality for elderly. This chapter describes the motivation and arguments for using robots for games in elder care, and also describes the main definitions which has been used in the thesis.
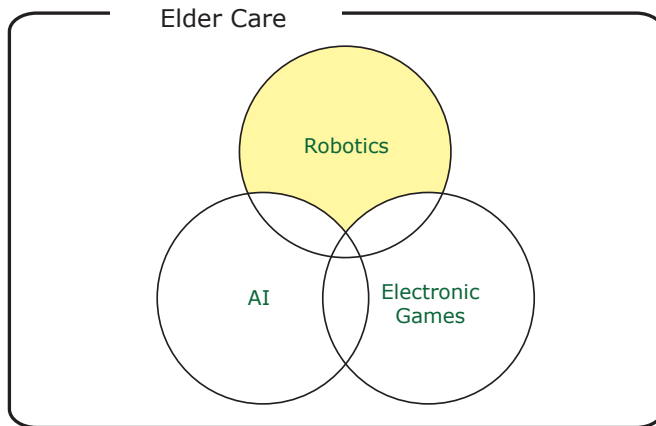
Figure 2.1: This chapter describes the background and state-of-art in robotics for elderly

2.1   Brief History of Robotics

Robots are often depicted in movies and literature as human-like machines with super-natural powers ready to conquer the earth. But although we often think of robots as a new invention, the antique civilizations had the same ideas. There are many tasks we as humans would like to avoid (sometimes noted as DDD for Dangerous, Dirty, and Dull) and the dream of letting machines do the hard work goes back to Aristotle (384-322 bc)

who wrote: 'If every tool, when ordered, or even of its own accord, could do the work that befits it... then there would be no need either of apprentices for the master workers or of slaves for the lords'. The fact that the topic has attracted man for many years, can be seen from Greek an Chinese legends about mechanical animals and human figures, e.g in the legend about Archytas from Tarentum who accordingly should have build a mechanical dove around 400 BC which could fly based on steam. Fast forward to the 14. century when it became possible to construct human-like mechanical figures, often used in different clock works e.g. the cathedral of Strasbourg and the church tower of Piazza San Marco in Venice. In 1495, Leonardo da Vinci designed a mechanical knight in armour as a result of his interest in human autonomy and Chinese techniques [296].

Modern Robotics

Modern robotics is related to the development of the computer. In 1822, Charles Babbage constructed an apparatus which could subtract numbers and in 1832 he started the development of one of the first calculators. In 1946, Eckert and Mauchly build the first digital computer Eniac based on radio tubes and two years later the transistor was invented which made the price of a computer go down. With the introduction of the computer, it became possible for George Devol and Joseph Engelberger to design a robot which was used to weld cars for General Motors from 1962.

This breakthrough is considered the birth of the modern industrial robot, which has been widely used in industrial production the last 30-40, making a significant improvement of production. In the beginning of the 90's there has been a paradigm shift, so the development and research focus now to a larger extend is on robots solving tasks outside production environments, e.g. for military use, in private homes and as assistive technology for elderly and handicapped. Partly due to this development, it has been predicted that robots will have the same impact on the world economy in this century as as the car industry had in the former [171].

Despite the increasing use of robots, there is big variation in public understanding of what a robot is and what is possible using robots. The construction of control systems for robots working in static and well-structured environments is well understood and much progress has been made during the last 30-40 years. On the other hand, constructing control systems for robots working in dynamic and unstructured environment is very difficult and very little progress has been made. The problem is partly caused by the fact that conventional techniques depend on an internal representation of the environment. This is relatively easy to handle when the environment does not change or changes in a predictable manner. However, this is surely not the case in most non-artificial situations, and therefore other techniques have been taken into account.

2.2   Definitions

Being trivial knowledge for most readers of this thesis, it is worth recalling that the term 'robot' has many different definitions and there is lack of consensus about what qualifies a machine to be a robot. According to Encyclopedia Britannica a robot is 'any automatically operated machine that replaces human effort, though it may not resemble human beings in appearance or perform functions in a human like manner' while Merriam-Webster

defines a robot as 'a machine that looks like a human being and performs various complex acts (as walking or talking) of a human being'. The robot pioneer Joseph Engelberger once stated that 'I cannot define a robot, but I know one when I see it.' In this thesis I will use the following definitions:

- The term **'Robot'** is defined as a machine which has one or more of the following characteristics: The ability to move, to move one or more joints, sense and manipulate the surroundings and/or show intelligent behaviour. **'Mobile robots'** is a specialized branch of robots which have the capability to move around in their environment and are not fixed to one physical location. In contrast, industrial robots usually consist of a jointed arm (multi-linked manipulator) and gripper assembly (or end effector) that is attached to a fixed surface.

- **Robot Technology** describes technology in the intersection of robotics and ICT, i.e. technology which includes sensors and/or manipulators not being standard ICT equipment like a PC.

- **Welfare Technology** is a popular term in Danish politics, describing technology that can help and assist users in their daily lives. Examples of welfare technology are intelligent aids such as cleaning robots, sensors in clothes, smart homes, etc. Welfare technology is closely linked to Ambient Assisted Living (AAL) but whereas AAL focuses on "addressing the needs of the ageing population" [260], welfare technology addresses not only the elderly but also other users of public services such as the handicapped, schools, day care centres, etc. [298].

Robots for elderly can be split into Assistive Robotics (AR), Socially Interactive Robotics and Socially Assistive Robotics (SAR).

- **Assistive Robotics (AR)** largely refers to robots that assists people with physical disabilities through physical interaction. Assistive robotics itself has not been formally defined, but an adequate definition of an assistive robot is one that gives aid or support to a human user. A wide number of different assistive robot platforms for elderly have been developed, and an overview can be found in Appendix L.

- **Socially Interactive Robotics** was coined by Fong [81] to describe robots whose main task was some form of interaction. The term was introduced to distinguish social interaction from teleoperation in human-robot interaction. Although there is still debate about the term, a sociable robot is one that is capable of engaging humans in natural social exchanges ([34], page 40), and the psychological grounding is related to Reeves and Nass' 1996 book on social aspects of human-computer interaction [221]. Sociable robots depend on social signal processing which is the ability of recognizing human social signals and behaviours [274] and a claimed to offer advantages not found in on-screen agents or technology embedded in the environment, such as an increased sense of social presence in an interaction and the capacity for touch and physical interaction [133].

- **Socially Assistive Robotics (SAR)** shares with assistive robotics the goal to provide assistance to human users, but it specifies that the assistance is through social interaction. Because of the emphasis on social interaction, SAR has a similar focus

Figure 2.2: Two sociable robots. From left to right: Kismet [33] and Leonardo [37]

as SIR. In SIR, the robot's goal is to develop close and effective interactions with the human for the sake of interaction itself. In contrast, in SAR, the robot's goal is to create close and effective interaction with a human user for the purpose of giving assistance and achieving measurable progress in convalescence, rehabilitation, learning, etc. [75].

As will be described in further detail in the next chapter, sociable robots have been investigated as a means to secure natural and intuitive human-robot interaction and one of the most well known examples are the robots Kismet and Leonardo developed at M.I.T by Cynthia Breazeal (See Fig. 2.2). Kismet combines social attention and machine learning components to learn tasks effectively from interactions with a human teacher [33].

Human-Robot Interaction

The vision of robots participating in our day-to-day lives is a main part of the focus in the research field of **Human Robot Interaction (HRI)**, being at the intersection of psychology, cognitive science, social sciences, computer science, robotics, and engineering [62]. The vision is supported by progress in computing, visual recognition, and wireless connectivity, which open the door to a new generation of mobile robotic devices that see, hear, touch, manipulate, and interact with humans [86].

Research in human-robot interaction accelerated in the mid-1990s - a milestone was Mark Scheef's work on Sparky which was used for studying children's and adults' reaction to it [234].

The HRI research has been fast growing ever since and a highlight was in 2006, where the first annual conference on Human-Robot Interaction emerged. In addition, a number of large European projects concerning HRI related research have been funded e.g. Cogniron [54], Cosy [57], Lirec [154] and Auroroa [17].

HRI has a fair amount in common with HCI (Human-Computer Interaction). HCI is an established research field in which much has be learned how people perceive and think about computer-based technologies, about human constraints on interaction with machines, about the factors that improve usability and about the primary and secondary effects of technology on people and organizations. Much of this work is potentially applicable to robots, but nonetheless robots are distinctive cases for several reasons:

- People seem to perceive autonomous robots differently than they do to most other computer technologies.

- Robots are like to be mobile, bringing them into physical proximity with other robots, people and objects

- Autonomous robots make decisions and respond changes to the environment.

Conducting and evaluating interaction studies that meet the requirements and standards of human-human interaction studies as conducted in related areas such as psychology or social sciences is still a big challenge [62] and in [21], Bartneck et. al. emphasize the need for standardized measurements tools in HRI in order for different studies to be able to be compared. Today a number of robots have been applied for assisted therapy or social interaction but although there has been several attempts to develop evaluation taxonomies in HRI, the community has yet to develop a consensus for a standard framework [247]. The primary difficulty in defining common metrics is the diverse range of human-robot applications and many metrics are highly application or task specific. To arrive at a common robot platform would require an agreement on the critical scientific questions of HRI, which are still in their early stages of development [95]. Although metrics from other fields (HCI, human factors, etc.) can be applied to satisfy specific needs, identifying metrics that can accommodate the entire application space may not be feasible [247].

Robots as Persuasive Technology

The thesis aims at motivating elderly to move physically by playing a game with a mobile robot which is related to the field of **Persuasive Technology**. Persuasive Technology is broadly defined as technology designed to change attitudes or behaviours of the users through persuasion and social influence, but not through coercion or deception [80].

Much research about persuasive technology is related to how to create persuasive screen based systems (see [204] for a good overview of persuasive design principles). In certain areas persuasive technology is especially useful, e.g. health care software applications to motivate people towards healthy behaviour, and thereby possibly delay or even prevent medical problems as well as ease the economic situation in public health care [124].

The term **Persuasive Robotics** has been defined as the study of persuasion as it applies to human-robot interaction [241]. Persuasive robotics includes the body of research relating social influence to HRI and within the framework of sociable robots and presents a structure through which both human and robot belief and behaviour can be mutually influenced [241]. According to Siegel [241], persuasion as it applies to HRI has received almost no research attention, and it is typically mentioned only as a small portion of a larger research focus.

An example can be seen in [134] where Kidd and Breazeal have shown the effectiveness of a sociable robot which serves as a weight loss coach. Fasola describes the design and implementation of a socially assistive mobile robot that monitors and motivates a user during a seated arm exercise scenario [74] and Kang [130] describes a robot that provides motivation and support for cardiac patients who must perform painful breathing exercises. Another example can be found in [155], in which it is investigated whether a socially intelligent robot is able to change the behaviour/lifestyle of a diabetic.

2.3 Using a Mobile Robot for Physical Games for Elderly

Many robots for elderly have been developed to assist users with specific physical tasks and an overview of these can be found in Appendix L which gives an overview of Assistive Robotics. However, the overall goal of this thesis is to investigate how to motivate elderly to move physically by playing a game with an autonomous, mobile robot. The robot has a social function related to changing the behaviour of the elderly users and the thesis is therefore in the intersection of Persuasive Robotics and Socially Assistive Robotics. The main reason for using a robot for creating physical games is that robots offer autonomous behaviour and an increased sense of social presence due to their capacity for touch and physical interaction [133]. Additionally the robot supports users relying on assistive tools like wheelchairs and walkers.

The work presented in this thesis is based on a commercial mobile robot platform from FESTO which has been added an expressive face as described in Chapter 6 and an analysis of the pros and cons of using the platform compared to related technologies can be found in Chapter 3.

Robot based games constitutes a distinct subset in the field of physical, electronic games, as the tangible nature of autonomous robots catalyses interaction and encourages humans to anthropomorphize them even when their physical aspect is obviously different from that of a human being [84]. Although much research exists about robot based games, the use of an autonomous, mobile robot applied in elder care is still in its infancy as documented in Chapter 3.

Although AI and robot control has advanced greatly in the last, the goal of creating a game using a mobile robot which operates autonomously in a open-ended scenario is not as simple task. An overview and comparison of different AI techniques and control paradigms is presented in Chapter 4 and the implemented robot games which are presented in the thesis are analysed and compared.

Creating games is today an academic research discipline as well as a million dollar commercial industry and the characteristics of both field are outlined in Chapter 5. This chapter hold an analysis of the implemented games from an AI perspective and reflections about creating interesting robot games are described.

2.4 Motivation for Using Robots in Elder Care in Denmark

A major motivation for developing robots for elder care is due to the fact that the demographic development in most western countries shows that the ratio between elderly and young people will move to a clear overweight of elderly. This is likely to cause a relative increase of people with mental and/or physical disabilities while the amount of people to take care of them will decrease [319], [11]. In recent years, commercial robots have been applied for non-industrial purposes such as cleaning, entertainment and for assisted therapy and social interaction. This development has fostered the idea of using robot technology in elder care in order to reduce the workload of assisting personnel and secure life quality and self sustainability for the elderly.

In Denmark, elder care is mainly a public responsibility funded by taxes and levies. Through a decentralized structure, health care is organized in 5 regions, while the 98 municipalities have the responsibility of elder care and handicap assistance.

Figure 2.3: Cartoon from Jylland Posten 2006 about the use of robots in elder care.

The Lack of Hands

The economic burden of elder care for the public sector has been reinforced by the finical crisis and informally, the municipalities have labelled the year 2015 as 'Dødens Gab' literally meaning 'The Jaws Of Death' being a reference to the American thriller 'Jaws' from 1975. Besides the fact that the elder care sector has an increasing amount of people to take care of, the sector also suffers from recruitment problems as more than 38 % of the employees are expected to retire within the next 10-15 years [219]. Currently 106.000 people are employed in elder care in Denmark, and it is predicted that 7.000 more people are needed in 2015 and 12.000 people are needed in 2020. However, investments in technology have been estimated to diminish the demand with 6500-7500 persons in 2020 [219]. Being considered a low-status job, it is hard to attract and maintain labour in elder care, making the municipalities to look for alternative solutions. As a consequence, a number of projects have been initiated to evaluate the advantages and disadvantages of the practical use of robots in e.g. nursing homes (Explained in more detail in Paper A, [108]). An example, which illustrates the need for new solutions, recently occurred in the municipality of Billund where it became a requirement for elderly to buy a robot vacuum cleaner in order to receive public help for cleaning [129]. Although this initiative is still considered political controversial, there are reasons to believe similar approaches will become the standard in a few years from now.

Public Reactions to Robots in Elder Care

Centre For Robot Technology at Danish Technological Institute started to look into the possibilities of using robots in elder care around 2006. At this point, the use of robots in elder care was practically unknown and considered very controversial. An interview for a major Danish news paper about the possibilities of the use of robots resulted in the cartoon in Figure 2.3.

The cartoon displays a worst case scenario of the inhumanity of using robots in elder care: the old lady is left alone with the robot, and her grandchild has to fix it in order for it to take time to drink a cup of coffee. Under the figure the text says that Danish

Figure 2.4: Cartoon from Politiken 2007 about the use of robots in elder care.

Technological Institute informs that it is matter of time before elder care is performed by robots. This was the journalists interpretation of a statement about the fact that DTI was looking into the possibilities of using robots. The article initiated a tsunami of journalist inquiries and interviews, and another cartoon (Figure 2.4) was published in the newspaper Politiken some time after.

This time the robot is as **humanoid** equipped with a rubber spatula. The robot is thrown out by an exited elderly citizen who cries that he will not be wiped in the bottom by a robot. The robot is drawn as a reference to the science fiction movie "'The Terminator"' from 1984 starring Arnold Schwarzenegger.

In June 2010 a viral marketing campaign was launched by a Danish workers union, **FOA**, aimed at creating awareness of the work conducted by health-care workers in the public sector [78]. The campaign was not launched using FOA's own name but was presented as a commercial from a company called RoboCare who, supposedly, had invented humanoid-like robots able to take care of the sick, the elderly and children (see Figure 2.5). After a few days, FOA revealed themselves as the actual sender and explained that the commercial was meant to illustrate what might happen if we loose the human health- and elder-care workers. However, before FOA revealed themselves, several media (television, newspapers, internet blogs, etc.) had become dedicated to discus these robots and their (alleged) application in caretaking [61].

As these examples illustrate, there are high expectations to and at the same time a somewhat distorted picture of what robots can do in elder care. Although the examples are amusing, they display a false picture of state-of-the-art in robotics and somewhat misguides the public about what is actually possible. International surveys almost unanimously show that citizens lack scientific knowledge even in the most developed countries [49]. The fact that robots with complex skills are vastly present in science fiction and the entertainment industry being the main source of information for most people outside robotics, creates expectations which cannot be met with current technology. The use of
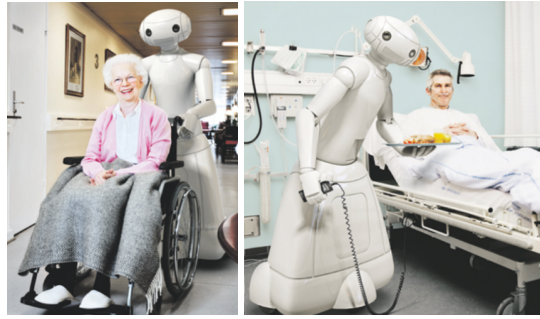
Figure 2.5: Pictures from the virtual campaign 'Real People' by the Danish worker's union FOA [78]

robots in elder care is often seen as a magic bullet capable of solving any given problem. A senior consultant from an elder care department in a major Danish municipality put it this way: 'You robot scientists have been sleeping in class. You already spent all this funding, and here we are drowning in problems.'. In her opinion robot scientists were basically wasting public money showing no sign of responsibility. Although this criticism is not completely fair, looking from outside, some robot projects could seem to have the character of being interesting gadgets rather than real solutions to present problems. There is a cry out from professionals and politicians for technical solutions in elder care, but so far there has been some disappointment about what current technology can offer. Robot research operating with a time horizon of 10 or 50 years before application, has no value for the elder care sector who needs practical, robust solutions that can be applied with benefit now.

Economic Perspectives

The fact that the use of robots and robot technology in health and elder care is a key topic in Danish policy, can be seen from an article published the 15th of October 2007 by Monday Morning [171] which is an independent political think tank. The article (in Danish only) had a headline saying "'The Nursing Home Assistant of the Future - Robo Sapiens'" (see Fig. 2.6). Below the text stated that "'robots can fill the gap in the working force in the health and service sector'" and that it is predicted that "'robot technology will have the same impact in this century, as the car industry had in the former'". According to the article, this development could potentially be extremely prosperous for Denmark.

A related testimonial describing the potential of robotics can be seen from an article from 2007 in Scientific America by the founder of Microsoft Bill Gates [86]. The article was called "'A robot In Every Home'" stating that "The leader of the PC revolution predicts that the next hot field will be robotics". In this article Bill Gates compares the development of robotics with the development of the computer in the 80's and predicts that robotics will have the same growth and impact in future society. Originally, computers were few in number and almost all placed at university labs. Later they have become a everyday tool and few people can work without one. Bill Gates claims that current robot

Figure 2.6: Article from Monday Morning describing the use of robots in elder care [171]

technology is at the same level as computers were 30 years ago, but with the development of common standards they will become a part of every home in the future. Bill Gates of course have commercial reasons for stating this, as Microsoft launched their Robotics Studio about the same time as the article was published. Although Robotics Studio is still a free piece of software, it is likely that Microsoft aims at getting world dominance within market of robotics software as they already have in the PC market.

According to World Robotics [305], the market for robots for handicap assistance is expected to increase substantially in the next 10 years although it is still relative small. The number of service robots for professional use was 76,600 units sold up to the end of 2009, while it is predicted to increase to some 80,000 units for the period 2010-2013. Service robots for personal and domestic use are recorded separately, and was about 5.6 million units for domestic use and about 3.1 million units for entertainment and leisure. It is projected that the total number will grow to about 11.4 million units for the period 2010-2013 [305].

Despite the widely acknowledged market potential, service robotics is still challenged by providing attractive cost-for-value solutions. Today, well over 200 companies world-wide offer service robotic products for professional and personal/domestic applications. Some 300 product ideas, demonstrators, prototypes and products have been documented, patented and presented for almost all conceivable tasks. Nevertheless, an abundance of product opportunities await take-up by industry [305].

Chapter Summary   The recent years, a number of robots have been developed with the purpose of being applied outside production in e.g. elder care in which robots have been used for rehabilitation, cleaning and therapy. The overall goal of this thesis is to investigate how to motivate elderly to move physically by playing a game with an autonomous, mobile robot which is research in the intersection of Persuasive Robotics and Socially Assistive Robotics. The main reason for using a robot for creating physical games is that robots offer an increased sense of social presence due to their capacity for touch and

physical interaction and that the robot has the ability to take the game initiative. A major motivation for developing robots for elder care is due to the fact that the demographic development in most western countries shows that the ratio between elderly and young people will move to a clear overweight of elderly. Despite the widely acknowledged market potential, service robotics is still challenged by providing attractive cost-for-value solutions.

3   Games and Robotics

This chapter describes the intersection of robotics and games and includes an overview of the state-of-art of robot based games and other electronic games which rely on the physical behaviour of the participants. The chapter holds an overview of research related to the combination of games and robots and describes the novelty of the thesis in relation to existing research.
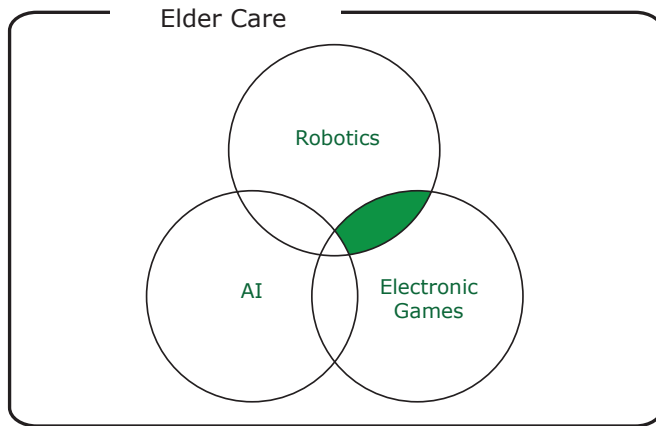
Figure 3.1: This chapter describes the shared elements of robotics and games and gives an overview of related work to the thesis

3.1   Exertion Games

The idea of using a mobile robot for a game which facilitates physical activity, is related to the term **Exertion Game**(also called exergames [243]) which is defined as digital games where the outcome of the game is predominantly determined by physical effort. It is stated that exergames can offer physical health benefits [144, 170], which can contribute to weight loss and address the obesity epidemic. Additionally, research has found that exertion facilitates social behavior in games [26], [153]. Since 2006, exergaming has

seen an upswing in activity and interest, and according to Sinclair [243] there are three major reasons for this:

- The release of Nintendo Wii and similar relative low-cost platform.

- Concern over the current high levels of obesity in Western society (especially in children).

- The potential for profit. Exercise equipment sales in the United States alone reached 5.2 billion by 2006 expected to increase. [284]

The exergame research community grew in earnest after publication of Mueller et al.'s Breakout for Two - a breakout-based distributed and competitive game using a soccer ball and a custom-built sensor wall [191], and many initial exergame system used specialized sensors to promote physical activity. Mueller's group continued to produce exergames using custom made sensors including the mat in Remote Impact [189], the table in Table Tennis for Three [190] and the force input device in Push and Pull [191]. Other examples of exergames are virtual, stationary bikes in [188] and social computer game which links a player's daily foot step count to the growth and activity of an animated virtual character can promote an increase in physical activity [56, 151]. Although the idea of exergaming is not new, it is still in its infancy when it comes to systematic research, particularly in terms of game design and unfortunately there is still a limited understanding of how to describe and design for compelling exertion experiences [67, 275]. Whitehead [288] has presented a survey of quantitative exergame studies to define a general set of elements that make exergames effective from a physical standpoint. The study shows that evaluation of exergames can be done with inexpensive heart rate monitors as there is a direct relationship between heart rate and energy expenditure. In [315] literature on exercise motivation are reviewed. The paper concludes that in order for exergames to be successful in motivating people to exercise they should provide strong guidance to players, providing access to a group of peers, and fostering a supportive and unintimidating environment.

Exergames for Elderly

Exergames have been applied for elderly e.g. in [222] describing the study of a digital coach which main goal is to increase physical activity in seniors who are at risk of acquiring or are already suffering from chronic diseases. Rosenberg [227] has studied how exergames can help against subsyndromal depression in older adults and Boschman [29] has investigated adoption of exergames by novice users over 40 through a literature review and a pilot study. In the Master's Thesis by Novak [203] older adults perception of exergames for physical activity has been studied based on a qualitative study. The study found that most participants did not embrace the new technologies, and barriers were identified to be system setup and game difficulty.

3.2   Commercial Video Platforms

With the introduction of commercial platforms like Nintendo Wii, Microsoft Kinect and Sony's EyeToy (see Figure 3.2), commercial computer games have taken a large step from the pure virtual domain into the physical world of exergaming.

The Nintendo Wii video game console is characterized by its wireless controller, the Wii Remote, which can be used as a handheld pointing device and detects movement in three dimensions. Wii Sports is a sports video game developed and produced by Nintendo as a launch title for the Wii video game console, and consists of five separate sports games: tennis, baseball, bowling, golf, and boxing. The games all use the motion sensor capabilities of the Wii Remote and Nunchuck attachment to control the actions of the on-screen character [293].

Figure 3.2: Three game platforms with motion sensor capabilities. From left: EyeToy from Sony [291], Microsoft's Kinect [292] and Nintendo Wii [293]

Kinect for Xbox 360, or simply Kinect (originally known by the code name Project Natal), is a 'controller-free gaming and entertainment experience' by Microsoft for the Xbox 360 video game platform [292]. Based around a webcam-style add-on peripheral for the Xbox 360 console, it enables users to control and interact with the Xbox 360 without the need to touch a game controller, through a natural user interface using gestures, spoken commands, or presented objects and images. According to Microsoft, the software technology enables advanced gesture recognition, facial recognition, and voice recognition and is capable of simultaneously tracking up to six people, including two active players for motion analysis with a feature extraction of 20 joints per player. One of the first games for Kinect, is the virtual pet game Kinectimals where players can interact with virtual animals.

Sony's EyeToy is a colour digital camera device, similar to a webcam, for the PlayStation 2. The technology uses computer vision and gesture recognition to process images taken by the camera. This allows players to interact with games using motion, colour detection and also sound, through its built-in microphone. The game 'Play' was the first game to make use of the PlayStation 2's video camera accessory, EyeToy and featured twelve mini-games played by moving one's body [291].

Using Commercial Video Platforms for Rehabilitation

In recent years, a growing number of occupational therapists have integrated video game technologies, such as the Nintendo Wii into rehabilitation programs. The term **'Wiihabilitation'** is often used to describe the use of the Nintendo Wii-platform in rehabilitation. The use of Wii has been reported successful in increasing patients' motivation and encouraging full body movement although the non-rehabilitative focus of Wii applications presents a number of problems: games are too difficult for patients, they mainly target

upper-body gross motor functions, and they lack support for task customization, grading, and quantitative measurements [12].

In [41] describes the use of the Nintendo Wii Fit for the treatment of balance problems for an elderly patient with a stroke. In [300] it was concluded that the physiological and metabolic responses of Nintendo Wii boxing would allow game activity to be a viable part of a programme of structured exercise in young adults to gain health benefits. In [301] describes a pilot undertaken to determine whether the Nintendo WiiFit was a feasible and acceptable intervention in community-dwelling in attempt to reduce falls. This pilot study showed that WiiFit exercises are acceptable for target group and it was concluded that the WiiFit has the potential to improve balance but that further work is required.

Nitz. et al. [201] describes research which has the goal to determine the feasibility of Wii Fit in improving balance, strength, flexibility and fitness for healthy women aged between 30 and 60 years. In this study, it is stated that activity fostered by Wii Fit showed an immediate effect on balance and strength but that the results needs confirmation by statistically powered studies. Halton [103] describes how occupational therapists have begun to use the Wii with adults as a part of their regular treatment at the Glenrose Rehabilitation Hospital. The study shows how initial responses from clients and occupational therapists have been positive, e.g. clients stay in therapy session longer than usual, engaging in social interaction and meaningful occupation. Some clients report that as their focus turned to the game, there was a less negative focus on the affected limb. Deutsch has investigated the positive effect of using Wii for rehabilitation of adolescent with cerebral palsy [69], while Sugarman [249] has described a study of using the Wii Fit System for treatment of balance problems for elderly. A similar study was conducted by Deutch in [68], where a Wii-based game was used to train balance and mobility rehabilitation for two individuals post-stroke patients.

Observed Problems using Commercial Platforms for Elderly

Gerling [87] discusses the accessibility of commercially available video games for frail elderly players by providing an focus group analysis of Wii Sports and Wii Fit mini games. According to this study, recent research results show that engaging with games may have positive effects of the overall well-being of senior citizens, but also that not all games are fully accessible to elderly players. Similar results have been reported in studies by Neufeldt [197] who describes the experiences with elderly people in a residential home who interacted with the Wii. The paper states, that while the haptic mode of interaction offers many opportunities for health related activities the authors observed hindrances when introducing the Wii to people who were sceptical about the usage of video games. Also problems were observed when playing Wii related to physical and/or coordination issues, such as problems in pressing or releasing buttons in the correct moment or being confused by menus opening accidentally when false buttons were pressed. Kathrin Maria has investigated the challenges of game design for an elderly audience with a focus on the development of safe and usable exertion games for frail senior citizens [88] based on a case study where different balance tasks for elderly players the Nintendo Wii Balance Board. The results indicate that age-related impairments influence the use of video games among frail elderly in many respects.

3.3   Playware

The term **Playware** is defined as the use of technology to create the kind of leisure activities we normally label play, i.e. intelligent hard- and software that aims at producing play and playful experiences among users and of which e.g. computer games are a sub-genre [164, 165]. Research in Playware originated at the Maersk Institute at the University of Southern Denmark, but is now mainly done at the Center for Playware at DTU in collaboration with a number of other European universities. The research has to a large extend been centered about the development and use modular interactive tiles (See Figure 3.3) which introduces technologies known from robotics, artificial intelligence and multimedia into play equipment [160, 169].

The Playware Platform

The modular interactive tiles can attach to each other to form an overall system, and are designed to be flexible and in a motivating way to provide immediate feedback based on the users' physical interaction following design principles for modular playware [166].

Figure 3.3: Modular tiles which are a central platform for research in Playware

Each modular interactive tile has a quadratic shape measuring 300mm*300mm*33mm and moulded in polyurethane. In the center, there is a quadratic dent of width 200 mm which has a raised circular platform of diameter 63 mm. The dent contains the printed circuit board (PCB) and the electronic components mounted on the PCB, including an ATmega 1280 as the main processor in each tile. At the center of each of the four sides of the quadratic shape, there is a small tube of 16mm diameter through which infra-red (IR) signals can be emitted and received (from neighbouring tiles).

Research using Playware

The modular tiles have been used for various purposes and target. In [167] experiments with children were conducted in order to record their playing behaviours on a Playware playground. A neural network capable of classifying the children's behaviour within eleven categories (i.e. favourite playing behaviour) was trained using a subgroup of the children. Similar study was conducted in [105] which introduces an approach on how adaptive playgrounds can be developed using multi-agent systems (MAS), artificial intelligence (AI) and Playware technology. The paper introduces a multi-agent system approach for modelling social behaviours in children's play. In [261] it is investigated how it is possible to implement adaptivity in modular playware, and allow the playware to adapt to the user's level of competency in multi-player games. In [314] an approach for capturing and modeling individual entertainment (fun) preferences is applied to users of the Playware playground. For this purpose children's heart rate (HR) signals, and their expressed preferences of how much fun particular game variants are, are obtained from experiments using games implemented on the Playware playground. In [163] soccer playing was facilitated based on a modular interactive wall composed of modular interactive tiles that respond with coloured light, sound and scores on the players performance. The playware game was set up to motivate players to engage in training of technical soccer skills by receiving motivating and immediate feedback.

Playware in rehabilitation

The modular interactive tiles have been used for rehabilitation, which e.g. has been shown in [162]. In this paper it is described how modular interactive tiles can be used for playful physiotherapy, which is supposed to motivate patients to engage in and perform physical rehabilitation exercises. Results based on qualitative feedback indicate that the patients find the playful use of modular interactive tiles engaging and motivating for them to perform the rehabilitation. Also, test data suggest that some playful exercises on the tiles demand an average heart rate of 75 % and 86 % of the maximum heart rate. Similar results were reported in [161] where the modular tiles were tested at a hospital rehabilitation unit e.g. for cardiac patients and for physical rehabilitation of stroke patients in their private home. In all pilot test cases qualitative feedback indicate that the patients find the playful use of modular robotic tiles engaging and motivating for them to perform the rehabilitation.

Modular playware as a playful diagnosis tool for autistic children has been reported in [159]. In this paper, it is studied how the modular playware can make automatic documentation of play activities by autistic children. Using artificial neural networks for automatic classification of the individual, the modular tiles are used as a supplementary diagnosis tool of the children's diagnosis based on free play. Related studies have been documented in [168] and [169]. In [166] two prototype systems using modular playware were developed and used by children with cognitive disabilities.

I-blocks and Other Tangible Media

Another modular electronic robot platform which has come out of the Playware research is the I-block system [200, 127] (See figure 3.4). Research using I-blocks is manly fo-

cused on how to create intelligent learning material for educational use, and an example can be found in [200] where children are allowed to experiment with musical genres without any prior musical knowledge or skills. Another example of the use of I-Blocks can be found [180] where users can do "'programming by building"' and thereby construct functionality of artefacts without the need to learn and use traditional programming languages.

Figure 3.4: i-blocks which are used for for educational use

A similar type of robotic devices are the so-called rolling pins which have been designed and developed to assist therapists in interacting with dementia affected patients. The results of the experiment demonstrate the positive effects with respect to engagement, coordination, and motivation with regard to therapy [178]. Related work which investigates tangible media for developing a therapeutic environment to stimulate patients' residual cognitive, behavioural and physical abilities can be found in [176].

The EU-funded project IROMEC investigates robots as companions engaging in social exchanges with children with different disabilities. As a result of this project, the papers by Marti and Guisti [177] and Robin et. al [225] describe user-centred design approaches to develop robots able to engage in meaningful interaction.

3.4 Robot Soccer

Robotic soccer is an adversarial multi-agent research domain, in which issues of perception, multiagent coordination and team strategy are explored. One area of interest is to investigate soccer competitions between teams of humans and robots, while another research area is the investigation and development of groups of autonomous robots who compete against each another. The **RoboCup** is an international robotics competition founded in 1997 which has the aim to develop autonomous soccer robots with the intention of promoting research and education in the field of artificial intelligence. The RoboCup has one definite goal: winning against the human world soccer champion team by the year 2050 [135, 136]. This implies real tackles and fouls between humans and

Figure 3.5: Three humanoid robots. From left to right: ASIMO by Honda [116], Sony's QRIO [297] and Nao by Aldeberan [9]

robots and rises safety concerns for the robots and even more important for the human players.

A number of robot platforms and AI techniques have been applied to reach this goal, and Hans-Dieter Burkhard et. have outlined a road map for future research based on interviews with representatives of different RoboCup robot leagues [46].

The following examples show the variety of robot soccer research. Browning et. al. have been active in addressing the challenge of using the SegWay platform for robots to play soccer against human beings [43, 42, 13], while [318] provides a description of a low-cost autonomous humanoid soccer robot called RoboErectus. The Nao platform (See figure 3.5) is an autonomous, programmable, medium-sized humanoid robot, developed by Aldebaran Robotics [9] which replaced Sony's robot dog Aibo as the robot used in the Robocups's Standard Platform League (SPL). Some research has been conducted by analysing football matches as in e.g. [100] who located and analysed safety critical scenes of soccer exemplified by two matches of the FIFA World Cup 2006 in Germany.

Games based on Humanoid Robots

There are several examples of how games are constituted using humanoid robots (See figure 3.5), e.g QRIO's routine of tracking and kicking a ball [297], and in [37] where the robot Leonardo is used to play an imitation game. In [199] the game consists of a memory card game between Honda's humanoid robot ASIMO [116] and a human player and in [147] a robot learns the game rules of rock-paper-scissors, muk-chi-ba and blackjack by watching human demonstrators. Some commercial humanoid gaming robots exist, e.g. Tri-Bot from WowWee which is able to play three simple maze-based games with the user.

Games based on Mobile Robots

Tapus [259] has shown a longitudinal pilot study in which individuals suffering from dementia and/or other cognitive impairments should play cognitive game based on a sociable mobile robot. In [185] by Michalowski describes the study of a mobile robot participating in a conference where it should deal with the human beings it encountered

Figure 3.6: Three social robots. From left to right: Paro [7], iCat [213] and AIBO [131]

by playing social tag. A game using a mobile robot which follows a person has been described in [174, 175] in which the robot plays with children who normally are prevented from playing due to cognitive, development or physical impairments.

In [181] a tag-playing mobile robot is introduced to promote the human-robot interaction through a motion, targeting maintenance, training, and recovery of human physical and cognitive functions for elderly. Dautenhahn [65] reports the results of a project where autistic children are playing with a small, non-humanoid mobile robot that can engage children in simple interaction games. As a part of the AURORA-project [17], the research of children with autism interacting with a mobile robot are presented in e.g. [64, 286, 287]. Robins [224] investigates how robotic toys can become social mediators, encouraging children with special needs to discover a range of play styles, from solitary to collaborative play (with peers, carers/teachers, parents etc) using a humanoid and a mobile robot. In [223] a humanoid robot is used to investigate robot-mediated joint attention for therapy and education.

3.5 Social Robots for Elderly

Much research on social robots interacting with elderly concerns the psychological effects of robots as companions e.g. for **Robot-Assisted Therapy**. This section presents a selected number of papers using three popular robot platforms; namely Paro, iCat and AIBO (see figure 3.6).

The Paro platform

Paro is probably the most famous and well-documented example of robot assisted therapy (see figure 3.6). Paro is a therapeutic robot baby harp seal, intended to have a calming effect on and elicit emotional responses in patients of hospitals and nursing homes, similar to animal-assisted therapy, but without its negative aspects. It also responds to sounds and can learn a name. It can show emotions such as surprise, happiness and anger. It produces sounds similar to a real baby seal and its surface is covered with white fur. A tactile sensor is inserted between the hard inner skeleton and the fur to create a soft feel and to permit the measurement of human contact with the robot. The psychological and social effects of using Paro with elderly have been investigated in a number of papers which can be seen in Table 3.1.

Paper	Description
[276]	Describes how a combination of different measurement techniques were collected to evaluate Paro in an nursing home. On this basis, it was concluded that Paro improved the ability to recover from stress. In addition, the paper concludes the using Paro reduces mental impoverishment, known as burnout, of nursing staff giving care to elderly people.
[277]	In this paper demented patients were analysed using electroencephalography before and after robot therapy. The results showed that their cortical neurons activity was improved by interaction with the seal robots.
[93]	The use of Paro was analysed using qualitative and quantitative speech analysis and the results show that the robot actively supports our natural disposition to attribute intentional states to inanimate or artificial objects.
[85]	The Danish Paro Project, examines the practical utility of Paro within the range of elderly and persons with brain damages in Northern Europe. The Paro project started in September 2008, and currently 150 Paro seals are distributed on 30 municipalities in Denmark as a part of the project. The project focuses on the effect of the seal robot and the goal is to document impact to project participants, public bodies and other stakeholders in the fields of elder care and healthcare.

Table 3.1: User interaction studies using Paro

The iCat platform

The iCat Research Platform is a research platform for studying human-robot interaction. It consists of a user-interface and the Open Platform for Personal Robotics ('OPPR') software. iCat is a plug and play desktop user-interface robot that is capable of mechanically rendering facial expressions. This capability is used for studying human-robot interaction. The robot has been made available by Philips Research to stimulate research in this area further and in particular to stimulate research topics such as social robotics, human-robot collaboration, joint-attention, gaming, and ambient intelligence. An overview of research using iCat can be seen in Table 3.2.

Paper	Description
[114]	Elderly participants in a nursing home (aged 65 and older) were exposed to an introvert and an extrovert version of the iCat interface to see whether this difference in interaction would lead to different scores in degree of acceptance. First analysis of data from the studies suggests that social abilities in a robotic interface contribute to feeling comfortable talking to it and invite elders to be more expressive.
[112]	Conversational expressiveness of elderly users interacting with a robot and screen agent were observed in an elder care institution. The paper concludes that participants showed indeed more expressiveness with a more expressive robot or agent.
[113]	The concept of enjoyment as a possible factor influencing acceptance of robotic technology by elderly people was investigated. The experiment confirmed the hypothesis that perceived enjoyment has an effect on the intention to use a robotic system.
[149]	An iCat robot and chess game scenario is described. The paper shows that a social robot with emotional behaviour can perform better the task of helping users to understand a gaming situation and the results suggested that user's perception of the game increases with the iCat's emotional behaviour, and that the enjoyment is higher.
[231]	A computational model to automatically analyse human postures and body motion to detect engagement of children playing chess with an iCat robot that acts as a game companion has been presented in
[148]	The role of emotions and expressive behaviour in socially interactive characters employed in educational games. More specifically, on how to use emotional behaviour to help users to better understand the game state.
[155]	This research focused on the question if a socially intelligent robot is able to change the behaviour/lifestyle of a diabetic. The paper was based on motivational interviewing and an experiment showed that the socially intelligent iCat had higher preference compared to a text interface.
[273]	Ruiten et. al has studied evaluation of empathy and objective control of elderly towards a a robotic game-and-train buddy. The results show that the level of empathy and the level of control did not have a significant main effect on the attitude of users towards the robot.
[50]	Castellano provides a general overview of some of the issues arising from the design of an affect recognition framework for artificial companions and show that children tend to look at the iCat and smile more when they experience a positive feeling and they are engaged with the iCat.

Table 3.2: Interaction studies using iCat

The AIBO platform

AIBO is one of several types of robotic pets designed and manufactured by Sony and is able to walk, sense its environment via camera and recognize spoken commands. Also

AIBO robotic pets are able to learn and mature based on external stimuli from their owner or environment, or from other AIBOs. There have been several different models since their introduction 1999 but AIBO was discontinued in 2006 [290]. Although AIBO originally was not created for elderly, it has been used as a research platform for this domain. In [104] AIBO was used as a tool for recreation for elderly people with dementia in a nursing home. The therapy was based on a robot participating in a card game and a ball game and the effects of the recreation was evaluated by observation, i.e. measuring the occurrence of an elderly person's actions which was judged by evaluators. The paper concludes that the games are useful for prevention of dementia progression. In [256] the study compared the effectiveness of AIBO with a toy when used in therapy of elderly people with severe dementia. The paper concludes that AIBO clearly was an effective rehabilitation tool in the treatment of severely demented patients.

Commercial General Purpose Mobile Robot Platforms

The Robotino mobile robot platform which has been in this thesis is based on a commercial general purpose platform from FESTO which has been added an expressive face, as described in Chapter 6. The FESTO platform in its basic form is not significantly different from many other commercial mobile platforms (see Figure 3.7) like e.g. the popular Pioneer P3-DX from Adept Mobile Robots [5]. PeopleBot is an extension of the Pioneer platform including a touch screen which facilitate interaction with people. The Scitos A5 robot from MetraLabs [184] is similar to PeopleBot but also includes an expressive face. However, the Robotino platform used in this thesis was given from the beginning of the project, and alteration of the physical design and functionality is considered out-of-scope.

Figure 3.7: Three commercial general purpose mobile platform robots. From left to right: Pioneer P3-DX and PeopleBot by Adept Mobilerobots [5] and Scitos G5 by Metralabs [184]

3.6   Analysis of Robot Platforms

As described in the introduction, the hypothesis of the thesis is how to motivate elderly to move physically facilitated by mobile robot games based on algorithms using spatio-temporal input about player behaviour. The main arguments of using the Robotino mobile platform for the robot based games proposed in this thesis are:

- The robot can operate autonomously with a speed that matches human beings

- The platform can operate robustly in an open-ended environment and supports laser scanner input

- The tangible nature of the robot catalyses interaction and offers support for touch and physical interaction - also for users relying on assistive tools like wheelchairs and walkers

- The robot's expressive face can be used as a feedback mechanism to tell about the game state and potentially influence game experience because of its human-like design

The limitations of the platform in its current form are that it only gives limited feedback (the expressive head is currently the only possibility to give feedback to the users) and supports limited input using the laser scanner. This is a constraint on the complexity of the games which can be implemented on the platform and will be discusses later (See Chapter 7).

