Adaptable Ambient Living Assistant

Collaborative Project

D6.1 Report on different navigation strategies to approach elderly people in a polite manner

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WP6 Navigation - Objectives	Reminder
- To ensure appropriate approaching behavior in the presence of a person in a home environment - To respect persons when passing by and signal own behaviour in an appropriate way - To follow or guide a person in an home environment	

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1 Executive Summary

This deliverable describes the means through which the robot will be able to interact with the elderly user. The robot is capable of navigating through a home environment without presenting any danger to the elderly user residing in the house, to itself or to the environment. For doing this, it constructs a model of the environment and it is able to dynamically avoid obstacles.

The process of navigating through its environment is not simply to travel from point A to point B. It also involves many different subtasks as observing a person, travelling to a certain point, following the care receiver, interacting with the care receiver by approaching him or her for vocal dialog or interaction via touch display.

This deliverable will show a comprehensive overview over psychological findings toward interaction of persons and robots and also delivers an overview of the different psychological background, older people usually have. It will also focus on the state of the art methods to approach persons today and also will show which approaches Ilmenau University of technology plans to provide and from which approaches this is influenced.

2 Introduction

2.1 Motivation

Social robotics will appear more often in the next future and will become an economic and also social part of our society. The work of Libin [34] characterizes the purpose of "social robotics" to the field presented in figure 1.

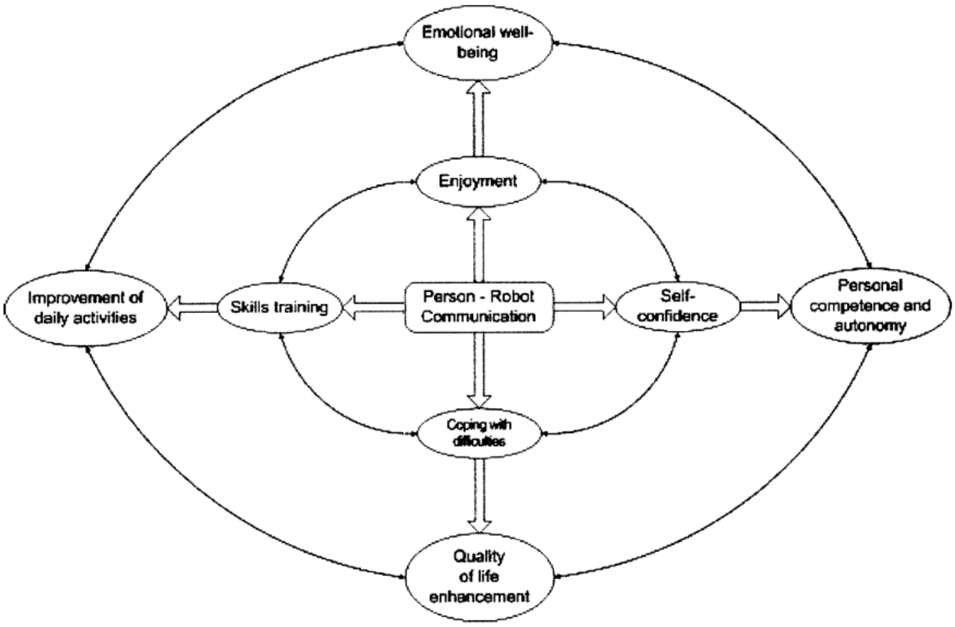


Figure 1: The different purposes "social robots" can be used for

To fulfil these purposes the robot needs to drive around in his environment autonomously. The key point here is the existence of person, unfamiliar with robots, within this environment, where the robot is a service provider for. So the robot has to communicate with these persons and the person has to accept the robot as an interaction partner. Motion is one part of this communication process, as will be seen in the following chapter.

Moving a robot without collision around a home environment is still a challenge today, but this challenge gets even harder if we deal with persons. These persons are not "normal objects that move" but have consciousness and their own thoughts, feelings and fears. These are often driven by experience and social conditioning.

To allow a robot to interact with persons, especially old persons, we have at first to consider what the feelings of (European) older persons are regarding home-robot systems when such systems move around in the home environment of these old persons. When we know these feelings and know, what behaviours to avoid, it is possible to construct such behaviours and to analyse what methods are best suited to implement such behaviours. The first step is done in the next chapter up to the point research can provide today. The second point will be discussed in chapter 4.

2.2 Scope of this Deliverable

This deliverable discusses the question how persons, which are unused with robots, can be approached by a robot in a polite manner. It gives an overview on the current work done within the robotic community to solve those problems, and also what psychological work has been done towards the question on how humans behave in the presence of a robot. It also discusses the question what considerations should be done additionally to the target group of elderly people.

Finally, the document focuses on the question on how to approach elderly people in a polite manner, which means that not only collisions are avoided, but also that the way to drive does not causes any fears or feels uncomfortable to the approached person.

2.3 Structure of this Deliverable

This deliverable covers the following topics:

- Chapter 3: This chapter covers the state of the art. Here the current work towards approaching behaviours is shown and it presents additional work on psychological investigations on how people feel about different speed, distances and directions when being approached by a robot. It also shows some details on the psychological differences from old people to younger, more technical focused ones.
- Chapter 4: The following chapter covers an overview on the proposed methods and strategies to approach an elderly person. It also covers the question on the inherent needed preconditions and what solutions should be used to fulfil these conditions.
- Chapter 5: The last chapter draws a conclusion and discusses some future work to do and what to expect next.

3 State of the Art

To start reasoning about motion strategies of mobile robots in the context of interacting with elderly people, we have to reflect on the knowledge the robot community and psychologists have collected. The most important question that arises in this field is: what is known about human thoughts and feeling about robots in the vicinity? Only when we know how people behave and feel in the vicinity of a robot, what people expect from a robot, we can construct useful approaching strategies.

3.1 Persons and Robots: the psychological approach

This subchapter focuses on the psychological foundations of the problem of "humans and robots interacting and existing in the same space".

What is expected?

Robots will become more and more common in human centred environments, like hospitals, schools and at home, in the near future. For a robot to operate successfully in human-centred environments, it needs to be able to behave in a manner that is socially appropriate. This means that it should perform its functions in a manner that does not upset or disturb any humans it may encounter. In this human-centred view, interaction with robots needs to be comfortable and acceptable to potential human users [35]. It is common sense that this goal can only be achieved when the users of robot applications perceive the robot as a social entity, which in term requires that the robot creates the same (or at least similar) behaviour pattern than a human, a pet or another social entity[36, 34, 37].

3.1.1 The psychological foundations

The first question, which was considered by psychologists, was the question how persons interact with persons. This is in fact the standard a robot has to mimic to be accepted as a dialog partner and as a "social behaving being". Hall [38] was the first, who investigated the spatial configuration between two persons in different situations like public passing by, talking to a stranger, talking to close friends, talking to own children and so on. He found out that certain kinds of interaction are happening in different distances to each other or spatial configurations. These configurations are dependant on the social status of both partners, e.g. if they are strangers, friends, relatives, children and parents.

Personal spatial zone	Range	Situation
Close intimate	0m – 0.15m	Lover or close friend touching
Intimate zone	0.15m - 0.45m	Lover or close friend only
Personal zone	0.45m – 1.2m	Conversation between friends
Social zone	1.2m – 3.6m	Conversation to non-friends
Public zone	3.6m ++	Public speech making

Table 1: the personal space model proposed by Hall

He also proved in later work that these spaces around each person depending on the culture the person live in. The values from table 1 are collected from North American citizen and are typical for this cultural environment. These spaces are also called “proxemics”. But these spatial spaces do also cover some meaning. As Satake [40] found out at his experiments to find persons interested in a dialog with a robot, it is important for the robot to communicate its willingness to start a conversation on the public space by looking at that person and drive to place the person may want to go to, instead of driving directly to the current position of that person. Also Paccherotti [37] stated that it is important to signal a “passing by” behaviour six meters before the person is reached and that a lateral passing distance of at least 40 cm is needed to signal a clear intention. This is also a way of communication on non-verbal level; just by using motion.

Humans communicate on many levels of interaction. What we understand as interaction by speaking with each other is only the last stage which happens only in from the social zone to the intimate zone. Even when two social entities are getting closer to each other (in the public space of Hall’s definition), communication takes place by such simple things as gaze estimation, walking direction, walking speed and body posture. These signals are interpreted by humans, which means that even motion is communication [18,41] and which also imposes the *requirement* that social robots has to interpret these signals and act according to them [41]. Cowley [42] arguments in his assay even one step ahead and states that humans, when growing up, are discovering and also developing common known, relative consistent symbols to communicate with each other, like language, mimic, body language, and that a whole society or culture is defined by these symbols. Also Hall [39] noticed that embodied non-verbal interactions, such as approach, touch, and avoidance behaviours, are fundamental to regulate human-human social interaction, representing very low level interaction signals. These very common signals enables on the one hand semantics, communication and also understanding, but on the other hand robots have to mimic these symbols in any way to become social entities.

In literature there is evidence that currently used technical devices already seem to mimic such symbols and are treated as social devices. So for example TVs, computers, cars and telephones are treated as “social objects” [21,22], which means that indeed humans interpret technical devices (and their behaviours) as kind of living, active “creatures”. It could also be shown that more autonomy of a given device, like a robot, leads to a higher social rank in communication with such a device [16].

Autonomy is directly correlated with the degrees of freedom a robot has. Libin [34] gives in his work a good overview on different types of robots today and characterizes their properties. He mentioned that the goal of creating a “social robot” is only the attempt to mirror the diversity of living beings into artificial creatures. This diversity also projects different roles into different robots. A robot can for example play the role of a companion to a human, an educator, explorer, entertainer and a rehabilitation or medical assistant. ALIAS focuses on the functionality of a human companion and an entertainer. He defines two features how to characterize a “social robot” (which he calls “interactive stimulation robots”):

> *A first major distinction* of interactive stimulation robots is that those creatures are designed for the purpose of communicating with a human being on a “personal” level. This type of personalized robot can be called an “artificial partner”. The concept of an artificial partner places the relationships between humans and robots into a psychological, rather than technological, context. A few features depict an artificial partner as a good human companion.
>
> - It imitates a real life (human- or animal-like) behavior.
> - It models motor, emotional, and cognitive behaviors normally experienced by animals or humans.

- It communicates with a person on various levels: tactile–kinesthetic, sensory, emotional, cognitive, and social.

These communications can be characterized using both verbal and nonverbal modes, and they can be evaluated as positive or negative. The above-indicated parameters make an artificial creature an interesting and engaging communicating, gaming, educational, or even therapeutic partner for people of all ages, cultures, and life experiences.

ROBOT			PERSON	
Type	**Physical appearance**	**Behavioral configuration**	**Need**	**Benefit**
Assisting robots				
Industrial robots	Machine–like appearance adjusted to the specifics of an executing function	Consists of basic physical movements with the purpose of providing mostly motor or sensory-based activities	To perform hard labor and hazardous work	Increase in productivity
Research robots			To expend and refine human sensors	Ability to obtain new scientific data
Military and rescue robots			To act in life-threatening situations	Safety of human beings
Medical robots			To carry out diagnostic and treatment of the human body	Health maintenance
Service robots			To help in performing activities of daily living	Housekeeping
Interactive stimulation robots				
Social robots	Anthropomorphized appearance or animated form of existing and non-existing beings or objects	Imitation of human facial expressions and complex gestures with social meaning or modeling basic emotional states and life-like behaviors	To provide company	Communication
Recreational robots			To stimulate engagement in educational process	Positive stimulation through entertainment
Educational robots			To entertain	Enrichment of learning skills
Rehabilitation robots			To recover from injury or to compensate for existing disability	Medical treatment and aids through rehabilitation
Robots with therapeutic potential			To alleviate negative mental states and psychological dysfunction	Therapy of negative states and behaviors

Figure 2: Characterisation of different types of robots, including social interactive robots

A second major distinction is that robots of the class of interactive stimulation artificial creatures are perceived as part of living and imaginary worlds. They exist in the forms of:

- anthropomorphic robots or humanoids;
- robots imitating animals;
- Artificial creatures imitating living beings other than humans or animals (e.g., fictitious creatures).

Important here is the fact that a social robot can be evaluated emotionally and not only functional, since it is a social device. This is off course also true for a “social accepted” movement of a robot. Many authors did this, which is shown in the next section, with different and contradicting results.

