Improving Spatial Awareness in an Indoor Environment with Wireless Positioning Technology

Masters Thesis

of

Vincent Alexander Gaiser

August 29, 2008

Supervisors:

Prof. L. Sonenberg, University of Melbourne
Dr.-Ing. habil. S. Winter, University of Melbourne
Dr. A. Kealy, University of Melbourne
Dr. ir. M. van Sinderen, University of Twente
Dr. A. Wombacher, University of Twente

University of Twente

information systems
faculty of electrical engineering, mathematics and computer science
enschede, the netherlands

University of Melbourne

department of information systems
department of geomatics
melbourne, australia

24 August 2008, Delft, The Netherlands

Abstract

The contribution of indoor wireless technology to solve the indoor wayfinding problem is potentially big. However, no structured way of describing indoor environments exists today. Also indoor wireless positioning technologies are just emerging and there is not yet a dominant technology. In this thesis a structure to functionally describe indoor environments is developed. Elements of indoor environments are identified. Using these functional elements it is possible to describe a position at four different layers of abstraction, ranging from local view to a rough view of the environment, based on the main functions. After experimental results indoor GPS is ruled out as wireless indoor positioning technology. Experiments with WLAN show that this technology is able to provide high accuracy at a low cost. This technology combined with the developed structure opens up possibilities for various applications, particularly in the area of indoor wayfinding and navigation systems. Especially the possibility to functionally describe the indoor environment at different layers of granularity will improve the spatial awareness of users.

The University of Twente

The University of Twente offers research and degree programmes in technology, and in the social and behavioural sciences. In keeping with its enterprising spirit, the University is committed to making an economic and social contribution to the region of the Netherlands where it is based. The UT collaborates with TU Delft and TU/e Eindhoven under the umbrella of the 3TU.Federation, and is also a partner in the European Network of Innovative Universities (ECIU).

The degree programmes at the University of Twente range from business studies and applied physics, to biomedical technology and psychology. The curriculum is broad, flexible and relevant to the labour market. Most students combine coursework in their major subject with a coherent set of minors in another discipline. A growing number of foreign students are finding their way to the UT. Almost all our postgraduate programmes are taught in English, and half of all our PhD students now come from outside the Netherlands.

The University of Twente has a world class research programme. In the applied sciences, the emphasis is on nanotechnology, process technology, engineering, information and communication technology, and the biomedical sciences. The University also has a strong track record in business studies and the behavioural sciences. UT research programmes are organised in six research institutes.

(source: University of Twente)

The University of Melbourne

Established in 1853, the University of Melbourne is a public-spirited institution that makes distinctive contributions to society in research, teaching and knowledge transfer.

Melbourne's teaching excellence has been rewarded two years in a row by grants from the Commonwealth Government's Learning and Teaching Performance Fund for Australian universities that demonstrate excellence in undergraduate teaching and learning.

Melbourne was also one of only three Australian universities to win ten citations – the maximum number of awards possible – under the Carrick Citations for Outstanding Contributions to Student Learning. The citations recognise commitment by university staff who have shown outstanding leadership and innovation in teaching, and dedication and enthusiasm for student learning.

Nationally, Melbourne is among the top-performing universities for competitive research funding, PhD completions and refereed research publications. The University is committed to maintaining excellence in research and development.

(source: University of Melbourne)

Preface

I gladly present you my master thesis, for a Master of Science degree in Telematics from The University of Twente, Enschede, The Netherlands. This thesis contains the results of my research during six months at The University of Melbourne (Australia). This research project was conducted at the University of Melbourne in cooperation with the Department of Information Systems and the Department of Geomatics. Supervision from the University of Twente was organized by the Department of Information Systems.

Working on this project in Melbourne has been a great experience for me. The fellow research students and colleagues at the University were of great inspiration to me. Not only did I get valuable input to my project during discussions at the office, also activities and trips outside the office have contributed to the fantastic experience in Australia.

I would like to thank all my supervisors for their support and feedback during this project. Especially Prof. Liz Sonenberg (University of Melbourne, Australia) for the supervision during the entire project and making it possible in the first place. Thanks for the useful feedback during our regular meetings and for the opportunity to present my work at the COSIT'07 conference in Melbourne. Thanks to Dr.-Ing. habil. Stephan Winter (University of Melbourne, Australia) for supervising me during the first three months in Melbourne and providing me with valuable support and feedback on part of the project related to wayfinding and spatial structuring. Also thanks to Dr. Allison Kealy (University of Melbourne, Australia) for providing me with the equipment used in the experiments and the supervision and feedback during the last three months in Melbourne. Finally I would like to thank my supervisors Dr. ir. Marten van Sinderen (University of Twente, The Netherlands) and Dr. Andreas Wombacher (University of Twente, The Netherlands) for reading many versions of my thesis and giving valuable feedback on each one of them.

It has been a pleasure working with all of you.

Delft, August 24th, 2008.

Vincent Gaiser

Contents

Chapter 1

Introduction

This chapter introduces the the motivation of the research and the research questions, followed by the approach of the research and structure of this thesis. The research questions which form the basis of the thesis will be evaluated in the concluding chapters of this thesis.

1.1 Motivation

Outdoor wayfinding is a booming market at the moment (Associated Press Financial Wire 2007). Portable devices for use in cars, while hiking or even to mount on bicycles are widely available for a fair price. More recently reasonably priced mobile phones have emerged with embedded GPS receivers (Nokia 2007, Nikkei Weekly 2007, Apple Inc. 2008). These devices make use of the Global Positioning System (GPS), which provides outdoor positioning accuracy up to several metres all over the world. With the added computing power of the portable device, often supporting digital maps and a dynamic turn-by-turn route planner, this makes a powerful technology, providing wayfinding assistance anywhere in the world.

While outdoor wayfinding systems have reached a mature state and are already widely available, indoor wayfinding systems are still under development. Technology used for outdoor wayfinding is not suitable in indoor environments, mainly because GPS requires line-of-sight communication with satellites. Instead other technologies are needed to solve the positioning problem indoors.

At first sight, indoor wayfinding assistance with the use of a portable device does not seem to provide huge advantages over conventional wayfinding with signs and maps. For small buildings with a closed group of frequent users this might be true. After an initial learning period, each user has enough knowledge of the building to navigate to any part without problems. However, in larger and more complex environments which are visited by a mixed group of non frequent users an indoor wayfinding assistant system will be of benefit to the users. For example, an indoor wayfinding system in an airport or hospital may be of use of any individual unfamiliar with the environment and help him to navigate more efficiently.

Especially to visually impaired users an indoor wayfinding system will be of use. Several concepts for outdoor assistance have been proposed or are already deployed and available (for example Trekker (Humanware 2007*b*)). Without a doubt visually impaired people have great benefit of a system that allows them to travel along complex paths, new environments and assists them in situations they would normally avoid. Current research shows visually impaired people travel more independent and more confident with a system that assists them in wayfinding (Golledge, Marston, Loomis & Klatzky 2004) (Crandall, Bentzen, Meyers & Brabyn 2001).

Key factor in the success of outdoor wayfinding systems is the ease of use, the wireless nature of the system and the equipment being small and easy to carry. In most cases switching on the device is the only action required from the user to get a visualization of his position and location. He does not have to be close to a certain communication point, connect the device to a wired infrastructure or interact extensively with the device to make it work.

Several problems rise when developing indoor wayfinding systems. First, indoor environments are not as clearly and unambiguously ordered as outdoor environments. Outdoors the world is organized in a pre-defined and generally accepted structure of countries, states, regions, cities, villages, suburbs, streets and addresses (not a complete enumeration). Indoors this is often not the case. Concepts like floors, corridors and rooms are easily understood, but more general structures, like a department or area, are more difficult to grasp. These descriptions which make a user aware of the environment improve his spatial awareness. Moreover multi-storey buildings add a level of complexity that outdoor systems do not face at all. Second, the nature of the built (indoor) environment, which includes walls, windows and furniture, provides a challenge for indoor positioning technology, since all these factors influence the technology.

This results in two main problems to be solved before an efficient indoor wayfinding system can be developed. First, a way of describing indoor environments has to be developed. The elements of indoor environments have to be identified and conceptualized. Eventually a structure in which these concepts fit must be developed, making them useful for wayfinding purposes. Second, technologies for indoor positioning have to be found that provide information that is accurate enough for indoor wayfinding. Furthermore the way visually impaired people can benefit from an indoor wayfinding system is of interest.

1.2 Goal

The considerations above lead to the research question, which can be divided into several research objectives.