Compared to the Robotino platform, commercial humanoid or pet platforms like Nao, Qrio and AIBO have the advantage that they support complex sensor input and feedback which could be useful for creating interesting games. Another advantage of using these platforms is that they are inexpensive. However, since they are relative small and moves relative slow compared to humans, they are not suited for implemented games where the spatio-temporal mobility of humans are central. A robot like Asimo fulfils the criteria, but this platform is very expensive and not relevant seen from a commercial market perspective.

Commercial video games platforms like Nintendo Wii, MS Kinect and Sony's Eye-Toy offer the advantage of advanced sensor input and feedback which allows for very elaborative games. One of the disadvantages of these platforms are they are stationary, and therefor cannot take initiative of playing a game like a robot potentially can. Another disadvantage is these platforms do not offer the physical presence that a robot does. Kathrin Maria has investigated the challenges of game design for an elderly audience with a focus on the development of safe and usable exertion games for frail senior citizens [88] and results indicate that age-related impairments influence the use of video games among frail elderly in many respects. Problems related to physical and/or coordination issues have been observed when playing Wii [197], such as problems in pressing or releasing buttons in the correct moment or being confused by menus opening accidentally when false buttons were pressed.

The modular tiles which have been used in Playware research have the main advantage that they can be configured in many different ways and that their modular structure make them relative robust (if one tile brakes, this does not necessarily affect the game).

However, a disadvantage is they are activated by people's steps and do not support assitive tools like wheelchairs and walkers as the mobile robot solution presented in this thesis does.

The hand-held tangible devices like iBlocks, Rolling Pins and Light and Sound Cylinders have the advantage that they are robust physical devices which can be used for cognitive training and training of the torso. A disadvantage is they have relative limited sensor input and feedback and as training devices for spatio-temporal behaviour they seem less suited unless they are connected to some location device mechanism.

They iCat platform has the advantage that is offers a very expressive feedback mechanism. However, since the platform is not mobile it is not suited for mobility based games. Paro has the advantage that a positive effect has been documented for elderly with dementia, but since the platform is not programmable and has limited feedback it is not interesting for developing new games.

Table 3.3 shows an overview of the different platforms which been used in research related to robot based games for elderly as described in this chapter. The tables describes the name of the platform along with the pros and cons of using the platform for robot based games.

Platform	Pros	Cons
Commercial humanoid/pets (Nao, QRIO, AIBO)	Mobile. Offers physical presence. Inexpensive. Supports complex sensor input and feedback.	Relative small and moves slow compared to humans. No possibility to include external devices (e.g. laser scanner)
Commercial video platforms (Wii, Kinect, EyeToy)	Robust. Inexpensive. Advanced input and feedback	Stationary. No physical presence.
Playware (Modular tiles)	Robust and configurable. Offers physical presence.	Limited sensor input and feedback. No support for assistive tools e.g. wheel chairs
Handheld devices (I-blocks, Rolling pins, Light and Sound Cylinders)	Robust. Offers physical presence. Supports cognitive training and training of torso.	Relative limited input and feedback. No support for spatio-temporal mobility
Social Robots (iCat)	Advanced recognition and feedback. Offers physical presence. Documented positive affect on elderly. Programmable	Stationary
Social Robots (Paro)	Offers physical presence. Documented positive affect on elderly with dementia. Limited recognition and feedback	Not programmable.
Robotino	Offers physical presence for users using assistive tools like wheelchairs and walkers. Is mobile with a speed that matches humans. Can operate robustly using laser scanner input	Limited feedback and therefore limited potential for game complexity.

Table 3.3: Overview and comparison of platforms related to robot based games based on spatio-temporal behaviour

3.7   Research Papers Related to this Thesis

Table 3.4 and Table 3.5 show an overview of the research related to robot based games for elderly as described in this chapter. The tables show a reference to the paper, the type of robot platform, the target group and a short summary of the research focus. As the table shows there a numerous examples of how robot technology and other tangible media have been used as exercise facilitators for elderly based on game activity. However, as can be seen in the table, most research combining mobile robots and games have been targeted at children. The papers which are most closely related to the results in this thesis are the work presented in [181], [259] and [74] which all explore the use of mobile robots in game activity for elderly. However, the implementation of the games presented in these papers differ substantially from the games presented in this thesis. In the first case, the robot game is based on Step-On Interface (SOI) displaying a bitmap image on the floor. The game does not rely on the spatio-temporal behaviour of the interacting person as such, but

on of the user interacts with the visual interface. In the second case, the paper presents a music based cognitive game. This paper focuses on methods for engaging cognitive skills whereas the thesis focuses on physical skills. In the third paper, the robot monitors the performance of a user during a seated arm exercise scenario, with the purpose of providing motivation to the user to complete the task and to improve performance. This game is based on analysis of the movement of the upper torso, but do not use the spatio-temporal information about the player behaviour. The papers by Marti [174, 175] present a game which is very similar to the game described in Paper B, in which a mobile robot follows a person. However, the work by Marti is targeted at children who are prevented from playing, either due to cognitive, developmental or physical impairments whereas this thesis focuses on elderly.

Id	Platform	Target group	Research focus
		Overview of robot related games	
[167]	Modular tiles	Children	Record playing behaviour
[105]	Modular tiles	Children	Record playing behaviour
[261]	Modular tiles	Children	Game adaptivity
[314]	Modular tiles	Children	Capturing and modelling individual entertainment
[163]	Modular tiles	Children	Engage in soccer training
[162]	Modular tiles	Elderly	Playful physiotherapy
[161]	Modular tiles	Cardiac and stroke patients	Playful physiotherapy
[159]	Modular tiles	Autistic children	Playware as diagnosis tool
[168]	Modular tiles	Autistic children	Playware as therapy
[169]	Modular tiles	Autistic children	Playware as therapy
[166]	Modular tiles	Children with different cognitive abilities	How modular robotic objects can enhance playful experiences
[200]	I-blocks	Children	Edutainment
[127]	I-blocks	Children	Edutainment
[180]	I-blocks	Children with linguistic problems	Programming by building
[178]	Rolling pins	Dementia affected patients	Assist therapists in interaction
[176]	Rolling Pins, Light and Sound Cylinders	Dementia affected patients	Stimulate cognitive, behavioural and physical abilities
[134]	Sociable non-mobile robot	Adults	Weight loss coach
[191]	Wall with sensors	N/A	Distributed interactions
[189]	Mat with sensors	N/A	Distributed interactions
[190]	Augmented video system	N/A	Distributed interactions
[188]	Virtual reality stationary bikes	N/A	Capture attention by playing a fitness game
[56]	Mobile phone	Women who wants to increase their physical activity	Four design requirements for technologies that encourage physical activity
[151]	Social computer games	People with sedentary lifestyle	Increase in physical activity by foot step count
[173]	Hybrid board/video game	N/A	Enhance natural and enjoyable recreational interaction between friends
[41]	Wii	Elderly patient with a stroke	Treatment of balance problems
[300]	Wii	Young adults	Physiological and metabolic responses
[301]	Wii	Elderly	Fall reduction
[201]	Wii	Elderly	Improving balance
[227]	Wii	Older Adults	Depression
[103]	Wii	Patient's at rehabilitation centres	Wii for occupational therapy
[69]	Wii	Adolescent With Cerebral Palsy	Rehabilitation
[249]	Wii	Eldery	Treatment of balance problems
[68]	Wii	Post-stroke patients	Balance and mobility rehabilitation
[87]	Wii	Frail elderly	Accessibility
[197]	Wii	Elderly people in a residential home	Accessibility
[88]	Wii	Frail elderly	Challenges of game design
[177]	Modular, mobile robot	Children with disabilities	Using a user-centred design approach to develop a robot able to engage in meaningful interaction
[225]	Robotic toys	Children with disabilities	User-centred development of play scenarios for robot assisted play
[43]	SegWay	N/A	Robot soccer against human beings
[42]	SegWay	N/A	Robot soccer against human beings
[13]	SegWay	N/A	Robot soccer against human beings
[318]	Humanoid robot	N/A	Robot soccer against human beings
[297]	Humanoid robot	Children	N/A
[37]	Leonardo	N/A	Robot learn how to play an imitation game
[199]	Asimo	N/A	Memory card game between humanoid and a human player
[147]	A teddy bear-like robot	N/A	How a robot learns the game rules by watching human demonstrators

Table 3.4: Overview of research related to robot based games (Part 2 of 2)

Overview of robot related games			
Id	Platform	Target group	Research focus
[64]	Mobile robot	Children with autism	Quantitative and qualitative techniques for evaluating interactions
[65]	Mobile robot	Autistic children	Engage children in simple interaction games
[181]	Mobile robot	Elderly	Recovery of human physical and cognitive functions using games
[223]	Humanoid robot	Children with autism	Robot-mediated joint attention for therapy and education
[224]	Mobile and humanoid robot	Children with special needs	How robotic toys can become social mediators
[74]	Mobile robot	Elderly	Monitors and motivates a user during a seated arm exercise
[130]	Mobile robot	Cardiac patients	Motivation and support
[287]	Mobile robot	Children with autism	Robots as an educational or therapeutic role for children with autism
[306]	Mobile robot	Children	Commercial toy
[259]	Mobile robot	People with dementia	A longitudinal pilot study in which individuals should play cognitive game
[174]	Mobile robot	Children with cognitive, developmental or physical impairments	A design case of a robot companion targeted to children who are prevented from playing
[185]	Mobile robot	People at conference	A social game of tag
[276]	Paro	Elderly with dementia	Robot assisted therapy for the ability to recover from stress
[277]	Paro	Elderly with dementia	Robot assisted therapy for improvement of cortical neurons activity
[93]	Paro	Elderly with dementia	How elderly attribute intentional states to inanimate or artificial objects
[114]	iCat	Elderly participants in a nursing home (aged 65 and older)	Degree of acceptance of an introvert and an extrovert version of the iCat
[112]	iCat	Elderly participants in a care institution	conversational expressiveness of elderly users interacting with a robot and screen agent
[113]	iCat	Elderly	The concept of enjoyment as a possible factor influencing acceptance of robotic technology
[231]	iCat	Children	Automatically analyse human postures and body motion to detect engagement
[148]	iCat	Elderly	The role of emotions and expressive behaviour in socially interactive characters in educational games
[149]	iCat	Elderly	Users' understanding of a gaming situation and enjoyment of the game.
[155]	iCat	Diabetics	Whether a socially intelligent robot is able to change the behaviour/lifestyle
[273]	iCat	Elderly	Perception and attitude of social robots using iCat as a game and train buddy
[104]	AIBO	Elderly people with dementia	Therapy by participating in a card game and a ball game.
[256]	AIBO	Elderly with severe dementia	Robot toys as an effective rehabilitation tool

Table 3.5: Overview of research related to robot based games (Part 2 of 2)

Chapter Summary   The last decade, the development of new interfaces has changed electronic games from being a desktop activity to a higher degree being a physical activity involving the entire body. Although much research has been done on the combination of games and robots, most research using mobile robots is often targeted at children. Relative little research literature has been found based on the use of mobile robot platforms for elderly in game scenarios, making it an interesting field to explore. The arguments for using a mobile robots for creating physical games for elderly are that the tangible nature of the robot catalyses interaction and offers support for touch and physical interaction - also for users relying on assistive tools like wheelchairs and walkers. Additionally the robot can operate autonomously and robustly in an open-ended environment using a speed that match human beings.

4 Robotics and AI

The creation of intelligent machines substituting for man labour is an ancient dream and today robots are common in industry. But although robots operating outside the laboratory have been predicted repeatedly for a number of years, we still do not see intelligent service robots in our homes, in our workplace or at the shopping centre. The main reason is that reliable long-term operation in dynamic and open-ended environments in many aspects still is an open research question. This chapter describes the history and the state of art of artificial intelligence and robot control and includes some of the problems, methods and paradigms which have been identified and developed in the attempt of creating intelligent robots operating in open-ended environments and relates this to the current thesis.
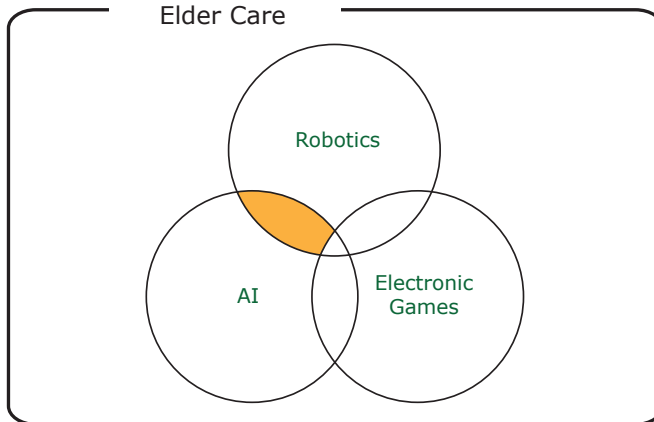

Figure 4.1: This chapter describes the history and state-of-the-art in robotics and artificial intelligence

4.1 Creating Intelligent Robots

Common principles of communication and control in animals and machines are known as **Cybernetics**, which is a coupling of control theory, information science and biology

[289]. Since the late 1940s, Norbert Wiener is generally credited with leading the development of the field. Wiener and Ashby [14, 15] elaborated the notion, describing an organism as a machine using mathematics developed for feedback control systems expressing natural behaviour. The birth of artificial intelligence as a distinct field is generally associated with the Dartmouth Summer Research Conference held in August 1955, and AI has almost always been related to the use of programmable computers. The goals of the conference involved the study of a wide range of topics including language use, neural nets, complexity theory, self improvement, abstractions and creativity [14]. A great deal of AI techniques have now been adopted in various domains, including robotics which is often defined as a subset of AI.

The field of AI is often divided into two distinct approaches:

- Computer-modelling of existing biological systems (for example artificial neural networks which attempt to model human or animal brains)

- The construction of systems which appear to be intelligent, but are designed without regarding natural biology of intelligence (for example a chess computer or a rule based expert system).

In the original proposal at the Dartmouth Summer Research Conference, Marvin Minsky indicated that an intelligent machine "would tend to build up within itself an abstract model of the environment in which it is placed. If it were given a problem it could first explore solutions within the internal abstract model of the environment and then attempt external experiments" [182]. This approach dominated robotics research for the next thirty years. During this time AI research developed a strong dependence upon the use of representational knowledge and deliberative reasoning methods for robot planning. In the 80's through the 90's, making robots to learn from experience and adapt to their environment became an integrated part of robot development and evolutionary and distributed approaches became popular. In recent years, statistical methods from machine learning like Bayesian networks, Markov models and Reinforcement learning have been widely applied [82].

From an overall perspective, the fundamental principle of all computer AI is to search systematically for a solution. The more you know, the less searching for an answer you need and the more search you can do, the less knowledge you need. That this is the way all intelligent behaviour arise, was suggested by researcher Newell and Simon in 1976. Despite having several solid and important features, this theory has been largely discredited [187], although recent work has proved this theoretically [303].

4.2   Overview of Robot Control

Many different techniques have been used for creating robot control systems, and Figure 4.2 by Arkin shows a spectrum of robot control strategies, in which most control systems can be placed [14].

The left side represents methods that employ **deliberative reasoning** and the right represents **reactive control**. If a robot control system is based on deliberative reasoning it requires relatively complete knowledge about the world. The system then uses this knowledge to predict the outcome of its actions. If the knowledge upon which the
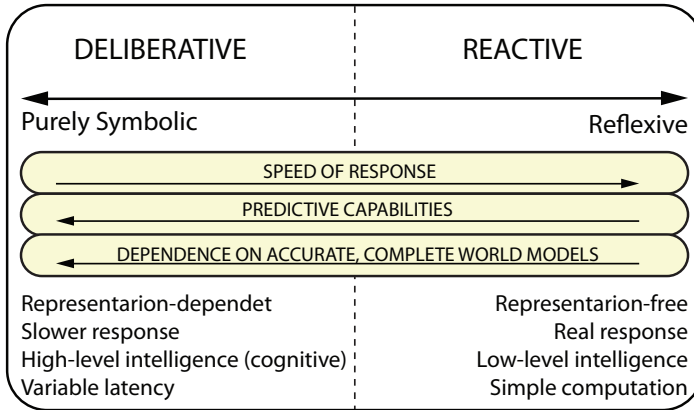
Figure 4.2: The spectrum of robot control [14].

reasoning is based is consistent, reliable and certain this strategy enables performance optimization relative to its world model. For example a rule based control system would be classified as employing deliberative reasoning. In a dynamic world, where many objects may be moving it can be dangerous to rely on past information, because it may not be valid any more. A purely reactive control system will always perceive the world as it is. This is one of the reasons for the success of the behaviour based control approach which will be described later; it is strictly reactive and therefore works very well in a dynamic environment.

Planning Based Control for Mobile Robots

One of the first general-purpose mobile robots was built by SRI for DARPA in 1967 and was nicknamed Shakey. Since then, robot navigation has become a well-established research discipline in which a great number of algorithms exist dealing with the problem of making the robot move safely from A to B. Many of these techniques are based on a global planning algorithm together with a local obstacle avoidance technique and a overview of planning algorithms can be found in e.g. [145, 262, 53, 240]. However, robot navigation is still not considered a trivial problem - especially not when the robot has to operate in an open-ended environment including human beings and/or moving obstacles. Many classic robot planning algorithms require a map in order to complete the planning and examples of popular methods are STRIPS, grid based, graph based and sampling based algorithms.

STRIPS (Stanford Research Institute Problem Solver) is a well-known example from the classic AI planning tradition which is a theorem-proving system using first-order logic to develop a plan [77]. STRIPS was first applied on Shakey in the 70's, but today STRIPS is used to refer to the formal language expressing automated planning problem instances. A STRIPS instance is composed of:

- An initial state;

- The specification of the goal states, i.e. situations which the planner is trying to reach;

- A set of actions. For each action, a precondition (what must be established before the action is performed) and post condition (what is established after the action is performed) must be defined..

Classical planning like STRIPS involves the generation of plans by state or partial plan space search in order to satisfy a given goal, but has been proved and experimented intractable [51, 140, 308]. As a consequence, different methods have been proposed to try to reduce the computational cost e.g. hierarchical planning [198, 230, 299]. The basic idea of hierarchical planning is to distinguish goals and actions depending on their different degrees of importance and solve the most important problems first. Solution obtained at a certain level, becomes the input for a problem-solver at the next level. The process ends when a concrete plan is found. The main advantage of this approach derives from the fact that it would be possible to obtain a much smaller search space in which to find a plan if certain activities are emphasized while other a temporarily ignored [308].

Grid Based algorithms   depend on a grid which represents the configuration space in which each cell is either occupied by an obstacle or free. The task for the algorithm is to compute a trajectory that passes only through free grid cells. When using this method there is trade-off to consider, as a low grid resolution will increase speed but potentially hide possible passages. On the other hand, a high resolution while result in increasing computation time. Also the number of cells grows exponentially with the dimension of the grid. A popular grid based path finding algorithm is the **Wavefront** algorithm [19] which works by expanding a wavefront from the goal towards the start configuration. Uncertainty in the mapping can be represented by associating each cell with a probability of being occupied and in this case the map is denoted an occupancy grid map.

Graph Based algorithms   works by defining a topological map (a graph) and then plan a trajectory on the graph. Example of different decomposition algorithms include Voronoi diagrams, plane weep algorithms and other cell decompositions techniques [16, 66, 52, 71]. Algorithms for searching for a path in a grid includes Dijkstra's algorithm, the A* and D* algorithm. All of these algorithms work by assigning a cost to the motion between two points in a graph and then finding the minimal cost path [248].

Sampling Based algorithms   are heuristics which exploits increasing computational power to evaluate a number of possible trajectories instead of searching for the one optimal solution. Sampling based algorithms work well for high-dimensional configuration spaces, because unlike combinatorial algorithms, their running time is not (explicitly) exponentially dependent on the dimension of the configuration space. Because of the randomness in the algorithms, sampling based planners do not give any guarantees of finding optimal solutions and within bounded time, they cannot guarantee to find a solution, even if one exists. However, they are probabilistic complete meaning that the probability of finding a solution, if one exists, goes to 1 as the number of samples goes towards infinity. A survey over sampling based motion planning and current issues can be found in [152]

Obstacle Avoidance . Many planning algorithms are often combined with a local obstacle avoidance algorithm, and examples obstacle avoidance techniques are Potential Fields and Vector Field Histogram. The potential field method is a popular approach originally developed for mobile manipulators and has been widely applied due to its versatility and simplicity [132]. The method uses the analogy of a charged particle moving in a force field, i.e. obstacles repel the particle, while the goal region will attract the particle. An example of the use of potential field in robot based games, can be seen in [271], where potential field functions are utilized for mobile robot navigation in a soccer environment. The vector field histogram was developed by Borestein [28] and is based on a polar histogram that represents the confidence of the existence of an obstacle at each direction. The histogram is divided into sectors and the sectors are analysed to find the most favourable direction to move. VFH has been further developed into the VHF+ ([270]) using the A* algorithm to verify that the robot is guided around an obstacle.

A problem with many local obstacle avoidance techniques are that they potentially lead to suboptimal paths, because they get stuck in a local minimum without being able to re-plan. Another problem is that most algorithms does not account for obstacles that move. Finally, in a interaction scenarios between human and robots, many obstacle avoidance techniques in their most basic form are not designed to represent the behaviour which a human would expect. However, many researchers have elaborated on these algorithms, and in this thesis we extend the potential field method to enable the robot to navigate adaptively (as will be explained in detail in Chapter 6 and the appended papers).

Behaviour based robot control

Map based planning algorithms presents two pervasive issues to robotics: The **close world assumption** and **the frame problem**. The close world assumption says that the world model contains everything the robot needs to know. If the closed world assumption is violated, the robot may not be able to function correctly. However, for practical and computational reasons representing the world often becomes computationally intractable. This is also known as the frame problem which initially was formulated as the problem of expressing a dynamical domain in logic without explicitly specifying which conditions are not affected by an action [196]. Despite inherent problems, classical planning was the dominant approach in robotics AI until the late 80's.

As a reaction to these traditions, **behaviour based robot control** was first defined by Rodney Brooks in 1987 at the MIT Artificial Intelligence Laboratory. The traditional decomposition for an intelligent control system is to break processing into a chain of information processing modules, proceeding from sensing via planning to action (see figure 4.3).

In the behaviour based paradigm (see figure 4.4) the decomposition is in terms of task-achieving modules (also called behaviours). Each behaviour is reactive to the sensor input and the states of the lower layers. All behaviours are rated and a behaviour has the ability to overrule or subsume the underlying behaviour. Layers are added incrementally and newer layers may depend on earlier layers operating successfully, but do no call them as explicit subroutines. In that way a control system can be build from the bottom up; first a layer of obstacle avoidance, and when this is operational a layer of wandering and so on.

Traditional control systems often fail since they demands an a priori symbol based de-
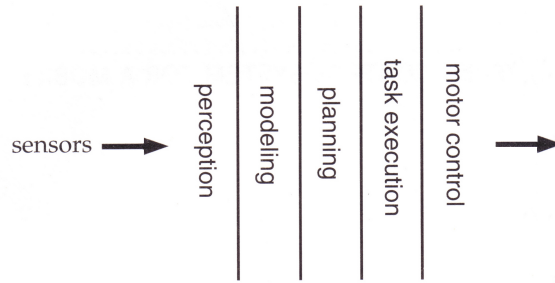
Figure 4.3: The traditional decomposition for an intelligent control system [38].
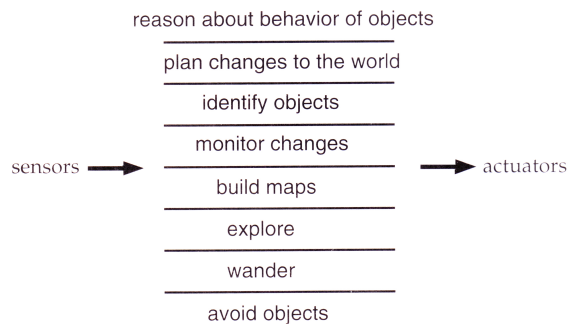
Figure 4.4: The behaviour based decomposition approach [38].

scription of the world and a plan of action has to be designed by an experimenter. Some of these problems are reduced by using the behaviour based approach, because there is no symbolic representation to be dealt with. This maybe is expressed best by quoting Brooks "Planning is just a way of avoiding figuring out what to do next." [39]. When introducing the behaviour based approach Brooks initiated a paradigm shift in which the notion of sensing and acting within the environment started to dominate AI-related robotics research [14]. But also the behaviour based approach have some problems because an experimenter must design a number of subsystems of the total control system [157]. According to Nolfi and Floreano there do not exist any good techniques telling how to do this decomposition today [202].

4.3 People Detecting and tracking

A common task in human-robot interaction studies it to detect and track people in a room and two types of method exist:

- Robot based techniques, in which sensors are placed on the robot

- Stationary techniques, in which different sensors are placed on fixed positions in the room.

Several types of sensors have been applied for tracking of people, e.g. 2D vision, 3D vision or thermal tracking [70, 195, 125]. Laser scanner based tracking is a common approach in applications where it is only desired to find the persons' position, but not the posture or facial expression. Laser scanner based methods are successful because it is relative easy to extract information compared to image based processing. Furthermore, laser scan based methods tend to work at longer distance than vision. On the other hand vision enables more accurate tracking of features and face tracking which can be important for close interaction. Combinations of laser scan and vision based methods can be found in e.g. [76, 186, 22]

In this thesis, we use a leg detection algorithm for person tracking. Leg tracking algorithms can be split in two types of methods.

- Detecting a person by finding the motion between each scan e.g. a particle filter. This type of method relies on the person to move, otherwise the person will be treated as a static obstacle.

- Estimating a position by analysing the geometric features of the legs. Laser range data are analysed for leg sized convex patterns, and as most people have two legs this gives a relative characteristic pattern.

In this thesis, we use the latter method. An inherent problem of people detection based on mobile robot platform is that the platform moves, which especially causes problems using image processing. Due to the high sampling frequency in laser based tracking, this is easier to account for and furthermore it is relative easy to compensate for the motion in a one-dimensional range scans using e.g. particle filter [94]

In decades, indoor stationary locations systems have been a challenging task in research and includes research using infrared light, ultrasound, camera, UWB, WiFi, cameras, RFID, etc, in systems like [4, 280]. There are often trade-offs to make between the required infrastructure, precision, update rates etc. which must be balanced in the design. In most the commercial setups, the systems are often limited to the last location registered, which could come from pressure sensors, passive tags (RFID) entering zones, or doors being opened. More advanced systems use algorithms to better estimate a user's current position based on pattern recognition or to predict a user's next location [98].

For both methods, there are challenges in evaluating the identity of the person when more than one user is present in the environment. Pressure mats, laser scans, image processing or movement sensors do not distinguish efficiently between different persons and many reports of experiments conducted with indoor locations systems therefore assumes that only one person will be present in the experimental setup.

4.4   AI and Robot Control in this Thesis

The AI in this is based on the Case-Based paradigm (CBR and CBP) which in general terms allows recalling and interpreting past experiences, as well as generating new cases to represent knowledge from new experiences. I use the Case-Based approach as low level adaptive control and Case-Based planning as a high-level planner which learns from human demonstration. CBR has proved successful in solving spatial-temporal problems in robotics in e.g. [139, 150, 128] and has the advantages that it allows runtime adaptation. Other advantages is the transparency of the method and that it is relative easy to

implement. CBP allows plan learning from human demonstration, and has been proven successful for strategic computer games in [205, 206, 207, 106, 97]. A deeper description of the methods are found in Chapter 5, the methodology section (see 6) and in the appended papers.

Game	1	2	3
Paper(s)	B, Video 1	C, D, E, F, Video 2	G
AI method	BC	CBR	CBP
Navigation	Local	Local	Local/Global
Algorithm	Simple Pursuit	Adaptive Potential Field	Dynamic Planning
Paradigm	Reactive	Reactive	Reactive/Deliberative
Use of map	No	No	Yes
Player(s)	Single	Single	Multiple
Robustness	High	Medium	N/A

Table 4.1: Selected characteristics of the robot control for the games implemented in the thesis.

Table 4.1 shows selected characteristics of the games which have been implemented and presented in this thesis. The table also serves as an illustration of a fundamental trade-off which is often present in robotics, namely robustness versus game complexity, i.e as the complexity of the robot behaviour increases, the robustness of the solution often decreases. In order to make the robot operate robustly and autonomously in an open-ended environment, it was initially mandatory to make the games relative simple and then gradually increase the complexity.

The work presented in paper B, C, D, E and F is based on the reactive paradigm, while the work in paper G relies on a hybrid of the deliberative and the reactive paradigm. The advantage of the approach presented in the papers using the reactive paradigm, is that the robot's motion do not rely on a map or a world model which means that the robot reacts immediately to the player's action and operates robustly in an open-ended environment making this approach suitable in a dynamic environment. However, the reactive paradigm also has its limits, i.e. it is hard to construct a sufficiently complex robot control to make an interesting game. To elaborate on this, a CBP approach has been introduced in Paper G.

The navigation behaviour of the robot in paper B is very simple, since the robot simply follows a person using a local based person detection and tracking algorithm based on laser scanner input. The advantage is robustness and speed in an open-ended scenario. A disadvantage is limited functionality of the robot game.

The navigation behaviour of the robot in the paper C, D, E and F is based on an extension of the potential field approach. The potential field is now adjusted dynamically with respect to the interaction scenario based on a CBR based learning algorithm. The advantage is reactive, adaptive robot control which is suitable in an open-ended environment. A disadvantage is that the robot needs a training period and some identification mechanism to adapt individually in an autonomous manner. To allow multiple players and enhanced game functionality, the CBP approach was added in Paper G which is the only game in this thesis which relies on a map. As this game has been evaluated in simulation only, the motion of the human players has been modelled using the Wavefront-algorithm in

combination with the VFH+-algorithm. Although this approach is big step away from the reactive paradigm, the arguments for using CBP as presented in paper G are twofold. Following the experience from the field studies presented in Paper B, it was suggested to include multiple players and cognitive training in future robot games. The CBR-approach did not seem to be well suited for this, whereas the implementation presented in Paper G offers a generic software framework which can be used for generating strategic multi player games. Secondly, the framework presented could technically be incorporated into the IntelliCare-project which was a requirement of the project (see Appendix J).

The games presented in paper B, C, D, E and F assume that only one person is present at the time, and localisation is based on estimating the geometric features of the legs using laser scanner images. In paper G, the game has been enhanced to also rely on a indoor localisation to estimate the location and identification of the multiple participants in the game.

Chapter Summary   A fundamental problem for robots operating in unstructured environments is to deal with non-determinism. In general, two major paradigms have influenced the development of control systems in modern robotics. The rule based (or deliberative reasoning) and the behaviour based (reactive control). The most important difference between these two approaches is the presence or absence of an internal representation of the world. This thesis includes examples of different mobile robot based games using the reactive structure and one game based on a hybrid between reactive and deliberative methods. However, the overweight of the contribution are based on the reactive paradigm to ensure robustness of the solution when operating autonomously in an open-ended environment.

5   Games and AI

The history of electronic games has evolved from basic lab experimentation to a billion-dollar mass-market industry. Game theory as studied by academics has advanced substantially over the years, and although much progress also has been done in relation to improving computer graphics and sound, AI for commercial games has not evolved with the same speed and is often relative basic. This chapter briefly describes the state-of-art in game AI and touches some of the psychological grounding of how to motivate people to play a physical game with a robot which is the main focus of the thesis.
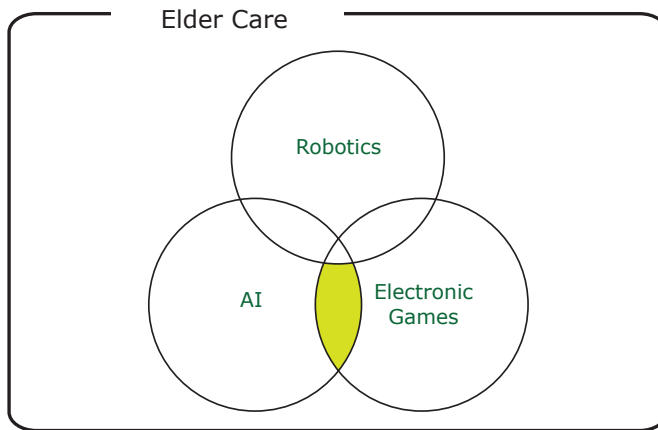
Figure 5.1: This chapter describes the history and state-of-art in electronic games and game AI.

5.1   Academic Game AI

There is an important distinction to be made between game AI studies by academics and AI used in commercial computer games. Academic research tend to focus on solving a problem optimally with less emphasis on hardware or time limitations, while commercial game programmers on the other hand have to work with limited resources as AI often will

be down prioritized for graphics and sound. Classic **Game Theory** is a mathematical discipline concerned with the study of abstract, idealized games. While academic AI is often concerned about solving a theoretic computational problem, the main goal of a successful games is to entertain the player. As game AI is all about fun it is often more important to design agents that provide the illusion of intelligence, rather than performing intelligently [45]. Although game theory only has weak application to modern real-time computer games it provides interesting abstractions of real-world situations, e.g. Axelrod's **Prisoner's Dilemma** [18]. In general, game theory classifies games according to the number of players, the kinds of goal those players have and the information each player has about the game.

- **Players.** Many traditional board games which inspired turn-based AI algorithms almost all have two players and most of the popular algorithms are therefore often limited to two players in the their most basic form. In addition, most of the optimization techniques for these algorithms assume that there only two players.

- **Zero-sum.** In most board games winning is equivalent to the fact that your opponent(s) loose(s), which is known as a zero-sum game. However for games with more players, this is not necessarily the case. In a casino game for example, all players can win or loose and hence this is a non-zero-sum game.

- **Perfect Information.** In many board games like Chess or Go the players know everything about the state of the game. In contrast, a game like Backgammon has a random element because it includes a dice roll.

The earliest applications of game theory was as opponents in simulated version of common turn-based board games like Chess, Tic-Tac-Toe, Connect Four, Reversi and Go which are all two-player, zero-sum, perfect information games. However, most modern turn-based strategy games are imperfect information, because it includes some random element. Nonetheless, the best known and most advanced algorithms for turn-based games are designed to work with two-player, zero-sum, perfect information games and a great number of AI techniques have been developed for these games.

Game Trees

Any turn-based game can be represented as a game tree, where each node in tree represents a board position and each branch represents one possible move. The number of branches from each board is equal to the number of possible moves that the player can make, and the number of branches at each branching point in the tree is called the **branching factor**. The depth of the tree depends on the game, in e.g. Tic-Tac-Toe there are nine spaces on the board leaving leaving a maximum of nine turns. While many simple games can been solved by brute-force techniques involving a look-op table of every single game position, most commonly played games (chess, backgammon, go) are not practically solvable in this way and a search heuristic has to be implemented.

Game Search Algorithms

Turn-based games are played by looking at the actions available and selecting the best one using an evaluation function which scores the current state of the board from the point of one of the players.

The most famous search algorithm for board games is by far **minimax**, which has dominated turn-based AI up to the last decade. Minimax is an recursive algorithm which calculates the resulting board position and recursively find the value of that position based on a tree representation of the game. If the algorithm is considering a position where the current player is to move, it returns the highest value - otherwise the lowest. To avoid infinite searches, the algorithm sometimes has a maximum depth.

The basic idea of the minimax algorithm is simply to minimise the maximum possible loss by choosing a move which offers your opponent the minimum gain in replying.
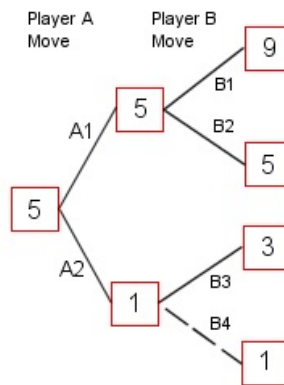
Figure 5.2: An example of the minimax algorithm with two players

In the example in Figure 5.2, player A can choose 2 moves, and player B has 2 replies to each. The first player A move A1 has a value of "5" as player B can choose moves B1 and B2 that lead to 9 points or 5 point with respect to A, so chooses B2 with the lower value of 5. Player A's move A2 leads to player B moves B3 and B4 with the value 3 or 1, for which B will choose B4. Therefore the second move A2 is worth only 1 for player A. The move chosen is therefore A1 with value 5.

The minimax algorithm is O(d) in memory and O(nd) in time where d is maximum depth and n is the number of moves at each board position. This means that the minimax algorithm is not efficient when the tree grows, and a number of techniques have been developed to optimize the algorithm. A common approach is **AB-pruning** which allows the algorithm to ignore sections of the tree that cannot possible contain the best move. Another way to optimize search is to use a transposition table, which basically keeps a record of board positions and returns the results of a search from that position. As the number of records and comparisons often grows rapidly, a hash value is often used to speed up **transposition table checks**.

Traditionally, most successful game playing strategies have been achieved through effective search strategies, but machine learning techniques are now often competitive with

and, in some cases, superior to handcoded algorithms [156]. An example can be seen in Ghory [89] who has investigated how an reinforcement learning can play board games. Also evolutionary computing has been applied for board games, and in [79] Fogel has investigated how evolutionary programming can create networks that are capable of playing tic-tac-toe, while Hughes has investigated how to play Checkers using a co-evolutionary on-line evolutionary algorithm [120]. Herik [272] presents an overview on the state of the art in games solved in the domain of two-person zero-sum games with perfect information and some predictions for the near future are given.

The Deep Blue chess computer which defeated Kasparov in a six-game match 1997 would typically search to a depth of between six and eight moves to a maximum of twenty or even more moves in some situations [48]. Deep Blue's evaluation function was initially written in a generalized form, in which many parameters were determined by analysing thousands of master games using a game database.

5.2   Commercial Computer Games

Initially, many computer games were implemented using a text based user interface. One of the first games using a visual display was "'Tennis for Two'" from 1958 based on an analog computer and an oscilloscope [294]. The game was created by American physicist William Higinbotham and could simulate a game of tennis or ping pong and (see Fig. 5.3).
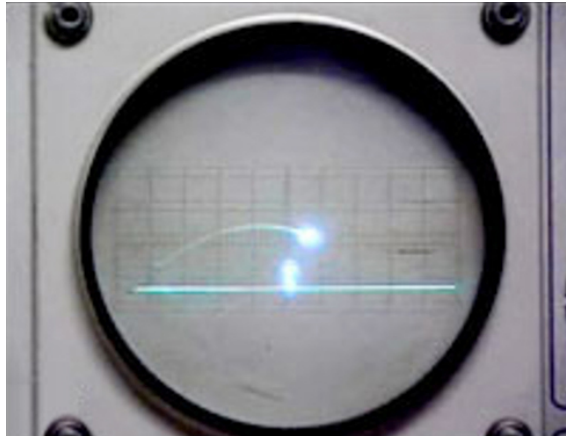
Figure 5.3: One of the first electronic games using a visual display. [294]

As computer technology has developed, more and more games emerged. The game Pong from 1972 started the push of mass appeal and Space Invaders from 1978 is considered to be one of the first classic games with levels, scores and increasing difficulty over time [236]. An overview of commercial games can be found Appendix M.

No common taxonomy for video games exists, but using the definition by Crawford [59], games can be divided in two main categories, namely **Skill-and-action games** and **Strategy games**. Skill-and-action games are characterized by real-time play and heavy emphasis on graphics and sound. The primary skills demanded of the player are hand-eye coordination and fast reaction time. On the other hand strategy games emphasize

cogitation rather than manipulation, and do normally require on motor skills. A newer and more comprehensive study of computer game genres can be seen in e.g. [3].

Overview of Commercial Computer Game AI

In contrast to the traditions of academic game AI and game theory, modern computer game AI often concerns non-zero-sum games with multiple players and imperfect information. The field of **Game Artificial Intelligence (Game AI)** has no formal definition, but Steve Rabin who is the editor of the Game AI Programming Wisdom series has defined game AI as:

- Technique that contributes to the perceived intelligence/behaviour of a computer controlled character

- Techniques to detect player's intent or what they are doing

- Techniques to automatically generate game content

As seen in the former chapters, the field of academic artificial intelligence consists of a variety of different fields and subdiciplines, and commercial game AI have taken advantage of nearly all techniques from academic AI with varying degree of success. Howevner, it is often the simplest techniques (finite-state machines, decision tress and production rule systems) that have most often proven their worth [187].

From an AI perspective, a corner stone video games was PacMan from 1980 which had simple but very functional game AI. Four ghosts would chase PacMan - each following different simple strategies, which would result in relative complex behaviour. Even today game AI is influenced by this early breakthrough, and although 3D rendering hardware and the quality of game graphics has improved enormously, game AI has often been a last-minute job, implemented in the final two or three months of the development and with the computational resources left leaving little time or memory for game AI [263, 183]. Today, many video games are based on scripting techniques (i.e. a proprietary programming language for a game engine) combined with relative simple game trees and search algorithms. Nonetheless, some games stand out in game history for their advanced AI implementation and an overview can be found in Appendix M and [236, 187].

Robotics AI and Games

AI in robotics has a fair amount in common with modern computer games as both have to deal with many real-time constraints like physics, computation speed problems and physical perception of the environment [236]. A more detailed overview is described in Chapter 5, but some of the common characteristics of robotics and computer games are as follow:

- Real Time Nature: The real time nature imposes constraints in terms of processing time that can be taken by the AI .

- Large Decision Spaces: most state of the art computer games have huge decision spaces [47], [6], and thus traditional search based AI techniques cannot be applied. The same applies for robots, which should act in open ended environment relying on multiple sensors.

- Unanticipated Scenarios: it is not feasible to anticipate all possible situations that can arise in a real game nor in real world scenarios. As a result, it is hard to design behaviors that can handle all the possible situations and respond appropriately to all possible actions.

- Human in the loop: everyday robots and state of the art games involve one or more interactive user(s) that can change the state instantaneously. Even small delays in AI decisions can be unacceptable.

Robots usually have to solve problems intelligently while dealing with the world directly and the challenges that robots face in attempting to perceive and comprehend the 'real world' is dramatically different from the accessible virtual world that inhabits game AI. However, control side techniques are very useful for game AI agents that need to intelligently maneuver around the environment and interact with the player. Path finding and navigation algorithms faced by mobile robots share much in common with the navigation problems in games and as a result, many techniques crafted by robotics end up in games [263], including the A* algorithm and the STRIPS paradigm which came out of robotics research [236]. A great variety of AI techniques have been used in robot based games, e.g. in [99] who have applied non-parametric regression to successfully teach a robot dog to first walk, seek and acquire a ball. In [226] an approach for robot's action selection in the robot soccer domain using Case-Based Reasoning techniques. Dynamic role switching and formation control have been applied using a fuzzy logic based strategy which assigns a robot to shoot or pass the ball [245] and an example of a machine learning techniques for robots can be seen in e.g. [192] where an autonomous soccer robot learns to intercept a rolling ball based on reinforcement learning.

Observed Game Intelligence

Robot based games constitutes a distinct subset in the field of electronic games, as humans tend to perceive robots differently from other machines. The physical and tangible nature of autonomous robots, catalyses interaction and encourages humans to anthropomorphize them even when their physical aspect is obviously different from that of a human being [84].

Incorporating features into a robot that improve humanization, makes the robot seem more intelligent to people, because they attribute agency [237]. The fact that physical robots often leave the observer with the impression of intelligent behaviour has been described in Valentino Braitenberg's book 'Vehicles' from 1984 in which he formulated a series of thought experiments involving simple robot control mechanisms [30]. One of his points was to show how relatively simple control mechanisms can make a robot act, so it will seem intelligent to an observer. On the other hand he claimed it is almost impossible to find the exact internal structure of a robot, just by observing and analysing the behaviour. He called this the 'law of uphill analysis and downhill invention', because it is easier to invent a behaviour which seems to be intelligent, than to observe and analyse what caused this intelligent behaviour.

In the computer game industry, the term **'smoke and mirrors'** is commonly used to describe relative simple game functionality that gives the impression of intelligent behaviour. Users play commercial games to have fun, and the goal is not necessarily for the agent do be intelligent, but leave the player with the illusion of intelligence [237].

This effect is related to the psychological construct **Theory of Mind** (ToM). ToM is a major field of investigation by both behavioralists and cognitive scientists, and is defined as knowing that others are intentional agents, and the ability to interpret their minds through theoretical concept of intentional states such as beliefs and desires [218]. In other words, ToM describes the ability to see the intent of an action, rather than just strict recognition of the action. The idea of attributing agency to objects in our environment is almost innate in humans, especially objects that move. In a simple experiment where observers would see two different coloured dots moving at the same line with different speeds, they would often explain the scene as 'the first dot being chased by the other'. When creating robot based games, this is worth noticing because it shows that when creating robot based games it is not necessarily a requirement to implement complex intelligent AI to leave the player with the impression of an intelligent robot.

AI and Real Time Strategy Games

Game playing has always been a good testbed for AI research and in particular, real time strategy (RTS) games are characterized by being complex environments which offer multiple opportunities for AI researchers [8].