3.1.2 Current research activity

This section covers the results of current research in the field of robot motion. It is focused to the question of approaching a person, but also results from other driving behaviours are presented. This is done to cover some extra findings, not found in approaching investigation. Note that most of the shown approaches are using a wizard-of-oz" strategy and so the robot does not drive autonomously, but is remotely controlled.

Scientific papers

One major research group, which was interested in social acceptable navigation and robot interaction, was established within the COGNIRON project. Within this project the group of K. Dautenhahn created some very interesting papers on approaching strategies and also the impressions these strategies had on test users.

Walters:

In his work [36] Walters investigates the comfortable distance humans approaching a standing robot and also the distance users let the robot drive towards them. In all tests the robot gets approached from the front and also approaching the person from the front. It was no special task given to the test persons, so they do not know in which context they have to approach the robot. The results were quite surprising. 60% of all persons act in the predicted way and stopped within the social distance to 45 cm. Surprisingly a large minority of 40% reached up to the close intimate zone.

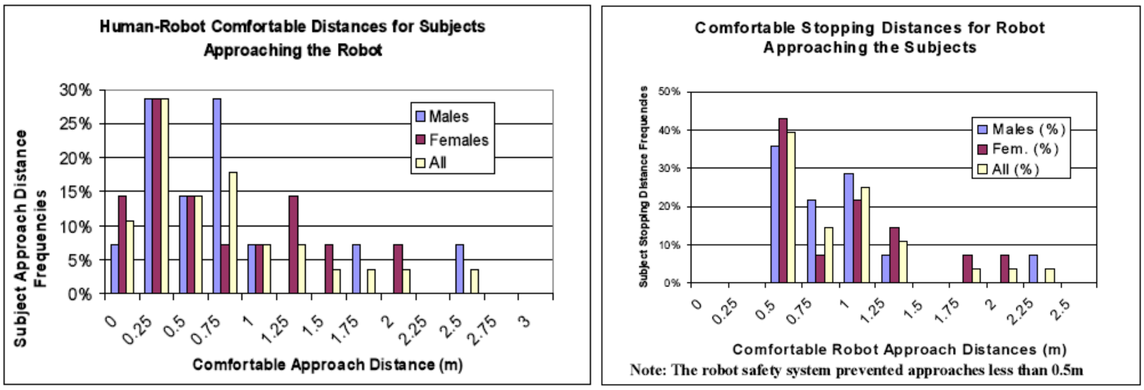


Figure 3: Difference in approaching comfort distances when a person approaches a robot (left) and when the robot actively approaches a person

This effect could not be reproduces when the robot actively approaches a person, because its safety system prevents the robot from driving into the personal zone (below 0.45m). The author examined the personality of these persons (by using Eysenck's three factor model [43]) and found that proactive persons tend to approach in the correct distance (up to the social zone), while others approach nearer. This effect is explained that robots are not automatically seen as social partners and so non-proactive persons seem to observe a robot more as a simple technical device and not a social being.

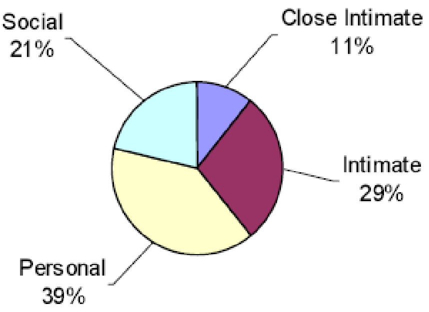


Figure 4: Percentage of persons to approach up to the personal zone (Personal + Social) and which approach up to the close intimate zone (Intimate + Close Intimate)

Dautenhahn 2006:

Another experiment was made by Dautenhahn [44], where a sitting person was approached by a robot from three different directions. Figure 3 shows the setup of this trial. Here the robot was also driven by a remote controller. The approached person should afterwards tell which direction he or she would prefer. The task was to catch a remote control, mounted on the robot.

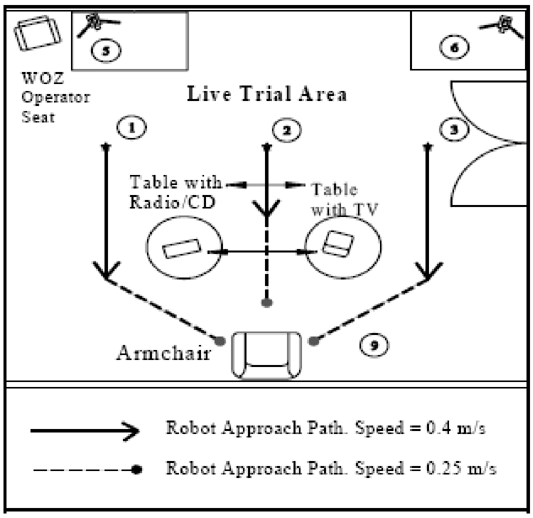


Figure 5: Scenario: approaching from different distances

Surprisingly almost none of the test persons liked to be approached from the front. Almost all test subjects liked to be approached from the right side, while others liked to be approached from the left side. This depends highly if the person is left- or right handed. Also males dislike the frontal approach more than females.

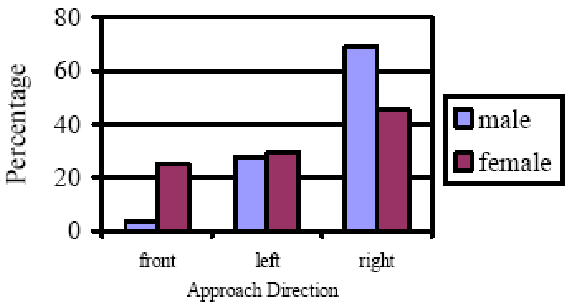


Figure 6: Dataflow diagram of autonomous mode operation

Dautenhahn used approaching speeds of 0.4 m/s and 0.25 m/s. 60% found these speeds appropriate while 40% found these speeds to slow. There are no further investigations on the personalities of these different person groups. Main conclusion of this work was, that approaching a person directly from the front is not observed as a comfortable situation.

Koay 2007:

In the work of Koay[45] the author assembled an experiment, where a robot has to approach a sitting person and hand over an object with its robotic arm. The test users have to select a distance and angle where he/she likes to place the robot for this task and also a point where he/she wants to have the robotic hand to hand over the object. The resulting statistic is shown in figure 7.

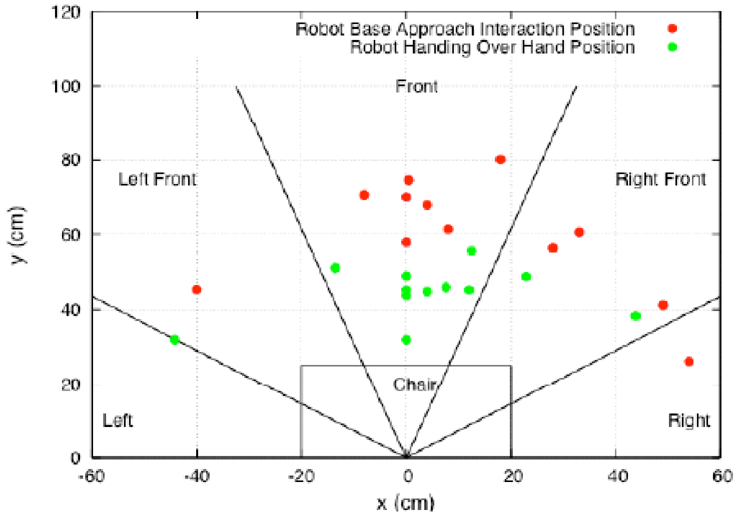


Figure 7: Results from the experiment from Koay, where the preferred robot position and hand position is shown

The results show that most users like to place the robot in front of them and also to hand over the object in front of them. The largest minority likes to place the robot at the right-front side.

Syrdal 2007:

The goal of the now presented work was to show the deficits of the above mentioned psychological and also experimental results. Obviously there are experimental results which support the theory of personal spaces of Hall at least to a certain point [5,6], but in his work [1,2,3,4] he found that the personal space is not a fixed rule but depends on many external parameters. The main critic is that Hall defines its proxemics (the different spaces) only for North Americans and are meant to differentiate different cultures in certain situations. These proxemics do not present a universal rule set especially *not* at human robot-interaction. Even on Human-to-Human interaction they fail, like other researchers showed in field observations [8]. The results depend also on the communication-partner approaching behaviour [9,10], the partners social status[11], gender [7,12] (for example males have a larger personal space than females and react more on intrusion within this space), health, physical attributes like height and weight, personality[13,14], acquaintance, and situation context[7,15].

To demonstrate the flexibility of the proxemics he constructs three experiments, where a robot has to approach a person from front and right front for

- Do no interaction at all
- Speaking to that person
- Handing over a cup

In these experiments the test person has to signal when the robot reaches comfort distance. He did this by letting the person stop the robot actively with a remote stop button (denoted as “person in control”) and by drive the robot to a very near distance where the person has to signal where he or she would have stopped the robot (“robot in control”). He repeated these experiments after 2 weeks and 5 weeks again and does also an assessment to acquire information about the personality of the persons.

It could be shown that personality and gender has almost no impact on the comfort stopping distance when the robot has control of his movement. When the human is in control of the distance personality and gender is important. Persons with a high extraversion let the robot drive near, while others don’t. Also persons with a low conscientiousness let the robot come nearer than others. Males preferred the approaching direction from right-front while females don’t care. So it could be shown that personal spaces vary with personality and gender when the robot is in control of humans. Only the approaching distance does not depend on the mode of operation (human-in-control or robot-in-control).

Also when dealing with different situation, people let the robot come nearer when handing over an object than on pure conversation or on “no-purpose-approaching”. So the dependency of the personal space on situation is demonstrated.

The last point was the repeating of the experiment after 2 and four weeks. Here it could be demonstrated that people let the robot come even nearer the more time goes by. This is mainly caused by the fact that these people get used to the robot. This impact is much more significant than the personality differences.

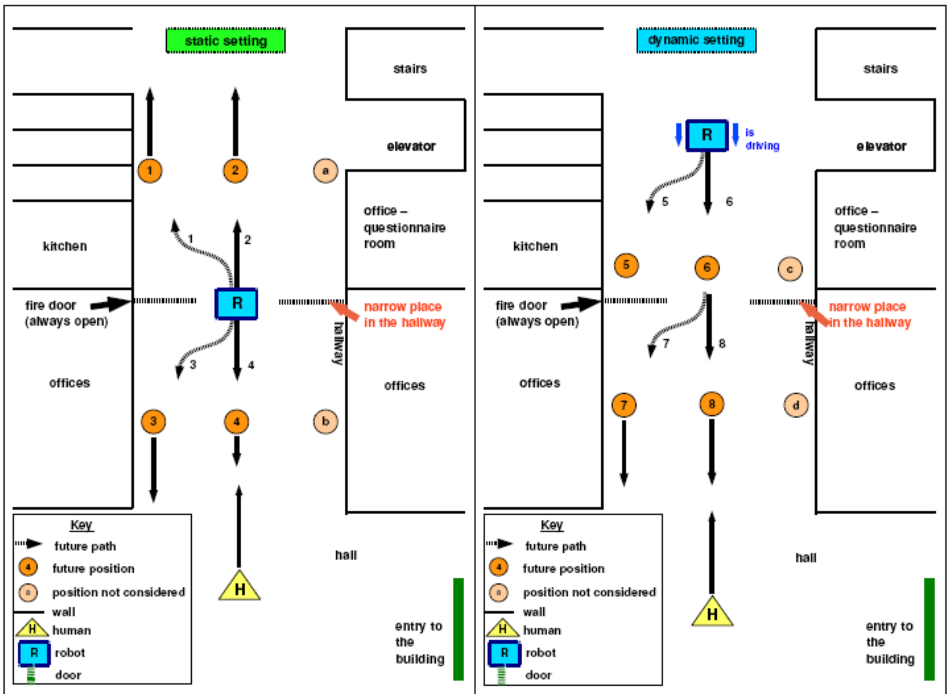
In this work it could be shown that personality, gender and time could (familiarity with the robot) have an impact on the configuration of the proxemics.

At this point we leave the group of the COGNIRON project and continue with several independent authors, also interested in the problem of social navigation.