> *How can wireless indoor positioning technology improve the spatial awareness of humans in an indoor environment?*

- How can the spatial properties of an indoor environment be organized into a usable structure for indoor location descriptions?
- Which (characteristics of) wireless technologies are useful for indoor positioning and in what respect?
- Can a combination of these technologies improve the performance of an indoor positioning system?
- How does an indoor wayfinding system provide useful information to visually impaired users?

In other words: Is it possible with indoor positioning technology to provide a user with useful information about the indoor environment he is in, in such a way that it enhances his current understanding of the indoor environment. Two aspects of this problem, providing useful information and wireless positioning techniques, are investigated to find an answer to this question. As a user group, visually impaired would have the greatest benefits of an answer to the main research question and are therefore good point of view for the evaluation.

1.3 Approach

An understanding of the process of wayfinding is necessary to address the research questions. For this purpose a literature study into wayfinding will be conducted. This will provide a basis for researching the more specific wayfinding problems indoors and how these can be resolved by a system.

Having laid the theoretical foundation, a methodology for describing indoor environments will be developed. Focus of this methodology is the functional organization of environments. The fundamental elements of such a structure are identified and a structure with several levels of granularity is introduced. It provides an answer to the question: How can an indoor environment be described by the functionality of its instead of their physical aspects?

To address the second aspect of the research question, wireless positioning technology, the literature study is complemented by a literature study to already available wayfinding systems, with special interest for wayfinding assistance systems for visually impaired and underlying technology.

Out of these positioning technologies, the research will evaluate by means of experiments if WLAN (WiFi) positioning techniques and indoor GPS receivers can assist in indoor wayfinding. Each technology has different characteristics and provides a different type of information. Of particular interest are combinations of these technologies for appropriate indoor positioning (depending on the positioning demands). Based on the characteristics of the evaluated technologies a combination of selected technologies will be made.

To assess if combining an indoor structure and wireless positioning technology will be able to improve a user's spatial awareness the results of the experiments, particularly regarding the accuracy of the technology, will have to be evaluated in respect to the indoor structure. Is it possible to cope with inaccuracy in the indoor functional structure of the environment? Does the proposed structure indeed improve the spatial awareness of humans?

1.4 Structure

The theoretical fundamentals on human wayfinding are outlined in Chapter 2, followed by Chapter 3, which introduces the concepts of spatial structuring and presents a way to identify the functional elements of indoor environments. Furthermore Chapter 3 introduces a way of structuring these elements into more general concepts and a methodology for describing indoor environments at different levels of granularity is developed.

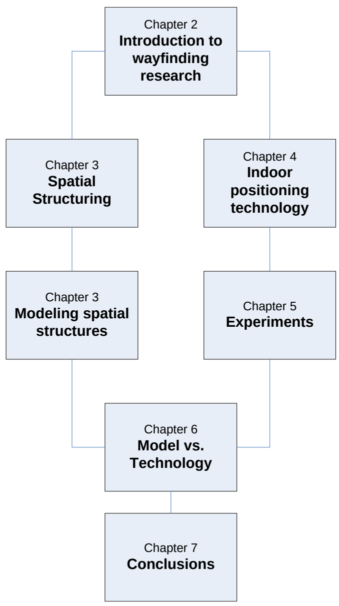


Figure 1.1: Structure of this thesis

Then the thesis focuses on the technology aspect with Chapter 4 giving an extensive overview of the research on both outdoor wayfinding systems for visually impaired and indoor wayfinding systems (not exclusively designed for visually impaired). Based on this study, characteristics for successful indoor positioning systems are described. Experiments with two low cost indoor positioning technologies are described in Chapter 5 and an evaluation of the combination of these two technologies as an integrated positioning technology is given. Chapter 6 links the methodology described in Chapter 3 to the results of the experiments of Chapter 5 with an analysis of the usability of the model and the requirements of the technology by the model. It also evaluates the question if this model and these technologies indeed improve the spatial awareness of humans. Finally Chapter 7 draws conclusions, answers the research questions one by one and provides room for discussion.

Chapter 2

Wayfinding research background

This Chapter presents a literature study into general wayfinding as a foundation for this thesis. It is an introduction to the subject and gives insight in the general principles of human wayfinding. This foundation is later used as a basis for the development of a spatial structure.

Extensive research has been done in the area of wayfinding. Research on wayfinding operates on the borders between several disciplines. Psychologists, geographers, architects and urban planners are interested in this area. Roughly the research can be divided into two parts. First, the research that has been done in the area of *architectural and urban planning* with regards to wayfinding. This research area focusses on how spaces should be designed in order for people to easily find their way. Factors like the design of paths, shape of the space, signage and complexity of the environment are the main focus. The design of both indoor and outdoor environments is considered. Essentially this research is on wayfinding *before* an environment has been built. The next area is *psychological and cognitive research.* Although it also takes the design of environments into account, the main focus is on understanding the process of humans finding their way in environments. Research of this type is generally supported by experiments where people have to find their way in a controlled setting. The influence of vision on the task of wayfinding is a main area of interest. Studies tend to focus more on indoor wayfinding than outdoor. This research is typically done *after* environments have been built.

It would go into too much detail to discuss both areas of research in detail, instead an overview of the most important aspects and studies will be given. First about architectural aspects, with a focus on organizing spaces. Later on cognitive aspects, which gives an insight in the process of wayfinding by humans.

2.1 Architectural wayfinding research

Pioneer in the work of wayfinding was Kevin Lynch, with the publication of *The Image of the City* (Lynch 1960). He was the first to speak of 'wayfinding' and to suggest a link between wayfinding and the ability of forming a cognitive model. His work was a result of a five year study on how people perceive and organize information about urban spaces. He also tried to understand how people use this structure for wayfinding and navigation. He identifies five key components in urban environments: paths, landmarks, nodes, edges and districts. These components are used by people in the mental models they develop and use for finding their way and remembering paths in urban spaces. The focus of the research is on wayfinding in (outdoor) urban environments, typically cities.

The publication of *Wayfinding in Architecture* (Passini 1992, 2nd ed.) by Romedi Passini, followed by the publication of *Wayfinding: People, Signs, and Architecture* (Arthur & Passini 1992) gives more insight in the planning of environments and wayfinding tasks in general. The work covers a broad range of aspects, from the design of paths, the use of open spaces, the use and formatting of signage, the different type of users to the more cognitive understanding wayfinding. More importantly, they define four important wayfinding settings with which people have to cope everyday. First the travel setting, including airports, railway stations and other transport terminals, next the working environment, including offices, educational and health buildings, next the recreational setting, including stadiums, zoos and theme parks and finally the retail setting, including shopping malls and stores. This work makes clear that wayfinding is a complex process in which many factors play a role.

2.2 Psychological wayfinding research

It is widely accepted that humans navigating in environments develop some sort of mental representation of the environment in their mind. They use cues from the environment to remember places, decision points or landmarks in this environment. These cues are all used by humans to keep track of their position and orientation. Factors like experience and familiarity with the environment are important as well. Passini (1992) states that humans form a cognitive map of the environment (this was first found in 1948 by Tolman (1948)). This is the ability of a human to form a mental representation that corresponds to peoples perception of the real world. This representation is constantly changing, as people travel to new environments or experience new cues in familiar environments. A common way to 'represent' a cognitive map is to let people draw a map of the environment they are in.

The term cognitive map is considered outdated at present time, because the general understanding is that this cognitive representation is not like a map. Therefore the term cognitive or mental representation will be used in this report. More recent studies try to understand the orientation of people, by letting them walk a path, make some turns and let them point to the origin. These path integration abilities also suggest people are able to traverse complex paths and still maintain their orientation (Loomis, Klatzky, Golledge & Philbeck 1999).

Wayfinding itself can be seen as a complex chain of spatial tasks and decisions, instead of one big operation. For example, people going to office 3.45 in the ICT building of the University of Melbourne will first proceed to Melbourne, next go to the University premises, next to the ICT building, next to the third floor (after finding the elevators) and finally to the office itself (which involves a lot of decisions itself as well, like making the right turns and not getting lost in the building). This example may be exaggerated and can be argued, but it shows a lot of subtasks are involved and decisions have to be made. Aspects like different routes to the same destination are not even considered yet. Tomko & Winter (2006) observe this division in subtasks as well and propose a way to use this granular route directions automatically to describe a route. Route descriptions consist of destinations with different granularity, getting more and more detailed when approaching the final destination. Important is that this way of describing a route is not turn-by-turn, but rather by destinations.