RTS games are a family of computer games that involve several players competing in real time. Typically, the goal is to kill all the other players in the game or to dominate most of the territories of the game. RTS games are very popular, and have been created by non-AI developers for a non-AI community. Therefore, RTS games have not been designed as synthetic domains where AI techniques can easily exhibit superior behaviours [238] as they are characterized by enormous state spaces, large decision spaces, and asynchronous interactions [6]. RTS games offer a large variety of fundamental AI research problems, unlike other game genres studied by the AI community so far [47], including decision making under uncertainty, spatial and temporal reasoning and collaboration.

One of the most famous RTS games is World of Warcraft from Blizzard Entertainment (often referred to as WoW), with more than 12 million subscribers estimated to hold 62 percent of the market [27]. **Wargus** is basically an open-source version of WoW, based on a free cross-platform real-time strategy gaming engine. The engine is configurable and can be used to create games with a wide-range of features, including support for playing over Internet/LAN, or playing vs. computer opponents.

The Wargus platform has been used for AI research, and one example of this can be found in [210] by Parker who has studied how to learn from demonstrations via structured prediction. Ponsen et. al. [217] has used Wargus to learn a state-based decision policy based on dynamic scripting and in [216] to generate tactics automatically using an evolutionary algorithm. Weber has used Wargus and case-based reasoning to determine the build order in strategic games [283], while [183] and [207] has done research using case based planning. This research has lead to the development of D2 (see Appendix N), which has been used a framework for the development of a strategic robot game which is presented in Paper G in this thesis.

5.3   Game Enjoyment and Flow

According to Crawford [59], the fundamental motivation for all game-playing is to learn. He states that games are a fundamental part of human existence and is the basic way that
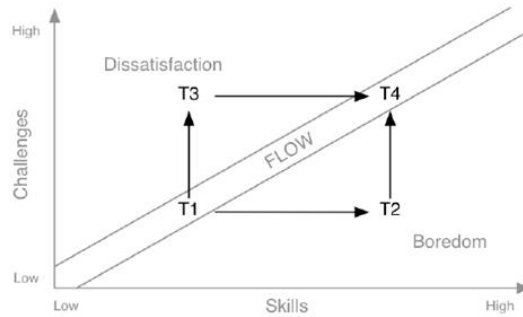
Figure 5.4: Illustration of the relation between skill and challenge. In state T1 and T4, there is a balance between skill and challenge and the player is in the state of flow. In state T2 and T3 there is no balance, and the player is either bored or frustrated, correspondingly [60]

humans (and many animals) learn to survive. According to Ralph Koster's theory of fun for games, all games are essentially "'edutainment'", teaching us the skills we might need in real life in a safe, low-stakes environment. A good game, according to him, is "'one that teaches everything it has to offer before the player stops playing.'" [141]. Lazzaro [146] conducted an independent cross-genre research study on why adults play games and found that games can offer an efficiency and order in playing that players want in life. The exciting and relaxing effects of games is very appealing and some apply its therapeutic benefits to get perspective, calm down after a hard day, or build self-esteem.

The Concept of Flow

Although player enjoyment is central to many commercial computer games, there is currently no universally accepted model of player enjoyment in games. Many heuristics are presented in the literature based on elements such as the game interface, mechanics, game play and narrative [253]. However, successful games are often characterized using the concept **Flow**, as proposed by Csíkszentmihály [60] which is a mental state when a person is fully immersed in what they are doing and equivalent to what is called in the sporting world "'being in the zone'". It is a feeling characterized by great absorption of energized focus, full involvement, and success in the process of the activity. As illustrated in Figure 5.4, Flow can only occur when there is an appropriate balance between challenge and skill. In the state T1, the difficulty of the challenge is in an appropriate relation to your (undeveloped) skills. T2 is the situation where you develop your skills to a level where the challenge becomes too easy and therefore boring. In T3, the difficulty of the challenge is higher than your skills, leading to discontent and frustration. T4 is also a flow state, but in a more complex situation than in T1. Flow is not a stable state because your skills will keep developing [126].

According to [60], there are nine components of the experience of Flow:

- Balance between perceived skills and perceived challenge (the activity is neither

too easy nor too difficult).

- The merging of action and awareness.

- Clear goals (expectations and rules are discernible and goals are attainable and align appropriately with one's skill set and abilities).

- Unambiguous feedback (successes and failures in the course of the activity are apparent, so that behaviour can be adjusted as needed).

- Concentrating and focusing, a high degree of concentration on a limited field of attention (a person engaged in the activity will have the opportunity to focus and to delve deeply into it).

- A sense of personal control over the situation or activity.

- A loss of the feeling of self-consciousness (no feelings of self-doubt or self-concern).

- Transformation of time (one's subjective experience of time is altered).

- Autotelic experience (the activity is intrinsically rewarding - it is undertaken for its own sake).

Although Flow is a well-established construct for examining game experience, an inherent problem is that it is not immediately obvious how to translate between the flow construct and an operative description of game-play [58].

Another inherent problem with the concept of Flow, is that there is no standard approach for measuring it. However Sweetser [253] has used the concept of flow to integrate heuristics into a validated model that can be used to design, evaluate and understand enjoyment in games. The concept called **GameFlow**, consists of eight elements - concentration, challenge, skills, control, clear goals, feedback, immersion and social interaction. A different approach is to introduce a statistical approach for capturing entertainment in real-time through physiological signals based on physiological measurement like e.g. heart rate signals [314]. In [172] Mandryk and Atkins present a method of modelling user emotional state for users interacting with play technologies based on a galvanic skin response (GSR), electrocardiography (EKG), and electromyography of the face (EMGsmiling and EMGfrowning). Yannakakis [311] describes a review on approaches for modelling satisfaction perceived by users interacting with entertainment systems and a research for optimizing player satisfaction in games in [310, 312, 309, 313].

5.4 Adaptive Robot Games

In the thesis, I use the theory of Flow to argue that the game challenge should adapt to player skill in Paper E and F. An adaptive approach is supported in [115] where it has been found that the elderly user's perceived adaptiveness of a robotic system directly influences the perceived usefulness. Unlike most traditional video games, adaptive games can cater the gaming experience to the individual user and not just a particular group of users and may hold the key for improving game play mechanics [91]. Creating robot games which e.g. adapts challenge and skills is related to the field of **Affective computing** which is

the study and development of systems and devices that can recognize, interpret, process, and simulate human affects. It is an interdisciplinary field spanning computer sciences, psychology, and cognitive science [258]. While the origins of the field may be traced as far back as to early philosophical enquiries into emotion, the more modern branch of computer science originated with Rosalind Picard's 1995 paper [214] on affective computing. A motivation for the research is the ability to simulate empathy, i.e. the machine should interpret the emotional state of humans and adapt its behaviour to them, giving an appropriate response for those emotions. According to Hudlicka, there are many cases where user affect is critical for the successful completion of a task, for avoiding (often disastrous) errors, for achieving optimal performance, or for maintaining reasonable user stress levels [118].

While much has been accomplished in the affective computing area since Picard coined the term, sensing and recognizing emotional and other cognitive states with computers is still considered a challenging task, requiring the integration of sensors, mathematical methods for data enhancement and filtering, pattern recognition and classification [119]. Another aspect is that some instances of "'simulated affect'", such as the notorious animated paperclip, can be very irritating [215]. While progress is being made in user-modelling and adaptive user interfaces, the majority of existing systems continue to assume normative performance, and fail to adapt to the individual characteristics of particular users [118].

Examples of Adaptive Robot Games

The Adaptive Systems Research Group at University of Hertfordshire lead by Kerstin Dautenhahn has been very active in creating adaptive robot games mainly targeted at autistic children (see Chapter 3). Sykes [254] has investigated the hypothesis that the player's state of arousal will correspond with the pressure used to depress buttons on a gamepad. Gilleade [90] describes the development of a software development kit that allows the interactions between man and machine to become dynamic entities during play by means of monitoring the player's physiological condition and in [91] it is discussed how frustration may be used in the design of adaptive videogames. In [158] Lund describes different adaptive AI techniques which can be used in entertainment robotics for children. In [257] proposes an integrated MDP and POMDP architecture for adaptation in modern games and an empirical proof of the concept is shown based on an implementation of a tennis video game. Rani and Sarkar [220] present an emotion-sensitive human-robot cooperation framework in which a robot is sensitive to the emotions of the human and describe using a mobile robot as a test bed in which the robot senses anxiety level of the human and responds appropriately. Based on the iCat-platform, Castellano2009 [50] provides a general overview of some of the issues arising from the design of an affect recognition framework for artificial companions and show that children tend to look at the iCat and smile more when they experience a positive feeling and they are engaged with the iCat.

5.5   Game AI Related to This Thesis

The games which have been presented in this thesis are all related to a pursuit-evasion challenge which is a fundamental principle in many children's games. Many pursuit-

evasion related problems can theoretically be solved optimally e.g. [25]. However, the main focus of this thesis is not on creating optimal solutions but on creating robust, autonomous, mobile games which can be applied for elderly. As described in detail in Chapter 4 and 6, the AI in this is based on the Case-Based paradigm which has proved successful in solving spatial-temporal problems in robotics and has the advantages that it allows runtime adaptation by recalling and interpreting past experiences, as well as generating new cases to represent knowledge from new experiences. I use the Case-Based approach as low level adaptive control and Case-Based planning as a high-level planner which learns from human demonstration. CBR has proved successful in solving spatial-temporal problems in robotics in e.g. [139, 150, 128] and has the advantages that it allows runtime adaptation. Other advantages is the transparency of the method and that it is relative easy to implement. CBP allows plan learning from human demonstration, and has been proven successful for strategic computer games in [205, 206, 207, 106, 97].

Table 5.1 shows an overview of how the case-based game AI has been implemented for three games in this thesis.

Game	1	2	3
Paper(s)	B, Video 1	C, D, E, F, Video 2	G
AI method	BC	CBR	CBP
Game Type	Skill-and-action	Skill-and-action	Skill-and-action/Strategic
Runtime adaptive	No	Yes	Yes
Player(s)	Multiple	Single	Multiple
Perfect information	No	No	No
Zero sum	No	No	Yes

Table 5.1: Selected characteristics of the AI for the games implemented in the thesis.

In Paper B the goal of the game is for the players to compete about getting and maintaining the attention of the robot. Besides the people detection algorithm, the game in this paper does not contain any AI of interest. However, the implementation offers a robust robot solution for a simple, physical skill-and-action game which can be played by a single player (try to keep the attention) or multiple players (compete about getting the attention). From an algorithmic perspective the game does not adapt the challenge to the skills of the users, but since the robot has a reactive approach to players movements, the difficulty of stealing the robot's attention depends on the player who is actually moving around with the robot. Since you cannot really win or loose this game, it cannot be considered a zero-sum game. However, they game could easily be changed to have a competitive dimension by keeping a score of the time each individual managed to keep the attention of the robot. Theoretically, the game does not present any random elements - either the robot detects and follows a person or it does not. However, due to the physical implementation of the game on a robot operating autonomously in a open-ended scenario there are many random elements in practice and it cannot be considered a perfect information game.

The research presented in paper C, D, E and F is based on CBR which allow the robot to learn from spatio-temporal behaviour and adapt the navigation behaviour. This approach is used to developed a skill-and-action game which is presented paper E and F which is a single player game with the goal of getting and handing back a ball to a moving

robot. I use the theory of flow to argue that the game challenge should adapt runtime to the mobility skills of the player. The game gets more or less difficult to play depending on your skills, but in its present form the are is no winner or looser of the game and it cannot be considered a zero-sum game. However, this could be changed competing about the mobility skill value which is detected during game play. Theoretically the game has no random elements, but due to the open-ended implementation it is not perfect information game.

Paper G describes a strategic multi player game with the goal of competing against the robot about first visiting a number of locations without getting tagged by the robot. The robot is controlled using the software framework D2 which originally has been developed for commercial strategic computer games allowing the robot to learn a strategic plan from human demonstration using CBP.

Since the players should compete about reaching a number of predefined positions it holds an element of skill-and-action. On the other hand you have to decide about which square to move to without getting tagged by the robot in competition with other players, so it also contains a strategic element. The game presented in Paper G can be considered a zero-sum game in the sense that if the robot wins, the humans loose and if one of the human wins, the robot and the other human loose. However, the game can also be considered a human-versus-robot game where both humans win, if just one of them beats the robot.

In the simulated environment presented in Paper G, the robot knows everything what there is to know about the game and it can rationally select an optimal strategy to win the game. However, the squares and players are placed at random locations and if the game was evaluated in the real world there would be random elements, e.g. the speed of the players. Therefore the game cannot be considered a perfect information game. As presented in Paper G, the robot learns a plan based on a goal definition and human demonstrations. Although the plan can adapt at runtime, the robot will only adapt to the skills of the players if this has been defined as a part of the goal definition.

Game Enjoyment

As described above, flow is a well-established construct for optimising and examining game experience. One of the nine components of the Flow theory is to keep a balance between perceived skills and perceived challenge. It has been found that adaptivity influences the perceived usefulness of robot systems [115] and improves game play mechanics [91]. However, it is technically very difficult to construct a system which does not fail to adapt to the individual characteristics of particular users [118]. In Paper E and F the theory of Flow is used to argue that the game challenge should adapt to player's skills based on spatio-temporal behaviour of the player. However, the problem of adapting to non-standard behaviour is present for mobile robot based games as documented in Paper F. Measuring whether the players experience flow while playing has been considered out of scope of this thesis since flow experiences cannot be easily observed [179] and there is no common metric for evaluating flow. Literature show that the people tend to attribute intelligence to robots because of their physical presence and behaviour and even more so if the robot has a human-like design. The robot used in this thesis has a human-like expressive face which is used as a feedback mechanism to tell about the game state. The expressive face is likely to affect the users' interpretation of the robot as facial expressions

are one of the most obvious manifestations of emotions. Results from HCI has shown that a computer can act as a social character, because it has some characteristics which make us behave as if it was a real person - we know it is piece of a technology, but can still feel happy about it or get angry with it [212]. According to Fogg, this effect is amplified if the system shows social signals we know from interaction with other people [80]. However, the users' reactions to the robot are also likely to be influenced by the novelty effect, i.e. a response of interest in new technology [239]. An exploratory and qualitative approach to investigate the elderly's reaction to the robot platform is presented in paper B but in-depth investigation of how participants relate emotionally to the robot platform is outside the scope of the thesis.

Chapter Summary   AI for games is split between academic game AI and commercial game AI and while AI which is often concerned about finding an optimal solution to a problem, commercial game AI is concerned about creating fun for the player. Modern computer games and robotics share some common properties like the real time nature, large decision spaces and unanticipated scenarios and algorithms which originally was developed for robotics have been widely used in computer games. However, mobile robot based games are distinct from computer games, because of the physical presence and because people has a tendency to attribute robots with capabilities they do not posses. The fundamental reason for children to play games is an inherent instinct to learn how to survive while for adults, playing a game can be a way to achieve excitement and relaxation. Successful games are often characterized using the concept Flow, which is in Paper E is used to argue that the game challenge should adapt to player's skills based on spatio-temporal behaviour of the player. An exploratory and qualitative approach to investigate the elderly's reaction to the robot platform is presented in paper B.

6   Methodology

Due to limited space in the publications presented in the thesis, this chapter explains some of the used components in more detail; namely the robot platform, the Player/Stage framework, case-based reasoning, case-based planning, D2, MMPM and the JavaClient for Player/Stage.

6.1   Robot Platform

The robot platform, which is in this thesis is based on a commercial platform from FESTO (See Fig. 6.1) is equipped with a head having 126 red diodes (LEDs) which enables it to express different emotions (see Figure 6.2). Technically, the face can show 8 expressions based on a 3 bit signal. The robot is 1 meter high, and has mounted an URG-04LX line scan laser placed $35cm$ above ground level, scanning 220 degrees in front of the robot. The fundamental control and design of the robot is a result of Master's Thesis [142].

Figure 6.1: Left: The original robot platform from FESTO. Center and Right: The modified platform by AAU called Robotino

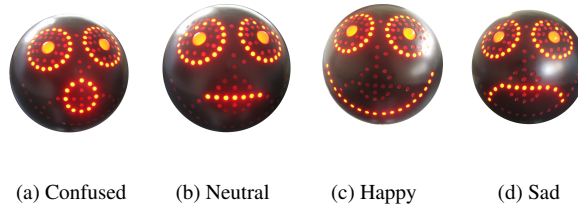(a) Confused   (b) Neutral   (c) Happy   (d) Sad

Figure 6.2: Using the LED face, the robot is able to express four emotional expressions: surprise, neutral, happy and sad. The robot randomly blinks its eyes independent of its expression.

The Robot Face

The design process of the robot face lasted about 6 months and was based on an iterative process where around 30 persons had the opportunity to comment the design. The design was originally inspired by the emotion icons (emoticons) known from web forums, instant messengers and online games representing facial expressions by punctuation and letters to express a writer's mood. Emoticons are often automatically replaced with small corresponding images, and a list of such images has been used as a design guideline e.g. to indicate the proportion between eyes and mouth.

Paul Ekman has been a pioneer in the study of emotions and their relation to facial expressions and has concluded that some emotions are universal [72] and that expressions associated with some emotions are biologically universal to all humans [73]. According to Ekman, the basic emotions are Anger, Disgust, Fear, Happiness, Sadness and Surprise. Although Ekman's theory of basic emotions was not the source of the facial characters of the robot, three of these basic emotions maps to the facial expression of the robot, i.e. the surprise, happy and sad. Many other theories of basic emotions exist and a review can be found in [208].

Facial expression of emotion (or "'facial affect"') is rapidly becoming an area of intense interest in the computer science and interaction design communities and in e.g. Schiano et. al. describes a user study on affect in a prototype robot face [235]. Cynthia Breazeal from M.I.T has been very active in similar research using the robots Kismet and Leonardo and has described the evaluation of the robot's expressive displays in [32, 31]. Joost Broekens presents a framework for the study of the relation between emotion, adaptation and reinforcement learning in [36].

The Simulation and Control Framework

The robotino platform is controlled using the open source robot framework Player/Stage [55]. Player is a device server that provides a interface to a variety of sensors and actuators (e.g., robots). Because Player uses a TCP socket-based client/server model, robot control programs can be written in any programming language and can execute on any computer with network connectivity to the robot. Stage is a scalable multiple robot simulator; it simulates a population of mobile robots moving in and sensing a two-dimensional

bitmapped environment. When used as a Player plugin, Stage provides virtual Player robots, which interact with simulated rather than physical devices. Stage can also be used as link library to create custom simulations.

6.2 Human-aware Navigation

In 1963 Edward T. Hall published the 'proxemics-theory' which was a large study of human-human spatial placement behaviour [102, 101]. The term 'Proxemics' refers to the study of how humans position themselves relatively to others, with respect to distance. According to Hall, distances between people can be categorised into four classes called the intimate, personal, social and public zone. These four zones governs the type of interaction which happens at the given distances (see Figure 6.3).

- The intimate zone ($d < 0 : 45m$), where only interaction like touching or whispering occurs.

- The personal zone ($0 : 45m < d < 1 : 2m$), where you have close conversations with people.

- The social zone ($1 : 2m < d < 3 : 6m$), is reserved for social interaction in e.g. a larger group.

- The public zone ($d > 3 : 6m$), is the zone, where there is not really interaction. 3:6m is the distance where you start to notice people, and the distance you at least try to keep when walking around.

Although the zones as defined by Hall were not designed with human-robot interaction in mind, studies by e.g. [278] and [138] have shown to support the use of proxemic distances within human-robot interaction. In this thesis, Hall's proxemics theory is used as a basis for the robot's navigation algorithm, e.g. the robot never enters the intimate zone and avoids approaching from the back. An advantage of using the theory is that it is relatively easy to transform to a mathematical formula which can be implemented on a mobile robot.

Studies in robot motion and proxemics can be found in Yoda and Shiota [316] who researched how humans pass each other and later used this study for robot motion research in [317]. Pacchierotti describes a person user study, where people in a corridor evaluated the behaviour of a robot that acted according to the proxemic theory [209]. The results show that the preferences for robot motion comply with the proxemic theory, and additionally ideal values for robot speed and lateral distance were found. Another study, [278], considers close encounters between robots and people (children and adults). Participants were asked to approach a robot, and stop at a distance, where they felt comfortable. In the second part of the study, the roles were inverted, such that the robot approached the persons. Follow-up studies on the stopping distances were performed in [138, 63, 252, 137]. More recent studies include user studies on proxemics including e.g. gaze direction. It is also studied how the social spaces depend on the person's sex, the experience with robots, the person's personality traits etc. [255, 279, 193].
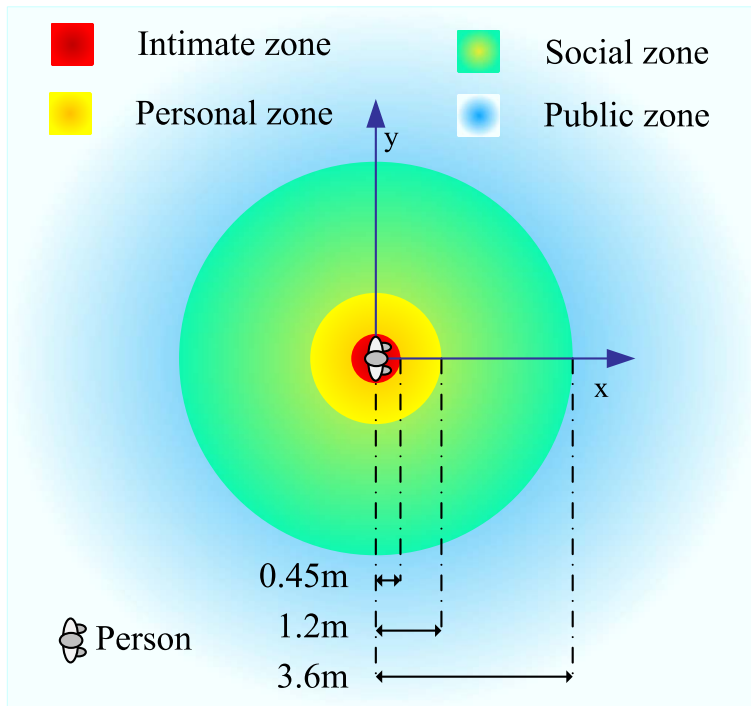
Figure 6.3: Hall zones [102, 101]

6.3 Case-Based Reasoning

Case-based reasoning is a problem-solving paradigm that in many respects is fundamentally different from other major AI approaches [282]. Instead of relying solely on general knowledge of a problem domain, or making associations along generalized relationships between problem descriptors and conclusions, CBR is able to utilize the specific knowledge of previously experienced, concrete problem situations (cases). A new problem is solved by finding a similar past case, and reusing it in the new problem situation. A second important difference is that CBR also is an approach to incremental, sustained learning, since a new experience is retained each time a problem has been solved, making it immediately available for future problems [2]. In the words of Slade [244]:

"'Expertise comprises experience. In solving a new problem, we rely on past episodes. We need to remember what plans succeed and what plans fail. We need to know how to modify an old plan to fit a new situation. Case-Based Reasoning is a general paradigm for reasoning from experience. It assumes a memory model for representing, indexing and organising past cases and a process model for retrieving and modifying old cases and assimilating new ones. Cases-Based reasoning provides a scientific cognitive model."'

The origins of CBR dates back to the work of Schank and Abelson on dynamic memory and the central role that a reminding of earlier situations and situations patterns have in problem solving and learning [233, 232]. CBR has grown out of psychological models and provides both a methodology for building intelligent systems and a cognitive model
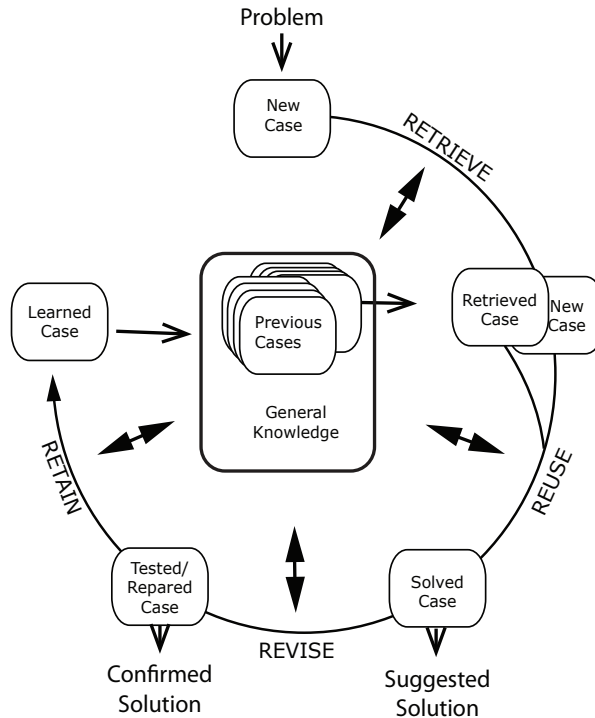
Figure 6.4: The CBR cycle [2]

of reasoning [139, 281, 2]. A particular strength of case-based reasoning over most other methods is its inherent combination of problem solving with sustained learning through problem solving experience [10].

CBR is commonly described as a cyclical process as shown in Fig. 6.4 after [2].

At the highest level of generality, a general CBR cycle may be described by the following four processes:

- Retrieve the most similar case or cases

- Reuse the information and knowledge in that case to solve the problem

- Revise the proposed solution

- Retain the parts of this experience likely to be useful for future problem solving

A new problem is solved by retrieving one or more previously experienced cases, reusing the case in one way or another, revising the solution based on reusing a previous case, and retaining the new experience by incorporating it into the existing knowledge-base (case-base) [2].

Another way to view CBR, is to see it as a general problem solving paradigm based on a local search strategy which starts from a previously generated solution and proceeds by

repairing the conflicts with the current problem. Its opponent is the systematic search that starts form an empty solution and systematically explores the space of solutions (classical planners like STRIPS are examples of systematic search) [246]. Unlike STRIPS, case-based reasoning uses the specific knowledge of previously experiences, concrete problem situations in order to solve a new problem. Part of its feasibility is founded on its psychological plausibility. Several studies have given empirical evidence for the dominating role of specific, previously experienced situations in human problem solving [228]. Philosophical and psychological foundations are in [302] and [267]. But even if a formal framework is available, sometimes a case-based approach might be the only practical way to solve problems.

CBR has been used for controlling e.g. robots playing soccer in e.g. [24] and a distributed case-based reasoning architectures has been used to solve a route planning problem in [92].

Implementing Case-Based Reasoning using the Player/Stage Framework

In order to implement the adaptive game algorithm based on CBR, I use a MySQL-database which is connected to the main control application to retrieve, reuse, revise and retain spatio-temporal data about the player(s). The control application is written in C++, while Player/Stage plugins (e.g. the leg-detection algorithm) have been written in C. Figure 6.5 shows the overall construction of the adaptive game, which consists on four parts. A Player-server which runs on the robot, a Player-client which runs on the PC, a control application which does the overall control of the robot including change of facial expressions and navigation behaviour and the database which holds all the cases about the spatio-temporal player behaviour which are collected and revised runtime.

Figure 6.5: The implementation of the CBR based game

6.4 Case-Based Planning

Case-based planning is the application of CBR [2] principles to planning, and as such, decomposes the process of planning into four stages: retrieval, reuse, revise and retain. Case-based planning involves reusing previous plans and adapting them to suit new situations instead of planning from scratch like in STRIPS [77].

Case-based planning has also been described as planning as remembering [106]. It is based on the reuse of past experience, namely the reuse of plans which have succeeded in past situations and the recovery from plans which have failed. This paradigm covers a range of different strategies for organizing and managing past and new plan (e.g. plans may be retained as concrete experiences or as generation traces). In inherits some of the motivation of case-based reasoning, e.g. the psychological plausibility. On the contrary, the lack of formal frameworks does not seem to be a recurrent motivation for case-based planning [246].
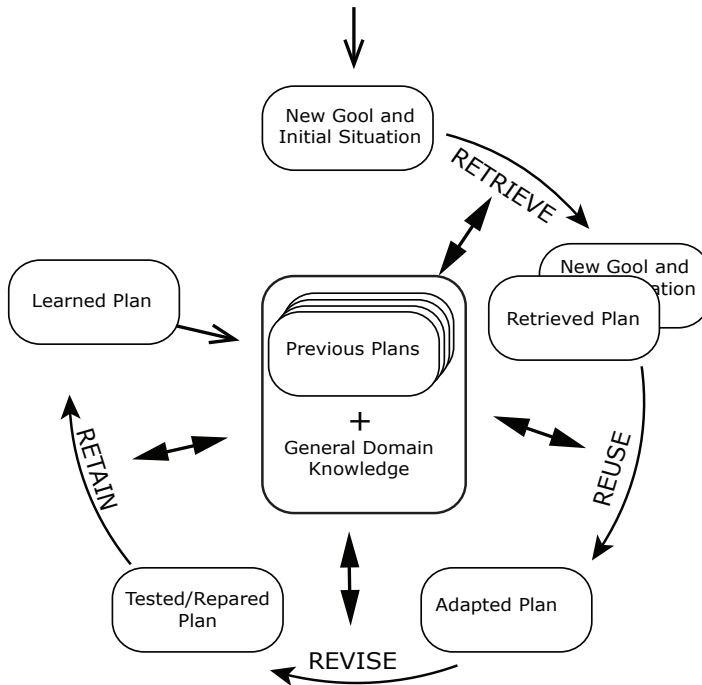
Figure 6.6: The CBP cycle [246]

Given a new problem description, a case-based planner first retrieves one or more relevant plans from a plan library and then it tries to reuse them (by adapting them if needed) to solve the new problem (during this process, more cases might be retrieved if the plan is decomposed hierarchically). After that, the case-based planner can already propose a solution to the problem. Additionally, the resulting plan can be revised (by executing it for example), and then the system will consider whether the new plan (or parts of it) is interesting enough to be retained into the plan base [194].

The design of a case-based planner usually involves the solution of problems which can be grouped in the following areas [246].

- Plan Representation. Basically deciding what to store and how to do this in order to retrieve and reuse old plans effectively and efficiently.

- Plan Retrieval. Retrieving one or more plans which solve problems similar to the current one.

- Plan Reuse. Reusing (or adapting) a retrieved plan in order to satisfy the new problem.

- Plan Revision. Testing the new plan for success and repairing it if failure occurs.

- Plan Retention. Storing the new plan in order be useful for future planning. Usually, when the new plan fails, it is stored with the justification of its failure.

Implementing Case-Based Planning using D2, MMPM and the JavaClient for Player/Stage

In order to implement a Case-Based Planning system on the selected robot platform, I have selected to use the Darmok 2 (D2) system [205]. D2 is an AI system designed to play real-time strategy games and is an extension of a case-based planning system is it implements the on-line case-based planning cycle (OLCBP) as introduced in [206] and details about the system can be found in Appendix N.

D2 was developed in the context of the **Make ME Play ME project (MMPM)**, which has the goal of creating a social gaming website, where users can automatically train artificial **intelligence entities (MEs)** to play RTS games and compete against the MEs created by other agents [96, 97]. D2 is the core learning and reasoning technique used by MEs, and the MMPM is a piece of software that creates the JavaFiles necessary for D2 based on an XML-specification of the game domain as described above. In other words, MMPM can interlink D2 with any given game by taking an XML-file about the game domain as input.

Although D2 has been used as an AI engine for several computer strategy games like Wargus, BattleCity, S2, Towers and Vanquich it has not yet been used for control of a robot based games. In Paper G, we describe a multi player game where the players compete against the robot about visiting a number of squares. Details about the implementation can be seen in Appendix L.
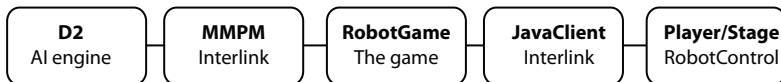
Figure 6.7: How the game is interlinked between D2 and Player/Stage using MMPM and JavaClient

As D2 and MMPM are both Java based, the robot game was also implemented using Java. In order to connect the game with Player/Stage we have used an OpenSource **JavaClient** [242], which allows development of applications for Player/Stage using the Java programming language. The client implements all interfaces described in the Player manual, plus several various additions. The overall construction of how the game is interlinked with D2, MMPM, JavaClient and Player/Stage can be seen in Figure 6.7.

7   Summary of Contributions and Discussion of Results

This thesis investigates robot based games promoting physical activity for elderly. The rationale for developing robot games is rooted in the demographic development, which in many countries forecasts an overweight of elderly citizens making it interesting to create technological devices which potentially can improve the health of elderly users.

The thesis is the result of an iterative process with the goal of creating and investigating robotic game applications for elder care using a mobile, this being a cross-disciplinary effort in the intersection of robotics, AI and electronic games. The first part of the thesis, gives an overview of the problems in the elder care sector (especially in Denmark), and explains why it is interesting to investigate the use of robots in this domain. Next, the section describes background, state-of-art and theory considered relevant to the thesis. The research questions, I wanted to answer in this thesis were:

- How to implement games on a mobile robot which can interpret the physical spatio-temporal behaviour of the interacting person while operating autonomously in a daily life environment?

- How can a robot learn about the user's game skills from interaction experience, and how should the robot adapt its navigation behaviour to the skills of the user throughout the game?

- How do elderly receive robot-based games, how do they play and what is the potential in elder care?

- How to implement future robot games for promotion of physical activity in elder care?

I answer these research questions based on the iterative process described in the introduction, and this chapter gives an overview of the contribution of the research and describes which academic and industrial communities who use the results.

The scientific contributions of the thesis are in the form of 7 papers and two video abstracts, which are appended after the conclusion. Paper A summarizes the problems in Danish elder care and characteristics a number of selected robot projects in Denmark. This paper was included to describe how the elder care sector in Denmark see the use of robotics and to explain in which paradigm the project were set out. Paper B and Video 1 describes a basic game and a user experiment using the robot, and these contribution

serves as fundamental research of users reactions to the robot. The papers C, D, E, F and Video 2 describes the implementation and the results of an adaptive robot based game and can be considered the core contribution of the thesis. Paper G describes how a software framework originally which was created for RTS games, can be applied for future robot games.

Iteration 1: How does the robot platform operate outside the lab?

First step of the thesis, was to investigate how the Robotino platform operates in an open-ended environment. An experiment was carried out in a shopping mall based on basic control of the robot, i.e. the robot could navigate autonomously based on the input of the on-board laser scanner and detect and follow random people using leg-detection algorithm by [307]. The goal was study the functionality of the robot in a public area and to see how people reacted to it. The results showed that the robot was robust enough to operate in this kind of open-ended and daily-life scenario and that people generally were positive towards the robot platform (See Figure 7.1).

Figure 7.1: Mother and child looking at the robot operating in a shopping mall [266]

Iteration 2: How do elderly react to a robot based game?

Next step was to investigate how traditional training of elderly could be improved using the robot platform.

Using the same robot platform, I designed a game to investigate whether it could be used as a tool for promoting physical activity (Fig. 7.2). The goal of the game was to attract and maintain the attention of the robot while moving around, and we used this setup to investigate seniors' acceptance of the robot game, obtain knowledge about their play patterns and get ideas about future improvements. One of the findings was that the elderly did not mind participating in the game as 23 of 26 people accepted playing actively, while the 3 remaining observed the others play.

Figure 7.2: Elderly in a nursing home playing with the robot [110]

A general observation was that the some elderly would tend to act towards the robot as if it was a living agent e.g. by talking to it as if it was a dog or a young man. Another observation based on testimonials from the elderly was that some elderly would tend to walk more freely when playing the game by e.g. walking backwards. The physiotherapists who monitored the evaluation, suggested that this could be useful for training the postural control, i.e. the ability to keep balance and fix orientation. A technical finding from the study, was that the robot was able to detect people using assistive tools crutches, walkers or wheelchairs. A third observation based on testimonials from the elderly was that they thought the game quickly became boring. They expressed that the robot should be able to do more, like singing or being capable of playing more challenging games. It was also suggested to develop games which were cognitive stimulating e.g. by designing the game so more people could should collaborate or compete.

Iteration 3: How can the robot read user behaviour?

To be able to create more interesting games based on the robot platform, we needed to be able to retrieve more data about the behaviour of the interacting person. In order to do this, we extended the person position detecting algorithm based on laser range scanner readings to also include pose estimation. This extension is based on a Kalman filter and provides information about velocity and pose of the person in the robot's coordinate frame, i.e. from the robot's point of view. The input to the filter are laser scanner readings and robot odometry data. It turned out that the rotational velocity of the robot, caused the Kalman filter to become nonlinear. This is not a desired property, and was solved by introducing a measurement driven Kalman filter [251]. This method gives the direction of the velocity vector, which was used to calculate the pose of the person using a autoregressive filter.

Iteration 4: How to learn from user motion patterns?

Next step, was to investigate how to use the spatio-temporal information about player behaviour to enable the robot to learn from and adapt to the interacting person. We developed a system based on CBR which was designed to estimate whether a given person was likely to interact with the robot or not, and use this estimate to adapt the navigation pattern of the robot.

When a person is encountered, the specific motion patterns of the person are estimated as described in iteration 3. The estimates are compared to what is stored in a case-base, which is obtained from previous interaction sessions. The outcome of previous stored sessions is used to update the current situation. This means that if the motion of the current person is consistent, the robot will get more and more certain about what will be the outcome of the interaction.

Iteration 5: How to create a robot game which adapts the challenge to the behaviour of the user

In order to create an adaptive robotic game, the CBR system developed in iteration 4 was now modified, The idea of the game was that the game challenge should adjust to the player's skill inferred from the level of mobility, i.e. the ability for a player to move around freely when playing. Player skill is estimated using spatio-temporal information from laser scanner images and is denoted the fuzzy predicate *PSI* which is a real number value between 0 and 1. High skills results in a *PSI* close to 1 and low skills results in a *PSI* value close to 0. The hypothesis is that the adaptive game algorithm based on case-based reasoning can be used to adjust the challenge of the robot game according to *PSI* which is estimated on spatio-temporal player behaviour. The rules of the implemented game are simple. A player should receive an object (a ball) from the robot, and try to hand it back while the robot moves away. The better the player is, the harder the robot makes the challenge of handing back the ball by changing navigation pattern. The operation of the robot is:

- If no player is detected, the robots searches for a player by moving randomly around until a player is detected.

- When a player is detected, the robot invites to play a game by approaching the player from the front.

- When the player has accepted to play a game by picking up the ball from the robot, the robot initially moves fast backwards away from the player.

- This triggers the actual start of the adaptive game and the robot keeps avoiding the player with a distance and velocity that corresponds to the estimated skill of the player. When the ball has been handed back, the game is complete.

Pseudo-code of the game algorithm is shown below:
Game Algorithm **Main**()

```
1: loop
2:    Roam()
```

3:     Approach()
4:     **if** Ball just picked up **then**
5:         Avoid()
6:     **end if**
7:     GameResult = Evaluate()
8:     UpdateCbrDatabase(GameResult)
9: **end loop**

Roam()

10: **while** Person not detected **do**
11:     Set facial expression = confused
12:     Drive randomly around
13: **end while**

Approach()

13: **while** Ball is on the robot **do**
14:     Set facial expression = happy
15:     Approach player to invite to play
16: **end while**

Avoid()

16: Set facial expression = neutral
17: Backup and turn around for T_2 seconds.

Evaluate()

17: **while** Time not expired (time less than T_1) **do**
18:     Set facial expression = sad
19:     Move according to PSI value
20:     **if** Ball returned to robot **then**
21:         Avoid()
22:         **return** Positive
23:     **end if**
24: **end while**
25: **return** Negative

The challenge of the game is changed by adjusting the navigation pattern of the robot with respect to the parameter *PSI*. The navigation system is modelled by introducing a person centred potential field calculated by the weighted sum of four Gaussian distributions of which one is negated (Fig. 7.3). The covariance of the distributions are used to adapt the potential field according to *PSI*.

When a player is considered to be unskilled (*PSI*=0), the robot will locate itself in the space right in front the player in a distance of 45 cm, making it relative easy for the player to hand the ball back. On the other hand, when a player is considered to be skilled ($PSI = 1$), the robot will end up at the lowest part of the potential function, approximately 2 meters in front of the person using the method of steepest descent (Fig. 7.3). This makes it more difficult for the player to hand the ball back, as he/she has to move relative fast towards the robot which constantly will try to back away from the player.

The robot behaviour is inspired by the spatial relation between humans (proxemics) as outlined in [101, 278] and the robot will avoid approaching the player from the back and not enter the intimate zone of the player making it uncomfortable to play with the

robot. When the skill of the player is undetermined ($PSI = 0.5$), the robot will approach the player person in approximate $45°$ according to [63, 304] studies.

(a) PSI=0. Unskilled player   (b) PSI=0.5. Player skill undetermined   (c) PSI=1. Skilled player
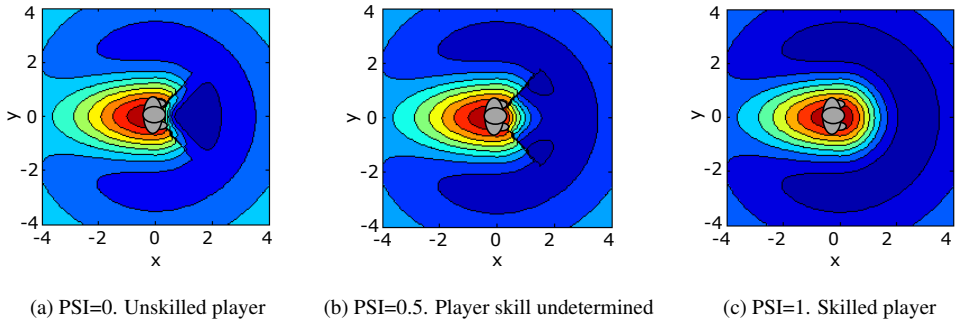
Figure 7.3: The potential field as a function of *PSI*. Using the method of steepest descent, the robot seeks towards the dark blue area and avoids the red area.

Iteration 6: How does the game algorithm adapt to users in the real world?

In order to evaluate the adaptive game algorithm described in iteration 5, experiments were conducted in two field studies in a rehabilitation centre (Study A) and a nursing home (Study B, Fig. 7.4). In each study, three participants with different mobility skills tried to play the game.

Figure 7.4: A participant using a wheelchair playing a game with the robot, trying to hand back a ball while the robot moves [109].

Figure 7.5 represents the evolution of the database for two players (A1 and B1). It plots the average *PSI* for all cases in the database which has been calculated for every time a revision of the database has been executed. Figure 7.5 starts with $PSI = 0.5$ for both players which is expected as the database starts being empty, meaning that the robot has no experience and hence is must use the default *PSI* value which is 0.5. When comparing

the two players, it is clear that the system believes that player A1 has higher skills than B1, as *PSI* ends at a higher level than for player B1. This makes sense as player A1 did not use assistive tools whereas player B1 was using a wheelchair (See Figure 7.4).
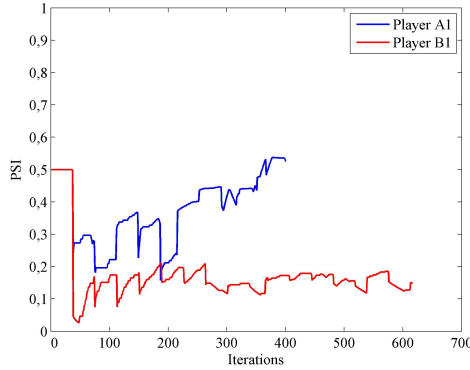
Figure 7.5: Illustration of how database evolves. The figure shows the average *PSI* for two players (A1 and B1) as a function of database revisions.

ID	PSI
A1	0.53
A2	0.71
A3	0.37
B1	0.15
B2	0.14
B3	0.11

Table 7.1: The average *PSI* value for each player

In general, the results showed that the system estimated players from the rehabilitation centre to have higher mobility skills than the players in the nursing home (Table 7.1), i.e. the average *PSI* are higher for the players at the rehabilitation centre (A1, A2, A3) compared to the nursing home (B1, B2 and B3). This is as expected, as more participants in the nursing home study used assistive tools and generally had more limited physical capabilities. However, the system fails when participants shows non-standard behaviour by e.g. deliberately not completing the game although able, which was observed for one player in the study (B2). This confirms that dynamic skill level adjustments can be hard to tune, because you have to filter out exploratory or non-standard behaviour [236].