Peters 2006:

The work of Peters [41] is remarkable in the point of describing the social navigation problem from a communication point of view. Relying on the work of Pacchierotti [17], who states that robots should mimic person behaviours to be accepted as social beings, Peters interprets the process of social navigation also as an act of communication (on non verbal level) [18]. So humans have to send signals to and from other humans to communicate their intention and in term to navigate in the right way. Also robots have to understand these signals and react accordingly to them. He also cites the work of Hüttenrauch [20] where the mutual influence of such navigation processes between partners is analysed. Hüttenrauch called this process “spatial promting”, which means that both interaction partners exchange messages between each other to force each other in “passing-by” scenarios are “make room for me” scenarios to cooperate. These signals are all exchanged within the public proximity, where communication in a classical way does not take place. To examine if this process also happens in social robotics between humans and robots he creates an experiment.

This is done by constructing a passing-by scenario, where the robot could block the path of a person which tries to pass the robot. Therefore the robot can pass a narrow door and blocks it. To avoid blocking several strategies with offensive or defensive, prompting and non-prompting character are constructed. The robot itself is standing in the passive case and can drive backwards and forwards whereas in the dynamic case the robot already drives but could wait until the person has passed the door or drive faster to reach the door before the person passes. The scenarios are shown in figure 8 while the character is shown in figure 9.



(a) not moving robot (b) moving robot

Figure 8: Static (a) and dynamic scenarios (b) for offensive and defensive, prompting and non-prompting passing-by strategies

Unfortunately results are only mentioned from other papers (which is a very weak point of this work). It is only mentioned that it is planned to use movement behaviour, gaze and sound of the human person to interpret his intentions and to decide which strategy to choose. In former works it is told that Butler found that 0.38 m/s and a floating, smooth passing movement is needed to understand the "communication intention" of passing-by by a human. Pacchierotti [19] also found out that a speed of 0.6 m/s and a signalling distance of 6m is needed to transfer the correct "intention". The signal is a drive-to-the-side signal and is only understand, if a lateral distance from at leas 40 cm is reached when passing by.

static social signals	more prompting	less prompting
defensive	1, (a)	2
offensive	3, (b)	4
dynamic social signals	more prompting	less prompting
defensive	5, (c)	6
offensive	7, (d)	8

Figure 9: Classification of the scenarios

Takayama 2009:

A very brief work of Takayama [46] is closely related to the work of Dautenhahn [44]. He starts with the so called media-equation-theory [21,22], which states that people treat computers and other technical devices as social beings and label these devices with human properties, to take a closer look at peoples personalities and experiences when being approached by a robot. He could show that the robots appearance influences the personal space (here the height and the technical look of the robot). This is conforming to the findings of Syrdal. Also the head gaze influences the proxemic space of persons. When at public distance the gaze towards the human head is needed to signal approaching behaviour, in the personal space a gaze toward the head lead in the case of male users to a larger comfort distance between user and robot, while in the female case the opposite is true. The measured difference is only around 10 cm. He also found out that pet owners and experienced users let the robot drive significant nearer, here from approximately 0.5 meters to 0.22 meters. This is also conforming to the work of Syrdal.

Satake 2009 & Bergström 2008:

Both authors work within the same scenario, which tries to approach unknown customers within a shopping mall environment. Here the approaching problem is even harder since the robot has to guess the intention of a customer and, if the robots decide to interact catch the attention of the customer. The approaching behaviour is part of that attention-catching.

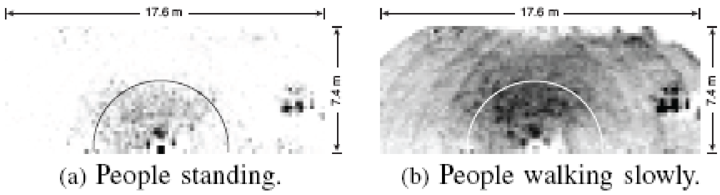
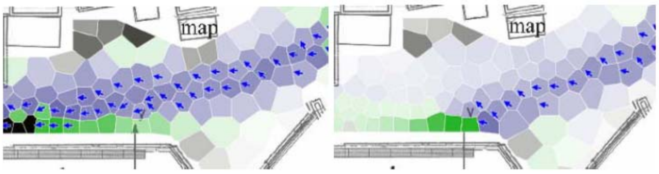


Figure 10: Person density of persons classified as "standing" and "walking slowly"

In the work of Bergström [47] the approaching behaviour is quite simple. The robot has several behaviours with varying degrees of pro-activeness, where the most pro-active behaviour consists of active speaking and looking to a person and afterwards driving to that person until the personal space of this person is reached. But that is not the interesting part: more interesting are the passive behaviours. When the robot is placed within this behaviour it does not drive any more but reacts only on the trajectories of the people. With the recorded trajectories it classifies the activity of the person and was able to build a statistic as shown in figure 10. Within this figure we can see that standing people almost only appear in a semi-circle area around this robot. Maybe by chance this area corresponds directly to the social space proposed by hall. Within the personal space we can observe three hot-spots of high person counts. These are in the front, on the front-left and front-right … quite interesting since this seems to correspond to the work of Dautenhahn and Koay, but with a much larger statistical background. The second observation is found in the picture of slowly walking people. Here the occupied area is much larger being present in all observable areas. But in front of the robot there is an accumulation of people walking slow, which is significantly larger than the rest of the area. Here people walking-by seem to check whether the robot sends some signals of interaction or intention or not, which happens typically in the public space. So both pictures gives strong evidence that the social, personal and public space really exists, and also of the form of those spaces.

The work of Satake [40] deals more with a practical question how to approach a person. It is presented in more detail later in this document. Since this chapter deals with the psychological question of approaching a person, the “lessons learned” of this paper are still interesting. In fact the classify person trajectories to get a value of interaction interest (shown in figure 11). But when they tried to approach potentially interested persons these persons do not react on these approaches. The author proposed a different strategy to drive where the person wants to go instead of where the person is.



(a) A “busy person” pattern (b) A “window shopper” pattern

Figure 11: Different typical motion patterns

The author states that the initial fault was mainly driven by sending the wrong (non-verbally) signals towards the customers. So the robot has always gaze towards the approached person and has to signal its intention:

An “Approach from a robot” is not an easy problem since the robot’s approach needs to be acknowledged nonverbally in advance; otherwise, the approached person might not recognize that the robot is approaching him/her or would be surprised by the robot’s impolite interruption. Humans do this well with eye gaze [23,24]

At this point we finish the detailed view on psychological findings toward human-robot communication in the light of navigation tasks. In the next section a summary will be shown with all theories, contradictions and evidence towards certain theories. Also the impact on the practical work will be sketched.

3.1.3 Conclusions

In the last section a lot of work is shown, which reflects the psychological foundation of the theory of interaction spaces. Up to today this is the most accepted theory around psychologists and robotic researchers also. What was shown in the research work of the last years was the evidence that this sort of space really exists. And also that robots has to be accepted as social beings and so has to follow the implicit (and without doubt very complex) configuration of these spaces. So we have some questions remaining on the psychological view of robot navigation:

- When did people accept a robot as a social being and to what extend?

  ➔ As Walters tells, most people accept robots as social beings, but there is a minority who doesn’t. For example in Friedman [48] it is shown that the AIBO robot dog is treated like a real dog but from a point of moral, it is not accepted like a real dog. The same seems to be true for robots, so there will be users who treat robots as humans and users who don’t. In navigation we have to deal with both.

- Hall’s proxemics model is a foundation, but depends on many external parameters like gender, personality, and situation. Is it still useful?

➔ Since it is the only model we have today: Yes, it is useful but we have to keep in mind that it was developed for the purpose of showing cultural differences and it is proofed that it is too generic to interpret it as a ground-truth rule.

- What evidence of existence do we have? What of non-existence?

➔ There is evidence of existence shown in the work of Bergström[47], Dautenhahn[44], Syrdal[35], Pacchierotti[37], Chen [25], Takayama[46]. Evidence of non-existence does not exist, only contradictions could be shown, like in the work of Dautenhahn & Syrdal (for males), where the robot best approaches from the right, and in Koay[45], where the robot best approaches from the front, just separated by different tasks.

- Is the proxemics model of Hall to simple? What do we have to consider?

➔ Yes, certainly it is. It could be shown that the proxemics configuration depends on a lot of parameters like gender, experience (or time), personality, the situation, and even such effects as spatial prompting [20]. Even age could influence the configuration. Up to today it is unknown how this configuration exactly looks like and how to use it in robotics. In the case of ALIAS, we want consider factors like experience and the situation.

- What situations do we want to capture?

➔ Since the proxemics space configuration is situartion dependant we want to capture the situations of: approaching a sitting person for access to the touch panel, approaching a sitting person for audio chat, approaching a standing person for accessing the touch panel, approaching a standing person for chat. All these configurations should adapt their underlying proxemics model over time.

3.2 Dealing with persons: the difference older people make

When dealing with the question how to approach elderly people, and also reflecting on the known psychological foundations, we have also to consider what it known about the changes aging performs. There is a whole research area concerned about this problem, known as gerontology.

In this chapter an abstract overview of this field of research is given, what key ideas are coming from that domain and what implication we could derive from that work. So let’s start with the foundations of gerontology.

Gerontology discusses the effects of biological and psychological changes when aging. From biology it is known that old people tend to have less flexibility in their movement, less muscular power, less information processing speed and a higher morbidity (they become ill more often). On this (rather pessimistic) finding the psychologists state the questions: “Are old people more unhappy than younger’s?” The simple answer is “No.”, the more specialized answer is “It depends”. Havighurst [31] creates a theory of developmental tasks:

> A developmental task is a task which arises at or about a certain period in life of the individual, successful achievement of which leads to his happiness and to success with later tasks, while failure leads to unhappiness in the individual, disapproval by the society, and difficulty with later tasks.

These tasks are closely coupled to biological development, social and cultural environment and the own personality. If these tasks could still be fulfilled, independent of the effort or way to solve, a human being is happy. There are developmental tasks within the human life time and these tasks are the “inner motor” of human beings, also of old people. We are focusing on the group of people beyond 61 years. Havighurst defines the following tasks:

Development Tasks (as of Havighurst)	
Life span	Development Task
Youth (0 – 19)	Autonomy from parents, identification with the gender-role, internal moral consciousness, choosing the profession
Early adulthood (19 – 29)	Marriage, birth of children, work and profession, choosing own life style
Mid adulthood (30 – 60)	Managing home and household, raise and educate children, professional career
Late adulthood (61 +)	Find new fields of activity, accept own life line, engage with thoughts on death

Table 2: developmental tasks of Havinghurst

If these tasks are reachable a person is considered happy. It can be seen that the focus of tasks changes significantly when aging.

To fulfil these development tasks people have to use their available resources like intelligence, physical fitness, sensory ability, social and cultural framework, and financial power and so on. When getting older some of these resources are getting worse, like intelligence, sensory ability and physical fitness, while others increase like decision-making and experience. It is told by Martin [33] and Lehr [32] that these missing resources are compensated with other resources when getting older. So not only the developmental tasks are changing, but also the ways these tasks can be reached. And because of such a wide spectrum of disabilities also a *wide spectrum of compensation mechanisms exists*. This is quite an important issue when dealing with old people. A potential robot has to support multiple ways to get a goal reached and should deal with the disabilities. In the face of navigation this is mainly the physical inability and the unwillingness to accept new devices. Any cognitive level should not be influenced since the navigation “communication” signals are very low level and common understandable.

But how is happiness achieved when aging? As we showed the tasks are changing and also a compensation mechanism happens. As Baltes [49] told in his theory of the “third and fourth age” happiness occurs as long as disabilities could be compensated, which happens in the third age. Here mainly cognitive and physical impairments are compensated by more social and cultural activities like family care, physical and cognitive stimulation training. Only when the amount of disabilities can not be compensated old people start to be uncomfortable, depressed and unhappy and are mostly suffering from dementia. He defines this state as the fourth age. So the goal should be to stay as long as possible in the third age stage. This is the core problem also in robotics: How to manage this?
There are two theories how this could be achieved: the Activity-Theory from Havighurst and the Disengagement Theory from Cumming & Henry [50].
The main point of the Activity-Theory is that successful aging depends on the amount of activity an old person can keep, that this person can have still a good performance in doing things and that these things are accepted in a social context as useful work. At least the person has to have this feeling to stay happy.
The Disengagement Theory states the opposite: old people become less engaged in social activity, concentrate more on their own lives and only stay in contact with a core group of

their social contact (like family and close friends). This leads to a higher satisfaction when getting old because now they have the feeling of letting things run, do not have to bother on any activities ongoing in the world and leave the field of activity to others. This is also one explanation why old people do not accept new things in their environment.