Some terms referring to cognitive representation of wayfinding tasks are of interest here. *Route knowledge* is knowledge of a series of actions that have to be taken to reach a destination. This is independent of knowing the exact position of the destination. For example, 'second street right and at the bookshop left' is route knowledge. Route knowledge is knowing *how to get there*, regardless of knowing where it is. In contrast, *survey knowledge* (also referred to as map knowledge) is knowledge about the direction and distances between objects, independent of knowing paths between them. For example, 'the train station is 500 metre east of the town hall' is survey knowledge. Thus survey knowledge has more to do with the knowing the *geographic position of an object*, than exactly knowing how to reach it (Meilinger, Holscher, Büchner & Brösamle 2006). These types of knowledge do not only apply to descriptions of environment, but also to the way humans learn and understand environments. In all types of spatial knowledge *landmarks* play a crucial role and are used very frequent. Landmarks are distinct objects that are used in remembering and describing environments or decision points. For example, if instead of saying 'turn left after 345 metres' 'turn left at the post office' is used, the post office is used as a landmark.

Quite some research has been done on strategies for human wayfinding. Strategies are approaches people prefer to find their way and differ from person to person. In multi-level building for example humans follow three main strategies. First, the central point strategy, where humans always start navigating from a central point. Next, the direction strategy where humans first head towards the goal in the horizontal direction and then in the vertical direction. Finally, the floor strategy, where humans first head in the vertical direction (to the right floor) and then in the horizontal direction (Hölscher, Meilinger, Vrachliotis, Brösamle & Knauff 2004). Strategies play a role in developing cognitive models and vice versa. Although an interesting area of research, wayfinding strategies are out scope for this report, because the main focus is on identifying the elements itself where people navigate to and not *how* they navigate to them.

Research on wayfinding by visually impaired people has been evolving over the years and consequently the generally accepted ideas about human wayfinding have changed as well. Without a doubt, most research finds that vision makes wayfinding easier and most experiments show that blind people have more difficulty finding their way than sighted people. However, the degree to which this differs or the reason of this difference varies. In general there are three theories about wayfinding and vision: deficiency theory, inefficiency theory and difference theory. First, the *deficiency theory* states that people who have been blind from birth (congenitally blind) lack the necessary experience (namely vision) to develop spatial understandings. They have never seen and experienced two and three dimensional spaces and arrangements. As a result they are unable to form a comprehensive idea about spaces and perform complex tasks like rotations and transformations, which are considered required for spatial understandings. This theory is supported by various studies which show that congenitally blind have more trouble understanding spatial concepts than adventitiously blind (people who lost their sight at a later age), who did experience spatial concepts. This explains visually impaired to perform worse in wayfinding than sighted, with the congenitally blind performing the worst.

Next, *inefficiency theory* states that visually impaired people can understand spatial concepts and perform complex spatial operations. Instead of vision they use other cues, like sound or haptic cues. However, the information obtained by other perceptions than vision is inferior and therefore visually impaired perform worse in spatial tasks and understanding spatial concepts. Finally, *difference theory* states that visually impaired people and sighted people are able to process and understand spatial concepts at the same level. However, any difference that may occur can be explained by other factors than vision, like stress, experience or limited access to information (not being able to see signs).

Most researchers currently acknowledge that visually impaired are able to process spatial data and participate in wayfinding tests. However, their performance varies and is in general poorer than sighted people. This suggests the deficiency theory is outdated. A more extended and excellent review of cognitive wayfinding research can be found in Kitchin, Blades & Golledge (1997), on which the last paragraphs are based.

One study that shows that there is no significant difference between sighted and (any type of) blind people in the ability to form a mental spatial model of a space is the one by Noordzij, Zuidhoek & Postma (2006). Both early-blind, late-blind and sighted people were able to construct spatial mental models based on verbal descriptions. Visual experience seemed not essential in forming an understanding of the space and developing a mental model. Like other studies they found visually impaired participants could easier construct more effective mental models based on route descriptions than models based on survey descriptions. They were even more efficient than sighted people. In contrast, sighted people were more effective in constructing mental models from survey descriptions than route descriptions.

The collection of knowledge of the environment a person is currently in is called *spatial awareness*. This is all the knowledge of the environment, including the mental model, visual clues and other information about the environment. When a user has little spatial awareness on the environment he is in, it is hard for him to describe his position or navigate to another position in the environment. Consequently, users which have a high spatial awareness on the environment that surrounds them, have knowledge of their position in relation to the entire environment and they have general knowledge of the environment.

2.3 Terminology

2.3.1 Position vs. location

The words 'position' and 'location' seem to be similar, but have a different meaning in the context of this research. For example the position of the ICT Building of The University of Melbourne is 37°48'05" South and 144°57'34" East, with an elevation of 55 metres above mean sea level. This exactly pinpoints the entrance of the building on the Earth, leaving no doubt about where to find it. This is what is called *position* and is also referred to as physical position.

Adding more abstract ideas of where something is to the position makes it a *location*. For example the location of the ICT Building is just south off the main campus, at University Square in Melbourne. More general, in the context of this research a location is a description of the spatial environment of the position. Other examples of location are: just South of the lake, around the corner or room 12 at the second floor.

The resolution or precision of the position has an effect on the abstract ideas that can be used to describe a location. For example due to an inaccurate measurement a location can only be described as 'on the third floor', whereas with a very accurate position measurement a location can be described as '45cm away from the door of office 3.55a'.

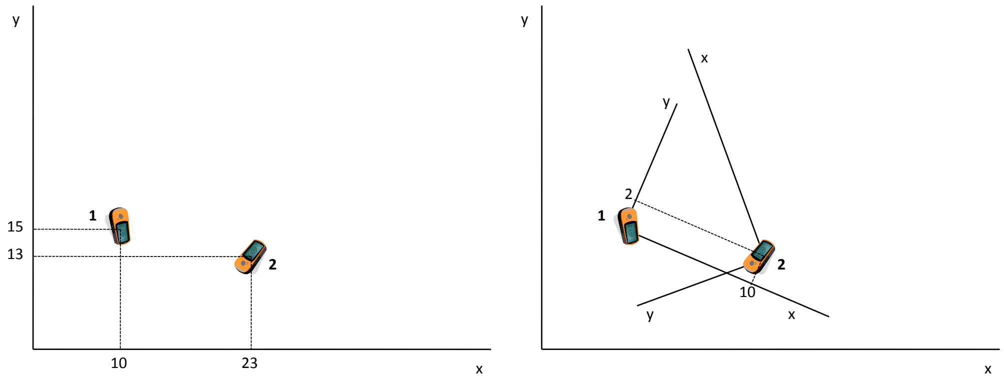
2.3.2 Absolute vs. relative position

Every positioning systems uses a reference framework to represent the position of an object. When this reference framework is shared by all objects in the system, the framework is called *absolute*. For example the GPS system uses latitude, longitude and altitude coordinates, based on the WGS-84 framework. Every point on the Earth has a unique coordinate in this system.

Every GPS receiver, placed at the same location, will report the same coordinates. Absolute positioning systems report a position relative to a general framework.

A system where every object has its own reference framework is called a *relative* positioning system. In systems like this, each object has it's own view of the surroundings, relative to itself. Imagine the following example, where two fighter jets fly the same path to a target, with 1 km distance between the two of them. A radar system in the first fighter jet reports the position of other jets, objects in the air and the target, relative to itself. The radar of the second fighter jet will show these objects and the target as a different picture, because the positions differ relative to in its own position. Relative positioning systems report positions relative to the devices.

It is possible to transform a relative location to an absolute location and vice versa, provided there is a second absolute reference point present in the relative framework. Alternatively several relative readings from an object (with a known absolute location of the reader) can be combined by triangulation to obtain the absolute position of this object. Figure 2.1 shows two positioning devices. In an absolute position system they have coordinates (10,15) and (13,23) (Figure 2.1(a)). However, both devices have their own relative positioning systems to make a map of their environment. In the relative system of device 1, device 2 is at position (10,2). Similarly the position of device 1 in the relative system of device 2 is (5,10) (Figure 2.1(b)).



(a) Absolute coordinates (b) Relative coordinates

Figure 2.1: Absolute position vs. relative position.

2.4 Conclusion

The literature reviewed in this Chapter suggests that humans are able to navigate in complex situations, using various cues from the environment. Distinctive elements in the environment are used to remember important places. All the environmental cues are stored by humans in a mental representation of the environment. The representation allows humans to remember paths, maintain orientation and perform new wayfinding tasks. Additionally recent studies with sighted, blindfolded and visually impaired people show that, although there is a difference in wayfinding performance between these groups, the wayfinding skills are fundamentally similar.