Iteration 7: How to create future robot games including multiple players

In the user comments from the field studies, it was repeatedly suggested to elaborate the robot game to include multiple players and cognitive training. To do this, I implemented a game which allows multiple users to play with the Robotino platform thereby stimulating collaborative behaviour. The game consists of a number of squares marked on the floor,

and the winner of the game is the participant who has visited all squares first. During a game, the robot can tag a person obligating the person to do a detour on the game board. The implementation of the game has been done by coupling D2 [205] (a case-based planning system designed to play real-time strategy games) with Player/Stage which is a robot control and simulation environment. The method of using D2 to control a robot is a new approach. As illustrated in Figure 7.6, I demonstrate how D2 learns a game strategy for controlling a robot in a simulated multi-player game.
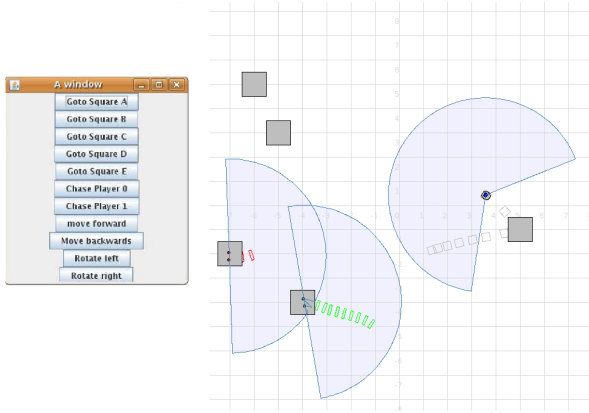

Figure 7.6: Screenshot from the simulated game which couples D2 with Player/Stage [264]

Although the use of D2 opens to a new world of creating strategic robot games, the actual benefit of using such a complex system is constrained by the limited functionality of the robot platform.

7.1 Discussion of Results

A fundamental problem for robots operating outside laboratories is to deal with non-determinism and noise. To create games which potentially can be used outside the laboratory, the control of the robot in this thesis relies on principles from two distinct paradigms; the reactive and the deliberative. The games presented in Paper B, C, D, E and F are reactive, while the game presented in Paper G is a hybrid of the deliberative and the reactive paradigm. The advantages of the reactive paradigm, is primarily the lack of a world model which means that the robot reacts immediately to the player's actions and operates robustly in an open-ended environment. The studies presented in this thesis confirms that the reactive approach works well for games based on autonomous, mobile robots in real-world scenarios. However, the reactive paradigm also has its limits, i.e. it is hard to construct a sufficiently complex games based on reactive control, which is therefore best suited for relative simple skill-and-action based games.

D2 presented in Paper G offers inbuilt functionality to design complex strategic games, but requires a world model which leads to the inherent frame problem. However D2 allows runtime adaptation of plans, making it more suitable in a robotics context than classical planning like e.g. STRIPS. Based on the relative simple game we have implemented using D2, it is not clear to say what are the perspectives of using D2 in robot games. Much functionality is offered by the framework, but using it also requires quite a lot of work in defining actions, entities, goals, etc. and as a consequence the implemented game in paper G could have been achieved with much simpler means. However, D2 might be used to create interesting strategic robot games in the future.

The simplicity of all the implemented games in this theses is to some extend a consequence of the limited functionality of the robot platform. Basically, the Robotino platform is only capable of moving around, detecting when a person is near and change facial expression. If a robot with more extensive capabilities had been available, it would be possible to create more interesting games using the presented approaches. Currently a popular AI method in robotics is to use reinforcement learning or other machine learning techniques. However, many machine learning techniques require a large number of iterations to converge and only do so if certain conditions are met meaning that in complex domains, these techniques are intractable and generalize poorly [183]. Nonetheless, many other interesting methods from AI could be successfully applied for robot based games, e.g. Alife and AE approaches which have been popular in computer games and for robotics pets, could probably also be used in a robotic game. It would be interesting to implement an evolving artificial personality of the game character similar to a robotic pet in order for people to stay interested in the robot's reactions.

The Users' Reactions

Interaction with robots in the laboratory, do not always provide insights into the aspects of human-robot interaction that emerge in the less structured real-world social settings in which they are meant to function [229]. In this thesis, I deliberately use explorative and qualitative methods to get a wide view of the elderly's reactions to mobile robot based games. It seems clear from the observations in the field studies presented in this thesis, that the robot platform triggers a number of emotional human reactions from the players, although they are perfectively aware that it is in fact a technical device. Although it is

not documented in the thesis, we know that the physical appearance of the robot has a strong influence on people, and e.g. making the robot operate without its head (which technically has no function) makes people react much less emotionally to it. Investigation of why people relate emotionally to robots and the consequence of this is outside the scope of the thesis, but has been studied by e.g. Sherry Turkle in [268, 269]. However, some of the positive reactions to the games are likely to be due to the the novelty effect, i.e. a response of interest in new technology [239] and longitudinal studies of robot games should be conducted in the future.

In this thesis, the robot's navigation algorithm is based on Hall's proxemics theory although this theory was not designed with robot games in mind. In the thesis, I assume that it is acceptable for the robot to enter the player's personal zone when handing over a ball, and to move to he public zone to increase challenge of the game. However, a recent study by Berg [23] based on elderly's reactions to autonomous vacuum cleaners show that agility predicts the distance elderly want to keep to an approaching robot, i.e. the worse the agility, the greater the distance which is in contrast to the implemented game. Whether agility as defined by Berg maps to mobility is not clear and furthermore the study by Berg is based on vacuum cleaners in another context. However, more in-depth study of this relation should be done. The study by Berg also shows that the elderly mainly perceive little activity and slow, small, irregular movements of the robot as an expression of negative emotion whereas medium, slow movement directly toward the elder is mostly interpreted as expressing attention to the person. A similar study based on the Robotino-platform in a game context could be interesting and relevant.

Explorative user studies have been done using observation and qualitative interviews. As defined by Kvale [143], qualitative research are attempts to understand the world from the subjects' point of view, to unfold the meaning of peoples' experiences, to uncover their lived world prior to scientific explanations and while quantitative results are sometimes dismissed on methodological grounds, it can be harder to dismiss the actual words of participants. We have used qualitative interviews as an exploratory step to gain insight into interesting or unexpected findings, but so far, only a few real-world evaluations on the implemented robot games have been conducted and much more research is needed. Quantitative user study research on the implemented games should also be conducted in the future, and measurements of e.g heart rate might be used to reveal information about physical and mental immersion. A quantitative measurement of the perceived experience of playing with the robot could been have achieved using a questionnaire, although good questionnaires are hard to design and are often dismissed for methodological reasons.

Flow and Adaptivity

I use the theory of Flow to argue that the game challenge should adapt to player's skill. An adaptive approach is supported in e.g. [115] where it has been found that the elderly users' perceived adaptiveness of a robotic system directly influences the perceived usefulness. However, the presented game algorithm fails to handle individual characteristics of particular users, which might improved by a more elaborate system relying on more multi-modal input. Another approach would be to manually select the level of difficulty before playing. I have not considered the many other aspects being a part of the definition of Flow (see Chapter 5). For example it could be interesting to see whether users felt that the subjective experience of time was altered, which could have been measured using a

questionnaire. Since evaluation was based on designed experiments, it was not clear to see if the games were perceived as autotelic experiences (i.e. undertaken for their own sake), and this could be studied in longitudinal studies. In general, it could be interesting do more in-depth studies of the reactions of the elderly, e.g. using the principles of GameFlow as defined [253]. However, as has been pointed out by Marti et. al., often flow experiences cannot be easily observed and users cannot articulate in straightforward ways what they experienced [179].

The Process of the PhD

This project has to a large extend been a technical driven, iterative process. The project started with a robot platform on which software elaborations were gradually added inspired by expert testimonials and comments from users based on what was technically feasible. However, for the potential of a robot game to come through, it should be considered meaningful and useful to people and a way to do this is to involve users early in the process. While technology is central to the development of autonomous robots, just as important drivers are the felt experience, emotional connection etc. that these technologies inform. Future work is to elaborate on the findings from the thesis based on a user-driven approach, and a project proposal based on the thesis has been submitted for the EU-call AAL.

7.2 Contribution to Industrial Communities

This Ph.D. has been made under the Danish Industrial PhD Program which has the goal to strengthen research and development in Danish business communities by educating scientists with an insight into the commercial aspects of research and development and by developing personal networks in which knowledge between companies and universities can be disseminated. As such, the project is already deeply interlinked into industrial communities and activities at DTI in e.g. generating new development projects and consulting services within the domain of robotics and elder care. The thesis has been a part of creating the welfare team at Center for Robot Technology at DTI dealing which has grown from 4 to 15 persons in less than 4 years.

Example of concrete contributions of the thesis seen from an industrial point of view are:

- Insight in how mobile robot platforms potentially can be used in the welfare and elder care sector. A contribution is the generation of a new EU proposal for the AAL-call which deals with training of the postural control using exercise activities based on robot based games. The project is collaboration with Copenhagen Institute for Interaction Design, RobotSoft and Roessingh Research and Development.

- Overview of the possibilities using robots in elder care. The thesis has contributed with an overview of commercial robots which are already available in elder care and also the thesis has summarized relevant robot projects have been conducted in Denmark. This has been a part of founding the background knowledge at the welfare team at DTI.

- Danish Technological Institute has gained insight in how adaptive games can be in cooperated in commercial welfare and elder care activities. A concrete contribution is that the DTI has been involved in an development project dealing with private and public partner with the creation of electronic games for young people with diabetes.

- Throughout the thesis, the author has involved been in dissemination activities where public and private stakeholders have gained insight in new technological possibilities using robots.

- From a software perspective, the thesis con tributes with a software framework which directly can be used for further experimentation about strategic robot games. This framework is already incorporated in the project IntelliCare where DTI is involved as a partner.

- The results and the framework can directly and indirectly be used by private companies who work with interlinking games and rehabilitation, e.g. the Danish companies   Innovaid   [123] and Personics[211].

7.3   Contribution to Academics

This thesis investigates how an autonomous, mobile robot can be used to mobilize physical activity for elderly in a real-world environment. Creating autonomous robots which can operate robustly in the real world is a difficult task, but the fact that this kind of research is wanted in the academic community can been seen by the fact that the main theme of both the RO-MAN 2011 and HRI 2011 conferences were on robots which can operate robustly in the real world.

Although much research has been found about games based on mobile robots for children with cognitive disabilities, less research has been found concerning games for elderly based on autonomous mobile robots. Hopefully the academic community can gain inspiration in how autonomous games based on a mobile robots can be used as an activity for elderly and potentially be used for mobility training. The thesis is cross-disciplinary and combines Game AI and Robotics with focus on applicability in real world evaluation.

As the thesis is the product of an Industrial PhD partly sponsored by DTI, it cannot be read or understood without realizing that it is linked with commercial and dissemination activities at DTI. The scientific contributions of the thesis are in the form of 7 papers and two video abstracts, which are appended after the conclusion.

- Paper A summarizes the problems in Danish elder care and describes the characteristics of a number of selected robot projects. The contribution is to give academics an insight in how the world looks like outside the academic community, more specifically how autonomous robots are currently being adopted by the elder care sector in Denmark. This paper is also included to explain in which paradigm the project were set out.

- Paper B and Video 1 describes a basic game and corresponding real-world user experiment. A technical contribution from the study, was that the leg detection algorithm on the robot was able to autonomously detect and follow elderly people using

assistive like tools crutches, walkers or wheelchairs in a real-world environment. Another contribution are the testimonials from the physiotherapists who monitored the evaluation, suggesting that autonomous games based on mobile robots could be useful for training the postural control. Additionally, the study shows that elderly seem to accept playing with a mobile robot (23 of 26 people accepted playing actively) and contributed with inspiration in how to develop future robot games.

- The papers C, D, E, F and Video 2 describes the implementation and the results of the evaluation of an adaptive robot based game. The academic contribution is the development, implementation and evaluation of an algorithm which uses spatio-temporal information about player behaviour to enable the robot to learn from and adapt to the interacting person while operating autonomously in a real-world scenario. A technical contribution is the CBR based approach which is modified into a game challenge to investigate the hypothesis that an adaptive algorithm can adjust the game challenge according to the mobility skill of the player which is estimated based on spatio-temporal player behaviour. The implementation is evaluated based on real-world studies where the robot operates autonomously in an open-ended environment.

- Paper G describes how an AI framework originally created for RTS computer games can be coupled with a robot control environment. The academic contribution is a new method on how computer game AI can be used in a robotics context as a generic software framework to implement strategic, multiplayer robot games. The work in an elaboration of the former papers and can be used as a basis for further research. Due to the public/private nature of the thesis, Paper G is linked with other activities at DTI and represent a relation between the thesis and the innovation project IntelliCare.

In summary, the thesis includes empirical results based on real-world studies in elder care institutions based on a fully functional game implemented on an autonomous, mobile robot. Although the overweight of the presented work is on the technical functionality and applicability of the robot in real world scenarios, the thesis attempts to keep a balance between different disciplines by including user studies. These results could potentially be relevant for e.g. the International Symposium on Robot and Human Interactive Communication (RO-MAN), the ACM/IEEE Conference on Human-Robot Interaction (HRI), International Journal of Social Robotics or the International Conference on Computer-Human Interaction (CHI). The Robotics and AI community might use the coupling of D2 to player-stage as a platform for further research which could be relevant for the IEEE Conference on Computational Intelligence and Games (CIG). Inspiration of how mobile robots can be used as an activity device, considerations about how this should be done and considerations about the potential benefit of using mobile robots for rehabilitation can be used in e.g. International Conference on Rehabilitation Robotics (ICORR).

8   Conclusion

In recent years, different types of robots have been applied in elder care as assistive technology, for social interaction and for rehabilitation purposes. However, motivating elderly users to move physically by playing a game with an autonomous, mobile robot is not extensively investigated. The tangible nature of autonomous robots catalyses interaction [84] as they offer an increased sense of social presence due to their capacity for touch and physical interaction. The hypothesis of this thesis is that **motivating elderly to move physically can be facilitated by autonomous, mobile robot games based on algorithms using spatio-temporal input about player behaviour.** To investigate this, the thesis describes the implementation of three different games for an autonomous, mobile robot platform and presents a series of studies on how these physical robot games can be used as a tool in nursing homes and rehabilitation centres for elderly with mobility problems. The implementation of the games differ from an AI perspective with increasing complexity, but all aims at operating robustly in a real-world scenario using the same mobile platform. The first game is based on a simple reactive control which allows the robot to autonomously follow a player in a specific distance. The second game is an implementation of an adaptive game algorithm which can adjust the game challenge to the player's mobility skills based on spatio-temporal information about player behaviour using case-based reasoning. The last game is based on an implementation of a RTS-computer game software framework which facilitates the development of strategic multi-player games based on case-base planning.

Explorative qualitative evaluation of the two first games in nursing homes and rehabilitation centres shows how that the robot can operate autonomously in a real-world environment although the players would use different types of assistive tools like walkers and canes. Observation and qualitative interviews shows a low degree of rejection of robot games among the elderly, and a general observation is that the autonomous robot catalyses physical interaction. Additionally, the study shows that the elderly tend to act towards the robot as if it was a living agent. Testimonials suggest that games based on mobile robots potentially can be useful for training the postural control which handles balance and fix orientation.

Quantitative evaluation of the adaptive game algorithm show that the robot robustly can detect and learn from the spatio-temporal motion patterns of the interacting person while operating autonomously in an open-ended environment. Evaluation in a real-world scenario show that the robot could successfully differentiate between a group of elderly with different mobility skills. However, the algorithm did not adapt adequately to people who deliberately played worse or better than their cognitive and physical skills allowed

them, this being an inherent problem in runtime adaptation.

The thesis describes a framework which consists in an elaborated case based planner created for RTS-computer games which is interlinked with a robot control environment. The framework can be used as a generic software platform to implement strategic games in which multiple human players can compete against a mobile robot. Using this set-up I demonstrate that the robot can learn different game strategies based on a few demonstrations. Although the framework potentially is powerful for creating strategic multi-player robot games, the practical functionality is constrained by the physical capabilities of the robot platform.

Future work is to create and evaluate games facilitating cognitive training and collaborative behaviour based on a more advanced robot platform with a multi-modal interface using the proposed software framework based on a user-driven approach and to do more in-depth user studies.

8.1 Contributions

The thesis summarizes problems and potential benefits related to the use of autnomous, mobile robot games in elder care, and gives an overview of scientific and non-scientific work related to elderly interacting with robots. The thesis presents mobile robot games for elderly as a combination of different fields, namely robotics, AI and electronic games and gives an overview of theory and background of these fields. The main three scientific contributions of the thesis are:

- **Algorithms for implementing games for elderly using a mobile robot operating autonomously in daily life environments.** Spatio-temporal information about player behaviour has been used to implement a robust and adaptive game algorithm which can be applied in a daily life environment on an autonomous, mobile robot. The algorithm is based on a combination of a Kalman filter method for pose estimation of persons, a robot navigation system based on an adaptive potential field and a method for learning from run-time motion pattern analysis based on case-based reasoning.

- **Knowledge about elderly's acceptance and use of robot games and reflections about the potential benefit in rehabilitation.** User studies based on observation and qualitative interviews in-situ show a low degree of rejection of the robot games and that the users tend to treat the robot as a living agent. Expert testimonials suggest that robot games based on the mobile platform potentially can be used for training the postural control which is a typical training activity for elderly who has been involved in fall accidents.

- **An implementation of a generic software framework for development of future robot games.** An extension of the research is to implement collaborative robot games which facilitates cognitive training and cooperative behaviour, and the thesis presents a generic software framework which combines an AI system developed for real-time strategy computer games with a robot control system. The thesis shows how this framework can been used to implement strategic, multi-player robot games in a simulated environment and shows how the robot can learn a strategy based on a few, human demonstrations.

8.2   Perspective

As mentioned in the introduction, there has been (and still are) very high expectation of the use of robots in elder care. This vision has repeatedly been illustrated in public media in for example Figure 2.3, 2.4 and 2.5 showing human-like robots which effectively replaces human beings in care scenarios. However, as stated by Brooks [40], we are not good at modelling living systems, at small or large scales and we cannot match the complexities of the simplest forms of life.

Not so long ago, the single living cell was called the simple cell and was thought to be a jelly-like mass of what was called protoplasm which simply means living substance but recently the complexity of a single cell has been visualized in animation created for Harvard's Molecular and Cellular Biology program [1].

Watching the vast number of complex parallel processes of a single cell and comparing these mechanisms to the relative simplicity of a computer, it is unavoidable to think that there might be a theoretic limit of what is possible to do with computer technology which is basically the foundation of modern robotics. In 1949 John Von Neumann stated that 'We have reached the limits of what is possible with computers.' and although the capacities of computers have developed greatly since then, the fundamental design is still the same. Von Neumann' dreams of imitating the brain's ability to solve ill defined problems have not yet been realized and neither AI nor Alife has produced artefacts that could be confused with a living organism for more than an instant [40]. On the basis of the current paradigm in computer technology, it seems to be a very ambitious goal to create robot based personal assistants replacing human care personnel.

Many robots (including the one used in this thesis) have a design or built in functionality which leaves the observer with the impression that high developed cognitive capabilities are present. Attributing agency or intelligence to robots apparently is a natural characteristic of the human mind, and the use of 'smoke and mirrors' in robotics can be useful for many purposes. However, it potentially also has the negative effect of creating false expectations among the end-users eventually leading to disappointment about what technology can offer.

Although the elder care sector is under pressure, one could state that the demographic challenge is a man-made problem, and as Bertneck has pointed out, the real solution to overcome the problems of an ageing society is not to create robots, but to have more children [20]. This is a good point, but some of the problems due to the demographic development are already a reality and cannot be solved within the next generation even if birthrate increases.

This thesis does not solve even a small subset of problems in elder care, but it shows a new way of using mobile robots with elderly, i.e. the approach of motivating elderly to move physically by playing a physical game with a mobilerobot has not yet been extensively investigated. I estimate that robot games are the level as computer games were 50-60 years ago, having the same potential in the future, but more research is needed.

Considering the demographic structure of most western countries, it is obvious that there is a big potential for robot based tools and devices in elder care. However, there is also a mismatch between public expectations, needs and technical feasibility. If the vision of robot based tools shall ever be fulfilled, the way forward is to have a close communication loop between different types of experts, stakeholders and the public.

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Contributions

Paper A

Practical Evaluation of Robots for Elderly in Denmark - an Overview

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Abstract

Robots for elderly have drawn a great deal of attention as it is a controversial topic being pushed forward by the fact that there will be a dramatic increase of elderly in most western countries. Within the field of HRI, much research has been conducted on robots interacting with elderly and also a number of commercial products have been introduced to the market. Since 2006, a number of projects have been launched in Denmark in order to evaluate robot technology in practice in elder care. This paper gives an brief overview of a selected number of projects and outlines the characteristics and results. Finally it is discussed how HRI can benefit from these.

1 Introduction

Based on the demographic development in most western countries, it has been predicted that the number of people with mental and/or physical disabilities will increase while the amount of people to take care of them will decrease [1], [2]. At the same time, an increasing number of commercial robots have been applied for non-industrial purposes such as cleaning (e.g. the iRobot Roomba or Electrolux vacuum cleaners), entertainment (e.g. Pleo, AIBO) for assisted therapy or social interaction (Paro, iCat and ifBot). These factors have fostered the idea of using robot technology in elder care in order to reduce the workload of assisting personnel and secure life quality and self sustainability. Although the use of robots in elder care was a very controversial topic in Denmark only three years ago, a number of national funded projects have been launched in order to evaluate different commercial robots in this sector. The projects are typically not organized as scientific experiments, but often as semi-structured subjective evaluation. Nevertheless they do reveal some relevant information which can be used in HRI research. This paper briefly outlines the structure of the Danish elder care system, analyzes the implementation and results of different projects and concludes what can be learned from these.

2 The Danish Care system

In Denmark (as for all Nordic countries), health care and elder care is mainly a public responsibility funded by taxes and levies. The health care sector is organized in 5 regions which primary responsibilities are the hospitals, while the 98 municipalities have the responsibility of elder care and handicap assistance. As in other countries, the demographic development in Denmark will cause an increased burden for the public sector due to a decrease in tax income, increased expenses in service costs, but also recruitment problems as more than 38% of the employees in the elder care sector are more than 50 years old and are expected to retire within the next 10-15 years [3]. Currently 106.000 people are employed in elder care in Denmark, and it is predicted that 7.000 more people are needed in 2015 and 12.000 people are needed in 2020 [4]. This forces the municipalities to look for alternative solutions and as a consequence, a number projects have been initiated to evaluate the advantages and disadvantages of the practical use of robots in nursing homes.

3   Projects

In the project 'Robot Technology In Elder Care' the purpose was to evaluate robot technology for cleaning and nursing tasks in a nursing home. The target was primarily staff (39 people) and residents (37 people) although relatives were also involved. Evaluation was done using qualitative interview in 10 consecutive meetings and the project was finalized in a small seminar. The project was concluded in December 2008 and results were summarized using subjective statements and disseminated in an evaluation report recently published [5]. An interesting result from this project was that the robot vacuum cleaners seemed to add an entertainment value - the elderly simply liked to watch them move around and also liked to give them names. Another unexpected result was that the level of noise caused by the equipment seemed to be very important, even though the same residents claimed they had severe hearing loss.

The Danish Paro Project examines the practical utility of Paro within the range of elderly and persons with brain damages in Northern Europe. Currently more than 65 Paro seals are distributed on 20 municipalities in Denmark as a part of the project. The project focuses on the therapeutic effect of the seal robot and the goal is to document impact to project participants, public bodies and other stakeholders. In the Paro project, it is the institutions, entities and project participants subscribed in the project that decide and run the implementation, testing, experimentation and professional development of the use of the seal robot. The project participants keep different types of self-selected records, run evaluations and measurements which they consider relevant and appropriate. In this way, the Paro project collects practical experience from a number of users, based on techniques used in dementia therapy and elder care [6]. Results have so far been disseminated through newsletters and media but no evaluation report has been published yet.

Rasmussen [7] describes the results of a pilot study where four municipalities evaluated four different robot vacuum cleaners in 9 different nursing homes. The evaluation was based on questionnaires measuring user satisfaction and attitude towards the robots among employees and residents and laboratory tests measuring noise and efficiency. The results of the pilot study was used to develop a performance specification for robot developers. In 2008, the municipality of Odense evaluated three types of robot vacuum cleaners in two nursing homes and the goal was to measure improvement of care quality and reduced use of resources. The analysis was based on qualitative interview of cleaning staff, and concludes that the robots 'have been a very effective help in the nursing homes' [8]. A cost/benefit analysis of the benefit of using robot vacuum cleaners in the public sector has been presented in [9] based on the evaluation results of 6 municipalities. This rapport estimates that approximate 1000 cleaning jobs could be saved in the public sector using current technology. The ´Be Safe-project´ (2006-2008) evaluated different types of technological equipment including 12 Paro seals in one nursing homes [10]. The evaluation was based on qualitative interview of people with dementia, questionnaires and focus group interview of nursing staff and analysis of patient journals. Around 137 senior citizen, 47 relatives and 130 members of nursing staff was involved in the evaluation. A comprehensive report was recently published, recommending to keep using Paro as a tool in dementia therapy.

4   Project characteristics

Between 2006-2008, there was little coordination between different projects in Denmark. Effort was not organized and knowledge was not disseminated between municipalities. As a consequence, many municipalities have done similar or overlapping evaluation projects. From 2007, several organizations (CareNet, SundhedsNet) have been established to try to mitigate this. Some characteristic of the projects are outlined below:

- Scope. The initial goal of many projects is to investigate robot technology as such, but since the list of commercial available robot products is still limited, many projects have focused on evaluating different robot vacuum cleaners and/or the Paro seal. Sometimes a very broad definition of the term robot is used, including products with mechanical and/or computational systems. Sometimes the term 'welfare technology' and 'robot technology' is used interchangeably.

- Evaluation - Evaluation is often based on qualitative interviews, subjective observations and questionnaires while empirical, structured experiments are not frequently used. Often projects do not only involve the residents but also relatives and employees in the nursing home and at different administrative levels in the municipality.

- Dissemination and documentation. Often the documentation consists in an evaluation report and/or newspaper articles mostly in Danish. Due to political considerations, sometimes the evaluation reports are not public available or get published with delay.

5   Discussion and conclusion

The mentioned projects are very practical oriented, and basically have the goal to evaluate whether specific products are usable in elder care or not. Evaluation reports are often based on high-level subjective statements which can be difficult to use directly in HRI research. Another basic problem is that most reports are in Danish only. Nevertheless, the overall contribution from these projects is that very little resistance towards robot technology in elder care has been reported. Although the general attitude towards introducing robot technology in nursing homes is positive, nursing staff have high requirements and products which are considered unstable or complicated to use are not tolerated. As a consequence, most evaluation reports are positive but vague about concluding clear benefits from using robot technology. Another contribution is that projects sometimes leads to research questions, e.g. the relation between the entertaining, social and practical effect of using e.g. robot vacuum cleaners or how equipment noise (being visual or auditive) affect personal and elderly. Additionally it is an open question whether the positive results from these projects are caused by the novelty effect of introducing robots and if longterm use will give the same results.

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Video 1

The SantaBot Experiment - A Pilot Study of Human-Robot Interaction

Søren Tranberg Hansen, Mikael Svenstrup, Hans Jørgen Andersen, Thomas Bak, Ole B. Jensen

1   Description

The video shows how an autonomous mobile robot dressed as Santa Claus is interacting with people in a shopping mall. The underlying hypothesis is that it is possible to create interesting new living spaces and induce value in terms of experiences, information or economics, by putting socially interactive mobile agents into public urban transit area. To investigate the hypothesis, an experiment was carried out using a robot capable of navigating autonomously based on the input of an onboard laser scanner. The robot would detect and follow random people, who afterwards were asked to fill out a questionnaire for quantitative analysis of the experiment. The presented video is the corresponding video documentation of the experiment used in the evaluation. The results showed that people were generally positive towards having mobile robots in this type of environment where shopping is combined with transit. However, it also showed harder than expected to start interaction with commuters due to their determination and speed towards their goal. Further it was demonstrated that it was possible to track and follow people, who were not beforehand informed on the experiment. The evaluation indicated, that the distance to initiate interaction was shorter than initially expected, but complies with the distance for normal human to human interaction.

Paper B

Robot Based Game for Elderly - A Qualitative Field Study

Søren Tranberg Hansen, Dorte Malig, Thomas Bak

Abstract

This paper presents a qualitative study on how a physical game based on a mobile robot can be used as a tool for promoting physical activity for elderly. The game is investigated in two independent field studies - one in a nursing home and one in a rehabilitation centre for elderly. An analysis of the interaction is made based on video recordings, observations and qualitative interviews focusing on the usability in everyday scenarios. The primary goal of the study is to observe seniors' acceptance of the robot, to obtain knowledge about their game play patterns and get ideas about future improvements of the game.

1 Introduction

Based on the demographic development in most western countries, it has been predicted that the number of people with mental and/or physical disabilities will increase while the amount of people to take care of them will decrease [1], [2]. Digital games hold a significant promise for enhancing the lives of seniors, potentially improving their mental and physical well-being, enhancing their social connectedness, and generally offering an enjoyable way of spending time [3]. Games linked to physical activity seems especially promising, as it has been shown that mental and physical health can be improved through a small amount of physical exercises [4], [5]. Examples include the use of e.g. Nintendo Wii as way to increase physical activity among elderly [6], [7].

A natural extension is to explore if the physical and tangible nature of a mobile robot can catalyse interaction and motivate users to play a game. It is related to persuasive technology, which is defined as technology designed to change attitudes or behaviours of the users through persuasion and social influence, but not through coercion [8]. An example can be seen in [9] where Kidd and Breazeal have shown the effectiveness of a sociable robot which served as a weight loss coach.

Robots encouraging social interaction have been studied using the robot seal Paro. In [10] Paro was applied as a robot-assisted activity for elderly at a day service centre, while Kidd et. al., has investigated how a sociable robot encourage social interaction among the elderly [11].

Tapus [12] has shown a longitudinal pilot study in which individuals suffering from dementia and/or other cognitive impairments should play cognitive games based on a sociable mobile robot, and Fasola describes the design and implementation of a socially assistive mobile robot that monitors and motivates a user during a seated arm exercise scenario [13]. In [14], a robot that provides motivation and support for cardiac patients who must perform painful breathing exercises is described [13] and retirement home staff and residents' preferences for healthcare robots was investigated in [15]. To our knowledge, the use of a mobile robot as being the basis of a physical game which motivates for physical action has not yet been investigated.

In this paper we present a robot game as a way to motivate elderly to do physical exercise. The game is investigated in two independent field studies and an analysis is made focusing on usability in everyday scenarios. This includes results on game acceptance, play patterns as well as ideas for future improvements.

2   The Robot Game

Traditionally, training of elderly with mobility problems is performed by physiotherapists who instruct a number of people (5-10) at the same time. Training is often based on exercises where the participants sit on a chair and do different movements with their arms and legs while listening to music (Fig. C.1). It is often difficult for the therapists to motivate the elderly to train hard and long enough, making it interesting to try robot games as a new tool.

Figure C.1: Traditional training while sitting down.

We introduce a simple game where the goal is to get and maintain the attention of the robot while moving around physically. When the robot detects a player it will follow the interacting person within a specific range. Once the robot is following a player, the goal is for another participant to try to 'steal' the robot's attention from the current.

We have chosen to use this relative simple game setup as it has shown to be very robust when operating in everyday scenarios [16]. A similar game has been described in [17] where a robot plays with children who normally are prevented from playing due to cognitive, development or physical impairments.

The Robot Platform

The used robot platform (Figure C.2) from FESTO is equipped with a head having 126 red diodes (LEDs) which enables it to express different emotions (Figure C.3). The robot is 1 meter high, and has mounted an URG-04LX line scan laser placed $35cm$ above ground level, scanning 220 degrees in front of the robot. To detect persons, the robot rely on the scans from the laser range finder using the leg detection algorithm presented in [18].

Control of the Robot

Controlling the robot is done using the programming framework Player which was installed on the platform. The robot game uses the following behaviour scheme (Fig. C.4):

1. Roam randomly around while looking confused until a person is detected.

2. Start smiling

3. Follow that person keeping a specific distance while looking happy, until the person is lost.

Figure C.2: The modified FESTO Robotino robotic platform.
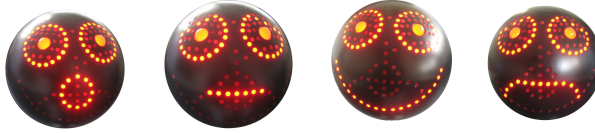
Figure C.3: Using the LED face, the robot is able to express four emotional expressions: confused, neutral, happy and sad. The robot randomly blinks its eyes independent of its expression.
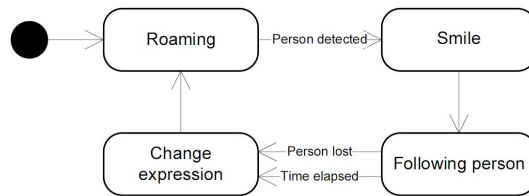
Figure C.4: The state diagram, which was implemented on the robot for the experiment.

4. Change facial expression, and start roaming again.

To keep the desired distance to the person being followed, two decoupled PID controllers were used; one for velocity and one for rotation. The system is designed to be able to experiment with different distances, as a subtle change of the distance may make a significant difference in the user's degree of comfort [19]. The desired distance was set to 1.3 meters in this study.

Based on this game, two field studies were organized - one at a nursing home and one in a rehabilitation facility for elderly with mobility problems. The main difference between the users in the two field studies is that the elderly attending the rehabilitation centre in general are in better cognitive and physical shape as they are capable of living in their own home whereas the group living at the nursing home are not.

3 Procedure of the study

Each study followed the same procedure: After an initial introduction to the robot and the experiment (lasting half an hour), an initial participant was asked to try to get the attention of the robot. At some point the robot would detect the person, approach him/her and position itself at the specified distance. When the participant had walked around with the robot, another participant would try to steal the robot's attention from the current player. The order in which the participants tried to play with the robot was random and the duration differed between 1 to 5 minutes. After all who accepted to participate had played with the robot (around 1 hour), everyone would gather around a table and finish the session with a general discussion about their experiences (half an hour). Finally the employees of each place were interviewed about their observations and thoughts (15 minutes).

Method

The study was based on observation [20] of participants, and focus group interviews and qualitative interviews [21] of participants and nursing staff serving as expert witnesses. We observed the participants interaction with the robot including their physical behaviour, talk and company with one another. The interaction was video recorded and we have made notes about the behaviour. The qualitative interviews were conducted on the basis of a loose structure consisting of open-ended questions that defined and explored the participants behaviour and experience. These two methods together provide an insight into how and why elderly interact with the robot, and what this means in relation to the development of robot based games. We have carried out a thematic analysis focusing on the seniors' acceptance of the robot game, their game play patterns and suggestions about future improvements of the game.
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4 Field Study at the Rehabilitation Centre

There was a total of 10 persons invited (Table C.1), and all but one accepted (P5) to participate in playing the game. All lived in their own home, and attended the rehabilitation facility due to mobility problems caused by e.g. spinal stenosis, a broken hib, osteoporosis or problems with knees, legs or due to surgery. Two of the participants used a crutch (P10 and P6) and one used a walker (P5). One participant had cognitive problems (P4) due to dementia. Two physiotherapists working at the facility were monitoring the elderly playing with the robot. A transcription of 12 minutes of the trial can be seen in table C.2. This snippet has subjectively been selected as a representative subset of the entire experiment.

ID	Sex	Age	Disability	Status
P1	F	N/A	N/A	N/A
P2	F	82	Self sustainable. Drives car	Lives alone
P3	F	77	Self sustainable. Has spinal stenosis, Bad knee, drives car	Married
P4	F	80	Dementia and cognitive problems	N/A
P5	F	72	Self sustainable. Uses a walker, Problems with right leg	Lives alone
P6	F	62	Self sustainable. Broken hip and has osteoporosis	Married
P7	M	85	Self sustainable. Had surgery in back	Lives alone
P8	F	84	Self sustainable. Waiting for operation in right knee	Lives alone
P9	F	80	Receives help for bathing	Lives alone
P10	F	73	Self sustainable. Uses a crutch. Was working until last year	Lives alone

Table C.1: Short description of the 10 participants. P5 did not want to participate actively in playing the game.

Figure C.5: Participants at the rehabilitation centre competing about the robot's attention.

ID	Minutes	Comments
P1	1:03	What's it called? Most guys are looking for legs. He is not making a pass on me. Should we try whether it will follow you?
P7	1:02	Let's do that. Just come here you.
P8	0.59	Laughs. It does not bite does it? It's like a dog. You do not get much exercise doing this.
P2	1.12	Now we go the other way. You are not interested, but it's me you have to look at.
P9	1.20	Thanks a lot. You are going at it, ha. You have to wake up now, little fellow.
P10	3.00	Come on. Now we're turning around. Come on. The dogs I know do not listen much better. Stop young man! Then the other way. Come on.
P9	2.10	Laughs. P8 and P1 tries to get the robot's attention, but does not succeed.
P2	0.40	..

Table C.2: Transcription of 12 minutes of the field study.

Seniors acceptance of the robot

One participant (P5) did not want to try, but observed the entire session, while others tried several times (P2, P1, P8 and P9). When not playing with the robot, the participants would stand around in a circle and watch how the robot moved and how the other participants were playing.

As can be seen in the table C.2, participants would use the personal pronoun "he" about the robot (P1), or "we" about the robot and themselves (P2), indicating that they created a relation to the robot and thought about it and themselves as a common "we".

When playing, participants often acted towards the robot as if it was a boy or young man (P1, P9, P10) or a dog (P8 and P10). One of the participants was wearing a skirt which stopped just below the knee (P1) (Figure C.5). When explained that the robot may not be able to detect her because of the skirt, she said "Most boys reacts on a women's legs.", indicating that she saw that robot as a boy.

When playing, participants spoke to the robot is if it was humanlike, and described it as "funny" and "charming" and seemed to perceive it as boy or young man (P1, P9, P10) e.g. by asking for the robot's name. P1 indicating that she saw the robot as a boy by stating e.g. "Do you think we should go over to her? Oh I see - you don't think so. "Don't look for others. Stay with me". When the robot finally left her, she said "Shame on you!". Similar behaviour was observed when a participant asked the robot for a dance. When she had walked around with the robot she said "Thanks for dancing with me", as if she had been dancing with a man. P8 indicated that she thought the game was meaningless by stating 'you do not get much exercise doing this'.

None of participants showed any response of being frightened of the robot or thinking that the game was too complex. When asked directly, no one thought that the distance

to the robot was to short, thereby violating their personal space. One of the participants formulated this as "it does not make a pass on me" (P1).

Game Play Patterns

P5 who did not participate in the game, spent time looking at the others while training. She described the session as follows:

"Something happened when I was looking. Something happened. They concentrated about the eyes and disconnected. I could see they walked more freely. They just walked around and looked him in the eyes. They walked much faster too. They forgot to hold on to something when walking. (P5)"

As this statement illustrates, the participants seemed to ignore the other people in the room when playing, focusing on the robot and talking to it while walking around.

P4 explained how she was afraid of falling in her own home when she moved around. While playing with the robot she seemed to forget all about that and constantly changed her pace and turned around while looking at the robot in order to check whether it followed her. She kept balance, and did not seems worried about falling but focused purely on the robot. P10 used a crutch because she broke her hip 3 months before the study. While moving into the centre of the room, she left the crutch behind and afterwards told that this was the first time she walked without it after the operation. The physiotherapists who normally trained the elderly, stated that the participants seemed to walk more freely when using the robot. Due to the nature of the game, they noticed that several participants spent time walking backwards, forwards and sideways while constantly having to orient themselves in the room. Also they noted, that they often changed their pace, and walked in another direction than their gaze. According to the therapists, the potential positive effect of this behaviour was training of the postural control which has two main functions: first, to build up posture against gravity and ensure that balance is maintained; and second, to fix the orientation and position of the segments that serve as a reference frame for perception and action with respect to the external world.

Future Improvements Told by Study Participants

When asked directly, several participants claimed that the robot was not able do to enough. These participants thought that walking around with the robot was a a bit too easy a challenge for them, and that the robot reacted too slowly. They would like the robot to be able to do more, e.g. react faster, respond to voices, sing a song etc. The physiotherapists agreed on the fact the robot was not able to do enough, and that the game was too simple, making it to become boring fast. They suggested to include some kind of cognitive or social training when using the robot, i.e. a game where the elderly should work together as a team or solve a puzzle while moving around. The were positive about the idea of using technology to motivate elderly for doing exercises, because it was often a problem for them to motivate the elderly to train hard and long enough. They had earlier tried to

Figure C.6: A participant using a walker playing with the robot.

use Nintendo Wii, but did not use it much, as it took too long time to set up and instruct the elderly to use.

5 Field Study at the Nursing Home

This study took place in a nursing home and a total of 15 elderly residents were invited (one male and 14 female). In this study we could not get detailed information about the disabilities of each individual due to policy of the nursing home. The age of the participants varied between 65 and 95 - the average being 90 years old. Two of the participants were using a wheelchair, 6 were using a walker while two were using crutches. One had hearing loss and another had loss of sight. The nurse who normally trained the elderly was present in the room and was observing the study which was also video recorded.

Seniors acceptance of the robot

Two out of 15 participants did not want to interact with the robot but were observing the activities while other tried several times. When not playing with the robot, participants were paying attention to the activities discussing the robot while waiting for their turn. As in the former study, many participants acted towards the robot as a living agent, e.g. a dog or a boy and tend to perceive the robot as having complex capabilities like the ability to hear, see or feel. E.g. when the first participant played with the robot she said "This is like walking with the dog" while another participant said: "Come on my friend, let's show them what we can do".

Game Play Patterns

Although 10 of the participants in this study used assistive tools like wheelchairs, crutches or walkers (Figure C.6) this did not posses any technical problems for the robot.

A participant suffering from gout initially explained that she could not do any exercises because of the pain. When she had the opportunity to interact with the robot she wanted to play anyway and did so without problems. Another participant said that it was not uncomfortable to train with the robot even though she had to move backwards. She

explained that the robot actually made her move in different ways because she wanted to test it and explained:

"I tried to run to see how the robot reacted and to see if it was able to follow me. In that sense the robot made me do other things than I do normally. Also to walk backwards for example."

Future Improvements

One of the participants said that he did not find the robot difficult to use, but it seemed easy to confuse. One woman said that the robot should be more human, as it looked too much like a machine. A woman said that the robot moved way too slow. It should move faster because it quickly got boring. Another participant said that the activity got boring because there was not much to do with the robot. She suggested that the robot might be better if it could speak, move faster and more smooth. When asked directly if the distance between the robot and the participant was fine, everyone agreed that the distance was good. Another participant said she found the robot a bit contusing and explained that it was not easy to know whether or not the robot was following you. The nurse who participated in the study, pointed out that people would like to touch it, speak to it and communicate with it. Also, she said, that it would be good if it had some sounds that could signal when the robot recognized people. They had tried to use Nintendo Wii for training purpose, but thought that the existing games were to complex for most elderly.

6   Discussion

The observations show that although the elderly are well aware that the robot is an inanimate object with limited capabilities, they behave towards the robot as if it had personality and emotions. This is not surprising as the same effect has been documented in literature in e.g. [22]. How the effect influences the engagement in robot based games is not well investigated, but this study indicates that it compensates for the fact that the robot game is relative simple and that the proposed game lacks complex challenges. Inherently the participants associate the robot with functionality it does not have, like the ability to hear, see and feel. Their fascination by the robot means that they allow it to exist on its own terms, and that the participants tolerate it although it does not live up to their expectations. It has been observed, that the robot motivates for social interaction between the participants, e.g. by being an interesting topic of discussion. This can be seen as positive cognitive training as many elderly lack intellectual stimuli causing further passivity and functional decline.

When comparing the two field studies, the biggest difference is that the nursing home group have more severe disabilities and therefore more participants need tools like wheelchairs and walkers. This resulted in a slightly more passive behaviour during the study, e.g. most participants would sit down when not playing. This group also included more participants, which might have affected their behaviour. A technical finding of the study is that the combination of the laser scanner and leg detection algorithm is capable of detecting people although they use wheelchairs, walkers or crutches. The robot worked

well in the environments it was investigated, and we did not observe any major technical flaws based on the current game setup.

7   Conclusion

In this paper, robot based games have been proposed as a way to motivate elderly to do physical exercises. Based on a mobile robot we have developed a game which has been investigated in a nursing home and in a rehabilitation centre for elderly. Based on qualitative research, we have observed seniors' acceptance of the robot game, obtained knowledge about their play patterns and suggestions to future improvements of the game.

The results using the game showed that the elderly did not mind participating in the game. Out of 26 invited, 23 accepted playing actively while 3 observed the others play. The study showed that the elderly had no problems in understanding that the robot is an inanimate object with limited capabilities, but nonetheless tended to treat it as a living creature with extensive capabilities. When playing, they would often talk and point to it although they knew it could not see or hear them. A number of the elderly expressed disappointment about the limited functionality of the robot, and some described the game as confusing or boring. Nonetheless, when playing many participants seemed to get immersed in the game and forget about their respective disabilities. The study showed how the nature of the game made the elderly do a number of physical movements which they would find difficult, frightening or even painful under normal conditions, e.g. walking backwards. This potentially can be used for training the human postural control system which builds up balance and orientation. Additionally, the game showed to have a social function as it made the elderly interact with each other while discussing the goal and the functionality of the robot and the game. A technical finding from the study, was that the robot worked well in an everyday environment and was able to detect people using assistive tools crutches, walkers or wheelchairs.