So what conclusions could we draw from these gerontological results? One is: there are disabilities when getting older and they are compensated in practical life by “workarounds”. The robot has to accept these disabilities and support the workarounds, which means in the context of navigation to reflect the low mobility and the need of more space when moving. The second conclusion is: old people do focus more on themselves and do not accept new devices as easy as mid-age people (or children) do. So we have to adapt the behaviours of approaching distance more slowly and drive more patiently.

3.3 Approaching persons: a methodical view

This subchapter reflects the known methods how to approach persons in general. It is not focused on approaching persons in home environments but in any environment.

Scientific Papers

Robots will become more and more common in human centred environments, like hospitals, schools and at home, in the near future. For a robot to operate successfully in human-centred

Wong 1995:

A very early work in approaching a person is the work of Wong[51], which uses camera and sonar sensors to detect a persons and approaching this person up to a given distance. The visual person detection is simply done by a color clusterer, filtering only those pixels corresponding to the upper body color. This cluster is enclosed with a bounding box. In the direction of the bounding box the distance measurement of the sonar system is used to approach to a certain distance. After approaching a neural-net-based classifier is used to detect the identity of a person.

Hu 2007:

These kind of approaches are developed over time and on of the most actual approaches is presented by Hu[52]. Here also a camera image is used to detect the upper-body pixels. This time this model is adaptive over time and modelled by a mixture of Gaussians. In this way also a bounding box from the upper body is extracted. Afterwards the bounding box is used to perform an head-shoulder-silhouette search.

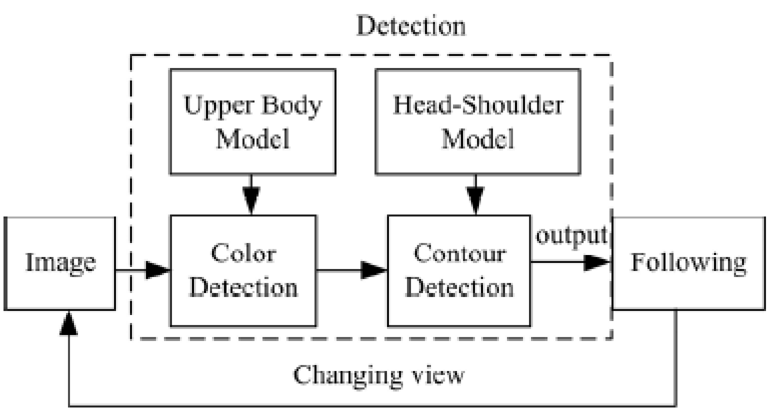


Figure 12: Detection scheme for visual person detection

The width of the matched silhouette and the deviation from the image centre is now used for driving control to centre the robot view to the person and allow a given width. This procedure is called “visual servoing” and is a well known technique to use information from image space to control a robot in 3D space. There are various other works in this field, all differ in the method of extracting persons in the image, on which feature a control is calculated and what kind of controllers are used. For example in [53] the above algorithm is extended with a fuzzy controller. The benefit is that these techiques do not require a projection form image space into 3D space to create a control command. The drawback is the control on a very coarse level and the computational burden to detect (in a sophisticated way) the person in the image.

Figure 13: Upper body bounding box and shoulder contour from different views

Pacchierotti:

In his work Pacchierotti [37] tested the influence of a passing by scenario, not an approaching scenario. The results where already shown in section 3.1.1 (passing by works best with a signalling distance of 6 meters and a lateral distance of 0.4 meters). Here only the simplicity of the method to pass a person should be shown. When a person is detected (6 m beforehand) the robot drives to the right side of the corridor until the person has passed. This is done by spline interpolation of the original strait path. Here a new point is set on the right side of the corridor, where one coordinate reflects the required lateral distance and the other coordinate reflects the 6 meters signalling distance and also depends on the speed. Afterwards this changed path is followed by the robot and the robot automatically returns to the previous path when the person is passed. When two or more person are approaching this method fails.

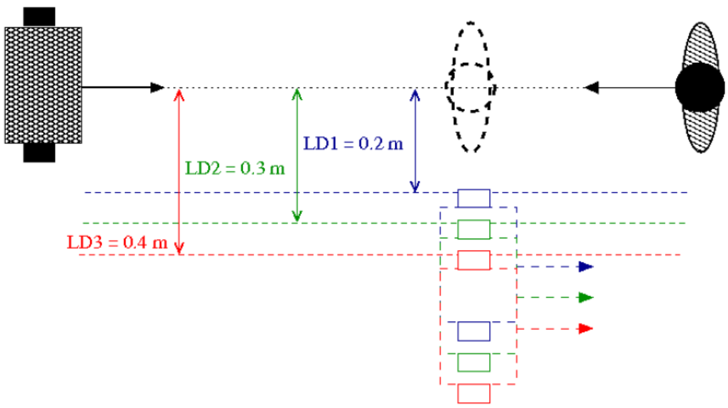


Figure 14: Robots passing trajectory on different lateral distances

Höller 2007:

Another interesting approach is presented by Höller[54]. The task of his robot was to follow a person, which is very similar to the task of approaching a person. To do so, also regions around the person are defined. Instead of defining these regions in front of the person, these regions are defined in the back (this time without taking notice of the qualities proxemics implies and by just using heuristic definitions). These regions have different priorities and when one region is blocked by an obstacle the next region is chosen.

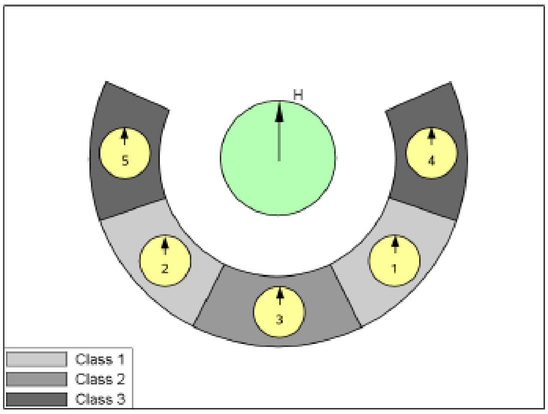


Figure 15: Target regions to follow a person. Regions own different priorities.

But this is not the interesting part of the paper since such regions are described more plausible in Anderson [55]. Interesting is the way the path (and motion) is planned towards any of these regions. A common strategy to control the motion of a robot is the dynamic window approach [58], which is described in greater detail in the next chapter. This approach finds an optimal motion command for the next time step only and can be augmented with multiple properties to influence the driving behaviour. The main drawback is that planning over multiple time steps is a huge computational burden and so complex sequences of motion command cannot be planned in real time. The approach of Höller presents a way to do exactly this by using a so called “expansive spaces tree” [27][26][28][30]. This tree is calculated in the configuration space of the robot, which is its position x,y,ϕ and its rotational velocity V_{rot} and its translational velocity V_{trans}.

It basically draws some samples from the same domain V_{rot} and V_{trans} like the dynamic window and predicts a set of robot configurations for the next time step. This set of new configurations are the leafs of the tree. Now a heuristic is used to expand the most promising nodes, like it is done in A* [29]. So this approach uses, unlike the dynamic window, a directed search to find a good motion command. This way the tree grows in configuration space towards the goal configuration x_g,y_g,ϕ_g, V_{rot_g}, V_{trans_g}, which corresponds to the target region. The transition from node to node is calculated by using a physical correct robot motion model. So time is implicitly represented within this tree. This can also be used to include knowledge of moving persons to avoid future collisions, when their predicted trajectories are known.

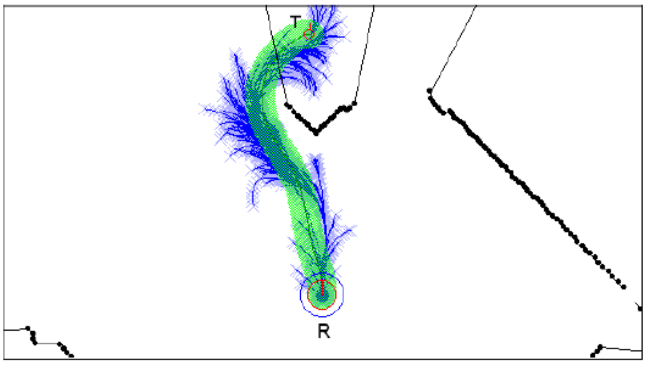


Figure 16: Example of an expansive spaces tree

Another positive property of such an approach is the any-time property. So when there is no time to calculate the full tree until the target region is reached, search can be stopped at any time and the optimal path through the tree up to the known best configuration can be used to generate the next motion command. A great benefit of this approach is also that motion planning and path planning has effectively been merged to one approach.

The authors also presented an idea how to predict the motion of known persons to include this knowledge in the expansive spaces tree. This is important when the robot should try to follow a person and also should avoid other persons. The movement prediction is done by using the information of the local obstacle configuration plus the position and speed of the person to predict the motion. From this knowledge a potential field is constructed where all obstacles and the person have a positive potential. The goal has negative potential. Since it is unknown where the person's goal is, the authors assume a perpendicular line to the persons speed vector few meters in front of the person, as the goal the person wants to reach. The goal has negative potential, so the person gets attracted towards the goal and pushed away from other obstacles. The persons speed does not change while moving through the potential field towards the goal, so a good local trajectory estimation can be achieved with including not only the person speed and moving direction, but also the local obstacle configuration. The results of such a prediction step are shown in figure 17.

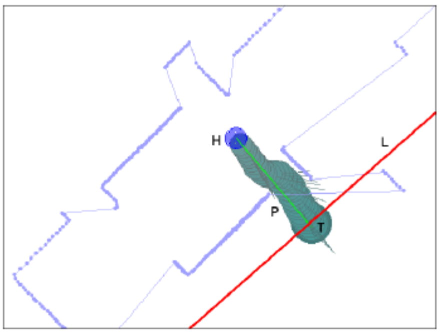


Figure 17: Predicted trajectory of a moving person by using the potential field method. The red line is the negative attraction potential.

Andersen & Svenstrup:

The work of Andersen[55] & Svenstrup[56] is quite interesting, since these two authors model the approaching process with different parameters. They state that the approaching of a person is equal to a minimum-cost path within a scalar field, reflecting the "social acceptance" of a robot driving through this area. An equal approach was shown within the work of Sisbot [57], but not modelled as complex as this approach.

Core idea behind a universal formula, describing the social space, are the findings from different other authors. So the lateral distance, the frontal and backward distance (the persons view direction has to be known) and the persons interest into a dialog, are considered. Also an attractor is defined, which can be adjusted to give the robot information to which extend he should approach a person or avoid these person.

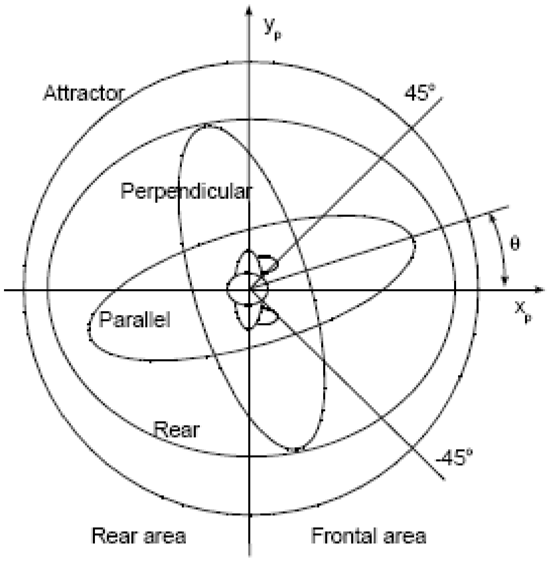


Figure 18: Different aspects that model the personal space from Andersen & Svenstrup

All parts of the function are modelled as simple Gaussian distributions, weighted, added and normalized together, so a simple Multiple-of-Gaussian approximation is done. Only the frontal area of -45 degree to 45 degree is modelled in radial coordinates and not with a Gaussian. The effect of changing the parameter "person interest" PI is shown in the figure below. It can be seen how the personal space changes with the situation of "not interested" on the right side to "very interested" on the left side.