The method that will be described in the next Chapter is also based on the way people naturally perform wayfinding tasks, previously referred to as Tomko & Winter (2006).

Chapter 3

Spatial structuring

Major step in getting an answer to our research question is to research if there is a way to identify spatial properties of indoor environments and structuring these elements. This Chapter presents a methodology to identify spatial properties, based on a user perspective of the functions of the environment. Having identified these elements, a way to organize these elements in a logical structure is presented. Eventually, some applications of this developed structure are presented, which motivate the development of such a structure.

Essential step in providing information about environments is collecting and structuring this environmental information first. Overall information about indoor environments is called *spatial information*. The term *spatial context information* refers to the more detailed case of information about relations between several objects in space or the relation between objects an the current position of an individual (for example "the water cooler in on your right" is spatial context information).

Surprisingly there is not many literature on identifying and organizing indoor spatial information for human wayfinding. This chapter will summarize existing literature on describing spatial structures and context, following by a proposal for a general approach to develop an indoor spatial structure. Applications using indoor spatial knowledge need a pre-defined spatial structure to work efficiently. Ad hoc solutions are often used to develop these structures, which are specific to one case and not suitable for general use. The reasoning behind these ad-hoc hierarchies is vague and unclear. The development of a general layered model of an indoor environment will create new possibilities for implicit wayfinding and dealing with uncertainty in positioning measurements. Also it will give clear guidelines for developing a model of other indoor environments. The structure presented later in this chapter will be based on offered functions from a user's perspective. The layered model will be able to describe a location from different viewpoints. It can describe a location and its surroundings in detail or at a more global level and support natural wayfinding and location descriptions, used by humans in real life.

3.1 Research in structuring spatial environments

A major piece of work on structuring urban environments is the *Pattern Language* developed by Alexander, Ishikawa, Silversein, Jacobson, Fiksdahl-King & Angel (1977). This work is related to the previously introduced research of Lynch (1960), but the goal of this research is to develop a language in which every environment can be described, using the same set of semantics. They define a set of 253 patterns, from high level 'Towns' to the 'Construction blocks' of buildings and are less concerned about the cognitive aspects of spaces, but more focusing on identifying elements for describing urban environments. All patterns are related and essentially provide a language in which a building, town or any spatial structure can be described. Although the language itself focuses more on the architectural considerations of a town or building (for example 'House cluster' or building 'Houses facing the sun') and some may be a bit outdated (for example 'Shopfront schools') there are useful patterns for structuring indoor environments. A similar, extremely reduced, language could be defined for indoor spatial references.

Research on spatial structuring focuses mainly on analysing urban structures. Like the *Space syntax* developed by Hillier (1996). The goal of the space syntax is to break down spaces in components and networks, and analyse the movement of people in this environments. These movements relate to social aspects of the environment, which can be a city or a building. The Space Syntax tries to link physical aspects of the urban environment to social and other aspects that comprise the functioning of an urban area (Hillier n.d.). Axial maps, representing the main routes people move on, are used to analyze the complexity of (part of) the city. In essence they provide a common language for describing and explaining social, economic and environmental functioning of cities.

Kuipers (2000) developed probably one of the most advanced models for structuring spatial knowledge with *The Spatial Semantic Hierarchy* (SSH). Although partly based on human cognitive models, it is heavily linked to robot exploration and robotic map building. The basis of the model is an hierarchy of five layers, containing two types of information, qualitative and quantitative. The layers organize information in a sensor and control layer, responsible for sensing the environment and making sure the robot does not collide with objects, is able to follow walls, etc. On top of these two layers there is the causal layer, which links and abstracts the sensed world to actions, using local metrical maps. It positions the robot in a local reference framework with orientation information. The next layer is the topological layer, which introduces paths, places and regions. Finally the metrical layer provides a general reference framework, which is not considered essential, but rather useful. The idea of the model is to separate information and be able to operate, even if there is a lack of information. Although stated as future work in 2000, there is no iteration of this model which incorporates verbal environment descriptions yet.

Key in the SSH is the distinction between local control level and overall navigation capabilities. The lowest level in the hierarchy only provides rules and information which allow robots to traverse hallways and environments without problem. Higher levels in the hierarchy control the actual movements and track the robot's position. This way it will be sufficient to issue higher order commands like 'enter corridor' instead of detailed information about the robot's track.

This idea of splitting up the environment in local areas at lower levels and more global levels in higher levels will also be exploited in the structure presented later in this Chapter. However, in human navigation layers which issue robot control commands can be omitted, obviously. Also, the hierarchy must be able to give much more descriptive information about the environment, than needed in robotics. Especially in generalizations of spaces this introduces challenges. Robots can just refer to 'the North part' in their generalization, whereas this might not make sense for human interaction systems.

3.1.1 Summary

The literature study shows that very little research has been on on describing indoor environments in at various levels of abstraction. Research related to wayfinding focuses on the performance and perfection of turn-by-turn instructions or creating route descriptions that can be efficiently used. Research in robotics does focus on creating different levels of abstraction from an environment, but this is very much focused on discovering and defining the physical aspects of the environment and lacks any notion of the functional aspects of a space. However to accurately describe indoor environments in a way that is understandable and useful for humans, these functional aspects have to be included. This is not only useful for wayfinding applications, but for any application that would need a more functional and human understandable description of an indoor environment.

3.2 Developing an indoor spatial structure

3.2.1 Need

Indoor structures like airports or an academic buildings can be represented in many ways. Most common is a generalized map, which depicts the important areas in the environment, like the map of Amsterdam Airport in Figure 3.1. Sometimes the current location of the user is also drawn on the map, the so called 'You-Are-Here' map. Although there is discussion on what is a 'good' map, many agree it is the right way of representing an indoor environment. The main disadvantage is that this representation does not provide much information to *describe* a location or the surroundings of a location. It is a static picture, roughly representing the most important locations. It is not dynamic and does not describe the context of *where* something is, which is a common way of humans describing a place.

One way of describing an indoor environment is by looking at the physical properties, like surface area, spaces, walls, coordinates, etc. This is what has been researched in the robotics field (Kuipers 2000). It is possible for robots to survey an environment and locate all the obstacles, thus forming a map of the environment that identifies walls and open spaces. However, this way of describing an environment is like a map without any text, symbols or icons. It can accurately describe an environment, but it provides no information about the functions of the environment at all.

Functional descriptions of an environment will enhance the understanding of this environment to users and enhance their spatial awareness of this environment. However there must be a structure to support this way of describing an environment. Currently no means of functionally structuring an indoor environment exist.

3.2.2 Requirements

The indoor spatial structure must be able to provide information, which is useful for environmental descriptions to humans. Typical usage will be in digital you-are-here map descriptions, wayfinding systems and navigation systems. It is not intended to be a framework for turn-by-turn instructions. However, it could enhance turn-by-turn navigation systems. Main advantage of a structure will is that it can be used to describe the environment at different levels of granularity, which allows for generalizations of the environment to efficiently describe larger parts of an environment. However, these generalizations must still be correct and accurate. In order to create generalizations, the smallest identifiable element in the structure must be identified first.

Figure 3.1: Generalized map of Amsterdam Airport arrivals area (source: www.schiphol.nl)

The structure must be functionally oriented, since physically oriented structures can already be developed with approaches from robotics. A functionally oriented structure will be more valuable to humans, because it incorporates information about what the environment 'offers', which is more valuable to humans than the physical properties of a space.

3.2.3 Scenarios

The construction of the indoor spatial structure will be supported by two examples. The scenarios are oriented to the usage of the building, rather than the physical structure. The first scenario is a typical academic building at a university campus. It provides spaces for students, teachers and researchers, like study rooms, tutorial rooms, offices and laboratories. The second scenario is an mid-size airport, typically with domestic and international flights, which are operated by several carriers.

Academic building

The academic building in this example consists of several storeys and inhibits all services of one department. Students visit the building for meetings with their teachers, attending lectures, working on study projects with other students and attending tutorial sessions. Some students even have their own desk in the building, for example PhD students or students working on a Masters project. Staff members of the department are mainly professors and associates, the academic staff. Academic staff is organized in research groups, which all have their own laboratories and spaces for students. Offices and laboratories of the same research group are often located close to each other. Students sometimes share an office. The majority of the academic staff is also involved in teaching. However, supporting services like management, IT support, financial services and educational support are also located in the building. There are also four lecture theatres and there is a food court in the basement.

This environment is characterized by the homogeneity of the environment. There are many spaces which are similar, like offices. In general it is organized following the structure of the department or faculty. Members of the same research group are in offices close to each other.