Although the study in this paper does not tell us whether robot games have any physiological or mental benefits for the users, it proposes a new way to use robots in rehabilitation scenarios by combining games and physical activity as an alternative to using e.g. games for Nintendo Wii which is often considered too complex to use for the elderly. There are no indications in this study that the participants found the suggested robot game to complex, but a drawback is that it is a single-player game thereby only capable of training one person at the time. The studies indicate that the elderly like playing games with a robot, and that such a physical implementation offer something that can be difficult to obtain using traditional training, e.g. the motivation for training movements which are instinctively avoided by the elderly in traditional training. However, more research about how robot games should be designed and applied is needed.

8   Future Work

Only a few real world evaluations on robot games for elderly have been conducted and and there is a need to do more longitudinal studies about user acceptance and perform quantitative measurements of physiological benefits of using robot games.

The implemented robot game should be elaborated in order for it not to become boring for the participants too quickly. Future work is therefore to create and study more

complex games which stimulates cognitive training and/or collaborative behaviour. The design of the robot should also be enhanced, making it look less like a machine and include multi-modal interface like speech recognition, sound or more complex gesture recognition which opens for a new world of social signal processing.

9 Ethical considerations

The study was approved by The Danish Data Protection Agency. Informants consented to video-recording. Prior to the fieldwork, participants were informed about the study orally and in writing. The informants were told the purpose of the investigation and that participation was voluntary and that they might withdraw at any time; they were assured that any information given would be treated in confidence and reported anonymously.

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Paper C

Pose Estimation and Adaptive Robot Behaviour for Human-Robot Interaction

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Abstract

   This paper introduces a new method to determine a person's pose based on laser range measurements. Such estimates are typically a prerequisite for any human-aware robot navigation, which is the basis for effective and time-extended interaction between a mobile robot and a human. The robot uses observed information from a laser range finder to detect persons and their position relative to the robot. This information together with the motion of the robot itself is fed through a Kalman filter, which utilizes a model of the human kinematic movement to produce an estimate of the person's pose. The resulting pose estimates are used to identify humans who wish to be approached and interacted with. The behaviour of the robot is based on adaptive potential functions adjusted accordingly such that the persons social spaces are respected. The method is tested in experiments that demonstrate the potential of the combined pose estimation and adaptive behaviour approach.

1   Introduction

Mobile robots are moving from factory floors out into less controlled human environments such as private homes or institutions. The success of this shift relies on the robots ability to be responsive to and interact with people in a natural and intuitive manner and accordingly human-robot interaction is a novel and growing research field [1, 2].

   To allow close, more effective and time-extended relationships it is first necessary to determine the persons willingness to engage in interaction, followed by a coordination in time and space that respects the persons interest and privacy. Several authors [3, 4, 5] have investigated the willingness of people to engage in interaction with robots that exhibit different expressions or follow different spatial behavior schemes. In [6] models are reviewed that describe social engagement based the spatial relationships between a robot and a person with emphasis on the movement of the actors. Human-aware detection, tracking and navigation were discussed in [7, 8].

   As a step in the direction of human aware robot behaviour, we present a novel method for inferring a human's pose from 2D laser range measurements. Here we define pose as the position, and orientation of the body. Compared to vision based pose estimation, such as [9], or 3D range scans [10], using 2D laser range scanners provide extra long range and lower computational complexity. The extra range enables the robot to detect the movement of persons moving at a higher speed. The approach takes advantage of the inherent mobility and typical sensors of a mobile robotic platform and does not require any determination of the persons facial expressions or other gestures, and hence the person does not have to be facing the robot. The method relies on an algorithm for detecting legs of persons. The algorithm has been tested in a public transit space [11].

   While the focus of this paper is on the pose estimation, the use of the estimates in determining persons willingness to engage in interaction is analyzed from the recorded kinematic state of the person. By looking at knowledge from previous encounters, the robot behavior is adjusted as described in [12]. When the persons willingness has been determined it is used as a basis for human-aware navigation using adaptive potential functions centered around the person, inspired by [7]. The navigation is adapted such that it respects the persons social spaces as discussed in [5].

   The pose estimation is validated through a number of experiments. In addition, experiments indicate the effectiveness of the combined algorithm for human-aware navigation.

2 Materials and Methods

The basis for any interaction is the ability of the robot to detect if a person is present, and if this is the case to estimate the kinematic state of that person. The algorithm for detecting legs of persons and converting these to person position estimates is described in [13], and [14] been implemented and adapted to keep track of individual persons. The implementation has been proved robust for person speeds up to $2\frac{m}{s}$ in a real world public space setting described in [11]. The position estimates from this algorithm form the basis for deriving a pose estimate of a person.

Person Pose Estimation

The setup, where a person is moving around, while the robot is following, can be seen in Fig. D.1. The basic idea for estimating the pose of a person (θ), is to take the position estimates from the laser range finder algorithm and combine them with robot odometry information to obtain a pose estimate. Because we have both position and velocity measurements to estimate a pose, it can not be calculated directly, and a Kalman filter is therefore used to filter the measurements. The filter produces a velocity estimate of the person relative to the robot. After this a post filter is added to obtain the person pose from the velocity estimates.
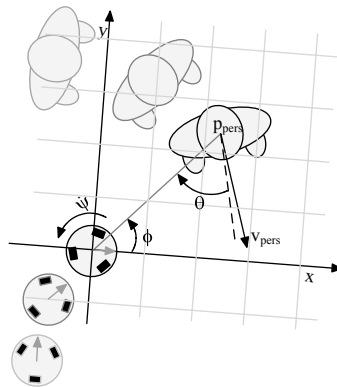
Figure D.1: Person position and pose. The state variables $\boldsymbol{p}_{pers}$ and $\boldsymbol{v}_{pers}$ hold the position and velocity of the person in the robot frame. θ is the pose of the person. The variable θ is approximately the angle between ϕ (the angle of the distance vector from the robot to the person) and $\boldsymbol{v}_{pers}$ (the angle of the person's velocity vector), but not entirely the same because the body is not necessarily oriented in the moving direction. $\dot{\psi}$ is the rotational velocity of the robot.

A standard discrete state space model formulation for the system is used:

$$\begin{aligned} \boldsymbol{x}(k+1) &= \Phi\boldsymbol{x}(k) + \Gamma\boldsymbol{u}(k) & \text{(D.1)} \\ \boldsymbol{y}(k) &= H\boldsymbol{x}(k) \quad, & \text{(D.2)} \end{aligned}$$

where the state is comprised of the person position and velocity and the robot velocity

$$\boldsymbol{x} = \begin{bmatrix} p_{x,pers} \\ p_{y,pers} \\ v_{x,pers} \\ v_{y,pers} \\ v_{x,rob} \\ v_{y,rob} \end{bmatrix} . \tag{D.3}$$

Here p is positions and v is velocities, all given in the robot coordinate frame. The position of the person relative to the robot depends both on the person velocity and the robot velocity. In this stage we omit the rotation of the robot:

$$
\begin{aligned}
p_{x,pers}(k+1) &= p_{x,pers}(k) + T(v_{x,pers}(k) - v_{x,rob}(k)) && \text{(D.4)} \\
p_{y,pers}(k+1) &= p_{y,pers}(k) + T(v_{y,pers}(k) - v_{y,rob}(k)), && \text{(D.5)}
\end{aligned}
$$

where T is the sampling time. This yields the following state transition matrix:

$$\Phi = \begin{bmatrix} 1 & 0 & T & 0 & -T & 0 \\ 0 & 1 & 0 & T & 0 & -T \\ 0 & 0 & 1 & 0 & T & 0 \\ 0 & 0 & 0 & 1 & 0 & T \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} . \tag{D.6}$$

The measurements used are the person position, and the odometry velocity data from the robot.

$$\mathbf{H} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} . \tag{D.7}$$

To overcome the nonlinear effect the robot rotation has on the state, a measurement driven Kalman filter, which is used in [15, 16]. The idea is to use sensor readings to drive the process model as an input - in this case odometry data from the robot. Using polar coordinates, the position vector of the person relative to the robot can be written:

$$\boldsymbol{P}_{pers} = \begin{bmatrix} d\cos(\phi(t)) \\ d\sin(\phi(t)) \end{bmatrix} \tag{D.8}$$

where d is the distance to the person, and $\phi(t)$ is the angle to the person. The change, i.e. the derivative becomes

$$\dot{p}_{pers} = \begin{bmatrix} -d\sin(\phi(t)) \\ d\cos(\phi(t)) \end{bmatrix} \dot{\phi}(t) , \tag{D.9}$$

where $\dot{\phi}(t)$ has the opposite sign of the rotation of the robot itself $\dot{\psi}$, so the derivative becomes

$$\dot{p}_{pers} = \begin{bmatrix} -d\sin(\phi(t)) \\ d\cos(\phi(t)) \end{bmatrix} (-\dot{\psi}) = \begin{bmatrix} p_{y,pers} \\ -p_{x,pers} \end{bmatrix} \dot{\psi} . \tag{D.10}$$

Using an Euler integration, we can substitute Γu in the model by

$$\Gamma u = \begin{bmatrix} p_{y,pers}(k) \\ \text{-}p_{x,pers}(k) \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} T\hat{\psi} \quad , \tag{D.11}$$

where $\hat{\psi}$ is the estimated robot rotation from the odometry data.

The velocity vector is not necessarily equal to the pose of the person. Consider a situation where the person is standing almost still in front of the robot, but is moving slightly backwards. This means that the velocity vector suddenly is in the opposite direction, but the actual pose is the same. Therefore the velocity estimate is filtered through a first order autoregressive filter. The filter is made with adaptive coefficients relative to the velocity. So when the person is moving fast, we rely very much on the direction of the velocity, but if the person is moving slow, we do not change the pose estimate very much and rely on the previous estimate. The autoregressive filter

$$\theta(k+1) = \beta\theta(k) + (1-\beta)\arctan\left(\frac{v_{y,pers}}{v_{x,pers}}\right) \quad , \tag{D.12}$$

where β is chosen relative to the absolute velocity v as:

$$\beta = \begin{cases} 0.9 & \text{if } v < 0.1 m/s \\ 1.04 - 1.4v & \text{if } 0.1 m/s \geq v \leq 0.6 m/s \\ 0.2 & \text{else} \end{cases} \quad . \tag{D.13}$$

Evaluating a Person's Willingness to Interact

Although the robot is not perceived as a human being when encountering people, the hypothesis is that human behavioral reactions are the same as in human to human encounters. If a person is interested, he or she will undoubtedly approach the robot in a straightforward manner. On the contrary, if in no interest the person will carefully avoid the path of the robot.

However, there may be many trajectories where the interest of the person will be difficult to determine, i.e. many valid trajectories are possible and trajectories variate for each robot-person encounter. In previous work [12] an adaptive person evaluator based on a Case Based Reasoning (CBR) system has been used. The CBR system is basically a database system which holds a number cases describing each encounter. The specification of a case is a question of determining a representative set of features connected to the event of a human robot encounter which can serve as input. In this case we use the features velocity, position and pose illustrated in Fig. D.1. The output is the Person Interest indicator, $PI \in [0, 1]$ which store the probability or indication of the detected person's interest to interact. The value 0 indicates no interest whereas 1 indicate interest.

The starting point of the CBR system is an empty database holding no a priori correspondence between trajectories and interest. When interacting, interest is confirmed by handing over an object to the robot. Lack of interest is triggered if no interaction has

occurred after a fixed period of time. By adding cases, the system gradually learns how to decode trajectories into a interest level.

Human-aware Navigation

The robot behavior is inspired by the spatial relation between humans (proxemics) as described in [17]. Hall divides the zone around a person into to four categories, 1) the public zone $> 3.6m$, 2) the social zone $> 1.2m$, the personal zone $> 0.45m$, and the intimate zone $< 0.45m$. Social spaces between robots and humans were studied in [18] supporting the use of Hall's proxemics distances and the human robot interaction is therefore designed to be able to experiment with different distances.

For modeling the robots navigation system a person centered potential field is introduced. The potential field has high values where the robot is not allowed to go, and low values where the robot should be. All navigation is done relative to the person, and hence no global positioning is needed in the proposed model. The method is described in [12], but is slightly changed in this implementation. The potential field is designed by the weighted sum of four Gaussian distributions of which one is negated. The covariances of the distributions are used to adapt the potential field according to *PI*.

The four Gaussian distributions are illustrated in Fig. D.2 and has the following functions:

Attractor, this is a negated distribution used to attract the robot to the person. Its variances σ_x^2 and σ_y^2 are both set to 7.5 and its covariance σ_{xy} is set to 0.

Rear, this distribution ensures that the robot does not approach a person from behind. Its variances σ_x^2 and σ_y^2 are respectively set to 2 and 1 and its covariance σ_{xy} to 0. It is only applied when the robot is behind the person.

Parallel, this distribution is initially placed with its major axis parallel to the x_p-axis in the persons coordinate frame. Its variances and covariance are adapted according to the person interested in interaction.

Perpendicular, this distribution is initially placed with its major axis perpendicular to the parallel distribution. Its variances and covariance are adapted according to the person interested in interaction. This distribution as well as the parallel is only applied when the robot is in front of the person.

The attractor and rear distribution are both kept constant for all instances of the person interest indication *PI*. But the parallel and perpendicular distributions are interactively scaled and rotated according to the person's changing *PI* during interaction. This means that the robot continuously adapt its behaviour to the current *PI* value. The potential functions are scaled and adjusted according to Hall's proximity distances, and the preferred robot to person encounter reported in [5].

The resulting potential field contour can be seen in Fig. D.3 for three specific values of *PI*. In the extreme case with $PI = 0$ the potential field will like look Fig. D.3a where the robot will move to the dark blue area, i.e. the lowest potential app. 2 meters in front of the person. The other end of the scale for $PI = 1$ is illustrated in Fig. D.3c, where the person is interested in interaction and as result the potential function is adapted so the
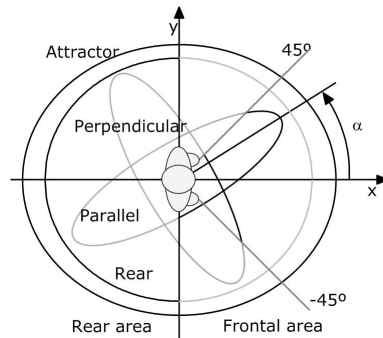
Figure D.2: Illustration of the four Gaussian distributions used for the potential function around the person. The rear area to the left of the y axis. The frontal area (to the right of y axis) which is divided in two, one in the interval from $[-45° : 45°]$ and the other in the area outside this interval. The parallel and perpendicular distributions are rotated by the angle α.

robot is allowed to enter the space right in front of him or her. In between, Fig. D.3b, is the default configuration of $PI = 0.5$, in which the robot is forced to encounter the person in approximately $45°$, while keeping just outside the personal zone.

Instead of just moving towards the lowest point at a fixed speed, then the gradient of the potential field is derived. This allows the robot to move fast when the potential field is steep, for example if the robot has to move fast away from a person if getting in the way. On the other hand, the robot has slow comfortable movements when it is close to where it is supposed to be, i.e. near a minimum of the field.

3   Experimental Setup

In order to validate all parts of the system, the above algorithms have been tested in three steps by integrating one feature at the time. First the basic person detection and pose estimation algorithm is tested. Then this is combined with the human aware navigation. Finally, also the person interest estimation has been included. Each step has been validated in real world experiment. All experiments have been done with only one human in the area, since the purpose is to demonstrate the proof of concept of the methods. However, the methods should be valid with more persons around the robot.

Test Equipment and Implementation

The basis for evaluation of the proposed methods was a FESTO Robotino platform on which a head, capable of showing simple facial expressions, is mounted (see Fig. D.4). On the platform, the robot control software framework Player/Stage [19] has been implemented, which also enables simulation before real world tests. The robot is equipped with a URG-04LX line scan laser range finder and a contact to press if you are interested in interaction. The case database has been implemented using MySQL.

(a) *PI*=0

(b) *PI*=0.5

(c) *PI*=1
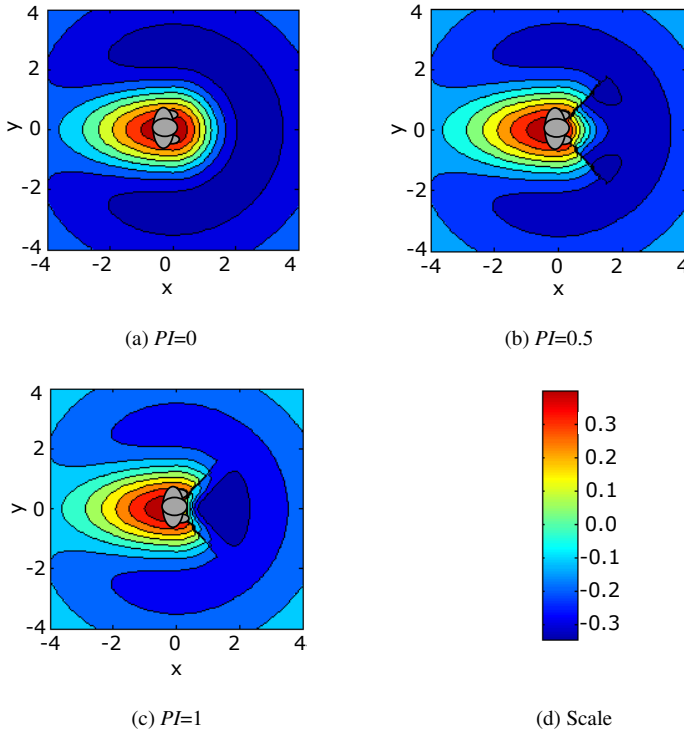
(d) Scale

Figure D.3: Shape of the potential function for (a) a person not interested in interaction, (b) a person considered for interaction, and (c) a person interested in interaction. The scale for the potential function is plotted to the left and the value of the person interested indicator *PI* is denoted under each plot.
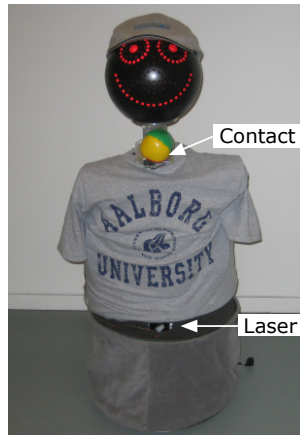

Figure D.4: The FESTO Robotino robot used for the experiments.

A 3D motion tracking system from Vicon (typically used for indoor UAV applications) has been used to validate the functionality of the algorithm through laboratory experiments.

Pose Estimation

The pose estimation algorithm was validated through laboratory experiments. The pose algorithm was tested isolated from the system, i.e. all navigation and learning algorithms were disabled. During the experiment, the robot was placed on a fixed position in the lab, while a test person entered the robot field of view and wandered around following different patterns at velocities around $0.5 - 1.5\frac{m}{s}$. While the robot estimated the pose of the test person, the stationary tracking system was concurrently reading the movements.

Human Aware Navigation

In this step, the human aware navigation algorithm was added to the pose estimation system and tested in the robot laboratory. In order to isolate the navigation algorithm, the level of *PI* was set to a fixed value through each experiment and was completed for $PI = \{0, 0.5, 1\}$. As in the former experiment, the stationary tracking system was set to read the position of the test person while he would approach the robot following different patterns. Since the navigation algorithm was enabled in this experiment, the movement of the robot was also tracked.

Integration Test

In this step, the complete system was tested, i.e. the CBR system was added. The test took place in a foyer at the University campus with an open area of 7 times 10 meters. This allowed for easily repeated tests with no interference from other objects than the test person. The contact on the robot was used to get feedback from the test persons whether they were interested in interaction or not. The test persons were asked to approach or pass by the robot in different ways. In approximately half the cases, the test person would end the trajectory by pressing the switch indicating interest in interaction. The test started with an empty database, so that the robot had no experience to start from. During the experiments the *PI* values, the position, pose estimates were logged in the database.

4   Results and Discussion

Pose Estimation

Fig. D.5 shows the different trajectories performed. The black dots are the position estimates from the robot, and the lines extending from the dots are the corresponding pose estimates. Some underlying coloured dots can be seen in Fig. D.5a and in the left line in Fig. D.5b. These are the correct position estimates as measured by the motion tracking system. The correct underlying positions are omitted in the other plots, since they clutter the image unnecessarily. In Fig. D.5a, a u-turn movement is performed where the person stands still for a few seconds close to the robot in the lower left corner. This demonstrates that even though the person stands still (and might even move slightly backwards), the

(a) U-turn movement

(b) Circular movement.

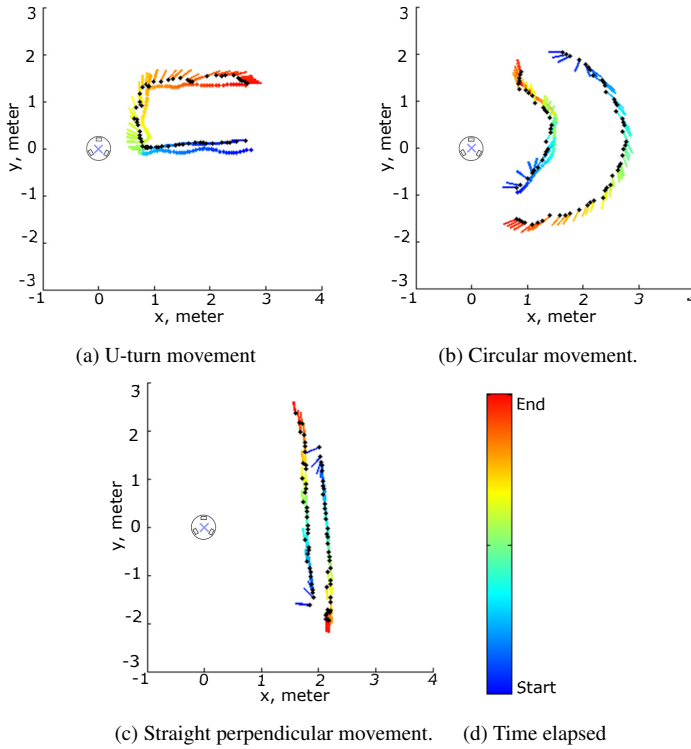(c) Straight perpendicular movement.

(d) Time elapsed

Figure D.5: While the robot was standing still, three types of movement was performed. The dots indicate the person positions, which the robot has estimated. S robot, and in the left figure and the left trajectory of the middle figure, the correct trajectory measured by the Vicon underlying dots. The time evolution is shown as colours.

pose estimate keeps being correct towards the robot. When the robot recognizes a person, it assumes that the pose is close to 0, which explains the blue lines always pointing towards the robot in the beginning of a trajectory. However, as soon as the person start to walk, the pose estimate turns and follows the motion. Note that it is not the Kalman filter which estimates the velocity wrong, when the lines do not follow the trajectory exactly. But it is the autoregressive filter that does not allow the pose estimate to change too quickly. The figures show that the pose estimator works satisfactory and can be used to estimate pose in real world. Although this laboratory test confirm that the pose algorithm works as expected, the test is limited to only a few test runs and the algorithm is not really fine tuned yet.

Human Aware Navigation

In this experiment, the robot is set to move according to prespecified person indication (*PI*) values. The person moves from the bottom left corner (in Fig. D.6a-D.6c) towards the robot. The elapsed time is shown by the trajectory colour changing from blue to red.
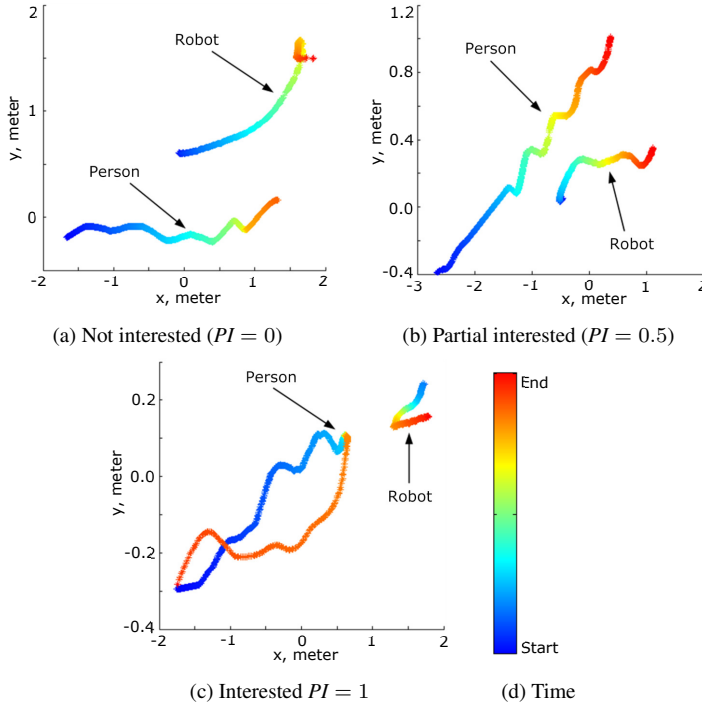
(a) Not interested ($PI = 0$)

(b) Partial interested ($PI = 0.5$)

(c) Interested $PI = 1$

(d) Time

Figure D.6: This figure shows the motion of the robot when the person interest indication (*PI*) is fixed at three different levels. The colour bar shows the time evolution. It can be seen that the robot keeps at a comfortable distance when the *PI* is low, and approaches the person from the front when $PI = 1$.

When $PI = 0$, it can be seen that the robot tries to get away from the person. When it reaches a comfortable distance, it settles around that position relative to the person. When the person is partially interested, the robot avoids the person and tries to stay at an angle of approximately $45°$ degrees. Finally, when the person is interested, the robot approaches the person from the front until the border of the intimate zone is reached at around $45cm$. The major colour change at the person trajectory indicates that the person has been standing still. As soon as the person starts to move away, the robot finds out that it is behind and too close to the person, so it starts to move away.

The shaky sinusoidal movement of the person trajectory is due to the tracking of the person. It is caused by the fact that the central part of the body moves like this when a human walks. The experiment proves that the potential field enables the robot to keep at the correct position relative to the person, and that the pose estimator also works when the robot is moving.

Integration Test

The output of the integration test was a trained CBR database. The database can be seen in Fig. D.7. The dots show recorded test person positions, which was rounded to a grid

size of $40 \times 40 cm$. Note that the positions are not global coordinates, but relative to the robot while it is moving. The extending lines, show the direction of the pose estimates, and the colour the corresponding *PI* value, where red indicates an interested person, and blue indicates a person which is not interested. The database shows that that persons right in front of the robot with a pose close to $0°$ is typically interested in interaction, whereas a pose pointing away from the robot indicates that the person is not interested. The results reflect the fact that the potential field makes the robot move so only persons who are estimated as interested are allowed to come close to the robot.

Clearly, the experimental work is still in its initial stage and is not exhaustive. However, the tests demonstrates the potential of the methods and of combining the pose estimation algorithm with the proposed method for human aware navigation.
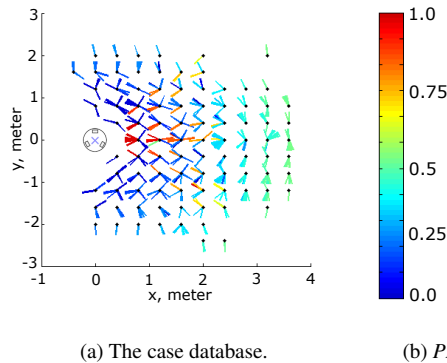

(a) The case database.   (b) *PI*

Figure D.7: The figure shows the values stored in the CBR system after completion of 20 test runs. Each dot represents a position of the test person in the robot coordinate frame. The direction of the pose estimate of the test person is shown by the extending line, while the level of interest (*PI*) is indicated by the color range of the line.

5   Conclusions

This paper describes a new method for estimating the pose of a person in an interaction scenario with a mobile robot. The algorithm only relies on laser range finder data, which makes it applicable for moving persons at larger distances than normal vision techniques allow. A Kalman filter is used to filter the measured positions of persons within view and outputs a pose estimate.

The position and pose estimates are used in a Case Based Reasoning system to estimate the person's interest in interaction, and the spatial behavior strategies of the robot are adapted accordingly using adaptive potential functions. The human robot interaction methodology described in this paper is supported by laboratory and real world tests which demonstrate the applicability of the pose estimator and the spatial behaviour of the robot.

The real world tests demonstrate the potential of the integrated system, which can be used for robots moving in human environments. Generally, the conducted experiments on the robots cognitive functionality show that the method of CBR implemented can advantageously be applied to a robot, which needs to evaluate the behavior of a person.

An interesting aspect for future work would be to combine this pose estimation technique with a vision based technique. This could give a more accurate pose estimate for close interaction.

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Paper D

Adaptive Human aware Navigation based on Motion Pattern Analysis

Søren Tranberg Hansen, Mikael Svenstrup, Hans Jørgen Andersen, Thomas Bak

Abstract

Respecting people's social spaces is an important prerequisite for acceptable and natural robot navigation in human environments. In this paper, we describe an adaptive system for mobile robot navigation based on estimates of whether a person seeks to interact with the robot or not. The estimates are based on run-time motion pattern analysis compared to stored experience in a database. Using a potential field centered around the person, the robot positions itself at the most appropriate place relative to the person and the interaction status. The system is validated through qualitative tests in a real world setting. The results demonstrate that the system is able to learn to navigate based on past interaction experiences, and to adapt to different behaviors over time.

1   Introduction

The vision of robots participating in our day-to-day lives is a main part of the focus in the research field of Human Robot Interaction (HRI) [1]. The vision is supported by progress in computing, visual recognition, and wireless connectivity, which open the door to a new generation of mobile robotic devices that see, hear, touch, manipulate, and interact with humans [2].

Consider a robot supporting care assistants. At one time of the day, the support may include handing out food. In this case, the robot will interact closely with the care assistants and the persons being assisted. After a while, the persons around the robot will not need its assistance anymore and hence its behavior should be adjusted according to this new situation. For a robot to behave naturally in such situations, it will be necessary for it to learn from experiences and to adapt its behavior to the person's desire to interact.

To incorporate the ability to learn from experiences, researchers [3] have investigated Case Based Reasoning (CBR). CBR allows recalling and interpreting past experiences, as well as generating new cases to represent knowledge from new experiences. To our knowledge, CBR has not yet been used in a human-robot interaction context, but has been proven successful solving spatial-temporal problems in robotics in [4]. CBR is characterized by its adaptiveness making it well suited for implementing an adaptive behavior on a human interactive robot, as described in the case above. Hidden Markov Models and Bayesian inference algorithms have successfully been applied for modeling and predicting spatial user information [5], but a clear advantage of using CBR is the simple implementation and the relatively little need of parameter tuning.

We introduce a simple, robust and adaptive system for detecting whether a person seeks to interact with the robot based on the person's pose and position. We define a human's pose as the position and orientation of the body, and infer pose from 2D laser range measurements as explained in [6]. Other researchers [7] have investigated the use of laser scanner input and head pose information from a camera, but the approach here is limited to only using a laser scanner.

When the probable outcome of a person-robot interaction has been determined by the robot, it is used as a basis for human-aware navigation respecting the person's social spaces as discussed in [8]. Several authors [9, 10, 8, 11] have investigated the willingness of people to engage in interaction with robots that follow different spatial behavior schemes. In the method described here, navigation is done using potential fields which

has shown to be useful for deriving robot motion [12, 13]. The implemented adaptive navigation behavior is described further in detail in [14, 6]. The adaptive CBR and navigation methods have been implemented and tested in a real world human robot interaction test setup.

2 Materials and Methods

The robot behavior described in this paper is inspired by the spatial relation between humans (proxemics) as outlined in [15]. Hall divides the zone around a person into to four categories according to the distance to the person:

- the public zone $> 3.6m$

- the social zone $> 1.2m$

- the personal zone $> 0.45m$

- the intimate zone $< 0.45m$

Social spaces between robots and humans were studied in [16] supporting the use of Hall's proxemics distances.

In order for the robot to be able to position itself in the most appropriate position relative to the person, it should be able to estimate what will be the outcome of the human-robot interaction during run-time. If it is most likely that the person do not wish to interact, the robot should not violate his or hers personal space but seek to the social or public zone. On the other hand, if it is most likely that the person is willing to interact with the robot, the robot should try to enter the personal zone.

To accomplish this behavior an evaluator based on the motion of a person relative to the robot is introduced. The philosophy of the evaluator is that:

- There is a correspondence between human motion pattern relative to the robot, and the likelihood of close human-robot interaction.

- This correspondence can be automatically estimated based on continuously provided pose and position estimates, together with stored interaction information from previous experiences.

The output from the evaluator can be used to control the robot and enable it to navigate to an appropriate position relative to the person.

Evaluating human robot encounters

The central output from the person evaluator is the continuous variable *PI* which indicates what the robot believes will be the outcome of the human behavior at the current time (1 = close interaction, 0 = no close interaction). *PI* does not denote a probability but is a fuzzy predicate defined to denote to which degree the person is likely to seek close interaction with the robot.

The adaptive person evaluator is designed based on Case Based Reasoning (CBR). The CBR system is basically a database describing each encounter. Specifying a case in

CBR is a question of determining a distinct and representative set of features of the human robot encounter. In order to ensure simplicity, we have selected to rely on the simple features position and pose only. More advanced features such as person identification, gesture and facial recognition could be incorporated in the database but is considered out of scope here. The used features are illustrated in Fig. E.1, where:

Case, is a reference number of each case

x, is the x coordinate of the position of the person in the robot's coordinate system, sampled in 40 cm intervals

y, is the corresponding y coordinate of the position, also sampled in 40 cm intervals

θ, is the pose of the person sampled in an angular resolution of 0.2 radian = 11.5 degrees.

PI, is the value estimated by the CBR system.

The features **x**, **y** and θ are all stored in a precision which facilitates match-making when performing database queries. The database does not hold any explicit information about context or environment.

Case	x	y	θ	PI
:	:	:	:	:
76	0.8	1.2	98	0.2
77	0.8	1.2	80	0.35
78	0.8	1.2	65	0.9
:	:	:	:	:
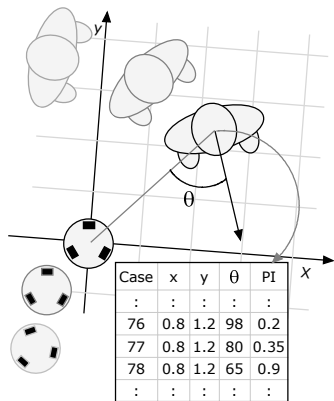
Figure E.1: Illustration of the input variables to the CBR system and the corresponding output *PI* stored in the CBR database.

The starting point of the CBR system is an empty database holding no a priori correspondence between trajectories and probability of interaction. Interaction is identified if the person hands over an object to the robot within a time period. If the person disappears from field of view of the robot or if no hand over has occurred within this time limit, no interaction is said to occur. There are basically two different stages of the robot operation.

1. A person encounters the robot, and the robot evaluates the person given all the previous experiences from the database.

2. The robot updates the database according to a person encounter, which has just passed.

When evaluating a person, a number of case lookups are performed starting at 4 m distance and afterwards for each 0.1 second. Initially, when a person is identified, the *PI* is set to 0.5, which indicates that the robot is not sure what is going to happen. Each time a case lookup is performed and a matching case is found, the *PI* value is updated using a first order autoregressive filter ensuring that past values of *PI* is reflected in the update. The consequence is that the entire trajectory history is reflected in the current value of *PI*. If for example a matching case is found where *PI* = 1 and the current value for the person is *PI* = 0.5, then *PI* is updated to a larger value. If the looked up case has e.g. *PI* = 0, then the current *PI* is decreased from 0.5 to a lower value. Because the robot updates the database after the encounter of all new experiences, the system gradually learns how to decode trajectories into *PI* values between 0 and 1.

A weight function is introduced in order for the robot to pay more attention to the reactions of the detected person the closer he/she is to the robot [14]. Such weighted alteration has been implemented utilizing the behavioral zones as designated by Hall [15] and the weight as a function of the distance between the robot and the test person is illustrated in Fig. E.2.
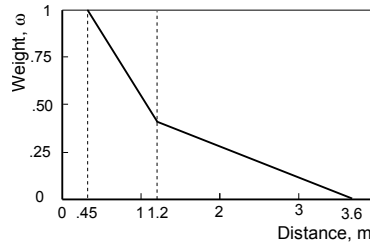
Figure E.2: The figure shows the weight ω as a function of the distance between the robot and the test person. ω is a weight used for updating the level of interest *PI*

Algorithm I outlines how *PI* is updated. The weight factor w ensures that observations close to the robot are given a higher impact on the database than observations further away. L is a learning rate that controls the temporal update of *PI*, i.e. how much *PI* should be updated due to a new observation. The closer L is to zero, the more conservative the system is and the less *PI* will be affected by new observations. In a progressive setup, L is close to 1 and consequently *PI* will adapt faster.

Algorithm I

```
if (Interested) then
    PI = PI + wL
    if PI > 1 then
        PI = 1
else if (Not Interested) then
    PI = PI - wL
    if PI < 0 then
        PI = 0
```

Human-aware Navigation

The human-aware navigation is described in detail in [14, 6], and is here briefly summarized.

For modeling the robots navigation system, a person centered potential field is introduced. The potential field is calculated by the weighted sum of four Gaussian distributions of which one is negated. The covariance of the distributions are used to adapt the potential field according to *PI*.

In the extreme case with $PI = 0$, the potential field will like look Fig. E.3a. Using the method of steepest descent, the robot will move towards the dark blue area, i.e. the robot will end up at the lowest part of the potential function, approximately 2 meters in front of the person. The other end of the scale with *PI=1*, is illustrated in Fig. E.3c. Here the person is interested in interaction, and as result the potential field is adapted such that the robot is allowed to enter the space right in front of him or her. In between Fig. E.3b is the default configuration of $PI = 0.5$ illustrated. In this case the robot is forced to encounter the person in approximate $45°$, according to [8, 17] studies.

(a) PI=0, person not seeking interaction   (b) PI=0.5, interaction unclear

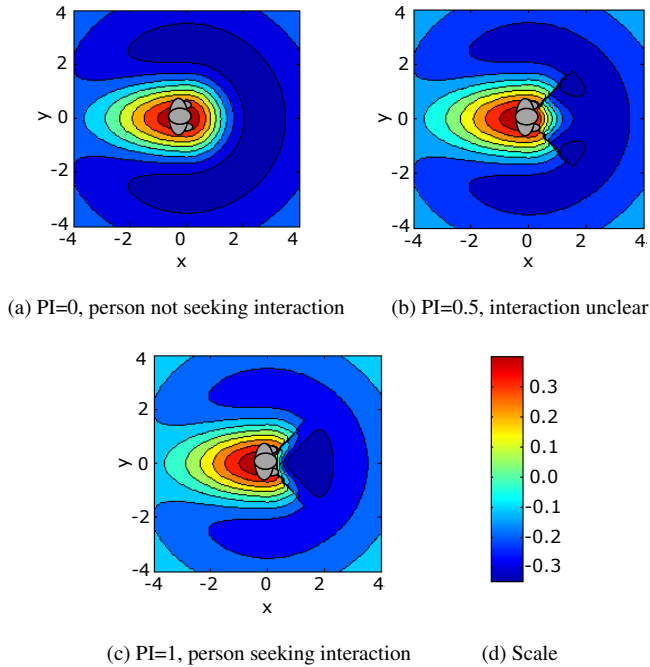(c) PI=1, person seeking interaction   (d) Scale

Figure E.3: Shape of the potential field. The scale for the potential field is plotted to the right. The robot seeks towards the point with the lowest value.

3   Experimental setup

The basis for the experiments was a robotic platform from FESTO called Robotino. The robot is equipped with a head having 126 red diodes (see Fig. E.4) which enables it to express different emotions. The robot is 1 meter high, and has mounted an URG-04LX line scan laser placed 35 cm above ground level, scanning 220 degrees in front of the robot. In order to get feedback from the test person, a simple on/off switch was placed just below the robot's head, 75 cm above ground level. The software framework Player [18] was installed on the platform and used for control of the robot and implementation of the CBR system.
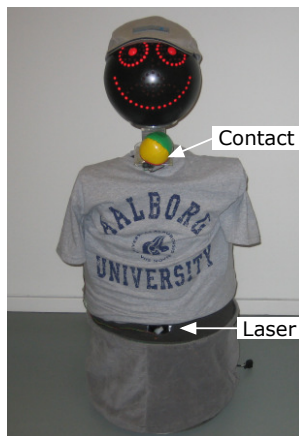

Figure E.4: The modified FESTO Robotino robotic platform.

To detect persons the robot rely on the scans from the laser range finder using the leg detection algorithm presented in [19]. The algorithm is further supported by a Kalman filter for tracking and estimation of the person pose [6].

Experiments. Evaluation of the proposed method were performed through two experiments:

In experiment 1, the objective was to see if estimation of *PI* can be obtained based on interaction experience from different persons. The test should illustrate the learning ability of the system, making it able to predict the outcome of the behavior for one person based on former experience from others. A total of five test persons were asked to approach or pass the robot using different motion patterns (see Fig. E.5). The starting and end point of each trajectory were selected randomly, while the specific route was left to the own devices of the test person. The random selection was designed so the test persons would end up interacting with the robot in 50% of the cases. In the other 50% of the cases, the test persons would pass the robot either to the left of the right without interacting. The output values (*PI*), the input values (position and pose), and the database were logged for later analysis.

In experiment 2, the objective was to test the adaptiveness of the method. The system

should be able to change its estimation of *PI* over time for related behavior patterns. A total of 36 test approaches were performed with one test person. The test person would start randomly in P1, P2 or P3 (see Fig. E.5) and end his trajectory in P5. In the first 18 encounters the test person would indicate interest, while in the last 18 encounters the person did not indicate interest. The output values (*PI*), and the input values (position and pose) were logged for later analysis.
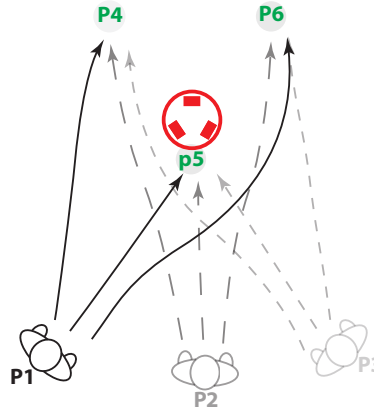

Figure E.5: Illustration of possible pathways around the robot during tests. A test person starts from either point P1, P2 or P3 and passes either P4, P5 or P6. If the trajectory goes through P5, an interaction occurs by handing over an object to the robot

The test took place in a foyer at the University campus with an open area of 7 times 10 meters. This allowed for easily repeated tests with no interference from other objects than the test persons. If the test persons passed an object to the robot, they would activate the on/off switch, which was recognized as interaction by the system. If the test person did not pass an object within 15 seconds or disappeared from the robot field of view, this was recognized as if no close interaction had occurred. The test persons were selected randomly among the students from campus. None had prior knowledge about the implementation of the system.

For all experiments, a learning rate of L = 0.3 was used. The result was a fairly conservative learning strategy, giving a clearer illustration of the development of *PI*.

4   Results

Experiment 1

The starting point of the CBR system is an empty database. As robot-person encounters get registered by the robot, the database gradually gets filled with cases. All values in the database after different stages of training are illustrated by four-dimensional plots in Fig. E.6. The first two dimensions are the dots in the 40 by 40 cm grid, which illustrate the position of the person in robot coordinate frame. At each position, the direction of the person is illustrated by a vector. The color of the vector denotes the value of *PI*. Blue

(a) After 1st test person

(b) After 3rd test person
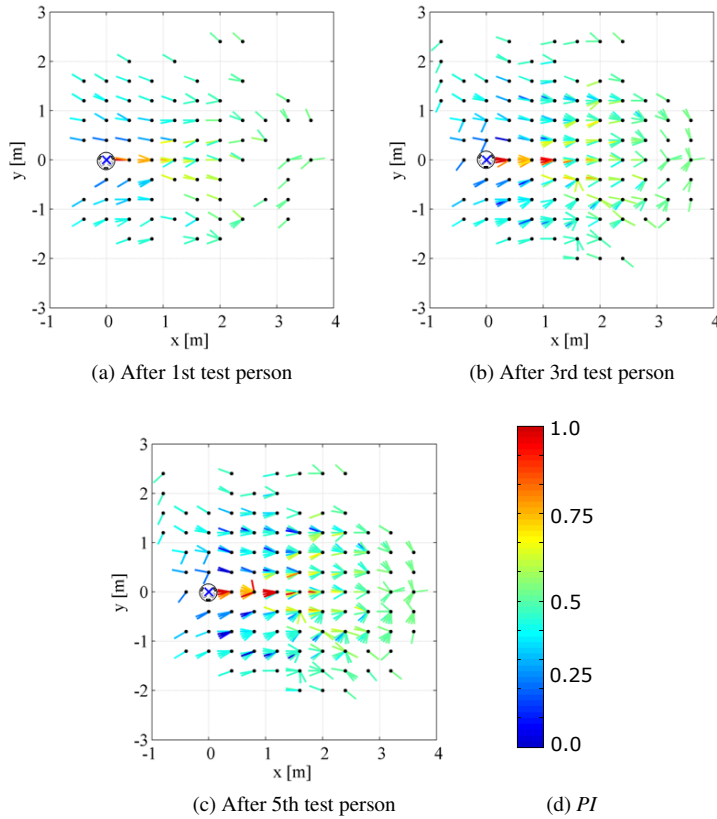
(c) After 5th test person

(d) *PI*

Figure E.6: The figures show the values stored in the CBR system after completion of the 1st, 3rd and 5th test person. The robot is located in the origin (0,0), since the measurements are in the robot coordinate frame. Each dot represents a position of the test person in the robot coordinate frame. The direction of the movement of the test person is represented by a vector, while the level (*PI*) is indicated by the color range.

color indicates that the person does not seek interaction, while the red color indicates that the person seeks interaction, i.e. $PI = 0$ and $PI = 1$ correspondingly. A green vector indicates $PI = 0.5$.