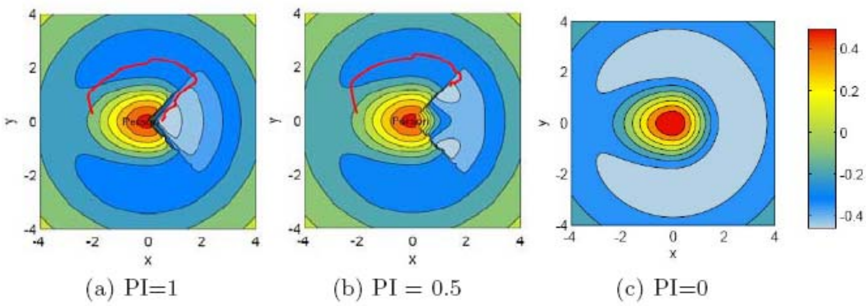


Figure 19: Form of the personal space function, depending on the person interest (situation)

Also the path from the current robots position to the minimum of the personal space function is shown (red line). Here standard algorithms like E-Star [59] could be used to find this path. Only the search for the minimum has to be done here. The authors present some experimental results on how this parameter influences the driving behaviour of the robot. Since the persons pose is known and changes over time the next motion step and the path has to be re-planned each time step to reach the minimum of the personal space function. Results are shown in figure 20.

The results are quite interesting. While no interest is shown the robot drives in a safe distance of 2 m beside the person. When a slide interest is shown the robot tries to drive 45 degrees left or right in front of the person. When interest is sure the robot drives in front of the person.

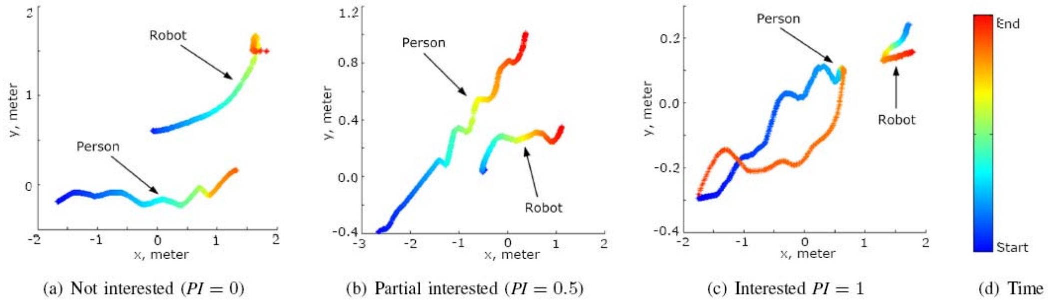


Figure 20: Results from approaching results with different levels of interest

Bergström & Satake:

While the work of Bergström[47] focuses more on "How to behave to catch the interest when the robot is more or less immobile" it only implements a very simple approaching strategy. Here the most "aggressive" behaviour to catch the interest of a customer, was to drive strait to the person of interest and stop at the distance of the social space (3,6 meter).

Satake[40] was more concerned on how to approach customers who are moving (even away from the robot). In his work he showed that a simple approach to drive to a position in front of the person, like it is done in the work of Andersen & Svenstrup, is not sufficient, because most people did not recognize that the robot is approaching them or are very uncertain about it. That's why he states that it is not only important to reach a certain point, but also the time this point is reached is important.

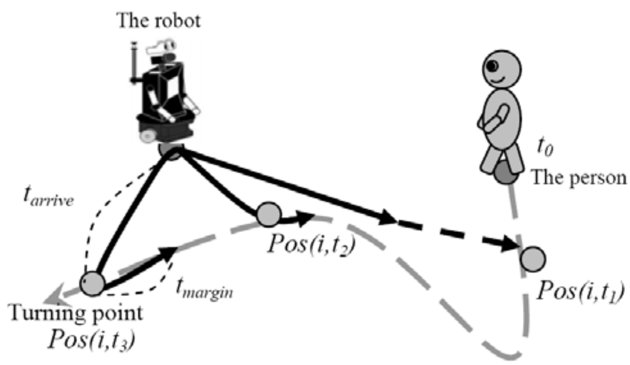


Figure 21: The approaching strategy of Satake, which uses time and the estimated trajectory

He proposed a method to create a path that uses the estimation of the person trajectory to cross this trajectory before the person reaches that point and also to have enough time to turn towards that person. It is also mentioned to focus the person to signal an approaching behaviour.

3.4 Conclusion

Psychologists told us that

a) there exists a proxemic configuration, which handles our social interaction and bears some meaning because different communication acts are signalled in different spaces

b) that the configuration of this space is highly dynamic and depends on situation, gender, personality, social status and familiarity with the interaction partner

c) old people tend to adapt to new devices very slowly and like more to have long known behaviours and environments

So a polite behaviour is characterised by keeping within the conventions of the space configuration. It also implies that there has to be a model of this space within the robot knowledge.

When dealing with real implementations on approaching a person, the findings from psychologists are translated to real mathematical models. On class, which represents the majority, constructs artificial regions & rules by defining threshold and are in fact user designed and static. The work of Satake tells us that we do not have to consider a static setting, but time has to be taken into account when approaching persons. Also time is important when avoiding persons. How this can be handled in an elegant way is shown by Höller. At last only in the work of Andersen & Svenstrup a dynamic and rather sufficient configuration of the personal space is shown. This has to be connected to motion planning methods in an elegant way.

So almost all needed pieces and aspects are shown in this chapter. In the next chapter three different strategies are shown how all aspects could be connected into one consistent approach to approach a person in a polite manner. Only the effect of navigation with aged persons is not considered in previous robotic work and has to be examined within the ALIAS project.

4 Planned realization of approaching strategies

This chapter sketches the concrete approaches which are used to approach a person. When speaking of approaching a person we mean a sitting person and a standing person. We also consider different situations, where the person has to reach the robots touch screen (like browsing in the internet) and where the robot has to reach the person just for audio conversation (like on reminding of something).

The chapter is structured as follows: in the first part we are discussing prerequisites, which have to be established to create an approaching behaviour. In the second section we are discussing strategies depending on the methods of the dynamic window approach[58], the reinforcement learning approach[60] and the expanded configuration space tree[27] approach, found within the state of the art search.

The goal is to test all of these approaches and compare the strengths and weaknesses of them. This will be the key point of the deliverables D6.3 to D6.5, where experiments and their results are presented.

4.1 Required functionality

To interact and navigate in the presence of persons, three major problems have to be considered. First the robot has to know where the person currently is. Second the robot has to know how this persons pose is (if he/she is sitting or standing and to which direction he/she is viewing) and third what the next future movements probably be.

None of these prerequisites are covered within the ALIAS project, so we have to choose already known solutions to have a state of the art system. We present what approaches should be used to solve each of these problems to have at least a solution to work with and to be able to create real world experiments.

Person recognition & person tracking

When dealing with person tracking we have to focus first on the sensors provided by the robot. These sensors are a 2D laser-scanner, parallel to the ground plane, and a single fisheye camera. Both sensors can give hypotheses where persons may be. The tracker has the task to fuse all hypotheses coming from both cannels.

To detect persons via 2D laser scanner we plan to use the detection algorithms used within the ROS framework of willow garage (ROS = robot operation system). It has the advantage that it is already implemented and free, so we can re-use most of the code for our own tracker. But how does this tracker work in its laser based part? (described in [61])

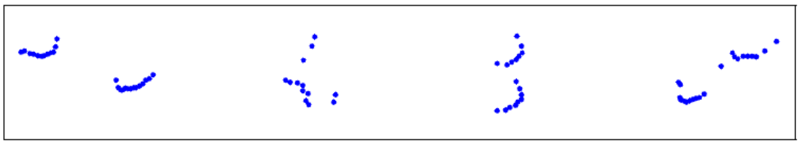


Figure 22: samples of leg pairs with different appearance

First the whole scan, consisting of a sequence of measurements $M=\{(\phi_1,\rho_1), (\phi_2,\rho_2),\ldots, (\phi_n,\rho_n)\}$, where ϕ_i is the scan angle and ρ_i is the measured distance, is clustered into segments S_i. This is done by subsequent comparing the distance measures and when the difference reaches a threshold a new segment starts. From these segments features are extracted and afterwards classified with an AdaBoost classifier. Feature calculation and classification is done within Cartesian coordinates. There are 14 features defined.

1. Number of points in Segments: n = $|S_i|$
2. Standard deviation: $\sigma = \sqrt{\frac{1}{n-1}\sum_j \|x_j - \bar{x}\|^2}$
3. Mean average deviation from median:

   $\varsigma = \frac{1}{n}\sum_j \|x_j - \tilde{x}\|$

   with $\tilde{x}$ the median of the point set
4. Jump distance from preceding segment
5. Jump distance from succeeding segment
6. Width: the Euclidean distance from first and last point
7. Deviation from optimal fitted line:

   $s_l = \sum_j \left(x_j \cos(\alpha) + y_i \sin(\alpha) - r\right)$

   where α and r are the regression results
8. Deviation from optimal fitted circle: Here we have to determine first the optimal circle, given a set of points P derived from M: P = $\{(x_1,y_1),(x_2,y_2), \ldots , (x_n,y_n)\}$ with $x_1 = \rho_1 * \cos(\phi_1)$ and $y_1 = \rho_1 * \sin(\phi_1)$. To estimate the optimal circle (in the least squares sense) we have to solve the following equation system:

   $$x = \begin{bmatrix} x_c \\ y_c \\ x_c^2 + y_c^2 - r_c^2 \end{bmatrix} \quad A = \begin{bmatrix} -2x_1 & -2y_1 & 1 \\ -2x_2 & -2y_2 & 1 \\ \vdots & \vdots & \vdots \\ -2x_n & -2y_n & 1 \end{bmatrix} \quad b = \begin{bmatrix} -x_1^2 - y_1^2 \\ -x_2^2 - y_2^2 \\ \vdots \\ -x_n^2 - y_n^2 \end{bmatrix}$$

   Here x_c and y_c denote the centre of the circle and r_c denoted the radius. Since A*x = b is almost always an overdetermined system it cannot be solved directly but only in a least square sense by using the pseudo inverse:

   $$\mathrm{A} \cdot \mathrm{x} = \mathrm{b} \quad \Rightarrow \quad \mathrm{A}^\mathrm{T}\mathrm{A} \cdot \mathrm{x} = \mathrm{A}^\mathrm{T} \cdot \mathrm{b} \quad \Rightarrow \quad \mathrm{x} = (\mathrm{A}^\mathrm{T}\mathrm{A})^{-1} \cdot \mathrm{A}^\mathrm{T} \cdot \mathrm{b}$$

   And once the circle parameters are estimated we can also calculate the deviation from the circle:

   $$s_c = \sum_j \left(r_c - \sqrt{(x_c - x_j)^2 + (y_c - y_j)^2}\right)^2$$
9. Radius of the fitted circle r_c.
10. Boundary length of the segment: $l = \sum_j \sqrt{(x_j - x_{j+1})^2 + (y_j - y_{j+1})^2}$
11. Boundary regularity: The standard deviation of the distance between consecutive points in the segment
12. Mean curvature: the mean curvature each triangle of consecutive point triples has
13. Mean angle between consecutive point triples
14. Segment speed for consecutive time steps

Now these features are classified by using the random forest classifier, if a leg is present or not. All leg hypotheses are tracked over time by using a simple 4D Kalman filter to estimate the legs x,y position and also the x,y speed.

The ROS tracker uses also other channels like stereo vision but we cannot use these sensors and have to adapt the tracking framework at this point. Instead we are planning to use another visual queue to also solve the question of pose estimation: the also free available AR-Toolkit (which stands for augmented reality toolkit).

The AR-Toolkit is able to track artificial markers in 3D space with also estimating the perpendicular vector of the area plane. This does not only give the 3D position of the marker in space but also all three rotation angles of the plane. So we can also use this approach to track virtual “viewing directions” of such a plane. Because of this property we will describe the algorithm in the next section in more detail. Here we will only state that the person has to wear such a marker pattern used by the AR toolkit to enable the visual detection channel. This channel is fused with the hypotheses coming from laser tracker channel by using the previously mentioned Kalman filter framework. Here correspondences between the Gaussian hypotheses have to be found and when established the hypotheses can be fused using the Kalman filter update equation.

Pose estimation

This section covers the detailed description of the AR Toolkit, as described in [63], to track artificial patterns in the environment. Since pattern recognition is very robust we use this technique to simulate the pose of a head, an upper body, and by tracking two patterns we are even able to recognize if we are viewing the front side or back side of a person.

Like the laser based leg detector, the pattern detector is also free available software. On the first stage Kato relies on the extraction technique of [64] to find black rectangular regions on white backgrounds. These rectangles are known in size.