Airport

The airport in this example is a mid-sized international airport. It consists of three terminals, two for domestic flights and one for international flights. The terminals are of the same size, but the international terminal has a tax-free shopping area with some luxury shops. In all terminals there are shops for drinks, food and travel needs. Drivers wait for most of the business travellers to drive them to the city, because the airport is a thirty minute drive from the city and public transport to the city is slow and overcrowded. Despite this, many travellers on holiday use the public transport system. The terminals of the airport have approximately 30 check-in desks each and about 10 gates each. All the other usual services of an airport are also present, like security checks or baggage belts.

This environment is characterized by the diversity of the environment. There are many different spaces in an environment. Airports are structured by function and designed to assist in the processes that take place at the airport.

3.2.4 Approach

To describe an environment in a functional way, the functions of the environment have to be understood first. The underlying thought is to look at an environment from a functional perspective and ignore the physical properties. Why would someone enter this environment? What is his goal? Indoor environments (or *buildings*) are visited by various types of users, who all try to accomplish a goal in the building. They are there for a reason. Referring back to the scenarios, a person arriving at an airport has a different goal than a person departing at an airport. However, they both use the same environment to accomplish this goal. How is the environment organized to provide this function to both visitors?

To reveal the functional structure, the first step has to be the identification of all types of users. Who is visiting the building and how can these persons be classified? Even more important, what are they doing in the building? Which location do they visit? Or do the even visit more than one location each visit? With the answers to these questions it must possible to reveal the functions of a building. It should break the physical spaces in a building into functional spaces. An office is no longer considered as a space with four walls at a certain position, but it is a functional unit. A functional unit is a goal of a type of users visiting the building.

When users and functional units are identified, these functional units can be organized in a structure. Most functional units have a relation with other functional units. For example several offices may be part of the same department of a company. Using these kind of similarities between functional units they can be grouped into bigger structures.

3.3 Offered functionality of the environment

The first step in functional description of an indoor environment is the identification of users and functional elements of the environment. This section will present a way to identify the users and an approach to discover the functions of an environment, which can be broken down to functional elements.

3.3.1 Identifying users and usage

People visiting a building have a reason for entering that building. The building has something to offer, it provides a service or allows a person to do something. The functions can differ from person to person and can be diverse. Important functions to some users might be worthless to others. However, it is possible to compile a list of main functions for each building.

First the types of people that visit the building (users) are identified. This can be done by surveying or observing people at the entry points or more imaginary. Think of all the people entering the building and identify their reason of entering the building. A person entering a building wants to accomplish something. He has one primary goal for entering the building. A list can be made for all users that enter the building with their goals. An entry in this list will be the person itself (*user*) and what he wants to do (*action*).

User A user is a person, who has some characteristics and a relation with the building. The key here is to identify the main types of users, based on their usage of the building. In general this distinction is based on how often users visit the building. One obvious distinction is occasional users and frequent users. Another distinction, based on the abilities of the users, might be made as well. For example blind, deaf, literacy impaired or mobility impaired. Also the age of the users may be a factor. For example children, teens, adults and elderly. All these distinction are valid, but for this goal the types of users that are the *main users* are of use. This is generally defined by the function of the building they use and not affected by the characteristics of the user itself. Typical types of users in a school will be for example teachers, staff and students.

Action An action can be any action a user performs to reach his goal. The definition of an action has to be general and is ambiguous. This is not a problem, as long as consistent naming is used for the same action. The action can also include an object. The object is someone or something involved in the action. The person performs the action on the object. The level of detail in which an action is defined depends on the environment. For example one can define ‘visitor gets a double flame grilled burger’ and ‘visitor get a single flame grilled cheese burger’, but this will obviously result in numerous useless definitions of users and introduce differences in users who essentially want the same. The correct definition depends on the setting, but could be ‘visitor gets burger’ or ‘visitor gets food’. The first would make more sense in an environment with only food stores, whereas the latter would make more sense in an environment with hardly any foodstore.

In theory a long list of of users and actions can be compiled for each building. However, the goal of this phase is not to get an exhaustive list, but a general list of the main functions of the building. For example, if there are coffee machines in a building, it is unlikely that people just go to that building only to grab a cup of coffee and then leave again. But if their office is in

User	Action
User type 1	Action
	Action
	...
User type 2	Action
	Action
	...
...	

Table 3.1: Users and actions

this building, for sure 'getting coffee' is one of the goals of this user. However, it is not a main goal for people entering the building. That would be 'going to work' in this case. Table 3.1 is an example of such a list.

3.3.2 Adding Destinations

The previous enumeration of *user-action sets* gives insight in the users and their goals. If the goals of the users are known, essentially the functions of the environment are known as well. It is clear why someone (user) enters the building, he want to do something (action). But what is lacking now is *where* this user will accomplish his goals. Or in other words, *what do users need from the building* to accomplish their goal? What does someone need to go to work? Probably an office and maybe a meeting room. For users to accomplish their goal in the building, they must visit destination(s) in the building. Some destinations are mandatory to accomplish a goal, other are optional.

Destination A destination is always a space in the building. It might be very small (a toilet), big (a theatre, a foyer) or anything in between. The destination is the space where the person performs the action and accomplishes (part of) his goal. Essentially the destination is the reason why the user got to that building. The function that the building offers can be found at that particular destination. The goal is to identify the *types* of destinations, not each individual destination. For example not 'office 2.13' or 'office 2.14b', but general concepts like 'office' and 'gate'. The goal is to identify the important functional elements of a building.

Destinations can be mandatory or optional. Mandatory destinations are destinations that *must* be visited in order to accomplish the goal. It is impossible to achieve the goal without

User	Action	Destination
User type 1	Action	Mandatory destination A
		Optional destination B
	Action	Mandatory destination C
		Mandatory destination D
		Mandatory destination E
	...	... ...
User type 2	Action	Mandatory destination A
		Optional destination B
	Action	... ...
	...	
...	...	

Table 3.2: Users, actions and destinations in a usage table

visiting these destinations. Optional destinations are not required to accomplish a goal, but *may* be visited by part of the user group that accomplished a goal. It is possible to achieve the goal without visiting these optional destinations. For example, for people departing from an airport it is required to check-in and to pass a security check (mandatory). However, they are not required to do some tax-free shopping or wait in the airline lounge, but they *can* (optional).

Usage table A *usage table* summarizes all types of users, actions and destinations. The goal of this table is to list the main functions of the environment, from a user perspective. These tables identify a list of destinations for each user-action set. For each action there are mandatory and optional destinations that are involved in this action. The list of destinations consists of any destination that can be involved in this action, regardless if it is mandatory or optional. Table 3.2 is an example of such a table. Later on in generalizing the environment, this usage table is helpful as well.

Besides these destinations, a building contains several points of interest, which are in general not the primary goal/destination for entering the building, but which become important once inside. These points of interest (POI) are for example toilets, ATM's, candy bar machines, information desks, elevators or stairs. These are considered further on as *special destinations* and covered in Section 3.4.7.

3.3.3 Examples: Usage tables

Airport

Users An airport is a complex building, which is visited by many users daily. Two obvious user types are the *departing traveller* and the *arriving traveller.* A third type of traveller can be added, the *transit traveller.* Besides the travellers, people who wave goodbye to the travellers or wait for the travellers form a part of the users. Let's call them *relatives*, but the drivers who wait for business travellers are also part of this group. As with many buildings, employees who work somewhere inside the building are users. However the view on the environment of this group is different from the 'normal' user, because their goal of visiting the building is completely different. The point of view of the employee is for this example disregarded, because the scope of the methodology are the users of the environment.

Actions and objects The goal of a departing traveller is to leave the airport in an aircraft to some destination, but before he actually can depart he has to complete a chain of tasks and therefore visit various destinations. When the traveller enters the building he first has to find the appropriate *check-in counter* for his flight. At this check-in desk he receives a boarding pass and drops off his luggage (sometimes at a separate *baggage drop-off point*). A part of the travellers has questions or problems with their reservation and also has to visit the *airline service desk.* Now, after passing *customs*, he can proceed to the appropriate *gate* where he can board the aircraft, probably after some waiting time in a *waiting area* or *airline lounge.* A substantial part of the departing users arrives early at the check-in desk, so they do some tax-fee shopping in the one of the *tax free shops* or have a light meal or drink at one of the *bar and/or restaurants.*

The objective of the arriving traveller is to get out of the aircraft, grab his luggage and leave the airport. Again he has to complete a chain of tasks to accomplish this. First he leaves the aircraft at the *gate*, then he proceeds to *customs* and the *baggage claim* belt for his flight to collect his luggage. Then he proceeds to leave the airport, either after meeting with a driver, family or friends at the *arrivals area* who pick him up, or by own *transportation* or *public transport.* Travellers unfamiliar with the area or country might want to visit one of the *tourist information desks.*

A combination between the arriving and departing traveller is the transit traveller. This person arrives at the airport to transfer to another aircraft and continue his journey. He can skip some of the actions of both the arriving and departing traveller. His chain of actions is: leave the aircraft at the *gate*, pass *airport security*, possibly proceed to an *airline service desk* to confirm or check-in for his connecting flight and get to the *gate* to board the next flight. Also waiting in a *waiting area* or *airline lounge* and visiting one of the *bar and/or restaurants* can be part of this process.