Fig. E.6(a-c) illustrates the development of the database for the 5 test persons. Fig. E.6a shows all cases after one test person, Fig. E.6b after 3 test persons and finally Fig. E.6c shows all cases (around 500) after 5 test persons.

In Fig. E.7, the probability indicator *PI* for one specific encounter is plotted as a function of time. This is done for test person 1, 3 and 5. *PI* is plotted twice for each test person; once for a randomly selected encounter where the test person is interacting with the robot, and once for a random selected encounter where the test person passes the robot without interacting. For the first test person, it can be seen that *PI* increases to a maximum around 0.65 for an encounter ending with a interaction. For the same test person, it can be

seen that *PI* drops to a minimum of 0.48 for an encounter where no interaction occurs. For the 3rd test person, *PI* ends with a value around 0.9 for an encounter where interaction has occurred, while *PI* = 0.35 for an encounter where no interaction has occurred. For the last test person, *PI* rapidly increases to a value around 1 for an encounter where interaction occurs, and has *PI* around 0.18 when the person does not interact. Each run takes between 2 and 4 seconds depending on the velocity of the user. Changes in *PI* can be seen in first quartile of each run, while maximum (or minimum) is not reached before fourth quartile.
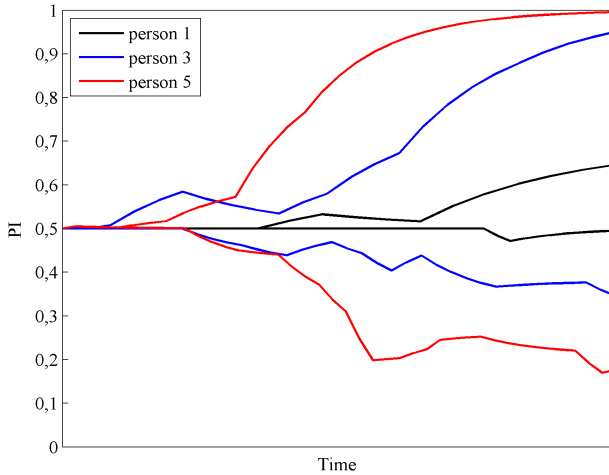
Figure E.7: The figure shows *PI* as a function of time for three test persons. For each test person, *PI* is plotted for an encounter where interacting occurs and for an encounter where no interaction occurs.

Experiment 2

This test should show that the estimation of *PI* can adapt over time to different interaction outcome. Stored values for *PI* in the database have been calculated as an average for three areas (see Fig. E.8) after each encounter:

- The frontal area of the robot (area 1)

- The small area including the frontal area (area 2)

- All cases stored in the database (area 3)

Fig. E.9 shows the development of *PI* for 36 person encounters for one person.

As can be seen from Fig. E.9, the mean value of *PI* increases for the first 18 encounters - especially for the frontal and small area having a maximum value at 0.9 and 0.85 correspondingly, but less for the mean for all cases (around 0.65). After 18 encounters, *PI* drops for all areas. Most notable, the frontal area drops to a minimum of 0.39 after 36

Figure E.8: The figure is a snapshot of the database after the second experiment was done. It shows how the mean value for *PI* is calculated for three areas: 1) the frontal area, 2) the small area and 3) for all cases. The development of the mean values over time for all three areas are illustrated in Fig. E.9
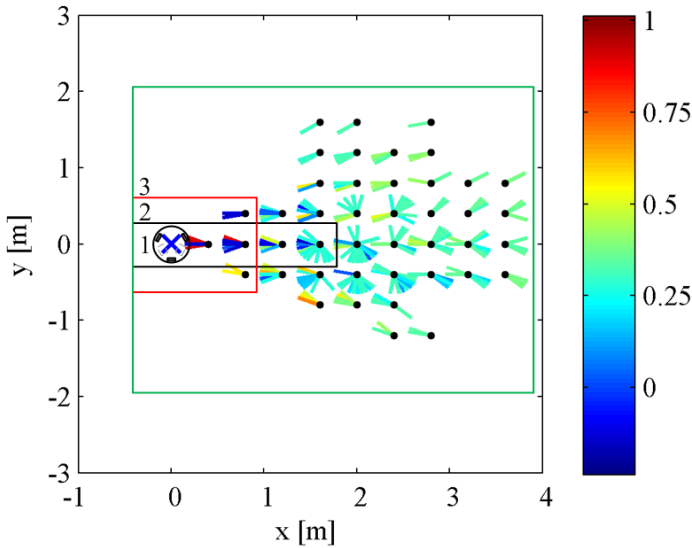
encounters. Although *PI* also drops for the small area, it does not fall to a value less than 0.42 which is approximate the same as for all cases 0.43 which has the smallest descent.

5   Discussion

The results demonstrate that using pose and position as input to a CBR system, it is possible to evaluate the behavior of a person adequately for human aware navigation system.

As can be seen in Fig. E.6(a-c), the number of plotted vectors increases as more and more cases are stored in the database. This shows the development of the CBR system, and clearly illustrates how the CBR system gradually learns from each person encounter. The number of new cases added to the database is highest in the beginning of the training period where few (or no) case matches are found. As the training continues, the number of new cases added to the database is reduced as matching cases are found and therefore causes an update. The growth of the database when training depends on the resolution of the selected case features and the time and complexity of the training scenario. Based on current experiments there are no indications that the size of the database will grow inappropriately. The system could be enhanced by incorporating information about the environment or the interaction context thereby accommodation more realistic cluttered environments. In Fig. E.6(a-c), it can be seen that the vectors are gradually turning from
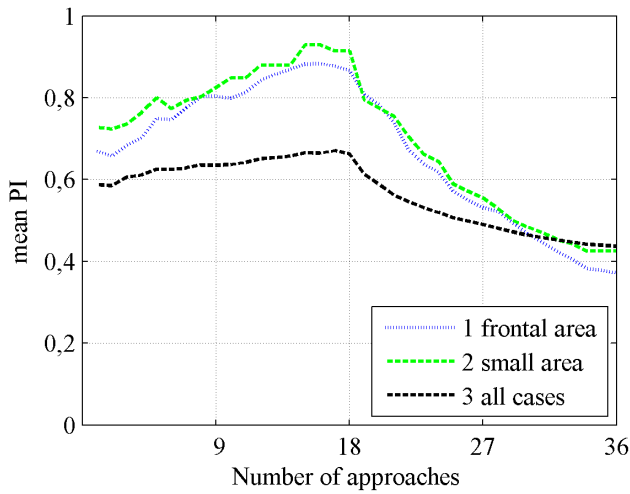
Figure E.9: Illustrates how the mean of *PI* evolves for the three areas indicated in Fig. E.8 for 36 person encounters for one test person.

either red or blue to green as distance increases. This is expected, because the weight with which *PI* gets updated, is as a function of the distance between the robot and test person (see Fig. E.2). This is reasonable as it gets more difficult to assess human interest at long distance.

In all three figures, the vectors in the red color range (high *PI*) are dominant when the direction of the person is towards the robot, while there is an overweight of vectors not pointing directly towards the robot in the blue color range (low *PI*). This reflects that a person seeking interaction has the trajectory moving towards the robot.

Fig. E.7 shows the development of *PI* over time when one test person changes behavior. It can be seen how maximum and minimum values for *PI* increases as more test persons have been evaluated. After evaluating one test person, the robot has gathered very little interaction experience, and thereby has difficulties in determining the correspondence between motion pattern and end result - hence *PI* stays close to 0.5. After the third test person has been evaluated, the robot now has gathered more cases and therefore has improved estimating the outcome of the behavior. For the last test person, the robot is clearly capable of determining what will be the outcome of the encounter.

Fig. E.9 shows the development of *PI* over time. It can be seen that *PI* changes more for the frontal area and small area than for all other cases. This is because most cases will be close to 0.5 at large distances, which affects the mean result when looking at all cases. Furthermore, most encounters goes through the frontal area thereby having the highest number of updates of *PI*. Fig. E.9 illustrates that the database quickly starts to adapt to the new environment, when the test person changes behavior to no interaction after the first 18 encounters.

By coupling the CBR system with navigation, the result is an adaptive robot behavior

respecting the personal zones depending on the person's willingness to interact - a step forward from previous studies [12].

6 Conclusion

In this paper, we have described an adaptive system for natural interaction between mobile robots and humans. The system forms a basis for human aware robot navigation respecting the person's social spaces.

Validation of the system has been conducted through two experiments in a real world setting. The first test shows that the Case Based Reasoning (CBR) system gradually learns from interaction experience. The experiment also shows how motion patterns from different people can be stored and generalized in order to predict the outcome of a new human-robot encounter.

Second experiment shows how the estimated outcome of the interaction adapts to changes of the behavior of a test person. It is illustrated how the same motion pattern can be interpreted differently after a period of training.

An interesting prospect for future work is elaborations of the CBR system, e.g. doing experiments with a variable learning rate and additional features in the database.

The presented system is a step forward in creating social intelligent robots, capable of navigating in an everyday environment and interacting with human-beings by understanding their interest and intention. In a long perspective, the results could be applied in service or assistive robots in e.g. health care systems.

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Paper E

An Adaptive Robot Game

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Abstract

The goal of this paper is to describe an adaptive robot game, which motivates elderly people to do a regular amount of physical exercise while playing. One of the advantages of robot based games is that the initiative to play can be taken autonomously by the robot. In this case, the goal is to improve the mental and physical state of the user by playing a physical game with the robot. Ideally, a robot game should be simple to learn but difficult to master, providing an appropriate degree of challenge for players with different skills. In order to achieve that, the robot should be able to adapt to the behavior of the interacting person. This paper presents a simple ball game between a single player and a mobile robot platform. The algorithm has been validated using simulation and real world experiments.

1 Introduction

Based on the demographic development in most western countries, it has been predicted that the number of people with mental and/or physical disabilities will increase while the amount of people to take care of them will decrease [1], [2]. Digital games hold a significant promise for enhancing the lives of seniors, potentially improving their mental and physical wellbeing, enhancing their social connectedness, and generally offering an enjoyable way of spending time [3]. It has been shown that mental and physical health can be improved through a small amount of physical exercises [4], [5], and e.g. Nintendo Wii has been suggested as a means to increase physical activity among elderly [6], [7].

In this paper we introduce a physical game which is facilitated and initiated using a mobile robot. A principal question is how to design a robot based game which ensures engagement of the participating players. Many known games are derived from a pursuit-evasion scenario e.g. the child games robbers and cops and the game of tag [8]. In this paper, we describe a simple pursuit and evasion problem played between a single player and a mobile robot. The robot will initiate the game by searching for a potential player in a room and hand over a ball. After that, the player should try to hand back the ball, while the robot should try to avoid receiving the ball.

Motivating elderly to move physically by playing a game is related to Persuasive technology which is defined as technology designed to change attitudes or behaviors of the users through persuasion and social influence, but not through coercion [9]. A similar term is Captology, which is an acronym for computers as persuasive technologies [10]. This term however, is not used as often as Persuasive Technology or Persuasive Design which is the term we will use here. Successful games are often characterized using the concept Flow, as proposed by Csíkszentmihály [11]. Flow is a mental state which can occur when there is an appropriate balance between challenge and skill. As the cognitive and physical capabilities of the users are expected to vary from each person, the robot should adapt the difficulty of the game to the end user.

The goal is to motivate elderly to do physical exercises in a fun and social manner by facilitating and initiating a simple physical game using a robot. The robot automatically initiates the game by autonomously approaching the user. This is a difference from using video games like Nintendo Wii, which facilitate games but does not itself initiate a game.
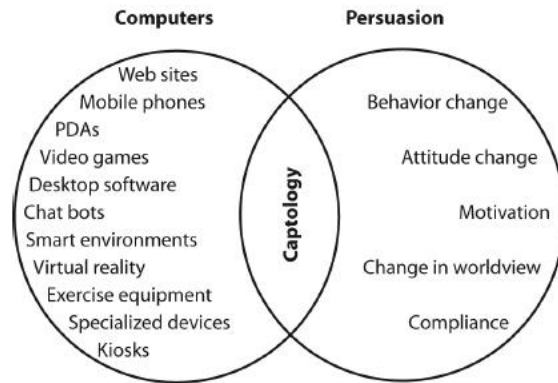
Figure F.1: Illustration of how Captology (or PD) is defined as an overlap between computers and persuasion

In this paper, we first outline the theory about persuasive design and the concept of flow. Next we explain the game algorithm, and demonstrate how it works when implemented in a physical robot.

2   Theory

The fundamental concept of Persuasive Design (PD) is persuasion, which is defined by Fogg as an attempt to change attitudes or behaviors or both (without using coercion or deception) [9]. The theoretic background is based on Computer Science and Social Psychology and has been developed mainly through empiric studies. Results from HCI, has shown that e.g. a computer can act as a social character, because it has some characteristics which make us behave as if it was a real person. We know it is piece of a technology, but can still feel happy about it or get angry with it [12]. According to Fogg, this effect is amplified if the system shows social signals we know from interaction with other people, and even more so if the system has a personality the reminds us of our own.

Figure F.1 shows how PD has been defined as a field where persuasion and computer technology overlap. The model was introduced in 1997 and has been continuously enhanced as new technologies emerge [10]. The focus of the theory is technology designed with persuasive intention.

We here extend the list of technologies in Figure F.1 to also include robots. The robot should act a social character which invites the users to play a physical game. By doing this, the user will be more mentally and physically active than would be the case without the robot. In order for people to be motivated to play the game it should appeal to the specific user. Ideally the player should be in the state of flow while playing, being a feeling characterized by great absorption and engagement as proposed by Csíkszentmihály [11]. As illustrated in Figure F.2, flow cannot occur if the task is too easy or too difficult.

In the state T1, your skills are not developed, but the challenge is not impossible. The difficulty of the challenge is in an appropriate relation to your (undeveloped) skills, and
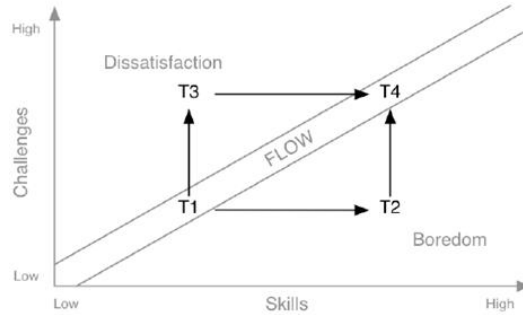
Figure F.2: Illustration of the relation between skill and challenge. In state T1 and T4, there is a balance between skill and challenge and the player is in the state of flow. In state T2 and T3 there is no balance, and the player is either bored or frustrated, correspondingly

you are in a state of flow. T2 is the situation where you develop your skills to a level where the challenge becomes too easy and therefore boring. In T3, the difficulty of the challenge is higher than your skills. This leads to discontent and frustration. Common for the state T2 and T3 is that in the long run, they are unsatisfying. In order to enter the state of flow, the difficulty of the challenge has to be changed or you have to improve your skills. T4 is also a flow state, but in a more complex situation than in T1. It is not a stable state because your skills will keep developing [13].

3   Implementation of the game

The game presented here, is based on a simplified pursuit and evasion scenario with a single pursuer (a human player) and a evader (a mobile robot). The player should try to hand over a ball to the robot, while the robot should try to avoid receiving the ball. Depending on the skill of the player, the robot should make it more or less difficult to hand the ball back. During a game, the robot can be in the following states:

- Roaming. If no player is detected, the robots should search for a player by moving randomly around until a person is spotted.

- Approach. When a player is detected, the robot invites to play a game by approaching the player from the front.

- Avoid. When the player has accepted to play a game by picking up the ball from the robot, the robot initially moves fast backwards away from the player for 3 seconds.

- Evaluating. The robot keeps avoiding the player with a distance and velocity that corresponds to the estimated skill of the player. When the ball has been handed back, the game is complete and the robot will go to the state Avoid and thereafter Roaming.

A more detailed outline of the game algorithm is sketched in Algorithm 1.

Algorithm 1

Main()

1: **loop**
2:     Roam()
3:     Approach()
4:     **if** Ball just picked up **then**
5:         Avoid()
6:     **end if**
7:     GameResult = Evaluate()
8:     UpdateCbrDatabase(GameResult)
9: **end loop**

Roam()

10: **while** Person not detected **do**
11:     drive randomly around
12: **end while**

Approach()

13: **while** Ball is on the robot **do**
14:     Approach player to invite to a game
15: **end while**

Avoid()

16: Avoid player for 3 seconds

Evaluate()

17: PSI = 0.5
18: **while** Time not expired **do**
19:     Move according to PSI value
20:     Update PSI using CBR database
21:     **if** Ball returned to robot **then**
22:         Avoid()
23:         **return** Positive
24:     **end if**
25: **end while**
26: **return** Negative

Player Skill Indication (PSI)

In order for the robot to adapt the challenge to the individual player, is should have a have an estimate of the player's skill but also information about the specific player's style of playing, i.e. the physical behavior pattern of the player.

The skill of a player is annotated using the parameter *PSI*, which means Player Skill Indication. $PSI \in [0; 1]$ is a fuzzy predicate, which gives an indication of the skill of the current player. When $PSI \approx 1$, the robot believes the player is skilled, and that the player is likely to complete a game within a fixed evaluation period. When *PSI* is close or equal to 0, the robot thinks the player is less skilled, and thereby less likely to complete the game within the time period. *PSI* is updated continuously throughout the game (line 20 in Algorithm I) , so when a specific player gets better at playing *PSI* will increase.

The rate by which *PSI* increases or decreases depends not only on the skills of the player, but is a function of the learning rate parameter, L. The learning rate L is set high if you the game should adapt quickly to changes in the player's skill, but low otherwise.

Learning using Case Based Reasoning (CBR)

The robot should learn about the specific player's style of playing with the robot, and therefore the skill is associated with the physical spatio-temporal behavior of the person. To incorporate the ability to learn the behavior pattern of the player, we have selected to use Case Based Reasoning (CBR). CBR allows recalling and interpreting past experiences, as well as generating new cases to represent knowledge from new experiences [14]. CBR has been proven successful solving spatial-temporal problems in robotics in [15] and is characterized by its adaptiveness, making it well suited for implementing an adaptive behavior on a human interactive robot. The CBR system is basically a database describing each encounter. Specifying a case in CBR is a question of determining a distinct and representative set of features, in our case *PSI*, position, pose and the id of the person. While playing, cases are continuously inserted, retrieved and updated. In other words, the robot adjusts the challenge to how the player moves around the robot when playing.

The behavior of the player is evaluated through a continuous registration of the players position and orientation of the body, which is inferred from 2D laser range measurements as explained in [16]. To detect persons the robot rely on the scans from the laser range finder using the leg detection algorithm presented in [17]. The algorithm is further supported by a Kalman filter for tracking and estimation of the person pose [16]. A more detailed description of the CBR database implementation can be found in [18].

Adaptive Robot Motion

The robot's navigation system is modeled using a person centered potential field, where the robot seeks towards the lowest values using a gradient descent. The potential field is calculated by the weighted sum of four Gaussian distributions of which one is negated. The covariance of the distributions are used to adapt the potential field according to *PSI*. When the player is inexperienced, the *PSI* values registered for a player will be closer to 0 and the robot will try to approach the player so he/she can hand over a ball to the robot. In the extreme case with $PSI = 0$ (an unskilled player), the potential field will like look
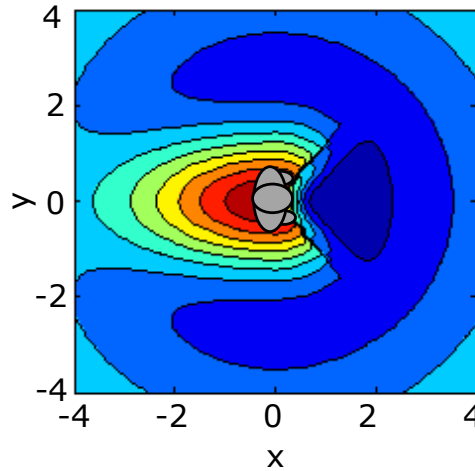
Figure F.3: The player's skill $PSI = 0$, and the robot will seek the dark blue area in front of the player

Figure F.3, and the robot will enter the dark blue space right in front of the player. On the other hand, if the player is skilled, PSI will be closer to 1 and potential file will look like illustrated in Figure F.4. The robot will try to avoid the player by moving towards the dark blue area away from the player, making it more difficult for the player to hand over the ball.

Since the potential field is person centered, it moves with the player. If e.g. a skilled player starts moving towards the robot, the robot will eventually be in the yellow or red area in front of the player. The result is that the robot will start moving backwards towards the dark blue area, thus avoiding the player.

4   Experiments

A series of experiments have been designed to demonstrate the following features of the implemented system:

1. The learning capability of the CBR database. The generation of cases in the database.

2. Adaptiveness of the system. How the CBR database adapts to the skill of a player.

3. The estimate of the PSI of a player.

4. Adaptive Navigation. How the motion of the robot depends on the player skill.

5. Effect of Learning Rate. How the learning rate affect the PSI.
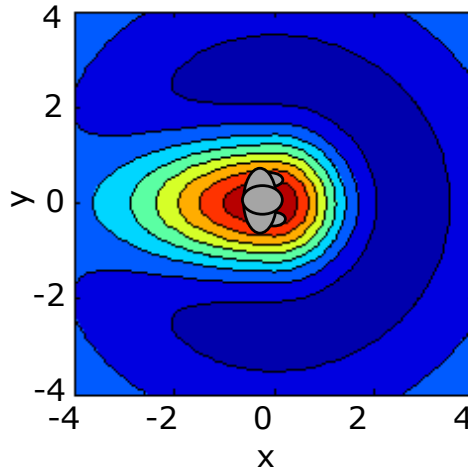
Figure F.4: The player's skill $PSI = 1$, and the robot will seek the dark blue area a bit away from the player

The learning capability of the CBR database.

This experiment should show that cases are actually created in the database and that these cases reflect the behavior of the player. To avoid a huge amount of repetitive playing time, simulations using the Player/Stage environment have been used to train the database. Using an empty CBR database, first the database is trained by a skilled player. Afterwards, a new database is created which is trained by an unskilled player.

Adaptiveness of the System

This experiment have been done using a combination of simulations and real world experiments. The two databases from the former experiment are used in a real world setting, where a test person is playing against the system. To show the system is capable of adapting to a new situation, an unskilled player plays with the system trained for a skilled player and vice versa. The average value of PSI in the whole database is logged continuously during the experiments.

Estimate of PSI

To show that the robot is able to estimate the player PSI, and hereafter adapt the motion accordingly, the trained databases are used again in the real world setting. This time the motion of both the person and the robot are recorded.
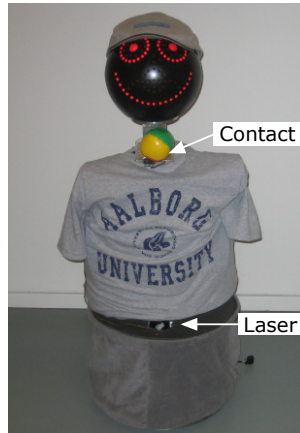
Figure F.5: The modified FESTO Robotino robotic platform.

Effect of Learning Rate

A central parameter of the game algorithm, is the learning rate L which is a numeric value in the interval $0 - 100$ used to control how fast *PSI* should adjust the estimate of the player's skill *PSI*. A simulation has been designed, such that in the first 10 games, the player needs 4 evaluation periods before he/she manages to hand the ball back to the robot. The effect should be that most of the cases in the database have a relatively low *PSI* value reflecting an unskilled player. In the last 40 games, the simulation has been changed so the player hands back the ball to the robot within one evaluation period representing the behavior of a skilled player. To demonstrate the effect of changing the learning rate, the same simulation setup has been tried with the learning rate set to $0, 20, 40, 60, 80$ and 100.

The robot platform

The robotic platform, which forms the basis of the experiment, is shown in Figure F.5. The robot is FESTO and is called Robotino. The robot is equipped with a head having 126 red diodes (see Figure F.5) which enables it to express different emotions. The robot is 1 meter high, and has mounted an URG-04LX line scan laser placed $35cm$ above ground level, scanning 220 degrees in front of the robot. In order to get feedback from the test person and find out when the robot has the ball, a cup with an on/off switch in the bottom, has been placed just below the robot's head, $75cm$ above ground level. The software framework Player [19] is installed on the platform and used for control of the robot and implementation of the CBR system.
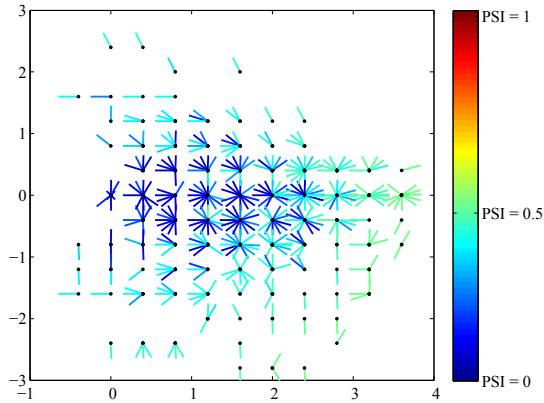
Figure F.6: A plot of the trained CBR database for an unskilled player. Each vector represents a case in the database using the features pose and position. The color of the vector denotes the *PSI* value using the color scale to the right. The robot is positioned in $(0, 0)$

5 Results

Trag the CBR System

Figure F.6 shows a plot of the CBR database, when the robot has been trained by an unskilled player. The position of the robot is $(0, 0)$. Each case in the database is represented by a short vector extending from a black dot in the figure. The color of the vector represents the value of *PSI* for the corresponding case. The pose and position of the player is represented by the corresponding position of the dot and angle of the vector. In Figure F.6, most vectors are in the color span between blue and green which represents *PSI* values between $0 - 0.5$, and the average of all *PSI* values is 0.25. This *PSI* range is as expected for an unskilled player, and it shows that the CBR system is capable of being trained for an unskilled player. Furthermore it can be seen that the database the is more densely populated closer to the robot. This is also expected, since a player will start off at a random direction away from the robot and will always move towards a point just in front of the robot.

Similar results have been obtained, when training with a skilled player. Here, most vectors are in the color span between green and red which represent *PSI* values between $0.5 - 1$. This is expected for a skilled player and the average *PSI* of the whole database is 0.74

Adaptiveness of the System

Using the trained database in Figure F.6, a skilled player is set to play in the real world. This makes the CBR database turn into the one shown in Figure F.7. It can be seen that the database has adapted to the player's skill, and has started to contain higher *PSI* values.

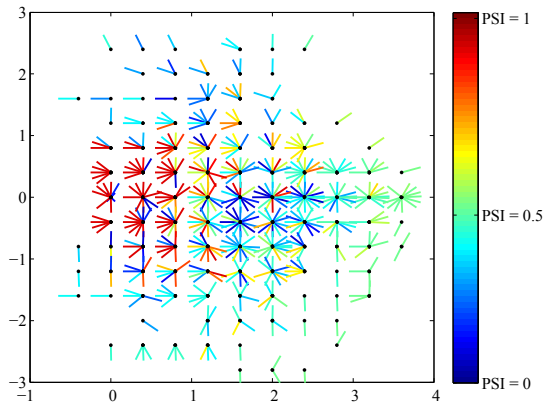Figure F.7: A plot of the trained CBR database in Figure F.6 after the player has started to become good. The robot is positioned in $(0, 0)$.

Especially in the areas close to the robot, the *PSI* values have changed which is expected as most case updates happens here.

In Figure F.8 the development of the average value of *PSI* in the database can be seen. The value is saved for each lookup in the database, i.e. each time Line 20 in Algorithm I is passed. Initially the value is slightly less than 0.5. After the database has been trained by an unskilled player for a while (after around 12000 iterations) the average value has stabilized around $PSI = 0.25$. Now a skilled player starts playing, and it can be seen that the average value starts to increase rapidly, as expected. The noise on the figure is caused by individual trajectory differences.

A similar result has been obtained when starting with the system, which was trained by a skilled player, and played in the real world by a unskilled player. Here the database values are adapted from relative high values to lower values. This could be the case if a player starts to have more severe physical disabilities caused by e.g. a stroke.

Adaptive Navigation

Figure F.9 shows the trajectory of a person and for the robot, for a game where the robot has been trained by a skilled player. The person starts from the right side, and goes to pick up the ball. Hereafter the robot and person moves away from each other. When the game starts, the robot approaches slowly because it is far away. But as soon the person comes too close (when the trajectory is orange), the robot starts to move away. The player then tries to cheat the robot by moving sideways. This is a behavior the robot has not learned yet, and therefore it lets the person approach a bit more.

Figure F.10 shows the trajectory of a person and a robot for a game where the robot has been trained by an unskilled player. The person starts from the lower right corner, and goes to pick up the ball. Hereafter the robot and person moves away from each other. Towards the end of the game, the robot approaches the person to make it easier for the player to hand back the ball. These two experiments show that the system is able to
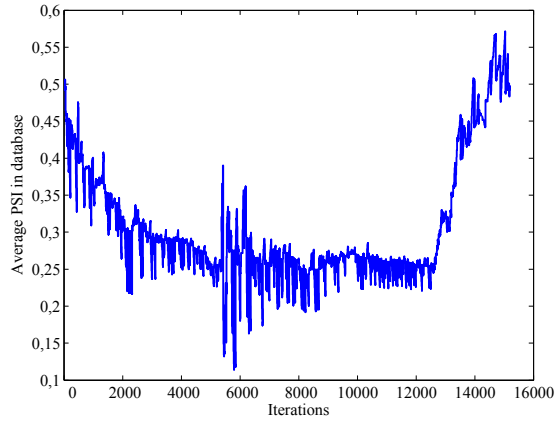
Figure F.8: The development of the average value of all *PSI* in the database after each iteration (each look up in the database). Initially *PSI* is around 0.5 and the game is played by an unskilled player. The player slowly improves his skills and the average value of *PSI* increases correspondingly.
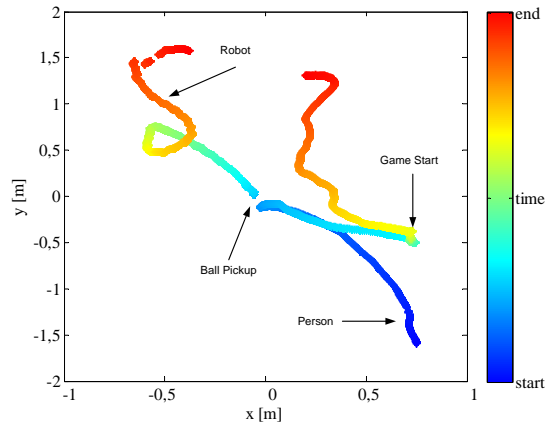
Figure F.9: The trajectory of a person and the robot for a game, where the robot has been trained by a skilled player. The color of the trajectory defines the time. Blue is the beginning and red is the end of the game.
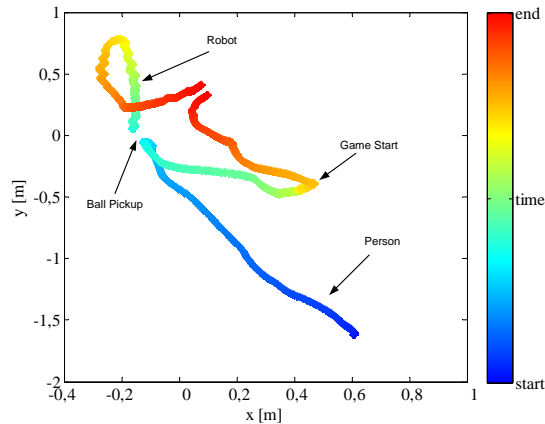
Figure F.10: The trajectory of a person and the robot for a game, where the robot has been trained by an unskilled player. The color of the trajectory defines the time. Blue is the beginning and red is the end.

estimate the *PSI* correctly and navigate accordingly.

Effect of Learning Rate

Figure F.11, shows the *PSI* values in the database for simulation set of 50 games with one player using a learning rate set to $L = 40$. In total, 249 cases are stored in the CBR database. Because the cases in the database are stored in the order they were observed, two consecutive cases do not necessarily have anything to do with each other and large fluctuations occur. A moving average gives an overview over what is happening, and as can be seen from the figure, the values of *PSI* decreases due to a gradually better trained database. Then, around case 100, there is a sudden increase in *PSI*. This corresponds to the time when the player changes behavior from being unskilled to skilled and manage to hand the ball back in one evaluation period.

Table F.1[1], shows the same scenario with a learning rate set to $L = \{0, 20, 40, 60, 80, 100\}$. As L increases, the deviation also increases which is expected. When the learning rate is 100, *PSI* is adjusted with every little change of player behavior. The fluctuations of *PSI* becomes high, which makes the game algorithm too varying to be usable. On the other hand, *PSI* stays constant at 0.5 when the learning rate is equal to 0. The robot simply does not learn from its experience, and the game algorithm will never adapt the challenge to the player. The development of *PSI* using a learning rate of 0 and 100 is illustrated in Figure F.12. It has been chosen to use a learning rate of $L = 40$ for all experiments, since this value gives an adequate balance of adaptability and stability.

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[1]This reference was wrong in the original paper. It has been corrected here.

Figure F.11: Shows the development of the player skill *PSI* in a simulated set of 50 games with one player using a learning rate on $L = 40$

Figure F.12: Shows the development of the player skill *PSI* in a simulated set of 50 games with one player using a learning rate on $L = 0$ and $L = 100$

L	n	σ
0	273	0.00
20	248	0.18
40	249	0.23
60	259	0.27
80	230	0.29
100	251	0.38

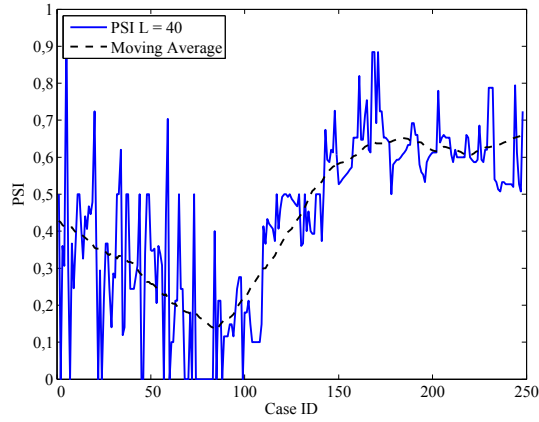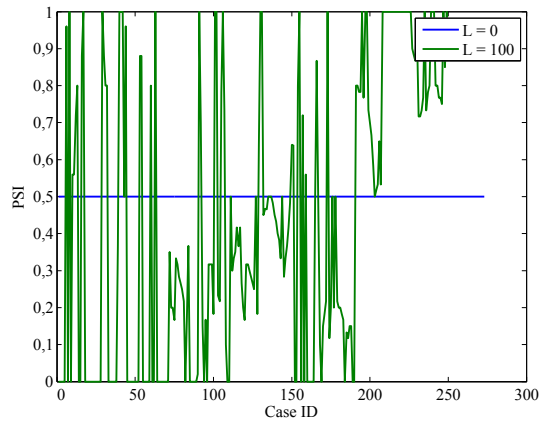Table F.1: The table shows the development of *PSI* for different learning rates (L) with respect to the number of cases in the database (n) and the standard deviation σ

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6   Conclusion

In this paper, we have presented the concept of a robot based game. The function of the game is to increase the health of the players by motivating them to do a regular amount of physical exercise in a fun and social manner. The fact that the robot autonomously initiates the game, is a major difference from similar types of technology driven approaches e.g. using Nintendo Wii which has been successfully applied in a nursing home setting. The robot game is based on a simplified pursuit and evasion scenario, where the player should try to hand over a ball to the robot while the robot should try to avoid receiving the ball. Changing the behavior of the user through the use of technology is related to the term Persuasive Technology which is explained in the first section of the paper. The term Flow is often used to describe an ideal user experience in games. As described, one of the primary requisites of Flow is to provide an appropriate relation between game challenge and the user's skills. Based on this fact, a game algorithm has been designed and it is outlined how the algorithm works. The algorithm is implemented in a physical robot and the game is validated in simulation and through a practical lab experiment setup. Trajectories of the player and the robot in the lab experiment are documented along with plots of the CBR database which form the basis of the learning algorithm. The experiments document the learning capability of the CBR database and the adaptiveness of the system. It also shows how the system estimates the skill of the player and how it adapts depending on the learning rate parameter.

The next step will be to do a real world experiment at an activity center for elderly with the goal of measuring the user feedback and experience. Also we will work on enhancing the game, so the robot game is based on multiple players which will strengthen the social aspect of the game.

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Video 2

Robot Games for Elderly

Søren Tranberg Hansen

Abstract

This video presents a study on how a simple physical game based on a mobile robot can be used as a persuasive tool for promoting physical activity in a rehabilitation scenario for elderly with mobility problems. The goal of the game is to take a ball the robot, and afterwards try to hand it back while the robot moves. The robot records the behavior patterns of each individual player and gradually adapts the challenge of the game to the skill of the player. The game was investigated in two independent field studies and the primary goal was to observe how the robot adapts to players with different mobility problems and secondly obtain knowledge about their game play patterns and get ideas about future improvements of the game. The video shows different examples of how the elderly would play with the robot and illustrates the variety of play styles.

1   Description

There has been a lot of research on robot assisted therapy, but movement recovery based on robots still mainly works at the level of repetitive, voluntary movement attempts by the patient and mechanical assistance by the robot [1]. Motivating users to move physically and act socially by playing a game with a mobile robot is not well investigated. Based on the demographic development in most western countries, it has been predicted that the number of people with mental and/or physical disabilities will increase while the amount of people to take care of them will decrease. Digital games hold a significant promise for enhancing the lives of seniors, potentially improving their mental and physical well-being, enhancing their social connectedness, and generally offering an enjoyable way of spending time [2]. It has been shown that mental and physical health can be improved through a small amount of physical exercises, and e.g. Nintendo Wii has been suggested as way to increase physical activity among elderly. Digital games have been a part of the evolution of computers, but are gradually moving from the pure virtual domain into the physical world with the introduction of products like Nintendo Wii, Microsoft Kinect, Sony's EyeToy and robot toys like Pleo and AIBO. This creates new possibilities for combining entertainment and physical activity. The physical and tangible nature of autonomous robots catalyzes physical interaction, but to our knowledge motivating users to move physically by playing game with a mobile robot is a new approach. This video presents a study on how a simple physical game based on a mobile robot can be used as a persuasive tool for promoting physical and social activity in a rehabilitation scenario for elderly with mobility problems. The game was investigated in a nursing home and one in a rehabilitation centre for elderly. The primary goal of the study was to observe how the robot would adapt the game challenge to players with different mobility problems and secondly obtain knowledge about their game play patterns and to get ideas about future improvements of the game. The video illustrates different examples of how the elderly play with the robot although they use assistive tools like crutches, walkers or wheelchairs and displays the variety of different play styles.

References

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Paper F

An Adaptive Robot Game for Elderly - A Field Study

Søren Tranberg Hansen, Thomas Bak

Abstract

This paper presents a study on how a physical ball game based on a mobile robot can be used as a tool for promoting physical activity for elderly. The game algorithm is based on Case Based Reasoning and adjusts the game challenge to the player's mobility skills by registering the spatio-temporal behaviour of the player using an on board laser scanner. We have investigated the adaptiveness of the game algorithm in field studies with two groups of elderly; one group attending a rehabilitation centre and one group living in a nursing home. The study shows that the game algorithm adjusts adequately to the two groups of players, but fails when players show non-standard behaviour.

1 Introduction

Traditionally, training of elderly with mobility problems is performed by e.g. physiotherapists who instruct a number of people (5-10) at the same time. Training is often based on exercises where the participants stand or sit on a chair and do different movements with their arms and legs while listening to music (See Fig. H.1). It is often difficult for the therapists to motivate the elderly to train hard and long enough, making it interesting to experiment with new types of tools.

Figure H.1: Traditional training while sitting down.

Tapus [1] has shown a pilot study in which individuals suffering from dementia and/or other cognitive impairments should play cognitive game based on a sociable mobile robot, and Fasola describes the design and implementation of a socially assistive mobile robot that monitors and motivates a user during a seated arm exercise scenario [2]. In [3], a robot that provides motivation and support for cardiac patients who must perform painful breathing exercises is described. In [4] we have investigated a related game for elderly, and the studies revealed a low degree of rejection and showed how the game potentially could be used to train e.g. the postural control of elderly. To our knowledge, the use of a mobile robot as being the basis of an adaptive physical game which motivates for physical action has not yet been investigated.

In this paper, we investigate how a game based on a mobile robot can be used to motivate elderly to move physically, as it has been shown that the physical and tangible nature of autonomous robots catalyses interaction even when their physical aspect is obviously different from that of a human being [5].

The game is a single player pursuit and evasion game and the goal for the player is to try to hand over a ball to the robot while the robot should try to avoid receiving the ball. The game is an elaboration of studies conducted in [6, 4]. In order for people to be motivated to play there should be a correspondence between the skills of the player and the challenge of the game according to the theory of Flow [7]. In this paper, player skill is inferred from the level of mobility, i.e. the ability for a player to move around freely when playing. Player skill is estimated using spatio-temporal information from laser scanner images, and the hypothesis is that an adaptive game algorithm based on case-based reasoning can be used to adjust the challenge of the robot game.

This paper focuses on the technical functionality of the game algorithm and how it adapts to the participants behaviour, i.e. measuring the subjective player response or the physiological benefits of playing the game are considered outside the scope. First we describe how the player skill is associated with the spatio temporal behaviour of the player. Secondly we describe how the algorithm can learn from player behaviour and adapt the challenge of the game by changing the robot's navigation patterns. Finally we describe how the game is evaluated by elderly users based on experimental work at a rehabilitation centre and a nursing home.

2 The Robot System

The robotic platform which has been used is shown in Figure H.2 and is developed at Aalborg University. It is based on a commercial platform from FESTO equipped with a head having 126 red diodes (LEDs) which enables it to express different emotions (see Figure H.3). The robot is 1 meter high, and has mounted an URG-04LX line scan laser placed $35cm$ above ground level, scanning 220 degrees in front of the robot. To detect persons, the robot rely on the scans from the laser range finder using the leg detection algorithm presented in [8]. A contact is placed in a basket just below the robot's head so the robot can detect when a ball is handed over to it. Evaluation of the physical design of the robot is outside scope of the experiment, but since the experiments were conducted in December 2010, the robot was dressed as Santa Claus.

Player Skill Indication (*PSI*)

Player skill is inferred from the level of mobility, i.e. the ability to move freely in two dimensions. In order for the robot to adapt the game challenge to the individual player, is should therefore have an estimate of the player's mobility. This estimate is derived on the basis of the spatio-temporal behaviour patterns of the person, i.e. how the person moves physically in relation to the robot. In order to ensure robustness, we have selected to rely on the features position and pose although more advanced features could be incorporated.

The skill of a player is annotated using the parameter Player Skill Indication (*PSI*). $PSI \in [0; 1]$ is a fuzzy predicate, which represents what the robot believes is the skill of the current player. When $PSI \approx 1$, the robot believes the player is skilled, i.e. that the player is likely to complete a game within a fixed evaluation period T_1. When PSI is close or equal to 0, the robot thinks the player is less skilled, and thereby less likely to complete the game within the time T_1.

The behaviour of the player is evaluated through a continuous registration of the players position and orientation of the body, which is inferred from 2D laser range measure-
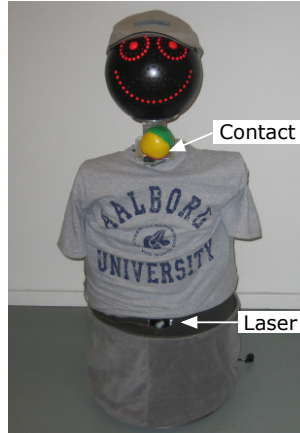
Figure H.2: The modified FESTO Robotino robotic platform.