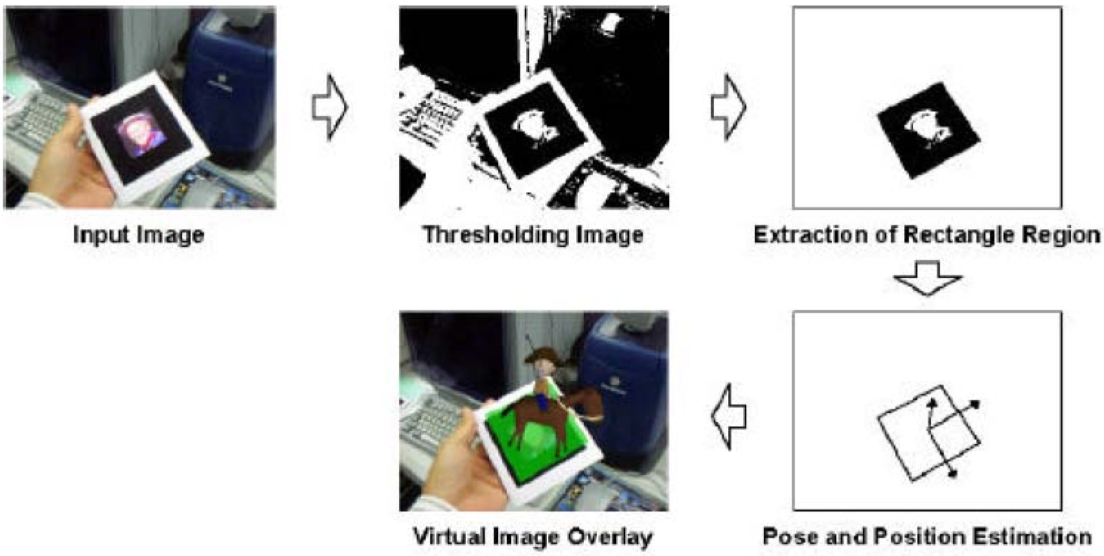


Figure 23: the processing chain to extract the 3D position of a black rectangle on white background

With the four corner points and a calibrated camera it is possible to estimate the 3D position of the rectangle in camera space.

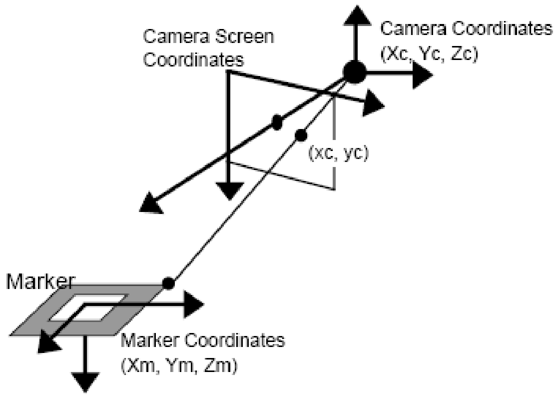


Figure 24: the different coordinate systems of marker detection

In the first step all regions in the image are detected that could be enclosed by four strait lines and witch are supposed to be rectangular. So opposite edges are parallel and have to different line approximations (due to perspective projection).

$$a_1 x_c + b_1 y_c + c_1 = 0$$
$$a_2 x_c + b_2 y_c + c_2 = 0$$

Here a_1, a_2, b_1, b_2, c_1, c_2 are the line parameters in image space. Via previously made calibration we can project each 3D point within the camera coordinate system to the image plane.

$$\begin{bmatrix} hx_c \\ hy_c \\ h \\ 1 \end{bmatrix} = \begin{bmatrix} P_{11} & P_{12} & P_{13} & 0 \\ 0 & P_{22} & P_{23} & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix}$$

With that transformation we can reformulate the above line equations to:

$$a_1 P_{11} X_c + (a_1 P_{12} + b_1 P_{22}) Y_c + (a_1 P_{13} + b_1 P_{23} + c_1) Z_c = 0$$
$$a_2 P_{11} X_c + (a_2 P_{12} + b_2 P_{22}) Y_c + (a_2 P_{13} + b_2 P_{23} + c_2) Z_c = 0$$

The variable h can be eliminated here.

Finally the goal is to find the following transformation matrix, which could calculate the camera specific 3D coordinates of the four corner points, and so also the normal of the patch.

$$\begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix} = \begin{bmatrix} V_{11} & V_{12} & V_{13} & W_x \\ V_{21} & V_{22} & V_{23} & W_y \\ V_{31} & V_{32} & V_{33} & W_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} X_m \\ Y_m \\ Z_m \\ 1 \end{bmatrix}$$

Trajectory prediction

Many authors deal with the problem of movement prediction of persons, some on long term and some on shorter time intervals. Some well known approaches are coming from Bennewitz [62], who clusters motion patterns with the EM algorithm into clusters of dimension K and estimates a probability distribution over these patterns to use them in navigation and also to estimate the future movement. These patterns are specific for specific places and are therefore coupled to these. Kanda [65] also classifies trajectories into different classes like “being in a hurry” or “relaxed shopping” and afterwards builds distributions on which persons with a special purpose are more likely to walk certain paths. This is also very dependant on the location. Both approaches need to build statistical models and have to observe each place a lots of times (with person being inside these places) to create those models and are in no way out-of-the-box approaches. Another approach comes from Höller [54] and does not require previous observations. It could also use the current obstacle configuration and person movement to predict the motion of a person. The approach is described in more detail in chapter 3.3. Unfortunately code is not available free, but we plan to re-implement this approach to use it on the robot.

All presented prerequisites are important to start with the task of approaching a person. Since they are not within the focus of development they will be only implemented with all constraints and weaknesses. But up to now we think they are appropriate to create useful experimental data. In the next sections we focus on the different approaches, how the problem of approaching a person could be solved with having working prerequisites in mind.

4.2 The dynamic window approach

One of the most successful motion controlling strategies is the so called “dynamic window” [58].

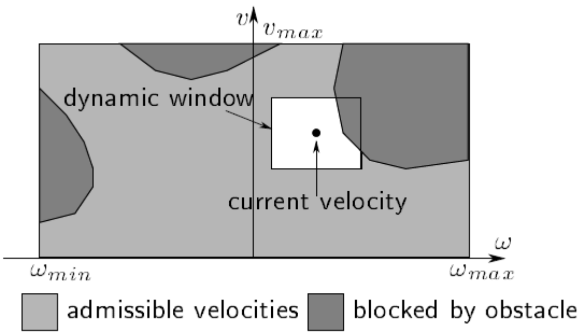


Figure 25: the dynamic window

It defines a window inside the possible action space (sometimes also called configuration space), which means rotational speed V_{rot} and translational speed V_{trans} for our robot. The window defines a physical plausible window around the current speeds. It is constrained by the maximal available acceleration and maximal deceleration. From this window samples are drawn for the next possible actions to take. Normally these samples are aligned in a regular grid within the window. Now each of these samples is checked, whether a collision will occur after driving a certain amount of time with the chosen speeds or not. If a collision is possible this sample is "not admissible". Else further evaluations are done with this action like: does this action reduce the distance to the target? , do the robot head towards the target after finishing the action? , is the robots speed appropriate?, is the distance to the next obstacle to small?. All these parts are called "objectives".

All these decisions are expressed by a single scalar value and for each action all values are summed up weighted and the best possible action is chosen by this sum over all possible actions. After executing the action the window is centred towards this action and the process restarts. Key point on action selection is a search for a local optimal solution by construction an evaluation function.

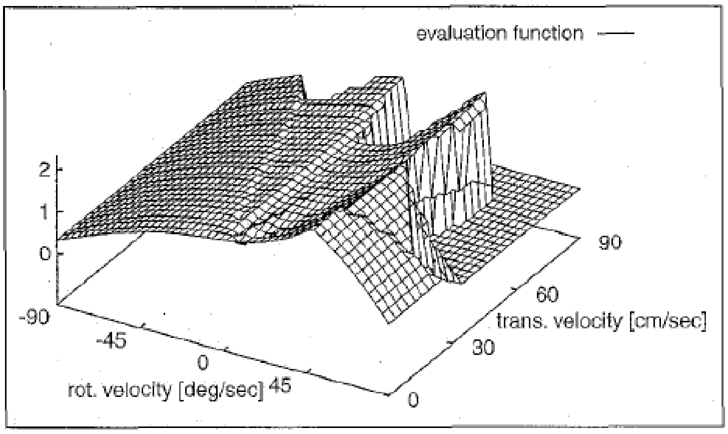


Figure 26: the resulting evaluation function with all objectives

4.2.1 The approaching strategy

First of all we have to participate to that evaluation function. It already includes objectives for following a path and reaching a target, controlling the speed and avoids collisions. We want to add an objective to approach a person. To do that we need a function which describes what position is feasible and social acceptable when the pose and position of a person is known. In the approach of Anderson & Svenstrup a parametric function is shown which positions are good positions and which are not.

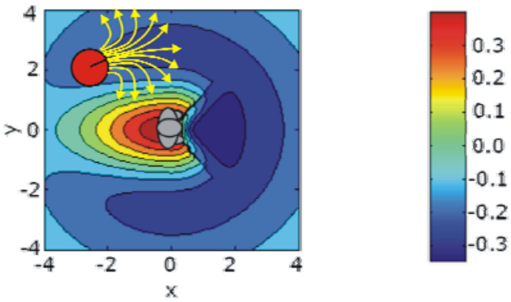


Figure 27: example of one dynamic window step and the proposed evaluation function

With such a given configuration we can now determine what a good action is, and which action is not. As shown in the figure above, each action (within the dynamic window) leads to a different motion trajectory and to a different position. The value of the "social acceptance" of that position can be directly used from that function, which leads to actions driving the robot towards the global minimum, if the function is monotone descending towards the global minimum.

Since we cannot guarantee this behaviour we have to treat this task more like a planning approach, where a minimum cost path to the global minimum should be found. So the global minimum has to be found first. After this target position is found we have to solve a full planning step to find the *optimal* path. Path planning solutions like E* could be easily used for that step but could be time consuming. It is a common trick, used in path planning, to switch to a directed search by using so called heuristics. This allows the directed search for paths which are more likely to be a short path and suppressing these paths which may not. A common heuristic is the Euclidean distance to the target.

With the heuristic our approach can be formulated as follows: the dynamic window proposes a set of actions $A=\{a_1,a_2,\ldots,a_n\}$. After a time Δt these actions lead to a set of new positions $X = \{\mathbf{x}_1,\mathbf{x}_2,\ldots,\mathbf{x}_n\}$. These positions can be evaluated with the personal space function $\boldsymbol{P}$, leading to a set of evaluation values $V=\{\boldsymbol{P}(\mathbf{x}_1),\boldsymbol{P}(\mathbf{x}_2),\ldots,\boldsymbol{P}(\mathbf{x}_n)\}$. When this function is not monotone descending towards the global minimum (for example when the robot is far away from the person and the function is almost completely flat) the robot may move to the wrong direction, because $\boldsymbol{P}$ is identical in many positions $\mathbf{x}$. This is mainly caused by the problem that the dynamic window optimizes only locally. When there is no local optimum the dynamic window fails. This effect could be overcome by planning a full path until the global optimum is reached (but this is not a dynamic window approach any more) or by using the heuristic. The latter case is quite simple, we simply add the Euclidean distance to the goal to each of the evaluation values, resulting in an altered set $V'=\{\boldsymbol{P}(\mathbf{x}_1)+|\mathbf{x}_1-\mathbf{x}_g|,\boldsymbol{P}(\mathbf{x}_2)+|\mathbf{x}_2-\mathbf{x}_g|,\ldots,\boldsymbol{P}(\mathbf{x}_n)+|\mathbf{x}_3-\mathbf{x}_g|\}$. From path planning it is proved, when using heuristic which *underestimates* the real costs, an optimal path could be found. This is true if planning is done until the goal is reached. Here only the first step of planning is done and the next will be done in the next time step. So only a possible global sub-optimal action is chosen, but anyway a directed movement could be guaranteed and the problem of equally good actions overcomes.

So we have a twofold strategy here. In the first step we use a one-step planning and the personal space function from Anderson & Svenstrup, directly supporting the dynamic window in a natural way. If experiments show failures because of global sub-optimality, a full planning approach (like E* [59]) will be established.

Another property to consider is the time variance of the personal space function. Since this function modelled as a mixture of Gaussians, the variance parameters can be seen as a function of time and in this way a time variance could be included. Also the pose (sitting or standing) of the person will influence these parameters.