Most of the relatives that are waiving goodbye to a traveller accompany him until the *check-in desk*, either before of after having a last meal or coffee at one of the *bar and/or restaurants*. When the traveller enters the secure area, only accessible to travellers, the relatives proceed to the *panorama deck* to see the aircraft take off.

Most of the relatives that are waiting for a traveller to arrive wait for him in the *arrivals area*. During the waiting they possibly have something to eat or drink from the *bar and/or restaurants*, something they might also do once the traveller has arrived. Eventually they will leave the airport with the traveller, using their *own transportation* of *public transportation*.

The above text can be summarized in a table, which states their goal as person-action combination. Also the destinations where they accomplish this are given in the table. See Table 3.3

Interestingly a feature of the functional decomposition approach based on users is shown clearly here. As can be seen in the example, both the 'Arrivals Area' and the 'Baggage Claim' are identified as destinations. The first is important from a travellers perspective, the latter from a visitors perspective. Obviously, the 'Arrivals Area' is of an higher level of abstraction than 'Baggage Claim', which is situated in the 'Arrivals Area'. This shows the different functions a building can offer. People picking up their friend are not interested in which baggage claim belt the suitcase of this friend ends up. However, the friend wants to retrieve his suitcase and will have great interest on which belt it ends up.

Academic building

Users The academic building is mainly visited by *students* and *staff*. The group of students can be divided into two groups. The first group visits the building for just a few hours a day to attend a lecture or a tutorial, the *regular students*. The other group of students is working on a daily basis in the building, for example PhD or Masters project students, the *research students*. Visiting professors are also member of the staff.

Actions and destinations The goal of the regular students is to *attend a lecture* in one of the *lecture theatres* or smaller *lecture rooms*. Other regular students want to *attend a tutorial* in one of the *tutorial rooms*. Depending on the time of the day, regular students may *have a lunch* in *the food court* before or after their lecture. Students that participate in subjects that requires them to work as a group *meet with other students* in *project rooms*. Lastly, regular students visit the building to *meet with one of the staff members* in the *office* of that staff member.

The goal of the research students is to *go to work* in their *office* or *laboratory*. From time to time they *meet* with their supervisor, typically another *staff member*. Also these students participate in the research programmes of the department and *attend meetings* in the *meeting rooms*. Of course many of these students *have lunch* in the *food court*.

User	Action	Destination
Departing Traveller	Starts travelling	Check-in
		Security
		Airline service desk
		Customs
		Departure gate
		Tax-free shop
		Restaurant / food stall
		Airline Lounge
		Waiting area
		Baggage drop off point
Arriving Traveller	Ends travelling	Arrival gate
		Security
		Customs
		Baggage claim
		Exits
		Tourist information desk
		Public transportation link
Transit Traveller	Transfers to another flight (continues travelling)	Arrival gate
		Security
		Departure gate
		Airline service desk
		Restaurant / food stall
		Airline Lounge
Relative	Waves goodbye to departing traveller	Departures area
		Restaurant / food stall
		Panorama Deck
	Picks up arriving traveller	Arrivals area

Table 3.3: Destinations an an airport

The goal for the staff members is to go *to work* in their *office*. Also they *attend meetings* with other staff or research students on ongoing projects in *offices* or one of the *meeting rooms*. Some staff members *do teaching* in one of the *lecture theatres* or *lecture rooms*. Tutorials are only given by research students. And again, also staff members *have lunch* in the *food court*.

All these goals can be summarized as in Table 3.4. Note the many duplicate entries for some goals that are shared by more users, for example having lunch in the food court.

User	Action	Destination
Regular student	Attends a lecture	Lecture Room
		Lecture Theatre
		Tutorial room
	Has lunch	Food Court
	Has a meeting with a staff member	Office
	Has a meeting with other students	Meeting Room
		Project Rooms
Research student	Goes to work	Office
		Laboratory
	Has a meeting with project members	Office
		Meeting room
	Gives a lecture	Lecture Room
		Lecture Theatre
		Tutorial room
	Has lunch	Food court
Staff member	Goes to work	Office
		Laboratory
	Has a meeting with project members	Office
		Meeting room
	Gives a lecture	Lecture Room
		Lecture Theatre
	Has lunch	Food court

Table 3.4: Destinations an an academic building

3.3.4 Deducting main tasks

The main functions of the building can be deducted from the usage table. Main functions of a building have a close relation with main tasks of the users, because users enter the building to use functions of that building in accomplishing a task. The main functions are defined by the user and his actions, not by the destinations. Looking at the usage table for the airport example (Table 3.3) the rows for 'Departing traveller starts travelling', 'Arriving traveller ends travelling' and 'Transit traveller continues travelling' clearly incorporate the most destinations. All three are main functions of the building: allowing travellers to start, continue or end travelling.

Thus the main tasks of the user are given in the usage table, is simply an enumeration of the 'action' column. They may be renamed to get more understandable, but no actions can be added that are not present in the usage tables. For the airport example the main tasks are given in Table 3.5 and for the academic building example in Table 3.6.

Airport

Action	Main Task
Starts Travelling	Depart from the airport
Ends Travelling	Arrive at the airport
Continue travelling	Transit at the airport
Wave goodbye	Say farewell to traveller
Pick up	Pick up traveller

Table 3.5: Main functions of an airport

Academic Building

Action	Main Task
Attend a lecture	Attending lectures
Have lunch	Having a lunch
Have meeting	Having a meeting
Go to work	Working
Give a lecture	Giving a lecture

Table 3.6: Main functions of an academic building

3.3.5 Functional Elements

Previously the types of users of a building, the actions these users want to perform and the destinations which allow the users to perform these actions are identified. This resulted in a clear list of functions of a building and types of locations where functions are offered. If we want to describe the indoor environment of a building in a functional way, this information has to be the foundation. The list of functions clearly describes the environment of the *entire* building. It defines all the functions and the locations where these functions are offered. It describes the *entire* indoor environment, it is yet impossible to describe *parts* of the environment.

Now there is a clear understanding of the destinations, it is possible to define the smallest functional units of the environment, the *functional elements*. A destination is a space where the user performs an action, where he reaches his goal. From a functional point of view, there is no need to further decompose these destinations. For example, we do not want to describe the exact layout of an office (with chairs, desks, cabinets, etc.), we only want to describe the function 'office', with some properties of that particular instance. These destinations are called *functional* *elements*, because they are the smallest elements (in terms of space) that can be identified in this model.

To transform destinations into functional elements, almost every destination is declared a functional element. But care must be taken, since sometimes a destination occurs more than once in the list. It is also possible that generalizations of a destination are in the list, which Figure 3.2 shows. Destination 4 completely covers destinations 1, 2 and 3. As such destination 4 is a generalization of 1, 2 and 3. Therefore destination 4 is not considered as a functional element, whereas destinations 1, 2 and 3 are. So all destinations which do not cover other destinations are defined as a functional element.

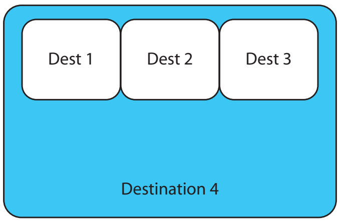


Figure 3.2: Destinations for different users.
Destination 4 is not a functional element, because it covers other destinations.

Functional element A functional element is a space in an environment. This space allows a user to execute (part of) an action. Functional elements can be part of one or more actions. Functional elements offering the same functionality are of the same type, they are identified by the same destination from the Usage table. Multiple instances of a functional element can exist in an environment.