(a) Confused   (b) Neutral   (c) Happy   (d) Sad
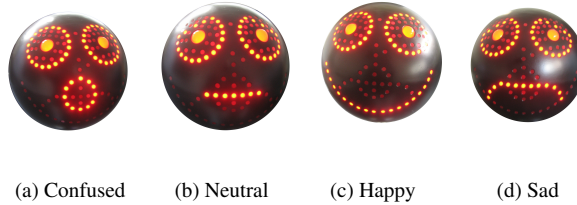
Figure H.3: Using the LED face, the robot is able to express four emotional expressions: confused, neutral, happy and sad. The robot randomly blinks its eyes independent of its expression.

ments as explained in [9]. To detect persons the robot rely on the scans from the laser range finder using the leg detection algorithm presented in [8]. The algorithm is further supported by a Kalman filter for tracking and estimation of the person pose [9].

Learning using Case Based Reasoning (CBR)

To incorporate the ability to adapt to the behaviour pattern of the player, we have selected to use Case Based Reasoning (CBR). CBR allows recalling and interpreting past experiences, as well as generating new cases to represent knowledge from new experiences [10]. CBR has been proven successful solving spatial-temporal problems in robotics in [11] and is characterized by its adaptiveness, making it well suited for the purpose. At the highest level of generality, a general CBR cycle may be described by the following four processes:

- Retrieve the most similar case or cases
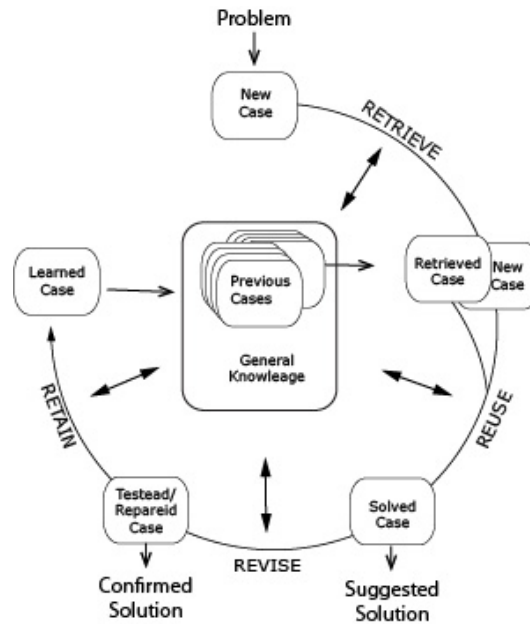
Figure H.4: Illustration of the CBR cycle.

- Reuse the information and knowledge in that case to solve the problem

- Revise the proposed solution

- Retain the parts of this experience likely to be useful for future problem solving

As illustrated in Figure H.4, a new problem is solved by retrieving one or more previously experienced cases, reusing the case in one way or another, revising the solution based on reusing a previous case, and retaining the new experience by incorporating it into the existing knowledge-base (case-base) [12].

In this paper, a CBR system has been implemented using a database which hold cases representing the spatio-temporal data of each player. A case is a representation of a distinct set of features of the behaviour, namely:

Case, is a reference number of each case

x, is the x coordinate of the position of the person in the robot's coordinate system, sampled in 40 cm intervals

y, is the corresponding y coordinate of the position, also sampled in 40 cm intervals

θ, is the pose of the person sampled in an angular resolution of 0.2 radian $= 11.5$ degrees.

PSI, is the value estimated by the CBR system.

Person ID, is an identifier of the interacting person.

The database does not hold any explicit information about context or the environment in which the game is played. The features **x**, **y** and θ are all stored in a precision which facilitates match-making when performing database queries, and the feature are represented in two tables in the database:

- Stored cases which serves as a library holding cases that have already been evaluated

- Temporary cases which serves as storage of cases during evaluation of player.

The starting point of the CBR system is an empty database holding no a priori knowledge about player behaviour in none of the two tables. While a person plays with the robot, cases are created in the temporary table for each 0.1 second. When creating cases in the temporary table, the system first tries to see if a matching case exists in the stored cases table. When retrieving a case from the stored cases table, two possible scenarios can occur:

- No match: The currently faced case is stored directly into the temporary case database with *PSI* = 0.5, indicating that the robot does not know the skill of the player for this specific case.

- Match: An existing case is found in the stored table and copied into the temporary table. When copying the case, the *PSI* value is updated using a first order autoregressive filter ensuring that past values of *PSI* is reflected in the update. The consequence is that the entire trajectory history is reflected in the current value of *PSI*.

When the ball is handed back or evaluation time T_1 has elapsed, the temporary table is revised and cases are retained in the stored cases table.

Algorithm I outlines how *PSI* of the cases are revised. The weight factor w is a function of distance to the player, and ensures that observations close to the robot are given a higher impact on the database than observations further away. L is a learning rate that controls the temporal update of *PSI*, i.e. how much *PSI* should be updated due to a new observation. The closer L is to zero, the more conservative the system is and the less *PSI* will be affected by new observations. In a progressive setup, L is close to 1 and consequently *PSI* will adapt faster.

Algorithm I

```
if (Ball handed back) then
   PSI = PSI + wL
   if PSI > 1 then
      PSI = 1
else if (Ball not handed back) then
   PSI = PSI - wL
   if PSI < 0 then
      PSI = 0
```

Because the robot this way continuously revises the database throughout a game, the system gradually learns how to decode player behaviour into *PSI* values between 0 and 1.

The Navigation System

The challenge of the game is changed by adjusting the navigation pattern of the robot with respect to the parameter *PSI*. The navigation system is modelled by introducing a person centred potential field which has been described in detail in [13, 9] and is briefly summarized here. The potential field is calculated by the weighted sum of four Gaussian distributions of which one is negated, and the covariance of the distributions are used to adapt the potential field according to *PSI*.

When a player is considered to be unskilled (*PSI*=0), the robot will locate itself in the space right in front the player in a distance of 45 cm, making it relative easy for the player to hand the ball back. On the other hand, when a player is considered to be skilled ($PSI = 1$), the robot will end up at the lowest part of the potential function, approximately 2 meters in front of the person using the method of steepest descent (Fig. H.5). This makes it more difficult for the player to hand the ball back, as he/she has to move relative fast towards the robot which constantly will try to back away from the player.

The robot behavior is inspired by the spatial relation between humans (proxemics) as outlined in [14, 15] and the robot will avoid approaching the player from the back and not enter the intimate zone of the player making it uncomfortable to play with the robot. When the skill of the player is undetermined ($PSI = 0.5$), the robot will approach the player person in approximate $45°$ according to [16, 17] studies.

(a) PSI=0. Unskilled player   (b) PSI=0.5. Player skill undetermined   (c) PSI=1. Skilled player
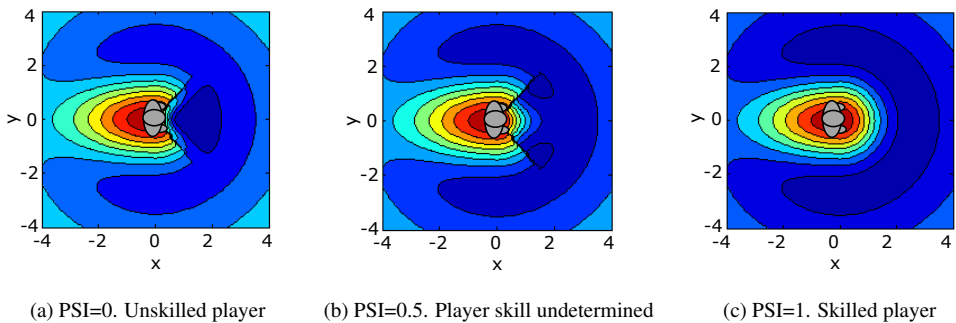
Figure H.5: the potential field as a function of *PSI*. Using the method of steepest descent, the robot seeks towards the dark blue area and avoids the red area.

Control of the Robot

Controlling the robot is done using the programming framework Player which was installed on the platform. The robot game uses the behaviour scheme in Fig. H.6 and can be in the following 4 states.

- Evaluation. This is the central state of the game, in which the robot navigates around the player in accordance to the estimated skill (*PSI*) of the player. Revision of the database takes place every time an evaluation period has elapsed or when the
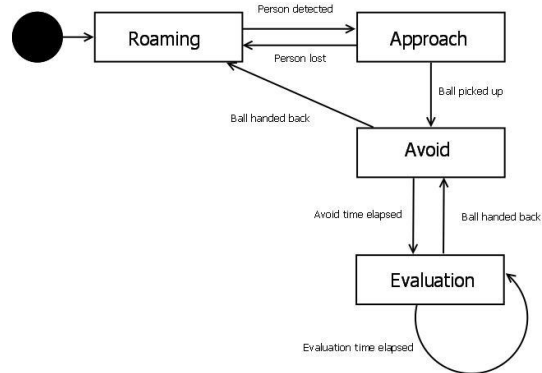
Figure H.6: State diagram and overall game functionality of the adaptive robot game.

ball has been handed back. In the latter case, the game is complete and the robot will go to the state Avoid and thereafter Roaming.

- Roaming. If no player is detected, the robot should search for a player by moving randomly around until a person is spotted.

- Approach. When a player is detected, the robot invites to play a game by approaching the player from the front.

- Avoid. In this state, the robot moves quickly backwards away from the player while turning around its own axis for T_2 seconds. The state is reached when a player picks up or hands back a ball, and the behaviour communicates to the player that a game starts or stops respectively.

The adaptive navigation according to *PSI* happens when the robot is in the evaluation state, while the states Roaming, Approach and Avoid are static navigation patterns working independently of *PSI*. The Roaming and Approach behaviour have been implemented for the robot to be able to search for a player and initiate a game, while the Avoid behaviour has been implemented to signal to the player when a game has started and when it has finished. For each state, the robot changes its facial expression reflecting the behaviour in the current state. A more detailed outline of the entire algorithm is sketched in Algorithm II.

Algorithm II **Main**()

1: **loop**
2:     Roam()
3:     Approach()
4:     **if** Ball just picked up **then**
5:         Avoid()
6:     **end if**
7:     GameResult = Evaluate()
8:     UpdateCbrDatabase(GameResult)
9: **end loop**

Roam()

10: **while** Person not detected **do**
11:     Set facial expression = confused
12:     Drive randomly around
13: **end while**

Approach()

13: **while** Ball is on the robot **do**
14:     Set facial expression = happy
15:     Approach player to invite to play
16: **end while**

Avoid()

16: Set facial expression = neutral
17: Backup and turn around for T_2 seconds.

Evaluate()

17: **while** Time not expired (time less than T_1) **do**
18:     Set facial expression = sad
19:     Move according to PSI value
20:     **if** Ball returned to robot **then**
21:         Avoid()
22:         **return** Positive
23:     **end if**
24: **end while**
25: **return** Negative

3   Design of the study

The first field study (A) took place at a facility for rehabilitation of elderly citizens. There was a total of 3 participants (labeled A1, A2 and A3 in Table H.1). All participants were female, lived in their own home and attended the rehabilitation facility due to different mobility problems. The average age was 80 years and one out of three used an assistive tool. None of the participants had technical background. A physiotherapist working at the facility was monitoring the elderly playing with the robot and the session was also video recorded for later analysis. The second field study (B) took place in a nursing home. A total of 3 elderly residents (labeled B1, B2 and B3 in Table H.1) were invited (two male and one female) with an average age of 87 years. One participant used a walker and another a wheelchair (See Fig. H.7). None of the participants had technical background. Two of the employees at the nursing home monitored the elderly playing with the robot, and the session was video recorded. Study A and B followed the same procedure. First there was a general introduction of the experiment, a demonstration of the robot and afterwards the players were asked to play one at the time. Finally there was a debriefing about the experiment. Each study took 2 hours. The learning rate parameter was set to $L = 1$ and the evaluation time was set to $T_1 = 3$ seconds. The avoid time was set to $T_2 = 5.5$ seconds, making the robot move backwards and turn around showing the back to the participant every time a ball has been picked up or handed back.

ID	Sex	Age	Notes	Number of Games (g)	Total Duration (min)
A1	F	82	Do not use assistive tools.	10	05.09
A2	F	86	Do not use assistive tools.	10	02.47
A3	F	71	Uses a crutch.	10	04.53
B1	F	85	Uses a wheelchair.	3	02.33
B2	M	86	Do not use assistive tools.	3	02.02
B3	M	90	Uses a walker.	3	02.53

Table H.1: Short description of each participant, the total number of games played with the robot and the duration of time played in minutes.

Figure H.7: A participant using a wheelchair playing a game with the robot, trying to hand back a ball while the robot moves.

4 Results

As can be seen in Table H.1, each participant in study A completed a total of 10 games. The total playtime of the 10 games varied between 2.47 and 5.09 minutes. In study B, the number of games to be played had to be reduced since player B1 complained about problems lifting the ball due arthritis after only 3 games. In order to make study B consistent, the number of games was reduced to 3 for all participants. The total playtime of three games in this study, varied between 2.02 and 2.53 minutes.

The starting point of the CBR system is an empty database. As participants starts to play, their movement gets registered by the robot and the database gradually gets filled with cases. Table H.3, shows the total number of cases in the database for each player. It also shows how these cases are located in different distances from the robot (i.e. in the distance 0-1 m, 1-2 m, 2-3 m and 3-4 m) and the average *PSI* value for all stored cases for each player.

The stored cases in the database are illustrated by four-dimensional plots in Fig. H.8 and Fig. H.9. The robot is centred in 0,0 and the first two dimensions in the plot illustrate

(a) Stored cases for player A1 (b) Stored cases for player A2 (c) Stored cases for player A3 (d) *PSI*
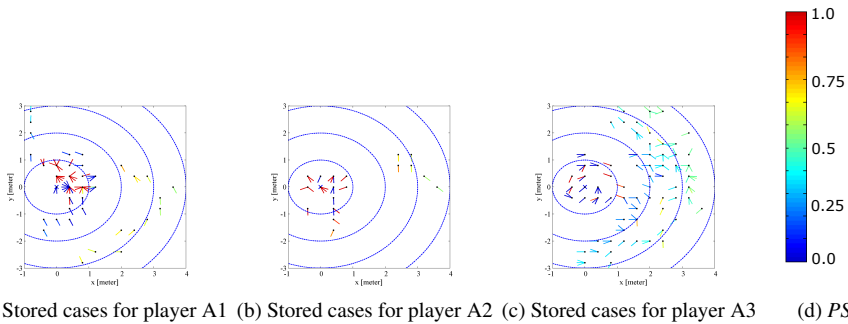
Figure H.8: The figures show the values stored in the CBR system after completion of player A1, A2 and A3. The robot is located in the origin (0,0), since the measurements are in the robot coordinate frame. Each dot represents a position of the player in the robot coordinate frame. The direction of the movement of the player is represented by a vector, and the *PSI* value is indicated by the color range.

(a) Stored cases for player B1 (b) Stored cases for player B2 (c) Stored cases for player B3 (d) *PSI*
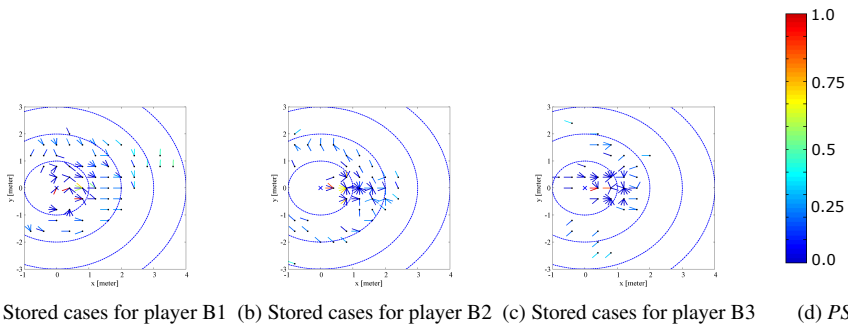
Figure H.9: The figures show the values stored in the CBR system after completion of player B1, B2 and B3. The robot is located in the origin (0,0), since the measurements are in the robot coordinate frame. Each dot represents a position of the player in the robot coordinate frame. The direction of the movement of the player is represented by a vector, and the *PSI* value is indicated by the colour range.

the position of the person in the robot coordinate frame. At each position, the pose of the person is illustrated by a vector. The colour of the vector denotes the value of *PSI*. Blue colour represents that the person is not skilled, while the red colour represents that the person is skilled, i.e. *PI* = 0 and *PI* = 1 correspondingly. A green vector represents *PI* = 0.5 meaning that the skill is undetermined. Table H.2 describes how the cases from the stored cases table are distributed for each player.

Figure H.10 represents the evolution of the stored case table in the database for player A1 and B1. It plots the average *PSI* for all cases in the table which has been calculated for every time a revision of the database has been executed, Initially *PSI* = 0.5 for both play-

Figure	Comment
A1, H.8a	Most vectors (45 out of 89) are centred around the robot in a distance less than a meter from the robot being either in the blue or red spectrum. A total of 28 vectors in the yellow/green spectrum are placed in a distance around 2-4 meters away from the robot
A2, H.8b	Most vectors (20 out of 30) are centred around the robot in a distance less than a meter from the robot. Approximate half of the vectors are in the blue spectrum and the other half in the red. A total of 6 vectors in the yellow/green spectrum are placed in a distance more than 2 meters away from the robot, none pointing towards the robot. 5 vectors in the red spectrum are located behind the robot.
A3, H.8c	Unlike the former two plots, most vectors (62 out of 133) are centred around the robot in a distance between 2 and 3 meters from the robot in the colour spectrum green and yellow. 35 vectors in a distance less than two meters 35 are in the blue or red spectrum.
B1, H.9a	41 and 46 vectors are located in the front of the robot in the distance between 0-1 and 1-2 meters respectively being - all in the green-blue spectrum. Three vectors in the red spectrum are located in front of the robot.
B2, H.9b	Most vectors (59 out of 119) are located in the distance of 1-2 meters in front of the robot in the green-blue spectrum. Approximate one meter from the robot at each side, there are located 22 vectors in the blue spectrum. Two vectors in the red spectrum are located in front of the robot.
B3, H.9c	Most vectors (52 out of 100) are located in the front of the robot in a distance less than one meter in the green-blue spectrum. In a distance two meters from the robot at each side, 41 cases in the blue spectrum are located. Three cases in the blue spectrum are located behind the robot.

Table H.2: Description of the distribution of the vectors in relation to the robot

ID	# of stored cases	$0 \leq D < 1$	$1 \leq D < 2$	$2 \leq D < 3$	$3 \leq D < 4$	Average PSI
A1	89	45	16	22	6	0.53
A2	30	20	4	3	3	0.71
A3	133	22	13	62	36	0.37
B1	114	41	46	24	3	0.15
B2	119	34	59	25	1	0.14
B3	100	52	41	6	1	0.11

Table H.3: The table shows the total number of stored cases for each player, how these cases are located in distance D from the robot and the average *PSI* value for all stored cases
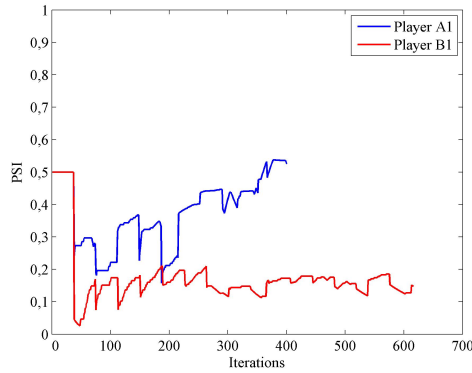
Figure H.10: Illustration of how database evolves. The figure shows the average *PSI* for all cases for player A1 and B1 as a function of the revision of the database.

ers, but as player A1 starts to play, the *PSI* value quickly falls to 0.24 (after 38 revisions) and after 187 revisions it has fallen to a minimum of *PSI* = 0.16. As player A1 keeps playing, *PSI* grows and ends in 0.53 which is also the maximum average *PSI* value for A1. When player B1 starts to play, the average *PSI* value falls to 0.05 after 38 revisions. Then the average value slowly increases ending with *PSI* = 0.15 after 400 revisions.

5   Discussion

A general pattern of all plots in Figure H.8 and Figure H.9, is that the vectors are gradually turning from either red or blue to green as distance increases. This is expected, as the weight of the update is a function of distance, making the cases more stable around 0.5 as distance increases. Also more updates to the *PSI* happen close to the robot (i.e. for most players, the physical behaviour happens close to the robot). Consistent behaviour makes adaptation go faster as more updates of the existing cases in the stored cases table occurs,

whereas changing behaviour pattern makes will make the average *PSI* move towards 0.5 as new cases are added with this default value.

In Table H.1, it can be seen that the player which uses the longest time to complete 10 games in study A is player A1, whereas player A2 completes the fastest. It seems surprising, that A1 spends more time completing the games than A3 because A3 uses a crutch. This might be due to the fact that A1 was the first participant playing the game and seemed insecure of how the game worked. In study B, the fastest player is B2 which seems reasonable as he is the only one not using assistive tools in this study. Comparing Table H.1 with Table H.3 for study A, it can be seen that there is a correspondence between time spent playing and PSI. Due to the nature of the game algorithm this is reasonable, as more revisions decreasing *PSI* happens the longer time is spent playing. The number of revision depends on the evaluation time parameter T_1, which in this experiment has been set to 3 seconds leaving (see Section 3) a relative short time for a player to complete before average *PSI* is reduced. If the parameter T_1 is increased, the average *PSI* also increases becasue the ball will be handed back before a negative revision occurs. Another parameter which affects the average PSI, is the learning rate L which for this experiment has been set to $L = 1$ to ensure quick adaptation. If the learning rate had been set lower, the average *PSI* would have been closer to 0.5 is the update of *PSI* would be smaller for every revision.

In Figure H.8a, there is a relative high number of red vectors in a perimeter close to robot compared to vectors in the blue and green spectrum which are in the distance 2-4 meters. The same pattern can be seen for A2 in Figure H.8b, where almost all vectors are in the red spectrum located close to the robot with a few outliers in the green spectrum. This could be due to the fact that relative few cases are registered for these two players (especially for A2) and that the players always kept close to the robot. The low number of cases for player A2, might be because she was wearing black trousers which can be difficult for the laser finder to detect. It is surprising that vectors are located behind the robot in H.8b, because this area is not in the field of view of the robot. This might be due a fast movement close to the robot. It is also surprising the a red vector can be located far away from the robot (more than 2 meters) not pointing towards the robot, as this behaviour should not result in game completion. This might be due to the fast speed of the player, spending only 16,7 seconds/game which is the track record for all participants. Figure H.8c is distinct compared to the two former figures in study A, because fewer vectors are located close to the robot in the red spectrum and more vectors are in the blue spectrum mainly located between 2 and 3 meters from the robot. This might be due to the fact that more cases are registered for A3 compared to A2 and A1 and this specific player moved more around in the room compared to the others. Again a number of vectors are located behind the robot, which might be due to fast movements close to the robot.

Figure H.9a shows the stored cases for player B1, and compared to Figure H.8a and Figure H.8b, very few vectors are in the red spectrum and all located very close to the robot. It is surprising that so many vectors in the blue spectrum points directly at the robot in the distance of 1 meter, indicating that the player has moved towards the robot without finishing the game. When watching the video recording this makes sense, as the specific player had a hard time handing the ball back to the robot because of the wheelchair, i.e. every time the player moved forwards the robot would backup.

When comparing Table H.1 with Table H.3 for study B, there is no correspondence between time spent playing and *PSI* which is in contrast to what was observed for study

A. B2 only spends 41 seconds/game thereby being the fastest player, but B2 does not have the highest average *PSI* as expected. This particular player had a very unique play style as he liked to toy around with the robot not handing the ball back although he could. He was the only participant in study B which did not use assistive tool and seemed very mobile. Nonetheless he decided to spend relative long time to hand the ball back as he apparently liked to tease the robot and see its reactions when moving around. As a consequence, the *PSI* for player B2 (=0.14) is on the same level as B1 (=0.15) and B3 (=0.11), although the latter two players were using a wheelchair and a walker correspondingly. This illustrates an inherent problem of dynamic skill level adjustment, as exploratory and non-standard behaviour has to be identified and filtered out. This problem has been recognized in the computer game industry which typically use static skill levels which are set before the game begin by the player [18].

Figure H.10 starts with *PSI* = 0.5 for both players which is expected as the database starts being empty, meaning that the robot has no experience and hence is must use the default *PSI* value which is 0.5. There seem to be more variation in the estimated skills of player A1 compared to player B1. This might be due to the fact that player A1 seemed insecure of how the game worked in the beginning. When comparing the two players, it is clear that the system believes that player A1 has higher skills as *PSI* end at a higher level than for player B1. This makes sense as player A1 did not use assistive tools whereas player B1 was using a wheelchair.

When looking at the average *PSI* values for the players in Table H.3, it can be seen that the average *PSI* values for the players in study B are lower than for the players in study A. This is fair, as more participants in study B would use assistive tools and generally have lower physical capability than in study A. It is supported by the fact that the average playing time in study A is 25,6 seconds/game, while it is 166 seconds/game in study B. However, as seen in the case of player B2 do time of completion and *PSI* not necessarily correspond. It can be discussed if the average *PSI* value is an adequate representation of a player's skill, as it is calculated on the basis of a spatio-temporal database. In theory, this means that a player can have high average *PSI* for one behaviour pattern and a low average *PSI* for another in the same game, resulting in an average *PSI* in between the two. For the sake of simplicity, the average *PSI* is used here as an indicator of the player's skill, but it should not stand alone and has to been seen in relation to other data describing the player behaviour.

6   Conclusion

In this paper, we have presented a game based on a mobile robot as a rehabilitation tool which can motivate elderly to move physically. The game is a pursuit and evasion game based on an adaptive game algorithm which can adjust the challenge of the game to the mobility skills of the player. Skill is represented using the variable *PSI* and is estimated on spatio-temporal registration of player behaviour and adaptation is based on case-bases reasoning. The game has been evaluated in situ in two field studies - one in a nursing home and in a rehabilitation centre for elderly.

The results show that the system estimates that players from the rehabilitation centre have higher mobility skills than the players in the nursing home, as the average *PSI* is higher for the players at the rehabilitation centre compared to the nursing home. This is as

expected, as more participants in the nursing home study used assistive tools and generally had more limited physical capabilities. However, the system fails when participants shows non standard behaviour by e.g. deliberately not completing the game although able, which was observed for one player in the study. The fact that skill level adjustments are very hard to tune, has been recognized in the computer game industry which typically use static skill levels which are set before the game begin by the player. In robot based games, incorporating more complex sensors technologies might mitigate this but more research is needed.

7 Future Work

Future work is to create and study more complex games e.g. games which facilitates collaboration between multiple players. The design of the robot should be enhanced, and include multi-modal interface like speech recognition, sound or more complex gesture recognition which opens for a new world of signal processing. There is a need to do more longitudinal studies about user acceptance and perform quantitative measurements of physiological benefits of using the robot games.

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Paper G

A Software Framework For Multi Player Robot Games

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Abstract

Robot games have been proposed as a way to motivate people to do physical exercises while playing. Although this area is very new, both commercial and scientific robot games have been developed mainly based on interaction with a single user and a robot. The goal of this paper is to describe a generic software framework which can be used to create games where multiple players can play against a mobile robot. The paper shows how an adaptive AI system (D2) developed for real-time strategy (RTS) computer games can be successfully applied in a robotics context using the robotics control framework Player/Stage. D2 is based on Case-Based Planning which learns from demonstration. Using the proposed framework, the paper shows how a robot learns a strategy for an implementation of a simple game.

1   Introduction

Based on the demographic development in most western countries, it has been predicted that the number of people with mental and/or physical disabilities will increase while the amount of people to take care of them will decrease [1], [2]. Digital games hold a significant promise for enhancing the lives of seniors, potentially improving their mental and physical wellbeing, enhancing their social connectedness, and generally offering an enjoyable way of spending time [3]. It has been shown that mental and physical health can be improved through a small amount of physical exercises [4], [5], and e.g. Nintendo Wii has been suggested as a means to increase physical activity among elderly [6], [7].

A senior consultant in the elder care sector in major Danish muncipality once accused the vasting public money in research. "'sleeping in class! You spent all this funding, and now we are drowning in problems.'"

In this paper we introduce a software framework for constructing robot games which motivates people to move physically when playing. The framework provides generic functionality which can be selectively overridden or specialized by user code providing specific functionality for creating a number of games using mobile robots. Many known games are derived from a pursuit-evasion scenario e.g. the child games robbers and cops and the game of tag [8], and in this paper we describe a concrete implementation of a game where multiple players compete against the robot.

The vision of robots participating in our day-to-day lives is the focus in the research field of Human Robot Interaction (HRI) [9]. The vision is supported by progress in the development of new sensor technology and computing, which open the door to a new generation of mobile robotic devices that see, hear, touch, manipulate, and interact with humans [10]. The development is reflected in the fact that computer games are gradually moving from the pure virtual domain into the physical world with the introduction of products like Nintendo Wii, Microsoft Kinect, Sony's EyeToy, etc. There are several examples of how games are constituted using a physical robot, e.g QRIO's routine of tracking and kicking a ball, and in [11] where the robot Leonardo is used to play an imitation game. In [12] we have described a game where a mobile robot can play a simple ball game with a human. Some commercial gaming robots exist, e.g. Tri-Bot from WowWee which is able to play three simple maze-based games with the user.

Although there has been a great advance in computer games in computer graphics, animation and audio, most of the games contain very basic artificial intelligence (AI) [13].

To deal with increasing complexity there has, however, been a push for the development of new AI algorithms, many of which shares requirements with those of robots operating in open-ended environments.

In this paper we will shortly summarize the background for making robot based games and outline some of the requirements. We introduce D2 which is an AI system based on case based planning. D2 is originally developed for real time strategy computer games and we show how it can be used in a robotics scenario also. This is done by implementing a game interlinking D2 with the robot control software Player/Stage.

2 Background

Motivating users to move physically by playing a game is related to persuasive technology which is defined as technology designed to change attitudes or behaviors of the users through persuasion and social influence, but not through coercion [14] and [15]. Robots offer advantages not found in on-screen agents or technology embedded in the environment, such as an increased sense of social presence in an interaction and the capacity for touch and physical interaction [16]. In [17] and [18] the concept of enjoyment as a possible factor influencing acceptance of robotic technology was investigated using the iCat Research Platform which is a robot research platform for studying human-robot interaction. The fact that sociable robots are more fun to play with was confirmed in [19]. Successful games are often characterized using the concept Flow, as proposed by Csíkszentmihály [20] which is a mental state which can occur when there is an appropriate balance between challenge and skill. As the cognitive and physical capabilities of the users are expected to vary, the robot should adapt the difficulty of the game to the end user. The fact that intelligent agents working in real time domains need to adapt to changing circumstance has been recognized in computer game industry as well as in robotics. The ability to adapt is necessary in order for autonomous agents to improve their performance and avoid mistakes in a complex and dynamic environment.

As robot sensors gradually get more reliable and new types of sensors emerge, the robot's knowledge about the real world is getting more precise and informative. Computer games are on the other hand developing towards more complexity with an increasing high decision space, involving interactive users and real time performance. This makes the AI requirements from these two distinct domains intersect and some of the common characteristics are:

- Real Time Nature: imposing constraints in terms of processing time that could be taken by AI approaches situated within these domains.

- Large Decision Spaces: most state of the art computer games have huge decision spaces [21], [22], and thus traditional search based AI techniques cannot be applied. The same applies for robots which should act in open ended environment relying on multiple sensors.

- Unanticipated Scenarios: it is not feasible to anticipate all possible situations and as result, it is hard to design behaviors that can handle all the possible situations and respond appropriately to all possible actions.

- Human in the loop: Games involve one or more interactive user(s) that can change the state instantaneously. Even small delays in AI decisions can be unacceptable.

A popular approach to deal with non-determinism is to use planners based on reinforcement learning, e.g. by modeling the problem as a Markov decision process and focus on learning a policy. These techniques, however, often require a large number of iterations to converge. In complex domains, they are intractable and generalize poorly [13]. While reinforcement learning approaches are good for low level control, symbolic approaches like Case Based Planning are good for high level strategic decisions which is the focus of D2 which we present here.

The D2 System

D2 [23] is a real-time case-based planning system designed to play Real-Time Strategy games (RTS). D2 implements the *on-line case-based planning* cycle (OLCBP) as introduced in [24]. The OLCBP cycle attempts to provide a high-level planning systems that operate on-line, i.e. that interleave planning and execution in real-time domains. The OLCBP cycle extends the traditional CBR cycle by adding two additional processes, namely *plan expansion* and *plan execution*. The main focus of D2 is to explore learning from human demonstrations, and the use of adversarial planning techniques. The most important characteristics of D2 are:

- It acquires cases by analyzing human demonstrations.

- It interleaves planning and execution.

- It uses an efficient transformational plan adaptation algorithm for allowing real-time plan adaptation.

- In case a simulator is available, D2 can make use of it to perform adversarial case-based planning.

For D2 to learn how to perform a given task, an expert has to provide demonstrations of such task. D2 can typically learn from a few demonstrations (1 or 2), but depending on the variability of the domain or the complexity of the task, many more traces might be needed.

D2 has been used used as an AI engine for several computer strategy games like Wargus (open source clone of Warcraft II), BattleCity, S2, Towers and Vanquish (clone of Risk), and is currently being applied to Starcraft. A previous version of D2 (Darmok) was applied to a game scenario where two virtual characters played a game of tag [13].

3   A Robot Game

In [12] we presented a game based on a simplified pursuit and evasion scenario. The human player should try to hand over a ball to the robot, while the robot should try to avoid receiving the ball. The robotic platform which formed the basis of these experiments, is shown in Figure I.1. The robot platform from FESTO is equipped with a head having 126 red diodes (see Figure I.1) which enables it to express different emotions. The robot is 1
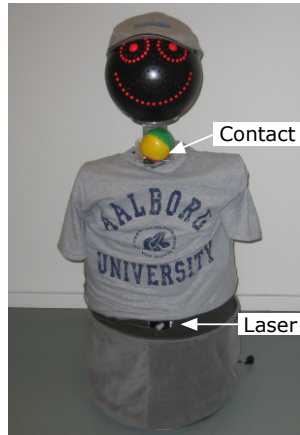
Figure I.1: The modified FESTO Robotino robotic platform.
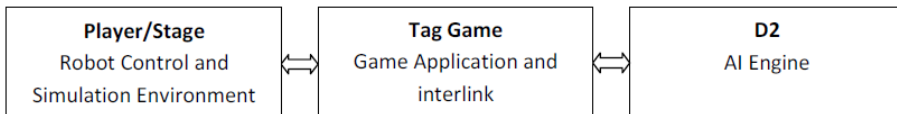
Figure I.2: Illustration of the three components of the framework; a robot controller (Player/Stage), an interlinking game application (Tag Game) and an AI engine (D2)

meter high, and has mounted an URG-04LX line scan laser placed $35cm$ above ground level, scanning 220 degrees in front of the robot. In [12], an on/off switch was placed to find out when the robot had the ball.

Based on the same robotic platform on which we have added a standard web camera, we suggest a similar simple pursuit and evasion game which allow multiple users to play with the robot. The game consists of a number of squares marked on the floor, a mobile robot and a number of human players. The winner of the game is the participant who has visited all squares first. During a game, the robot can tag a person which makes the person do a detour on the game board. The implementation of the game has been done using the following components (see also Figure I.2):

1. A Robotics Environment which takes care of control of simulation and control of the robot (Player/Stage)

2. An AI Engine which learns and executes the robot's overall gaming decisions (D2).

3. A Game Application, which defines the frame and the purpose of the game an works as the interlink between the two former elements. Here we have chose an implementation of a variation of the Game of Tag, but many other games could be interesting.

The AI Engine

In order to implement D2 as the AI engine for a game, the following elements should be defined in a XML file following a specific D2 syntax: Entities, Sensors, Actions, Preconditions, Postconditions and Goals.

An Entity is a definition of the basic units of the game. In this case there are four: the human players, the robot, the squares marked on the floor and a wall entity. The latter is used to mark the barriers of the game area and obstacles in the game area. Each entity specification holds the name of the entity and a list of which actions are available to the entity.

The Sensor definition describe the robot's sensor input in any level of abstraction. In this case, this is the position values of the entities. Securing that the position of the player and the robot is actually correct is not in the scope D2 but is handled by Player/Stage and will be described later.

The Action definition is a list of all possible actions the entities can do. The low level implementation of these robot actions is not in the scope of D2 either but is handled by Player/Stage. D2 has the function of learning to select the right actions during a game in order for the robot to win the specified goals.

The Goal definition is specification of how to win the game, which in this case is when the robot has visited all squares. With all elements above properly defined, the D2 framework can auto generate a number classes which forms the basis of the game in the Game Controller. This can be interlinked to a robot controller and simulation environment like e.g. Player/Stage.

Control and Simulation Environment

Player/Stage handles a simulation environment and the low level robot control including position detection, path planning and collision avoidance. It also holds a pre-defined map of the environment which is read from a file.

The position of the robot is done using the standard Player/Stage amcl driver which implements the Adaptive Monte-Carlo Localization algorithm described by Dieter Fox. The amcl driver maintains a probability distribution over the set of all possible robot poses, and updates this distribution using data from odometry, laser range-finders and the pre-defined map of the environment. The detection of the players' position is done by the robot using the mounted laser scanner using a leg detection algorithm [25] and [26].

Collision avoidance is done automatically in Player/Stage by implementing the Vector Field Histogram Plus local navigation method by Ulrich and Borenstein. VFH+ provides real-time obstacle avoidance and path following capabilities for mobile robots and in order to obtain global navigation, the wavefront driver has been layered on top of that. When simulating the game, the human players have been modeled using the obstacle avoidance and path planning functionality offered in Player/Stage. Each player has been modeled having a different color and a standard Player/Stage blob-detection algorithm for web camera input is used to distinct the players from each other.

The Game Controller

The game controller is basically the game definition and the interlink between the AI Engine and the Simulation Environment. It constructs the game scenario by passing selected actions from D2 to the robot implementation and sensor data from the robot the other way. The game strategy of D2 is created using initial demonstrations, allowing a game instructor to control how the robot should act. In this implementation, demonstration is done by facilitating a GUI where the instructor can choose between the different robot actions. During this process, the Game Controller generates traces which are used by D2 to learn a strategy about the behavior of the robot and the players. When a strategy has been learned, the game controller can let D2 control the behavior of the robot without human interference. In a simulated environment, the Game Controller to some extent also specifies how the persons play the game, i.e. it controls to which position the persons should move. In the current implementation, the game controller can handle any number of squares and players but only one robot.

4 Experiments

We consider a simplified game setup to illustrate and validate the basic functionality of the proposed framework. In each game, the players, the robot and the squares are placed at random positions. The participant who first visits all squares, wins the game. While the simulated human players use a nearest neighbor algorithm to select where to move, the robot can choose between the following actions:

- Move To Square. Make the robot move to a specified square.

- Tag Player. Make the robot follow a specific player. If the distance between the robot and the player is under a specific threshold, the player is tagged and he/she should do a detour by moving to a specific position on the game board.

- Rotate left/right. Rotate the robot left or right from its point of view.

- Move forward or backwards.

In order for D2 to learn a strategy, two games have been completed using a human demonstrator. This is sufficient for D2 to learn a strategy, which now can be used to control the robot. Five different variations of the game have been tried out.

1. The simulated players play against each other without the robot. Each person is moving with a max speed of 0.5 m/s.

2. The speed of one player is set to move slower, having a max speed of 0.1 m/s.

3. The robot is introduced in the game, having a max speed of 2 m/s.

4. As before, but the game field now consists of 10 squares.

5. As 3, but now a goal has been added which states that all players should have visited at least 3 squares before the game ends. In this experiment, the robot has been retrained using a human demonstrator.

Games won	Ex 1	Ex 2	Ex 3	Ex 4	Ex 5
Person 1	10	20	4	0	13
Person 2	10	0	0	0	2
Robot	0	0	14	13	2
N/A	0	0	2	7	3

Table I.1: Number of won games by each player in 5 experiments with 20 games in each.

Game rounds	Ex 1	Ex 2	Ex 3	Ex 4	Ex 5
Min	105	101	59	150	221
Max	278	207	139	238	707
Mean	169	189	103	181	435

Table I.2: The minimum, maximum and mean number of game rounds in 5 experiments with 20 games in each.
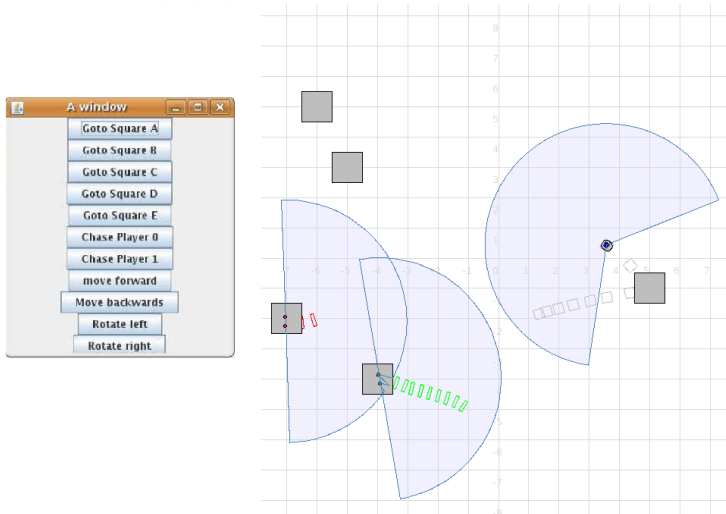
Figure I.3: The figure shows a screenshot of the implemented robot based game. Each player is moving from the initial position to a square marked on the floor. The window to the left is a GUI, which initially lets a human user demonstrate how the robot should behave in order for D2 to create a control strategy

Each game has been repeated a total of 20 times for each experiment, and the number of won games by each player can be seen in table I.1. The maximum, minimum and mean number of game rounds can be seen in table I.2. Figure I.3 shows a screenshot from a simulated instance of the implemented robot after a few seconds of playing time. On the figure, it can bee seen that each player including the robot has moved on to a square and is looking for a new square to visit.

5   Discussion

In the first column in table I.1, it can be seen that the two participating persons win an equal amount of times. This is as expected, as both persons use the nearest neighbor algorithm and move with the same speed. In experiment 2, person 1 wins all the games which is also as expected as this player is capable of moving faster than its competitor. In experiment 3 the robot is introduced and it wins 14 games. This shows that the robot has learned a valid strategy, and since it moves faster it is most likely to win. It is surprising that person 1 actually wins 4 of the games. This is considered to be due to the fact that the robot not has learned an optimal strategy, and to some degree due to a fortunate location of the squares in played games. Two of the games does not end with a winner, because the players are stuck in a deadlock where each one is blocking the way of the others. In experiment 4, the number of squares is increased. Now the robot wins 13 games, the persons win none, but 7 games ends without a winner because simulation has been aborted after a 1000 game rounds. In the last experiment, a goal has been added which states that all players should visit at least 3 squares. Although person 1 wins the majority of the games, person 2 actually manage to win 2 games although he/she is moving much slower than the other participants. Although the robot is capable of winning more often because of its higher speed, it only wins two of the games. This is due to the fact that a new goal has been added, and the robot now spends time on tagging person 1 to ensure that person 2 reaches at least 3 squares before the game finishes. Although more research is needed, this final experiment is included to illustrate that the robot can learn a strategy making all participants capable of playing although they have very different skills. Table I.3 shows the maximum, minimum and mean number of game rounds for all experiments. It is worth noticing that the mean number of game rounds increases in experiment 5, because the robot now spends more time tagging the other players.

The presented gaming framework is still at a very early stage, and therefore results have been obtained through simulation only. This reduces the complexity of the game scenario, because getting precise data like e.g. the location of the robot and the players is not a simple problem in the real world. The actual behavior patterns of the human players are also simplified and should be elaborated through real world experiments. The results show that D2 can be used to learn a playing strategy for robot based games. It is important to notice that here the goal of D2 is not necessarily to make the robot play optimal, as this could have been archived with simpler means. The focus is to create a strategy for the robot which ensures a balance between skill and challenge for the participating players during the game. The contribution of this paper is to introduce a generic software framework applicable for multi player robot games. The framework is constructed by interlinking D2 with Player/Stage, each of which have been validated many times in other papers and therefore forms a good basis for further research.

6   Conclusion

In this paper we have outlined a generic software framework which can be used to implement robot based games where multiple human players can compete against a mobile robot. The framework consist in a Case Based Planner (D2) which is interlinked with Player/Stage which serves as a robot control and simulation environment. We have im-

plemented a variation of the Game of Tag for a mobile robot competing against multiple human players. Using the framework, we have showed that the robot can learn different game strategies based on a few demonstrations. A possible application for robot based games is to motivate elderly to do a higher amount of physical exercises and thereby strengthen their mental and physical capabilities.