4.3 Reinforcement learning

Reinforcement learning is an unsupervised learning paradigm inspired by biological systems. The key idea behind reinforcement learning is the power of reward and punishment given as a direct feedback from the environment. It states that all learning systems do initially not know what actions are useful to them and what not. But all learning systems have mechanisms of reward, like the human system of dopamine, and punishment, like pain. These systems are stimulated directly from the environment and are effectively used to learn. Formally this is done by defining a reinforcement function, which gives the reward and punishment. The system itself has to realize in which state it is and what actions in this state results in reward (even in the far future) and which actions lead to punishment. One famous approach to model these state-action pairs is Q learning [60] , where a so called Q function is learned over time, which gives the system exactly the information over long term reward (or punishment) when certain actions are executed. The formulation of this Q function ranges from a simple table to complex representations like neural nets [66].

There are different policies to act upon this function, like a greedy policy which always prefers the expected maximum reward action, or random policies to explore all possibilities of reward and punishment.

There are several problems known to reinforcement learning. One problem is the initially “idiotic” system, which shows no intelligent behaviour at all. The system has to explore its environment and the possibility it has. The question when to explore and when to stop exploration, because enough knowledge is accumulated to solve the problem, is not solved today. Also the question in which state the system currently is, is not easy to answer. The system has to collect a lot of sensor information to even answer that question and has to use this information afterwards to start teaching itself what action are appropriate within these states. So reinforcement learning can expose a lot of smaller problems. Another drawback is also the unpredictability of the result. If the system misses some states or action, it may work sub-optimal or unpredictable. Nevertheless it is an interesting approach and should be used to compare a learning approach against the highly predictable approaches presented in 4.2 and 4.4.

4.3.1 The approaching strategy

The whole behaviour of the system is defined by a) the state estimation, b) the actions to be taken, c) the reinforcement function. Here we also want to approach a person, relying on the personal space formulation of Anderson & Sutton. But we have to define the state of the system first, which is in this case the direction to the person, the distance to the person, the robots translational speed and the robots rotational speed. Actions are defined also as combinations of translation speed and rotation speed.

Core of the problem solution is the reinforcement function. This function will give a positive reward when a robots position near the global optimum is reached and a negative reward when regions are approached which are socially not acceptable. Also impossible actions are punished. Collisions are handled outside the reinforcement learning approach, since these are creating a very high dimensional system state when being considered. This is done by masking out actions which lead to collisions. This improves the security of the system and also the real world testability.

Here also the parameters of the personal space will be changed over time and depending on the person pose. For each pose (sitting, standing) a different Q function will be used. It is assumed that the Q function will adapt automatically to the changed parameters of the personal space function.

4.4 Expanded-spaces tree

The approach of expanded space trees is the consequent improvement of the idea of the dynamic window [26,27]. While the dynamic window creates its movement commands only on considering the next time step, the expanded space tree calculates the consequences of movement over a whole series of motion actions. It plans the motion in the so called configuration space, where the robots pose and the robots speeds are defining the configuration. Like the dynamic window it draws also samples from reachable speeds and created new system configurations by extrapolating this movement in time. These single configuration samples (which grow over time through the space) are the nodes of the tree (see figure 28). Only possible movement are calculated from the current node and the tree is expanded in this way. The nodes also have costs associated to them. If a motion leads to a collision the costs are infinitely high and the corresponding branch of the tree will not grow further. Note that also moving obstacles can be included to determine future collisions.

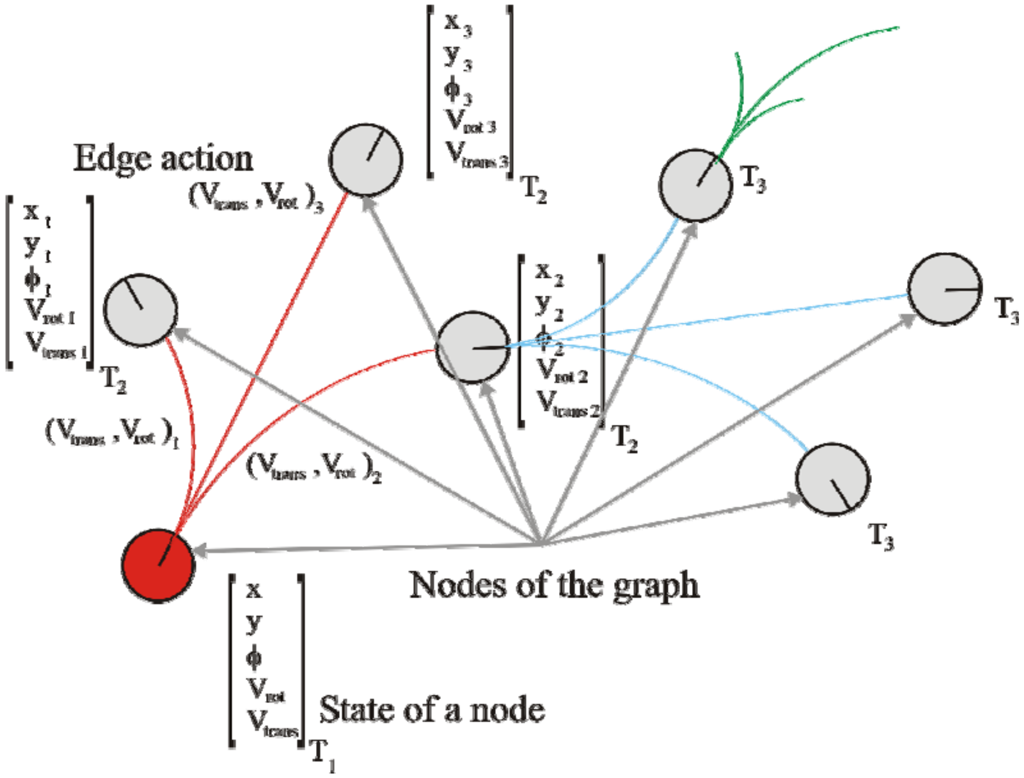


Figure 28: the key idea behind the expanding space tree. Shown are the set of nodes which are projected over time within the configuration space. Each node is expanded by predicting actions and creating further states.

The goal of this tree is to finally hit a target region with the desired target speed. From all hitting branches only the branch with the lowest costs is selected. To avoid the tree from growing into useless regions in configuration space a heuristic is used to select those branches of the tree which will probably hit this target region. Here also the Euclidean distance is used. Note that we are operating in a five dimensional space, so the Euclidean distance to the goal configuration is also five dimensional.

Within this approach path planning and motion planning are one and the same. The use of a heuristic also enables the so called on-time availability. This means that the target region does not have to be reached to get at least a guess, which action is a good one, but we can simply plan a certain time and after that time we pick from the nodes with the highest prediction time the node with the lowest (heuristic) costs.

4.4.1 The approaching strategy

Key to a successful motion planning is the calculation of the costs. Here again the function of Andersen and Svenstrup is used.

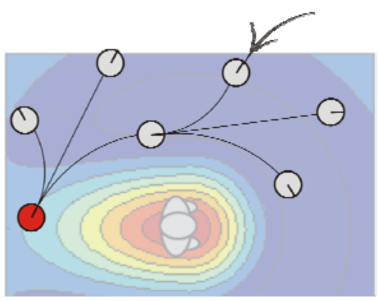


Figure 29: approaching a person with EST

This time the costs are also the function values $\boldsymbol{P}(\mathbf{x}_i)$ and the heuristic $|\mathbf{x}_i - \mathbf{x}_g|$. But since this approach is a full planning approach, we forward the previous costs also to nodes. So we have a cost formulation of:

$$c_i = P(x_i) + |x_i - x_g| + c_{i-1}$$

Here, the target region $\mathbf{x}_g$ can also change over time and this will be still covered by this approach. The risk of this approach is the sampling effort taken to create new branches. Calculation time is best with just a few samples, but this may cause sparse sampling of the configuration space and the optimal solution is missed. Also the solution may vary from one step to the next step. So a stable solution depends on the sampling density per node step and may overstrain the robots computational powers or miss the goal of real time capability.

The main advantage over the dynamic window is the ability to predict motion to a more distant point in time and also complex sequences of motion can be noticed, which lead to an optimal driving, pure local optimization couldn't have established.

4.5 Conclusion

In this chapter we have discussed single solutions, which have to be established on the robot and tested, to fulfil the prerequisites of an approaching behaviour. These are person tracking to know where a person is located, pose estimation to notice if a person is sitting or standing. The latter influences the personal space around the person. We also have to detect the motion speed of a person to predict the future motion of it. This is important to avoid collisions which lie in near future of motion planning.

Afterward three solutions for realizing an approaching behaviour are presented. Up to now these approaches are only sketched theoretically and have to be implemented and tested. We have chosen the approach of the dynamic window, which is a well established method to plan motion behaviour. Second the choice of a biological inspired unsupervised learning technique was done, to find how reliable and comparable such an approach is against the established approach of the dynamic window. And third we have selected an approach which goes beyond the possibilities of the dynamic window, but may needs to much computational power for a sufficient solution.

5 Conclusion and outlook

This deliverable has given an overview of the psychological findings of the human – robot relationship. It also has covered the human-human relationship, since most of the findings seem to be true for both worlds. The key insight is, that a personal space like Hall describes it, exists (also between robots and human) but that the configuration of this space depends on many factors, including familiarization with the robot, situation and gender.

On observing geriatric literature we also find that old persons are focused toward a small circle of “social beings” which they prefer to interact with. For our target group it should be expected that these persons all have different impairments which should be compensable by the robot. This fact is not important towards the navigational part.

What is important is the fact that old people do accept new social being more slowly than normal persons. So the adaptation of the personal space over time has to happen more slowly.

In the last section of this deliverable we focus on the work, which is done today to actually implement such behaviours on a robot. Most psychological articles use a wizard of oz approach or implementing simple rule sets, which are static defined by the developer. Only a few works go beyond this point and we focus on these works.

In the last chapter we have presented three different strategies, how to implement the approaching behaviour. One strategy has low risk of failure since it uses well established ideas while the other two are rather experimental.

It should be noticed that not only the approaching behaviour could be solved by these approaches, but also a passing behaviour. But this point is part of the next deliverable. The results from experiments are presented in the deliverables 6.3 to 6.5, where the state of the navigation system up to this point is presented.

6 References

[1] **Syrdal, D.S., Dautenhahn, K., Woods, M.L., Koay, K.L.** *'Doing the right thing wrong'- Personality and tolerance to uncomfortable robot approaches.* Proc. 15th IEEE International Workshop on Robot and Human Interactive Communication (RO-AIAN), 2007, pp. 183-188

[2] **Walters, M., Woods, S., Koay, K.L., Dautenhahn, K.**, *Practical and methodological challenges in designing and conducting interaction studied with human subjects*, AISB Symposium on Robot Companions Hard problems and Open Challenges in Human-Robot Interaction, 2005, pp. 110 – 120

[3] **Woods, S., Walters, M., Koay, K.L., Dautenhahn, K.** *Comparing Human Robot Interaction Scenarios Using Live and Video Based Methods: Towards a Novel Methodological Approach,*ACM 9th International Workshop on Advanced Motion Control, 2006, pp. 750-755

[4] **Woods, S., Walters, M., Koay, K.L., Dautenhahn, K.** *Methodological Issues in HRI: A Comparison of Live and Video-Based Methods in Robot to Human Approach Direction Trials*, Proc. Of the 15th IEEE International Workshop on Robot and Human Interactive Communication (RO-MAN),2006, pp. 51-58

[5] **Yan, H., Mataric, M.J..** *General spatial features for analysis of multi-robot and human activities from raw position data*, Proc. of the IEEE IRSJ International Conference on Intelligent Robots and Systems (IROS),2002, pp. 2770-2775

[6] **Hüttenrauch, H., Eklundh, K.S., Green, A., Topp, E.A,** *Investigating Spatial Relationships in Human-Robot Interaction*, Proc. of the IEEE IRSJ International Conference on Intelligent Robots and Systems (IROS),2006, pp. 5052-5059

[7] **Gillespie, D.L., Leffler, A.,** *Theories of nonverbal behaviour: A critical review of proxemics research*, in Sociological Theory, vol. 1 ,1983, pp. 120-154

[8] **Smith, H.W.,** *Territorial Spacing on a beach revisited: A Cross-National Exploration*, in Social Psychology Quaterly, vol. 44 ,1981, pp. 132-137