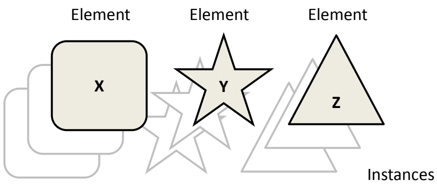


Figure 3.3: Multiple instances of an element can exist in an environment

Important aspect in defining the functional elements is to create a distinction between the different types of functional elements. Functional elements are derived from the destinations in the building. Destinations are part of the functional aspects of the building. If functional elements offer the same functions, then they belong to the same type. For example, in an office building, there are hundreds of offices, which have more of less the same functions. All offices provide a person with a space to work or to meet. The properties of the units may vary, for example the size and number of people occupying the office. But the function is the same and therefore offices belong to the same type of functional element: 'office'. Obviously, multiple instances of an element can exist.

In order to classify and group the functional elements into generalized structures, similarities and differences have to be identified. From a functional view, functional elements of the same type provide the same kind of functionality. For example, all offices are 'an environment to work in'. This is an obvious shared property, but gives no information why one office is different from another.

Properties can be divided into two classes of properties, properties regarding the functionality of the functional element and properties regarding the physical position and structure of the functional element. Table 3.7 shows an example of functional and physical properties. Functional properties answer questions like: What makes one functional element different than the one next to it, apart from the difference in their physical position? For an office it may be the person who is residing in it, for a ticketing desk the type of tickets it sells, etc. Usually also a numerical value is assigned with a functional element. For example, an office has number 2.34 or a ticketing desk has number 1. Although this value has nothing to do with the functionality, more often it is a way to represent physical location, it is important to include these values in the properties, as it is a commonly used way to identify a place. The emphasis in this conceptual method is more on the functional properties than on the physical properties, because we try to structure the environment in a functional way.

Physical	Functional
Room number	Occupant
Coordinates	Relation to other elements
Physical boundary	Maximum customers
Contact number	Open/Closed
Distance from entrance	User type

Table 3.7: Physical vs. Functional properties.

In theory many properties can be defined for a functional element. It provides some functionality to someone visiting the environment. But why would someone be looking just for functional element A and not B? Already, some properties can be derived by answering this question. What functionality is provided by the functional element? What makes this functional element different from another element, apart from the functionality? Which user is using the functional element? Besides that there are also physical properties, like the position of the element, the number or name that might already be associated to it (in the real world), etc. Figure 3.4 shows the wide array of properties that can be defined for each instance of a functional element.

To facilitate the generalization of the environment, a functional element needs to have a minimal set of properties. These are common for every functional element, regardless of the functionality. Table 3.8 lists the minimal required properties.

First property is the *pre-existing identifier*, which is the name or number that is currently used to identify the space. This is a physical property of the functional element. For example a room number. Besides this identifier the *discriminating factor* is defined, which is a property that is unique to that instance of the functional element. It is useful to define something that is related to the functionality, for example the occupant of an office. This property can be physical or functional, but it has to be the main factor that distinguishes instances of a functional element.

A functional element is always part of some organizational structure, which is the (functional) structure of the organization occupying the building. This has to be a functional property, for example a department or particular organization. The property *part of* defines this organization of this instance of the functional element. For example, 'sales department'.

While the previous properties can be difficult to define, the last two properties can be derived from the Usage tables. First property is the user that is *served by* this instance of the functional element. Often this value is the same for all instances of functional elements of the same type. Last required property is the *main task*, which is the main task that is served by this functional element. This was already determined when creating the usage table (see 3.3.4).

Summary

Once the functional elements and their properties are defined, the functionality of the environment is captured. For each function the points where this functionality is offered are defined. For each function a *type* of functional elements has been defined. This is the conceptual space

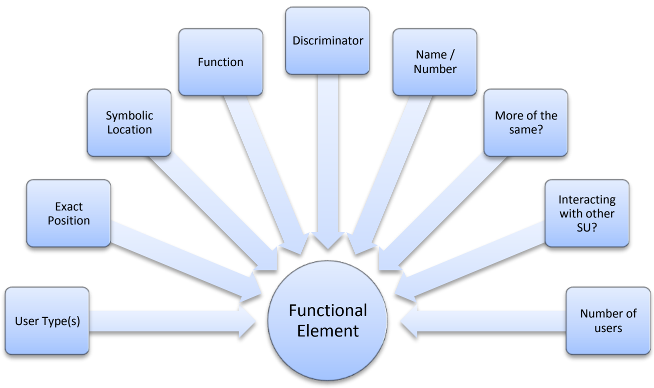


Figure 3.4: Many properties define an instance of a functional element.

where the functionality is offered. An *instance* of a functional element is the actual space where this functionality is offered. Instances slightly differ from each other, but provide in the same functionality.

The building can be seen as the container in which many instances of different types of functional elements exit (Figure 3.5). However, this container is somehow structured. Revealing this structure is the next step in the methodology.

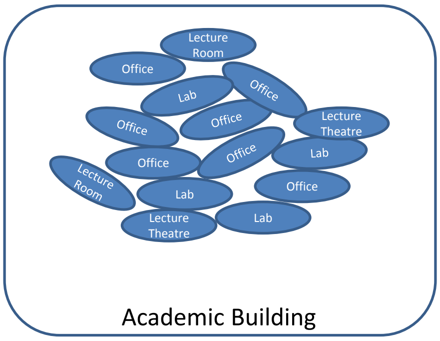


Figure 3.5: Functional elements describing the functions of an environment.
The structure is not clear yet.

3.3.6 Example: functional elements

Airport

Recalling Table 3.3 the following destinations were found at an airport: check-in, customs, airline lounge, departure gate, arrival gate, baggage claim, airline desk, shop, bar and/or restaurant, departure area and panorama deck. The departure area is a generalization of check-in and departure gate and therefore not considered as functional element. The other destinations are unique and thus a functional element. They are defined as functional element, with the minimal properties. Table 3.9 lists the properties of the check-in desk with some possible values. Similarly Tables 3.10, 3.11, 3.12 and 3.13 list the properties for other functional elements.

Property	Description
Pre-existing identifier	If there is any method that is used to identify the space of the functional element at this moment, include it here. For example: Room numbers.
Discriminating factor	What makes this instance of the functional element unique? Why is it different from a functional element of the same type? For example: Occupant of office.
Part of	The organizational structure that is the bigger part of an instance of this functional element. For example: 'Sales department'
Serves user	The users that perform an action at this functional element.
Main task	The main task where this functional element is part of.

Table 3.8: Minimal functional element properties.

Check-In

Property	Description and value
Number	This is the pre-existing identifier, the desk number. *1, 2, 3, ...*
Flight Number	This is the discriminating factor which distinguishes this check-in from the other check-in. *'KL-123', 'QF-09', 'XX-32', ...*
Part Of	The parent of this instance, from an organizational point of view. *'KLM Royal Dutch Airlines', 'Lufthansa', 'Qantas', ...*
Serves	The type of user that is served by this functional element. *'Departing Traveller'*
Main Task	The main task where this functional element is part of. *'Depart from the airport'*

Table 3.9: Functional element properties for a check-in desk. The values are just examples.

Customs

Property	Description and value
Identifier	*1, 2, 3, ...*
Discriminator	*'males only', 'non-EU passengers'*
Part Of	*'Airport Services'*
Serves	*'Departing Traveller'*
Main Task	*'Depart form the airport'*

Table 3.10: Functional element properties for customs. The values are just examples.

Airline Lounge

Property	Description and value
Identifier	*3.23, 5.54, 4.33, ...*
Discriminator	*'First class travellers', 'Executive program members'*
Part Of	*'KLM Royal Dutch Airlines', 'Lufthansa', 'Qantas', ...*
Serves	*'Departing Traveller'*
Main Task	*'Depart form the airport'*

Table 3.11: Functional element properties for airline lounge. The values are just examples.

Gate

Property	Description and value
Identifier	*3a, 4b, 5a, ...*
Discriminator	*'KL-332', 'QF-02', ...*
Part Of	*'KLM Royal Dutch Airlines', 'Lufthansa', 'Qantas', ...*
Serves	*'Departing Traveller', 'Arriving Traveller'*
Main Task	*'Depart form the airport'*

Table 3.12: Functional element properties for gate. The values are just examples.

Shop

Property	Description and value
Identifier	*3.1, 4.3, 5.5, ...*
Discriminator	*'Samsonite', 'LaCoste', 'Liquor'*
Part Of	*'Cosmetic shops', 'Electronics shops', ...*
Serves	*'Departing Traveller', 'Transit Traveller'*
Main Task	*'Depart form the airport'*

Table 3.13: Functional element properties for shop. The values are just examples.

Academic Building

Recalling Table 3.4, the following destinations were identified in the academic building: lecture theatre, lecture room, office, food court, laboratory, meeting room and tutorial room. Tables 3.14, 3.15 and 3.16 list the minimal properties for some of these functional elements.