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Appendix I

Abbreviations and Definitions

1 Abbreviations

AAU	Aalborg University
AE	Artificial evolution
AI	Artificial Intelligence
ALife	Artificial Life
AR	Assistive Robotics
BC	Basic Control
CBP	Case Based Planning
CBR	Case Based Reasoning
D2	Darmok 2
DAI	Distributed artificial intelligence
DTI	Danish Technological Institute
EEG	Electroencephalography
FOA	Fag Og Arbejde
GA	Genetic Algorithm
GaTech	The Georgia Institute of Technology
HCI	Human Computer Interaction
HRI	Human Robot Interaction
MDP	Markov Decision Process
MMOG	Massively Multiplayer Online Games
MMPM	MakeMePlayMe
RPG	Role Playing Games
RTS	Real Time Strategy Game
SAR	Socially Assistive Robotics
SDU	University of Southern Denmark
SG	Simulation Games
SIR	Socially Interacti ve Robotics
STRIPS	Stanford Research Institute Problem Solver
ToM	Theory of Mind

2 Definitions

AB-pruning	An optimizing technique for tree search
Affective computing	The study and development of systems and devices that can recognize, interpret, process, and simulate human affects
Animal Assisted Therapy	A type of therapy that involves an animal with specific characteristics becoming a fundamental part of a person's treatment
Artificial Intelligence (AI)	The intelligence of machines and the branch of computer science that aims to create it
Artificial Life (Alife)	Models of living biological systems through computer algorithms
Behaviour Based Robot Control	Robot control based on relatively little internal variable state to model the environment
Branching factor	The number of branches at each branching point of a tree
Captalogy	Persuasive Technology using computer technology
Computer Game	A game based on a personal computer
Cybernetics	The coupling of control theory, information science and biology
Danish Industrial PhD Program	A 3-year PhD-program constituted by a company and a university
Darmok 2	An AI system designed to play real-time strategy games
Deliberative Reasoning	A paradigm based on a symbolic model of the world, in which decisions are made via symbolic reasoning
Distributed Artificial Intelligence (DAI)	The idea that multiple competing or cooperating processes can generate coherent behaviour
Elder Care	The fulfilment of the special needs and requirements that are unique to senior citizens
Electroencephalography (EEG)	The recording of electrical activity along the scalp produced by the firing of neurons within the brain
Exergaming	The use of video games in an exercise activity
Fag Og Arbejde	Danish workers union
Flow	A mental state characterized by energized focus, full involvement, and success in the process of the activity
Game AI	The use of artificial intelligence in computer games
Game Theory	Reflects calculated circumstances where a person's success is based upon the choices of others
Humanoid	Robot that has an appearance resembling a human being
In Situ	Real world experiments conducted in a daily life situation
IntelliCare	Danish project creating the nursing home of the future
Iterative Development Strategy	The development of a system through repeated cycles in smaller portions at a time
Lab	Experiments using the physical robot conducted in the robotics lab
MakeMePlayMe	A social gaming website, where users can automatically train artificial agents
Markov Decision Process	A mathematical framework for modelling decision-making where outcomes are partly random
Massively Multiplayer Online Games	Games allowing thousands of players to play simultaneously through the internet
Minimax	A recursive algorithm for tree representation of game
Open-ended Environment	An unstructured environment without fixed limits or restrictions

Perfect Information Game	Games where the player(s) have complete knowledge of the game
Persuasive Robotics	The study of persuasion as it applies to human-robot interaction
Persuasive Technology	Technology that is designed to change behaviours of the users through persuasion
Playware	Intelligent hard- and software that aims at producing play and playful experiences among
Prisoner Dileamma	An aspect of game theory that shows why two individuals might not agree, even if appears that it is best to do so
Reactive Control	Control which operates in a timely fashion and hence can cope with highly dynamic and unpredictable environments
Real World	Experiment using the robot system, where it has been set loose in an open-ended environment
Robot	A machine with the ability to move, sense, manipulate the surroundings and/or show intelligent behaviour
Robot-Assisted Therapy	Therapeutic use of a robot - often as a replacement for Animal-Assisted Therapy
Robot Game	A game which is facilitated using a robot
Robot Technology	Technology in the intersection of robotics and ICT
Robotics	The design, construction, and application of robots
Robotino	A mobile robot platform created by AAU
Rule Based Control	Control based on a inference engine or semantic reasoner
Serious Games	Games designed for a primary purpose other than pure entertainment
Simulation	Experiments conducted in computer simulation without implementation on the physical robot
Skill-and-action games	Computer games with the emphasis on speed and action rather than strategic thinking
Smoke and Mirrors	An term in computer games industry describing impressive effects made with simple means
Social (Socialable) Robot	A social robot is an autonomous robot that interacts and communicates with humans or other autonomous physical agents by following social behaviours and rules attached to its role
Spatio-Temporal	Refers to objects existing in both time and space.
Stanford Research Institute Problem Solver (STRIPS)	A theorem-proving system using first-order logic to develop a plan
Strategy games	Computer games with the emphasis on strategic thinking rather than speed and action
The Closed World Assumption	The presumption that what is not currently known to be true, is false
The Frame Problem	The problem of expressing a dynamical domain in logic without explicitly specifying which conditions are not affected by an action
Theory of Mind (ToM)	A psychological construct defined as knowing that others are intentional agents
Transpositions Table	Tables which are used to speed up the search in games
Waterfall Model	A sequential design process, often used in software development processes
Welfare Technology	Technology that can help and assist users in their daily lives
Zero-Sum Game	Games where winning is equivalent to that the opponent is loosing

Appendix J

The Industrial PhD Programme and Collaboration With Partners

1 The Danish Industrial PhD Program

This Ph.D. have been made under the Danish Industrial PhD Program which is three year company focused PhD project conducted in cooperation between a private company, an Industrial PhD student and a university. The program is partly funded by the Danish Ministry of Science and partly funded by the company. The goal of the Industrial PhD Program is to strengthen research and development in Danish business communities by educating scientists with an insight into the commercial aspects of research and development and by developing personal networks in which knowledge between companies and universities can be disseminated.

The Ministerial Order on the PhD Program at the Universities under the Danish University Act, states that it is required to spend about 800 hours on dissemination during the project. It is not required to spend time giving classes as an 'regular' Danish PhD program, but the time can be spend on presentations in the company, writing papers, participation in conferences. Besides that, it is required that a report is sent to the Ministry every half year with an status update. A description of the dissemination effort can be seen in Appendix K.

The PhD programme states that 30 ECTS worth of Ph.D. courses should be completed. It is mandatory to participate special course for Industrial PhDs, which includes elements as project management, organisational theory, dissemination, IP and commercialisation. This course is ended by writing a 30-pages report related to one of the former topics.

As this thesis is made under the Industrial PhD program, the project's industrial involvement is stronger than a regular university PhD thesis. As the main function of Danish Technological Institute is technology transfer, the thesis has a strong focus on dissemination - primarily about the use of robotics in elder care.

2 Project Partners

This thesis has been initiated by the Centre for Robot Technology, Danish Technological Institute under the Danish Industrial PhD Program. The thesis has been conducted in collaboration with Aalborg University with the Centre for Automation and Control at Institute of Electronic Systems and Medialogy at the Institute for Architecture, Design and Media Technology. Half a year was spent at The Georgia Institute of Technology in the Cognitive Computing Lab lead by Ashwin Ram. I have also been collaborating with the project IntelliCare lead by Kasper Hallenborg at University of Southern Denmark, in which Center for Robot Technology is a partner.

The Danish Technological Institute

The Danish Technological Institute (DTI) is the leading technology service provider to the Danish industry and society and also holds a strong international project portfolio. DTI develops, applies and disseminates research and technology knowledge, and the Institute takes part in development projects of use to society in collaboration with leading domestic and foreign research institutions. DTI also carries out consultancy and standardization services, and the Institute holds courses, certifications and lectures for the continuing

education of the Danish work force. DTI was established more than a hundred years ago and today employs around 1.000 people in 33 specialist centers and five foreign affiliates.

Centre for Robot Technology . DTI's Center for Robot Technology's speciality is creating robotic solutions and knowledge on their use for the manufacturing, food, construction, agriculture, horticulture, forestry and garden industries and the health and welfare sector. Center for Robot Technology takes responsibility for a seamless route from the problem and the solution needed for the implementation to the actual impact of the robotics. The center's two main focuses are: To develop ideas, build and demonstrate solutions, test, measure and document the effects, and to innovate new businesses and usable products. To spread new robotic knowledge to manufacturing companies, research institutes, and other business partners. Consultancy, laboratory tests, transfer of knowledge at conferences, workshops, courses and in networks are some of Center for Robot Technology's means of knowledge sharing.

DTI's Center for Robot Technology is based in Odense, which is the Silicon Valley for robotics in Denmark. In 2008, the center occupied eight people, but in 2011 there will be between 40-50 robotics specialists working at the center. Center for Robot Technology is currently participating in more than 30 robotics projects spanning from pure research projects to prototype development of new components and systems in the following main areas: Manufacturing and Food Industry, Health and Welfare, Green Robotics, Intelligent Architecture and Edutainment. The center primarily cooperates with small and medium sized companies, SME's, employing between 15 and 200 people. Center for Robot Technology has 120 industrial partners and 10 partner universities.

Aalborg University

Aalborg University offers education and research within the fields of natural sciences, social sciences, humanities, technical and health sciences. Aalborg University currently consolidates and further develops its profile as a dynamic and innovative research and educational institution oriented towards the surrounding world. It is characterised by combining a keen engagement in local, regional, and national issues with an active commitment to international collaboration.

Automation and Control Automation and Control is concerned with mathematical and computational techniques for modelling, estimation, monitoring, and control of systems and processes. Automation and Control provides the field of electrical and computer engineering with paradigms for designing control solutions to existing and novel problems in a variety of application domains. Current applications range from space and robotics to ventilating and air conditioning.

Medialogy Medialogy focuses on education and research, which combine technology and creativity as means to design new processes and tools for art, design and entertainment - we do this to meet the requirements of our contemporary media industry. In authoring and designing Interactive Media, it is becoming increasingly evident that the largest challenge lies in bringing together different disciplines. Medialogy's interdisciplinary ap-

proach acknowledges that mastering and combining such a variety of disciplines requires a strong technical foundation, both in theory and in practice

Georgia Tech

The Ministerial Order on the PhD Program at the Universities under the Danish University Act, states that 'the PhD program must contain participation in active research environments, including stays at other, mainly foreign, research institutions' as one of the means to train the PhD student at an international level. In this case, a half year visit took place at the Cognitive Computing Lab (GA), Georgia Tech, Atlanta, US. The exchange period took place from the 15th of January to the 20th of June 2010. Georgia Tech is one of the US's top research universities, and is consistently ranked in U.S. News and World Report's top ten public universities in the United States.

The Cognitive Computing Lab (GA) pursues research at the intersection of artificial intelligence and human-centered computing, developing systems that are both intelligent and design to interact intelligently with humans. GA pursues fundamental and applied research in the context of real-world problems and applications which inform and constrain the research and provide an opportunity to demonstrate new technology in working systems. GA research lies at the intersection of AI (artificial intelligence) and HCC (human-centered computing). GA's focus is not cognitive science but cognitive computing, with an emphasis on computing and systems issues critical to tackling real-world, large-amounts-of-information, continuous-task, human-in-the-loop problems. It brings together relevant pieces of cognitive science and artificial intelligence with newer approaches from intelligent systems and human-centered computing. GA is part of the School of Interactive Computing in the College of Computing at Georgia Tech and directed by Prof. Ashwin Ram who was my primary supervisor during the stay.

IntelliCare

The thesis has been conducted in a collaboration with the project IntelliCare lead by Kasper Hallenborg at University of Southern Denmark, in which Center for Robot Technology is a partner. IntelliCare is a national project which aims at developing new technological solutions and creating a common IT platform making it possible to integrate intelligent assistive technology in elder care. The solutions should support the elderly in being as safe and self-sufficient in everyday life as possible while freeing some of the burdens from the nursing staff. The project is based on 17 partners from different lines of businesses, cooperating about a wide range of technological developing projects conducting cross-disciplinary research. The basis is the establishment of a common technological platform - the IntelliCare Platform. In Intellicare, Center for Robot Technology is mainly involved in three sub-projects: SocialBot, BotDialog and Servicebot. SocialBot is primarily concerned about developing adaptive and cognitive learning algorithms which can support the interaction between robot and human. The goal is to develop advanced assistive technology for use in service and healthcare. BotDialog deals with communication between robots and existing assistive technology while SocialBot deals with communicating between robots, e.g. distributed vacuum cleaning.

Appendix K

The Dissemination Effort Of The Thesis

1 Dissemination According to the Danish Industrial PhD Program

The Ministerial Order on the PhD Program at the Universities under the Danish University Act, states that it is required to spend about 800 hours on dissemination during the project. It is not required to spend time giving classes as an 'regular' Danish PhD program, but the time can be spend on presentations in the company, writing papers, participation in conferences. Dissemination in this PhD has mainly been done through activities in Center for Robot Technology at Danish Technological Institute, by doing the following activities:

- Presentations of papers and robot technology (see Table K.6 and Table K.3)

- Writing newsletters and giving interviews (see Table K.1)

- Writing contributions to funding applications (see Table K.2)

- Supervision of students (see Table K.5)

- Participation in related projects (see Table K.7)

- Networking conferences (see Table K.4)

Every year the Danish Organisation for Industrial PhD's (Erhvervs PhD foreningen) announces a dissemination competition about selected topics relevant for students in the industrial PhD program. I participated in the competition 2008 through 2010 and was awarded the the Ph.D. dissemination price 2009 and 2010.

Media	Type
Email Newsletter	Various newsletter articles for DTI
Newspaper articles	Interviews Politikken, Jyllands Posten,...
TV/Radio	Interviews for DR2, P3, P1, RTL, Croatian National Television

Table K.1: Description of dissemination to mass media.

Name	Call/Type	Role
EmoRob EU application, I and II	FP7	Participant
Marie Curie	FP7 (Marie Curie)	Participant
REAAL	FP7	Participant
RoboCare I, II, 'Baderum for alle'	EBST (National call)	Responsible
Adaptive Robot Games	FI (National PostDoc Call)	Responsible
DIAFIM	FP7 (ECHORD)	Responsible
SwopBox	FI (National Call)	Responsible

Table K.2: Contributions to funding applications

Name	Call/Type	Activity
AUTOMATICA, München	Industrial exhibition	Presentation of robot platform
AUTOMATIK, Brøndby	Industrial exhibition	Presentation of robot platform
RO-MAN	Scientific conference	Presentation of paper
HRI 2010	Scientific conference	Presentation of poster
AAL	The European Ambient Assisted Living Forum 10	Speech and presentation of robot platform

Table K.3: Presentation at robot conferences and exhibitions

Name	Type
CARE EUROP 2008	European robotics conference
Euron 2009	European robotics conference
FET 2009	EU Technology conference
NEXT 09	Danish Technology conference

Table K.4: Networking conferences

Name	Type	University
Using CogniMem	Bachelor in engineering	DTU
Distributed Household Cleaning	7th semester of engineering	AAU
Controlling iRobot using SunSpot	Mater's thesis	Université Lille

Table K.5: Supervision of student projects

Organization	Event	Description
Omsorgs-organisationerns Samråd	Annual meeting about prevention in health and elder care	Speech about robotics in elder care
The Muncipality of Aarhus	Meeting about elder care	Speech about robot technology
Danish Engineer Association	The first Danish national conference about welfare technology	Speech about robot technology
ÆldreForum	Annual Meeting	Robotics in Elder Care
Finansministeriet / ÆldreSagen	Meeting at DTI	Speech about Robotics in elder care
DTI	Intern presentation at Danish Technological Institute	Presentation of PhD
Rosengårdscenteret	Presentation about robots to the general public	Presentation of robot platform
Arbejdsmiljø-konference	Conference about working environment in elder care	Speech about robots in elder care
HanDiaTek, Aalborg	Conference about technology for handicapped	Speech about PhD and robots in elder care
Roskilde University	Virtual Archaeology Project Start-up	Speech about robots
Roskilde University	Guest Speaker at a Robotics Course for Computer Science Students	Speech about robots and AI
ScienceTalent	Conference for talented students	Speech about robot technology
Fox Media	Conference for school teachers	Speech about robot technology

Table K.6: Presentations and speaks

Name	Project	Describtion
CareNet	A Danish network for robotics in Healthcare.	Initial organisation of the network.
IntelliCare	Technology Project about The Nursing Home of the Future	Project management and implementation
Magrethehjemmet og Bedre Ældrepleje	National Project about the use of robot technology in nursing homes	Evaluation of commercial robot products

Table K.7: Participation in projects

Appendix L

Overview of Assistive Robots

1 Assistive Robotics

Assistive Robotics refers to robots that assists people with physical disabilities through physical interaction. Assistive robotics itself has not been formally defined, but an adequate definition of an assistive robot is one that gives aid or support to a human user. This Appendix gives an overview of different examples of assistive robots, which can be split into five categories.

- Prosthetics. Technology which replaces lost or damaged parts of the body.

- Mobility Aids. Non-prosthetic technology replacing or extending the functionality of e.g. a leg or an arm.

- Training and rehabilitation. Technology, which can be used for individual training, exercises and rehabilitation.

- Logistic and cleaning tasks. Technology, which solves specific tasks which does necessarily involve the user or the caregivers, e.g. vacuum cleaning.

- Personal Sanitation. Technology, which helps the user with his/her being getting clean or going to the toilet

Robot Prosthetics

Robot Prosthetics describes artificial fingers, hands, arms, legs, organs which electronically and mechanically resembles the human parts they replace. An example is the robot prosthetic PowerFoot from iWalk (see Fig. L.1), which is a system consisting in an ankle and foot containing a motor and battery which is recharged when walking [1]. The foot can change stiffness dependent of the surface and gives a natural walk. Two micro processors and 6 sensors evaluates and adapts the stiffness of the ankle. This gives a human-like walk and the patient uses less energy than if using passive prosthetics. Another example is the i-Limb hand prosthetic device from Touch Bionics [2]. I-Limb is an electronic hand (see Fig. L.1), where the control is done by electronic coupling with existing muscles. The electronic hand looks like and behaves like a human hand, but is made of hard plastic. Electronic signals from the remaining part of the patients joints, makes the control system open and close fingers. The signals are detected by electrodes which are placed on the surface of the skin and according to the manufacturer it is possible to learn using the hand in a couple of minutes [2].

Mobility Robots

Mobility robots describe robot technology, which can be used as replacement for lost functionality due to problems with control of e.g. legs or arms. An example is the iARM from Exact Dynamics (see Fig. L.2), which is a light-weight robotic arm designed for people with handicap of the upper body. It can be mounted on a electric wheelchair, and be controlled by different kinds of interfaces like a 4x4 keyboard or the joystick of the wheelchair. The technology from the robot arm builds on principles from industrial robots, but it has less weight and uses less energy [3].

Figure L.1: The PowerFoot from iWalk [1] and i-limb from Touch Bionics [2]

Figure L.2: The iARM from Exact Dynamics [3], the iBOT wheelchair [4] and the mySpoon robot [5]

iBOT is an advanced wheelchair developed for people with mobility problems (see Fig. L.2). The wheelchair works a bit like the more famous Segway, which was actually a spin-off company of the development of iBOT. It has a number of characteristics which separates it from other wheelchairs, e.g. it can be used to climb stairs and users can elevate themselves [4].

My Spoon is a meal assistance (or feeding) robot produced by Japanese company, SECOM Co. Ltd. [5] It is designed to help disabled people to eat using a robotic arm which has a spoon attachment. It is controlled using a small joystick, and works with most types of foods. The spoon stops at a pre-programmed position in front of the mouth so a user can eat from the spoon at his convenience [5].

Training, rehabilitation and fitness

Robot technology has entered the market for training and rehabilitation after e.g. operations. Movement therapy automated by a rehabilitation robot, has shown to be an effective way to train people with mobility problems caused by neurological deceases or injuries [6]. An example is a system from Lokomat [7], which assists the walking behaviour in order to improve the mobility of people who has suffered from e.g. heart attacks and sclerosis (see Fig. L.3).

A robot driven unit guides the patient's legs on a treadmill, which gives a range of training possibilities. It is possible to train longer and do more intensive training compared to traditional training. There is less burden on the occupational therapists and re-

Figure L.3: The Hocoma Lokomat rehabilitation robot [6] and the HAL exoskeleton [8]

habilitation is easier to monitor and evaluate. It can be programmed to do different kinds of rehabilitation programs and can be adapted to the individual user's needs. Experience from Hammel Neurocenter in Denmark, shows that the system makes it possible to start rehabilitation earlier than normal in the patients program [9].

Another type of technology is the exoskeleton, which is the accepted term for a suit which reinforces the strength in the body where functionality is reduced. Exoskeletons often work by electronic reading of the body's and/or the brains signal for movement. The sensor-input is translated to movements using motors in the exoskeleton, which is placed in relation to the body's natural joints e.g. a knee or a foot joint. An example is HAL-5 [8], developed by the University of Tsukuba, Japan (see Fig. L.3). The suits represent a new type of technology, where robots and human gets close connected. A type of integration which potentially can be used for rehabilitation and improvement of life quality for people with mobility problems.

Robots for Logistic and Cleaning Tasks

One of the most famous and used robots in elder care in Denmark is at present time the autonomous robotic vacuum cleaner like e.g. the Roomba from iRobot or Trilobite from Electrolux (see Fig. L.4). The idea of using robot vacuum cleaners in elder care, is that personnel can spend time more time on personal care than cleaning. There has been initiated a number of projects in Danish municipalities in order to evaluate robot vacuum cleaners in elder care, often with very different conclusion [10, 11, 12]. However, robot vacuum cleaners have been the first real step in implementing an autonomous robot device in elder care.

Robots for Personal Sanitation

Help for personal sanitation is one of the biggest consumers of man labour in elder care. Therefore there are big economic interests in minimizing time spent on helping elderly with this. An example of how technology can help is the implementation of automated toilets, also called a 'Japanese Toilet' or Washlet (see Fig. L.5) [15]. Automated toilets are widespread in Japan, but still not very common in Europe. The automated toilet from TOTO works by having mounted a nozzle which extends from under the seat for warm-water cleansing. The nozzle can be set to move back-and-forth using a panel which also

Figure L.4: Robot vacuum cleaners. From left: Roomba from iRobot [13] and Trilobite from Electrolux [14]

Figure L.5: Robots for Personal Sanitation From left: Toilet from TOTO [15], The automated bath Viami from AirWater [17] and the electronic diaper from Minelet [16]

controls if you want the seat to be heated. The philosophy of using the automated toilet in elder care is that users which are not able to clean themselves will get a higher degree of freedom and self sustainability, thereby decreasing the need for assistant personnel [15].

Another product in the same domain is the electronic diaper by Minelet (Figure L.5), which is aimed at people who needs help for toilet attending [16]. The device looks like an ordinary diaper, but works by automatically sucking urine and faeces from user. The automated bath Viami from AirWater is an electronic device for people who needs help taking a shower. A person can be placed in a vertical position or in wheelchair for an automated bath and the device is remote controlled by the user or nursing staff controlling water heat and pressure [17].

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Appendix M

Overview of Commercial Computer Games

1 Computer Games

According to Crawford, computer games can be split into sub-genres as can be seen in Table 1.

Skill-and-action games	Strategy games
Combat Games	Adventure Games
Maze Games	D and D Games
Sports Games	Wargames
Paddle Games	Games of Chance
Race Games	Educational and Children's Games
Miscellaneous Games	Interpersonal Games

Table M.1: A taxonomy of different types of computer games.

Since this taxonomy was developed in 1982, new types of games have emerged like **Massively Multiplayer Online Games (MMOG)**, **Role Playing Games (RPG)**, **Real Time Strategy (RTS)** and **Simulation Games (SG)** while other game types now are deprecated like e.g. paddle games.

Simulation and ALife Games

One of earliest examples of successfully applied AI, is the game SimCity which is a city-building simulation game first released in 1989 designed by Will Wright [1]. SimCity was one of the first games to prove the potential of Alife approaches and was later followed up by 'The Sims' series which is a strategic life-simulation computer from 2000 simulating the daily activities of one or more virtual persons in a suburban household [2]. It is characterized by not having any specific goal but deal with the emotional relationships and emotions between characters. The latest product by Will Wright is the game Spore which is a multi-genre single-player god game released in 2008 [3]. Spore allows the player to develop a species from a microscopic organism to its evolution into a complex animal, which ends up ruling the planet and move out to conquer other planets in outer space (See Figure M.1). The game series 'Creatures' is an Alife computer program series, created in the mid-1990s by English computer scientist Steve Grand [4]. The game is one of the first to employ machine learning to simulate the psychology and physiology for the 'norns' that populates the game. It includes digital DNA unique to each creature which is controlled by a neural network. In 2001 the game Black and White was developed by Lionhead Studios. Black and White is a god game that includes elements from artificial life, strategy and fighting games. It is built around the concept of teaching and training your 'creature' and the AI is based on reinforcement and observational learning to bring about highly emergent behaviours [5].

Digital Pets

Digital pets describes artificial agents kept for companionship or enjoyment. They are not games in a traditional sense as there is no particular goal besides keeping you pet alive and happy. An example is the game series Petz (Dogz and Catz) from 1995 by Mindscape

Figure M.1: Four simulation/Alife games; from left Simcity [1], The Sims [2], Spore [3] and Creatures [4]

Inc [6], being a series of virtual pet games in which the player can adopt, raise, care for and breed their own virtual pets (figure M.2). The characters are characterized by being adaptive, emotional and having memory. The Tamagotchi from 1996 is a physical implementation of a similar game in hand-held device [7].

Figure M.2: Digital Pets Games. From left: The Petz Series [6] and Tamagotchi [7]

Action Games

Another type of game is e.g. Grand Theft Auto by Rockstar North (Figure M.3) [8]. The player can choose missions to progress an overall story, as well as engaging in side activities consisting in driving, occasional role-playing, stealth and racing elements. From

an AI perspective, the game is considered a breakthrough as it represents living cities heavily modelled after American cities including pedestrians, cars and police. F.E.A.R. (short for First Encounter Assault Recon) is a horror-themed first-person shooter from 2005 [9]. It has a planning system similar to STRIPS and has inspired many other games to experiment with planners like Left for Dead which is a cooperative first-person shooter video game from 2008 [10].

Figure M.3: Three actions games. From left: Grand Theft Auto [8], F.E.A.R [9] and Left for Dead [10]

Massively Multiplayer Online Games

Massively Multiplayer Online Games (MMOG) describes a type of multiplayer video game which is capable of supporting hundreds or thousands of players simultaneously. By necessity, these games are played on the Internet, and feature at least one persistent world. The game World of Warcraft from Blizzard Entertainment (often referred to as WoW, see Figure M.4), is one of the most famous of its kind with more than 12 million subscribers and as of October 2010 it is estimated that the game holds 62 percent of the market [11]. MMOGs have been described to be the death of game AI, as the intelligence of the game characters is constituted by other human players being connected though the internet. World of Warcraft is particular interesting in this thesis, as an open source version (Wargus) is the basis for modelling the AI system D2 which will be explained in Chapter 7.

State-of-art in Computer Game AI

The majority of current commercial computer games rely heavily on scripting techniques, and are not particular advanced from an AI perspective. One of the consequences is that even in modern games, you will see that many game characters who do not behave as you would expect. Steve Rabin summarized the state of art in computer games in a talk at the Game AI conference at ITU in Copenhagen June 2010 by saying that most game characters move, act and talk like shit. He elaborated this by saying that, in general game characters often behave poorly, i.e. they are poor at path-finding, get stuck and do operate robustly enough in complex terrains. They are oblivious to the environment and conversation is tiring. Game characters do not play by the same rules as the player and therefore lacks fairness or perceived fairness. They are bad at finding out player intent, which according to Rabin might be a nearly unsolvable problem. As a consequence, many AI game agents are poor AI buddies which often require babysitting. According to Tozour

Figure M.4: World of WarCraft. A Massively Multiplayer Online Game [11]

[12], a number of early failures and inadequacies of game AI arose from an insufficient appreciation of the nature of game AI, referred to as a 'magic bullet' attitude which was usually manifested in an under appreciation of the challenges of AI development. However, recent years have witnessed the rise of dedicated AI programmer, solely devoted to AI from Day One of the project. According to Rabin, the future of game AI is to create more powerful tools and architectures, making the AI programmer able to do create nuances without hand-crafting. These tools should be holistic systems combining animation, physics and AI and AI programmers must become experts in acting, animation, psychology, sociology, economics and game design.

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Appendix N

Overview of the D2 system

1 The D2 System

Darmok 2 (D2) [1] is an AI system designed to play real-time strategy games and is an extension of a case-based planning system. D2 implements the on-line case-based planning cycle (OLCBP) as introduced in [2]. The OLCBP cycle attempts to provide a high-level framework to develop case-based planning systems that operate on-line, i.e. that interleave planning and execution in real-time domains. The OLCBP cycle extends the traditional CBR cycle by adding two additional processes, namely plan expansion and plan execution. The main focus of D2 is to explore learning from unannotated human demonstrations, and the use of adversarial planning techniques. The most important characteristics of D2 are:

- It acquires cases by analysing human demonstrations.

- It interleaves planning and execution.

- It uses a transformational plan adaptation algorithm for allowing real-time plan adaptation.

- If available, it can use a simulator to perform adversarial planning.

When any given game problem has been formally defined, D2 can initially learn a winning strategy based on human demonstration. When a strategy has be learned, D2 can continuously adapt this based on observed failures. The architecture of D2 consists in five parts:

- Plan Library in Representation Language. The representation language for authoring behaviours representing basic behaviours using various constituents namely, preconditions, alive-conditions, sensors and basic actions. Preconditions are a set of conditions that must be true in order to execute the behaviour

- Plan Execution Layer. The execution layer provides the ability to execute behaviours in real-time. The execution layers provide the means to look at the current state of the world and select appropriate behaviour for execution. When a behaviour fails, the execution layer needs to find an alternate behaviour to accomplish the goal

- Trace Recording. The execution trace is generated by storing each game state recorded at specific time intervals. An abstracted version of the execution trace is used to record important events happening during the execution. From each game state, various events are extracted and recorded in the abstracted trace.

- Failure Detection. Failure detection involves localizing the fault points. Once a set of failures are identified, they need to be appropriately revised.

- Plan Revision. Once the cause of the failure is identified, each failure needs to be addressed through appropriate modification. The collection of modification routines provide the necessary set of modifications to be applied
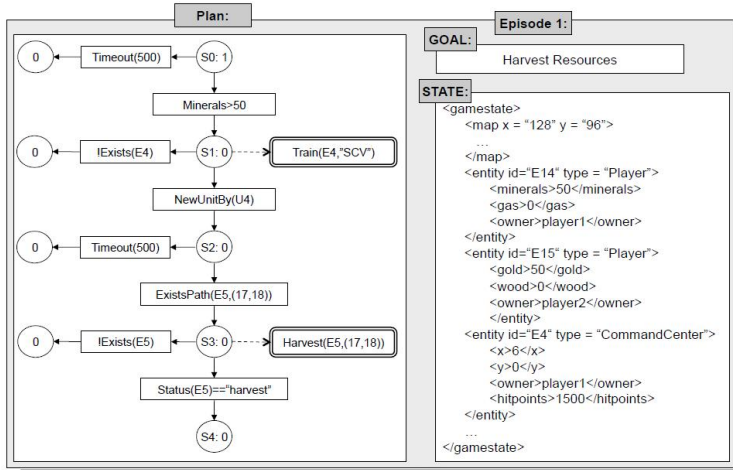
Figure N.1: A snippet of a plan, goal and state in D2 [1]

D2 learns a collection of cases by analysing human demonstrations(traces). Demonstrations in D2 are represented as a list of triples $[\langle T_1 S_1 A_1, ..., T_n S_n A_n \rangle]$, where each triple contains a time stamp T_i game state T_i and a set of actions A_i (that can be empty).

The set of triples represent the evolution of the game and the actions executed by each of the players at different time intervals. The set of actions A_i represent actions that were issued at T_i by any of the players in the game. The game state is stored using an object-oriented representation that captures all the information in the state: map, players and other entities (entities include all the units a player controls in an RTS game: e.g. tanks).

Each case $C = \langle P, G, S \rangle$ consists of a plan P (represented as a petri-net), a goal G, and a game state S. A case states that, in a game state S, the plan P managed to achieve the goal G.

Plans in cases are represented in D2 as petri-nets [3] which offer an formalism for representing plans that can have conditionals, loops or parallel sequences of actions. In short, a petri net is a graph consisting of two types of nodes: transitions and states. Transitions contain conditions, and link states to each other. Each state might contain tokens, which are required to fire transitions. The distribution of tokens in the petri net represent its status. When D2 executes a plan contained in a case, the actions in it are adapted to fit the current situation. Each action contains a series of parameters referring to locations or units in the map, and other constants. For example, if a parameter refers to a location, then a location in the current map which is the most similar to the location specified in the action is selected. For assessing location similarity, D2 creates a series of potential fields. Each location in the map, is thus assigned a vector, which has one value for each potential field. This allows D2 to compare map locations and assess which ones are more similar to others. For example, it can detect that a location is similar to another because both are very close to enemy units.

Fig. N.1 shows a case in D2 consisting of a plan, goal and game state. The snippet contains two actions and the game state representation is not fully included due to space limitations.

D2 shares a common based of domain knowledge that contains the following elements [4];

- Entities: the set of different types and entities that can appear in the game

- Actions: the set of actions that can be executes in the game by the player

- Sensors: Allow the system to perceive the game state. Although D2 has access to the complete representation of the game state, sensors allow the definition of an abstraction with which, e.g. preconditions and post-conditions actions can be defines

- Goals: A subset of Boolean Sensors are marked as Goals, and it used by the plan-learning module and planner to decompose plans into a goal/sub goal hierarchy (following ideas from HTN planning). D2 requires the user to define at least one goal, which corresponds to winning the game

An Entity is the primitive data type of D2's domain representation. Everything in the game state is considered an entity. For example a person or obstacle is considered an entity. Each entity has an owner (the player who owns it, or null if they are not owned by any player) and a unique ID. The base class to store entities is Entity and allows D2 to:

- Access the features of entities (their coordinates and other attributes)

- Compare entities to see if they are equivalents

- Check whether a particular action can be executes by an entity

Some entities are physical, i.e. they occupy some space in the game state. All those entities inherit from the class PhysicalEntity, which extends the entity class with appropriate information about the coordinates and dimensions of the entities and provides collision detection.

The GameState class represents the state of the game and contains two pieces of informations: the Map and a list of entities. D2 assumes that a game state always contains a map, and the map class represents static and non-active entities of the game, e.g. in PacMan it would contain the walls and remaining dots.

Sensors are used to define features about the game state that D2 uses to understand the world, and are also used to model preconditions, success conditions, etc. of the actions. For example, if we consider the game of PacMan, it would make sense to define sensors that return: the number of dots left, the distance to the nearest ghost, if there is a wall ahead, etc.

Sensors can return any primitive type that D2 supports: integers, strings, entities, co-ordinates, entity types, and directions. Sensors are specified also in the domain definition file. D2 contains a collection of built-in sensors, which can be used to build upon. For instance sensors to compute number of units of a certain type, distances, collisions, etc. are included. Additional sensors can be defined using a simple scripting language in the XML domain definition file, or directly in Java.

Actions in D2 differ from action definitions in traditional planning techniques such as STRIPS because traditional planning formalisms focus only on the plan formulation

phase of planning. D2 focuses on both plan formulation and plan execution. Additionally, D2 does not assume that actions always succeed, so they have to be monitored at run time to verify their success of failure. Moreover, STRIPS-like formalisms assume that it is possible to completely formalize the planning domain at hand into a set of actions and rules. However, many domains (such as modern RTS games) are too complex for achieving that. Instead, we can only have a partial domain definition.

An action is defined in D2 as a tuple containing 7 elements:

- Action name.

- Parameters, a list of named parameters with associated types. It is important to know the type of a parameter for plan adaptation purposes. Valid types are: integer, string, coordinates, entity identifier, or entity type (these determine the range of valid values). Additional constraints on the range of values can be specified.

- Preconditions, which must be satisfied for an action to start execution.

- Success conditions, which cause the action to succeed. Note that success conditions are not the same as post-conditions.

- Failure conditions, which cause the action to fail.

- Pre-failure conditions, which if satisfied before the preconditions, indicate that the preconditions will never become true, so it's useless to keep waiting. Notice that in RTS games, actions take time. It might be the case that if preconditions are not satisfied, they may become satisfied by merely waiting some time. Pre-failure conditions are useful for D2 to know when to stop waiting for the preconditions of an action.

- Post-conditions, which are a superset of the success conditions, and include conditions that might happen as a result of an action, but that are not necessary for considering an action succeeded. For example, the attack action will have a success condition that a particular entity will be attacking another entity. Destruction of the target entity would be specified in the postconditions as a possible outcome.

Thanks to the definition of success and failure conditions, D2 does not only allow plan formulation (as STRIPS formalisms) but also monitors action execution.
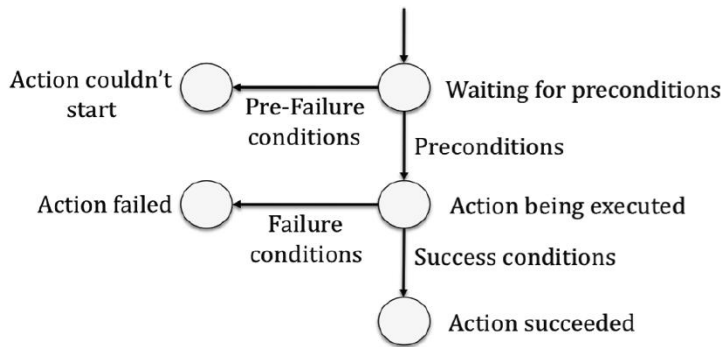
Figure N.2: An action diagram in D2 [4]

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Appendix O

The Implementation of the Multi Player Game

1 Class diagram

The multi player game described in [1] is implemented in Java using 8 different classes, and the relation between the classes can be seen in Figure O.1.
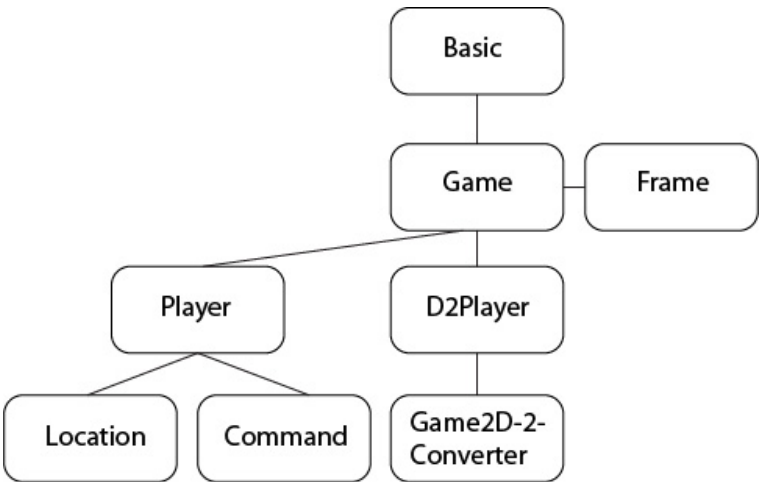

Figure O.1: The classes used in the implementation of the game in [1]

The Basic class holds the main method that starts the game, and initiated all other objects.

The Basic class

The Basic class hold the main method, and has a function which can randomly generate a game board, i.e. generate a text file for the player/stage framework with any given number of players and squares to visit. The squares and the persons are located at random locations. The class also initiates an object of the Game class which is the actual game implementation.

The Basic Class	
Int NumberofPlayers	The number of players in the game
Int NumberofSquares	The number of squares in the game
Int Xdim	The horizontal size of the game board
Int yDim	The vertical size of the game board
Main	The main method of the application
WriteGameBoard	Methods for writing a random board game, i.e. random positions of the squares, the players and the robot. This is written as a textfile for the Player/Stage, i.e. framework as a .world file which can be loaded by Player/Stage.

The Game class

The Game class is the actual game which is to be played by the robot. It connects to the player/stage framework and can also initiated player/stage if it has not been launched at execution time. It controls when any of the players has won the game, i.e. when they have visited all squares, and has methods for controlling the players and the robot and is also responsible for generating the trace for D2.

The Game Class	
Player robot	The representation of the robot
ArrayList playerList	A list of all the players in the game
Command command	A variable which holds the current command which should be sent to the robot
int gameround	Represent the current gameround
Trace trace	Represents the trace of current game being played
Void connectToplayer	This method connects to Player/Stage
Void LaunchPlayer	The method launches the Player/Stage framework if has
GameState getMap	Returns the game state
Void gotoSquare	Method for moving the robot to a specific square
Void chasePlayer	Method for chasing a player if he/she is visible using the laser-scanner
moveRobot	Moverobot for d seconds in forwards, backwards, rotate left or rotate right
boolean playerDeteced	Function which tells if a person is detected by the laser scanner
void startGame	Starts the game
void StopGame	Stop the game
void UpdatePlayerPositions	Makes a request for Player/Stage for the positions of the players
testPosition2D	This method is used by the chasePlayer method, and checks if the ID of the person corresponds to the player whichs is being chased. If the distance between the player and robot is less than a certain threshold, the player has to move to the center of the game.
void chasePlayer(int playerid)	Method for chasing a specific player (a player with playerid) in the game
void moveRobot(int direction)	Makes the robot move forwards, backward, rotate left or right for x number of seconds
waitARound()	Make the robot stand still for x number of seconds
gotoSquare(int squareid)	Makes the robot goto square with the ID specified in the parameter
UpdatePlayerPositions()	Updates all the positions of the players in the game. This game believes that the locations of the players are always known, so each player should be equipped with some locale GPS.
GameState getMap()	Returns the state of the game, i.e. the locations of all players, squares and the robot
initData()	Initiates the game state.

The MyFrame Class

The class MyFrame is a inner class of the Game Class and extends the JFrame class and is the GUI of the simulation enviroment. It let's a human instructor choose between the actions available of the robot.

The Command Class

The command class is generic class for holding the command which are sent to the robot. A command simply a name and a parameter. In this particular game, we use three commands:

- MoveToSquare, a command which moves the robot to a square, where the parameter is the ID of the square.

- Move, a basic control command of the robot. The parameter controls if should go the robot forward, backward or rotates it left or right.

- ChasePlayer, a command where the robot chases a player (if he/she is detected) and the parameter is the id of the person

The Command Class	
String Action	Name of action
Int Parameter	A parameter of the action
GetAction	Get method for the action
SetAction	Get method for the action
GetParameter	Get method for the action
SetParameter	Get method for the action

The D2Player Class

Initiates an instance of D2, and is used when D2 control the robot and holds a method for returning which command D2 believes that the robot should execute. Command getCommand - Returns the D2 representation of the command that D2 believes the robot should execute.

The Game2D2Converter Class

This class is used for conversion of action commands between D2 and the implemented game.

The Game2D2Converter Class	
toGameAction	Class which converts the D2 representation of an action to the local representation of the action.
toD2Action	Class which converts the local representation of an action to the D2 representation of the action.

The Location Class

Location is a helper class which represents the squares in the game and the location of the players (including the robot).

The Location Class	
float x	The x position of the square
float y	The y position of the square
float getX()	Get method for the x coordinate
float getY()	Get method for the x coordinate
getName()	Get method for the name id
setX(float x)	Set method for the x coordinate
setY(float y)	Set method for the y coordinate
equals(Object o)	Checks whether to locations are equal by comparing if the x and y coordinates are equal (with no decimal)
Location(float x, float y)	Constructor of the class
float euclideanDistance(Location a, Location b)	Calculates the distance between two location values
float manhattanDistance(Location a, Location b)	Calculates the Manhattan distance between to location

The Player Class

Player is a class which used for modelling the human players as well as the robot. It includes methods for detecting which squares are yet to visit and to define which square the player wans to visit next.

The Player Class	
String name	Name of the player, has to be unique for each player. The robot has to be name the reserved word 'robot'
ArrayList availableSquares	A list which holds all the square the player needs to visit in order to win the game
Location target()	The location of the current goal target of the player
Void setTarget(Location)	Set the target square that the player is heading at
String getName()	Get name of the player
getSquares()	Get the list of squares which is yet to be visited
boolean TargetReached()	Method which tells if the player has reached his target
Void printSquaresLeft()	Prints the number of squares left in the console
int squaresLeft()	Returns the number of squares left
void removeSquare()	Removes the square of the list which corresponds to the actual position of the player
void getNewTarget()	Find a new target for the player. When the player is human (not a robot) the player can stay on target, go to to the nearest square or go to a random square.

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