[9] **Albas, C.,** *Proxemic Behaviour: A Study of Extrusion*, in Journal of Social Psychology, vol. 131 ,1991, pp. 697-702

[10] **Albas, C., Albas, D.** *Aligning Actions: The case of subcultural proxemics*, Canadian Ethnic Studies, vol. 21 ,1989, pp. 74-82

[11] **Leffler, A., Gillespie, D.L., Conaty, J.C.** *The Effects of Status Differentiation on Nonverbal Behaviour,* Social Psychology Quaterly, vol. 45 ,1982, pp. 153-161

[12] **Krail, K.A., Leventhal, G.,** *The Sex Variable in the Intrusion of Personal Space,* Sociometry, vol. 39 ,1976, pp. 170-173

[13] **Eastwood, L.,** *Personality, Intelligence and Personal Space among Violent and Nonviolent Deliquents,* Personality and Individual Differences, vol. 6 ,1985, pp. 717-723

[14] **Williams, J.L.,** *Personal space and its relation to extraversion-introversion*, Canadian Journal of Behavioural Science, vol. 3 ,1971, pp. 156-160

[15] **Walters, M.L., Dautenhahn, K.m Koay, K.L., Kaouri, C., Rene te Boekhorst, Nehaniv, C., Werry I., Lee, D.,** *Close Encounters: Spatial Distances between People and a Robot of Mechanistic Appearance,* Proc. Of 5th IEEE-RAS International Conference on Humanoid Robots, 2005, pp. 450-455

[16] **Kim, T., Hinds, P.,** *Who should I blame? Effects of Autonomy and Transparency on Attribution in Human-Robot Interaction*, Proc. Of 15th IEEE International Workshop on Robot and Human Interactive Communication (RO-MAN), 2006, pp. 80-85

[17] **Pacchierotti, E., Christensen, H.I., Jensfelt, P.** *Evaluation of passing distance for social robots,* Proc. Of 15th IEEE International Workshop on Robot and Human Interactive Communication (RO-MAN), 2006, pp. 315-320

[18] **Butler, J.T., Agah, A.,** *Psychological effects of behaviour patterns of a mobile personal robot,* In Autonomous Robots, 2001, vol. 2, pp. 185-202

[19] **Pacchierotti, E., Christensen, H.I., Jensfelt, P.,** *Human-robot embodied interaction in hallway settings: a pilot user study,* Proc. Of 14th IEEE International Workshop on Robot and Human Interactive Communication (RO-MAN), 2005, pp. 164-171

[20] **Green, A., Hüttenrauch, H.,** *Making a case for spatial prompting in human-robot communication,* Proc. Of 5th International Conference on Language Resources and Evaluation, 2006

[21] **Nass, C., Steuer, J., Tauber, E.R.** *Computers are Social Actors,* Proc. Of the Conference on Human Factors in Computing, 1994, pp. 72-78

[22] **Reeves, B., Nass, C.** *The Media Equation: How People Treat Computers, Television, and New Medial Like Real People and Places,* CSLI Press, Stanford, 1996

[23] **Kendon, A.,** *Features of the structural analysis of human communicational behaviour,* Aspects of Nonverbal Communication, Walburga, 1980

[24] **Goffman, E.,** *Behaviour in public place: Notes on the Social Organization of Gatherings,* 1963

[25] **Chen, D., Yang, J., Wactlat, H.D.** *Towards automatic analysis of social interaction patterns in a nursing home environment from video,* Proc. Of 6th ACM SIGMM International Workshop on Multimedia Information Retrival, 2004, pp. 283-290

[26] **Hsu, D., Kindel, R., Latombe, J.C., Rock, S.,** *Randomized kinodynamic motion planning with moving obstacles,* International Journal Robotics Research, 2002, vol. 21, issue 3, pp. 233-255

[27] **Hsu, D., Latombe, J.C., Motwani, R.,** *Path planning in expansive configuration spaces,* International Journal of Computational Geometry and Applications, 1999, vol. 9, issue 4, pp. 495-510

[28] **Choset, H., Lynch, K.M., Hutchinson,S., Kantor, G.A., Burgard, W., Kavraki, L.E., Thrun, S.** *Principles of Robot Motion: Theory, Algorithms, and Implementations,* MIT Press, 2005, pp. 238-255

[29] **Phillips, J., Kavraki, L., Bedrossian,N.** *Spacecraft rendezvous and docking with real-time, randomized optimization,* AIAA Guidance, Navigation, and Control, 2003

[30] **Stachniss, C., Burgard, W.** *An integrated approach to goal directed obstacle avoidance under dynamic constraints for dynamic environments,* in Proc. Of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2002

[31] **Havighurst, R.** *Developmental Tasks and Education,* David McKay Company (Random House), 3rd edition, 1972, New York

[32] **Lehr, U.** *Psychologie des Alterns,* Verlag Quelle & Meyer, 11. Auflage, 2006

[33] **Martin, M., Kliegel, M.** *Psychologische Grundlagen der Gerontologie,* Kohlhammer Urban Druckerei, 2. Auflage, 2008

[34] **Libin, A.V., Libin, E.V.** *Person-Robot Interactions From the Robopsychologists' Point of View: The Robotic Psychology and Robotherapy Approach,* Proceedings of the IEEE, Vol. 92, Np. 11, 2004, pp. 1789-1803

[35] **Syrdal, D.S., Koay, K.L., Walters, M.L., Dautenhahn, K.,** *A personalized robot companion? The role of individual differences on spatial preferences in HRI scenarios.,* Proc. of the 16th IEEE International Workshop on Robot and Human Interactive Communication (RO-MAN), 2007, pp. 1143-1148

[36] **Walters, M.L., Dautenhahn, K., Rene te Boekhorst, Koay, K.L., Kaouri, C., Woods, S., Nehaniv, Ch., Lee, D., Werry, I.** *The influence of Subjects' Personality Traits on Predicting*

Comfortable Human-Robot Approach Distance., Proc. of the COGSCI Workshop on Social Mechanisms of Android Science , 2005, pp. 29-37

[37] **Pacchierotti, E., Christensen, H.I., Jensfelt, P.,** *Evaluation of Passing Distance for Social Robots,* Proc. Of 15th IEEE International Workshop on Robot and Human Interactive Communication (RO-MAN), 2006

[38] **Hall, E.T.,** *The hidden dimension,* Doubleday, 1966

[39] **Hall, E.T.,** *Proxemics,* Current Anthropology, vol. 9, no. 2, pp. 83+, 1968

[40] **Satake,S., Kanda, T., Glas, D.F., Imai, M., Ishiguro, H., Hagita, N.** *How to Approach Humans?-Strategies for Social Robots to Initiate Interaction,* Proc. Of ACM International Conference on Human Robot Interaction (HRI), 2009, pp. 109-116

[41] **Peters, A., Spexard Th.P., Hanheide, M., Weiss, P.** *Make room for me: A study on a spatial and situational movement concept in HRI,* Proc. of german conference of KI , 2009

[42] **Cowley, S.,** *Social Robotics and the person problem,* Proc. of the AISB Convention, 2008

[43] **Eysenck, H.J.,** *Dimensions of personality: 16,5 or 3? Criteria for a taxonomic paradigm,* Personality and Individual Differences, vol. 12, 1991, pp. 773-790

[44] **Dautenhahn, K., Walters, M., Woods, S., Koay K., Nehaniv, L., Sisbot, E.A., Alami, R., Simeon, T.** *How may I serve you? A Robot Companion Approaching a Seated Person in a Helping Context,* Proc. Of ACM International Conference on Human Robot Interaction (HRI), 2006, pp. 172-179

[45] **Koay K., Sisbot, E.A., Syrdal, D.S., Walters, M., Dautenhahn, K., Alami, R.,** *Exploratory Study of a Robot Approaching a Person in the Context of Handing Over an Object,* Association for the Advancement of Artifical Intelligence Spring Symposia, 2007

[46] **Takayama, L, Pantofaru, C.,** *Influences on Proxemic Behaviours in Human-Robot Interaction,* in Proc. Of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2009, pp. 5495 - 5502

[47] **Bergström, N., Kanda, T., Miyashita, T., Ishiguro, H., Hagita, N.,** *Modelling of Natural Human-Robot Encounters,* in Proc. Of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2008, pp. 2623 – 2629

[48] **Friedman, B., Kahn, H., Hagman, J.,** *Robot companions? What online AIBO discussion forums reveal about the human-robotic reltaionship,* Digital Sociability, vol. 5, 2003, pp. 273 – 280

[49] **Baltes, P.B.,** *Das Zeitalter der permanent unfertigen Menschen: Lebenslanges Lernen nonstop?,* Politik und Zeitgeschichte, vol. 36, 2001, pp. 24 – 32

[50] **Cumming, E., Henry, W.E., Damianopoulos,** *A formal statement of disengagement theory,* Growing old: the process of disengagement, Basic Books (NY), 1961

[51] **Wong, C., Kortenkamp, D., Speich, M.,** *A mobile robot that recognizes people,,* Proc. Of 7th IEEE International Conf. on Tools with Artifical Intelligence, 1995, pp. 346-353

[52] **Hu, Ch., Ma, X., Dai, X.** *A Robust Person Tracking and Following Approach for Mobile Robots,,* Proc. Of IEEE International Conf. on Mechatronics and Automation, 2007, pp. 3571-3576

[53] **Hu, Ch., Ma, X., Dai, X.** *Reliable Person Following Approach for Mobile Robot in Indoor Environment* , Proc. Of 8th IEEE International Conf. on Machine Learning and Mechatronics, 2009, pp. 1815-1821

[54] **Höller, F., Schulz, D., Moors, M., Schneider, F.E.,** *Accompanying Persons with a Mobile Robot using Motion Prediction and Probabilistic Roadmaps* , in Proc. Of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2007, pp. 1260 – 1265

[55] **Andersen, H.J., Bak, T., Svenstrup, M.,** *Adaptive Robot to Person Encounter by Motion Patterns* , in Proc. Of the EUROBOT Conference, 2008, Springer, pp. 1 – 11

[56] **Svenstrup, M., Tranberg, S., Andersen, H.J, Bak, T.,** *Pose Estimation and Adaptive Robot Behaviour for Human-Robot Interaction* , in Proc. Of the IEEE/RSJ International Conference on Robotics and Automation (ICRA), 2009, pp. 3571 – 3576

[57] **E.A.Sisbot:** *Towards Human-Aware Robot Motions*, PHD Thesis, Univ. of Toulouse, 2008

[58] **Fox, D., Burgard, W., Thrun** S., *The dynamic window approach to collision avoidance*. IEEE Robotics & Automation Magazine, 1997, vol. 4, no. 1, pp. 23–33

[59] **R. Phillipsen**, *Motion Planning and Obstacle Avoidance for Mobile Robots in highly cluttered dynamic Environments*, PHD thesis, 2004

[60] **Sutton, R., Barto, A.G.,** *Reinforcement Learning: An Introduction*, MIT Press, 1998

[61] **Arras, K.O., Mozos, O.M., Burgard, W.,** *Using Boosted Features for the Detection of People in 2D Range Data*, in Proc. Of the IEEE/RSJ International Conference on Robotics and Automation (ICRA), 2007, pp. 3402 – 3407

[62] **Bennewitz, M., Thrun, S.** *Adapting Navigation Strategies Using Motion Patterns of People*, in Proc. Of the IEEE/RSJ International Conference on Robotics and Automation (ICRA), 2003, pp. 2000 – 2005

[63] **Kato, H., Billinghurst, M.,** *Marker Tracking and HMD Calibration for Video-based Augmented Reality Conferencing System*, in Proc. Of the 2nd IEEE and ACM International Workshop on Augmented Reality (IWAR), 1999, pp. 85 – 94

[64] **Klinker, G., Stricker, D., Reiners, D.,** *Augmented Reality: A Balance Act between High Quality and Real-Time Constraintsl*, in Mixed Reality-Merging Real and Virtual Worlds, Springer Verlag, 1999, pp. 325-346

[65] **Kanda, T., Shiomi, M., Miyashita, Z., Ishiguro, H., Hagita, N.,** *A Communication Robot in a Shopping Mall*, in IEEE Transactions on Robotics, vol. 26, issue 5, 2010, pp. 897-913

[66] **Riedmiller, M.,** *Neural Fitted Q Iteration – First Experiences with a Data Efficient Neural Reinforcement Learning Method*, in Proc. Of the European Conference on Machine Learning (ECML), 2005, pp. 317 – 328