Laboratory

Property	Description and value
Identifier	*3.1, 4.3, 5.5, ...*
Discriminator	*'Craig SuperPC', 'Photometer', 'Robosoccer', ...*
Part Of	*'Research Group A', 'Research Group B', ...*
Serves	*'Student', 'Staff'*
Main Task	*'Go to work'*

Table 3.14: Functional element properties for laboratory. The values are just examples.

Office

Property	Description and value
Identifier	*3.24, 4.34, 5.51, ...*
Discriminator	*'John Smith', 'Jack Brown', 'Ann Sue', ...*
Part Of	*'Group A', 'Group B', ...*
Serves	*'Student', 'Staff'*
Main Task	*'Go to work', 'Have meeting'*

Table 3.15: Functional element properties for office. The values are just examples.

Lecture Theatre

Property	Description and value
Identifier	*1, 2, 3, ...*
Discriminator	*'Big Theatre', 'Small Theatre', ...*
Part Of	*'Group A', 'Group B', ...*
Serves	*'Student', 'Staff'*
Main Task	*'Attend Lecture'*

Table 3.16: Functional element properties for lecture theatre. The values are just examples.

3.4 Functional organization

In the previous sections a way of analysing the functionality of the environment has been presented. Functional elements provide a detailed description of the environment. They allow for descriptions in terms of each functional element and its properties. This is useful, but for describing large environments it becomes a problem. Generalizing functional elements is a solution for describing larger areas. A generalization from functional elements can be created by grouping elements that are similar, they share a property. With clever choosing of the property that defines the similarity the size of the groups can be controlled. This section introduces a method to generalize the functional elements in three different ways. As a result a model with four layers of information is created, each layer describing the environment in at a differet level of abstraction and at a different level of granularity.

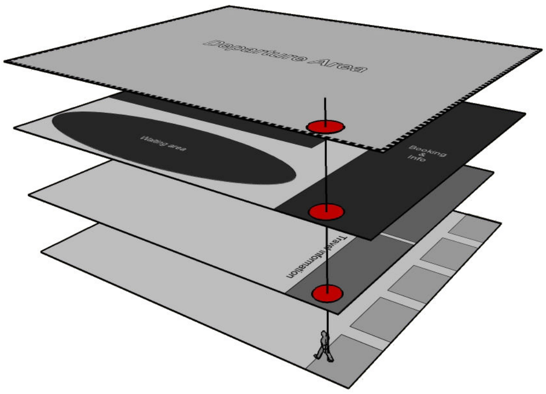


Figure 3.6: One position represented in different abstraction layers

3.4.1 Need for layers of information

A position in an environment can be described in many ways. The coordinates of a position are an accurate and unambiguous method to describe a position. A point at (x, y, z) is unique, there is no other position with the same vector and there is no uncertainty about where this point is. For this reason information systems often use a system of coordinates when dealing with a position. However this coordinate alone provides little information about the location, other than where it is. For example coordinates $(37°47'09.13"S, 144°57'27.22"E)$ would give most people no clue about a position other than that it is somewhere in the Southern hemisphere and quite far in the East. In fact it is the position of my apartment in Melbourne, Australia. The position can be described in various ways: by street address '92 The Avenue', by suburb 'Parkville', by occupant 'Vincent', by a nearby landmark 'The Carlton FC stadium' or 'Melbourne Zoo', etc. This enumeration makes it cleat that a position can be described at different layers of abstraction, as Figure 3.7 visualizes.

Tomko & Winter (2006) also researches how people tend to describe a position or navigate to it. For the outdoor environment they propose a method for hierarchical route directions, which are be better than the current turn-by-turn directions. Elements of the directions are derived from Lynch (1960), for example districts, streets and landmarks. The directions are partially based on the principle of narrowing down the destination from bigger to smaller places, until the destination is reached. On the other hand nearby landmarks play a role. For example to navigate to the address of the previous example, 92 The Avenue, Melbourne, first directions to Melbourne are given. Once Melbourne is reached, directions to the suburb (Parkville) are given. Then directions to a particular landmark are given (The Zoo) and eventually to the destination (100 metres left of the the Zoo). This creates a set of granular route directions.

Figure 3.7: Terms describing a position; all at a different abstraction level.

Different layers of abstraction are useful, especially in the context of wayfinding and navigation. These layers enable the description of a location and its environment in different ways. This practice is also used in traditional wayfinding and map representations of outdoor environments. The widely used Google Maps[1] has, for example, several layers of abstraction (at most 18 for particular locations). From the most general point view (most 'zoomed out') one can only see the continents of the world and the main oceans. When zooming in and going into more detail, additional information is shown. Country and state names become visible, capitals and major cities are shown on the map and the position of rivers becomes clear. Zooming in further reveals major and minor roads. Finally details of every minor road and village are shown. Obviously if all this detailed information was included in the overview of the world, the map would be too crowded, cluttered and useless. With abstraction of the world into many different levels of granularity, this service provides accurate and clear information at every 'zoom' level.

[1] http://maps.google.com/

In indoor environments it is more difficult to develop abstraction layers, because concepts that exist for outdoor environments, like streets, neighbourhoods or suburbs, cannot be used for indoor environments. For indoor environments equivalent concepts are not even defined. The next sections present a way to create four (generalized) layers of information, based on the functional elements and their properties that were presented above. Eventually the goal is to have information to describe a position (x, y) and its context both in detailed and global terms, as shown in Figure 3.6.

Arthur & Passini (1992) state that wayfinding has to be taken into account when an indoor environment still has to be designed. As a guideline they state that after the initial design of spatial elements of an indoor environment, these elements have to be grouped together. Three main reasons for grouping elements together are considered. First the need for human contact or the opposite, the need for privacy. Second, the necessity for information exchange and third, the sharing of certain services. Within these groups, each element is a potential destination for a user. From a broad design perspective the previously mentioned zoom levels are represented as destination, sub-destination and sub-sub-destination zones, similar to the granular route directions that Tomko & Winter (2006) introduce.

3.4.2 First layer: local view

Goal & Scope The most detailed representation of the environment is represented in this first layer with the finest granularity. This layer has the highest information density per square metre; environments can be described up to the details contained by this layer. It is the most 'zoomed in' view of the environment. All functionality of a position and its surrounding can be described. However these descriptions are most useful to describe the local view of the environment, unrelated to the bigger picture. No abstractions from functional elements are present in this layer. The goal of this first layer is to be able to describe the immediate surroundings of a point in detail. This layer allows for local descriptions of the location.

Content The most fine-grained elements that can be identified from a functional perspective are the functional elements that were identified in previous sections. These functional elements provide the functions and services that are of value to the users of a building. Consequently, to provide the most detailed view, this first layer of information must contains all instances of the functional elements that were identified, without any generalization. As a result this layer contains all destinations and functions of the environment. Using the properties (like the discriminator) that have been defined for each instance, distinctions can be made between the functional elements in this layer. Points of Interest are also contained in this layer, as described in detail later in section 3.4.7.

Example Figure 3.8 is a graphical representation of this layer. The point in the middle can be described as being surrounded by the functional elements in the picture. A possible verbal way of describing the position with this information is 'On the right, Lab 3.25 with Craig superPC and Lab 3.27 with Robosoccer. On the left Office of John Smith, Office of Jack Brown and Office of Ann Sue'. Again this is a very accurate, but local description of the position. It gives absolutely no clues about other things in the environment that are further away. Also these kind of detailed descriptions do not place the functions in a bigger context.

3.4.3 Second layer: functional zones

Goal & Scope As seen above, functional elements are useful for describing the immediate environment of a point. However these descriptions are missing the 'bigger picture', the relation between the functional elements and the rest of the environment. Suppose we 'zoom out' a bit on the environment, more functional elements become 'visible'. Layer one can still be used to describe this view of the environment very accurate, however the description will be elaborate. Instead of describing each functional element, a collection of functional units, sharing common properties, can be used to describe a space more efficient. For example, instead of describing each instance of 'office', a description which applies to all this offices can be used, the 'department'. It will be less detailed, covering a larger area, but still accurate. The goal of this second layer is to provide an abstraction of layer one, without abstracting from the functional structure of the environment. This is accomplished by grouping functional elements that have a close relation together. We consider a close relation between a functional element the sharing of a common property. The groups that are created are called 'functional zones', because the essential functions can still be distinguished in this layer. The goal of this layer is to be able to describe the local context of a location. Although individual functional elements cannot be distinguished anymore, the distinction between the functions itself can still be made.

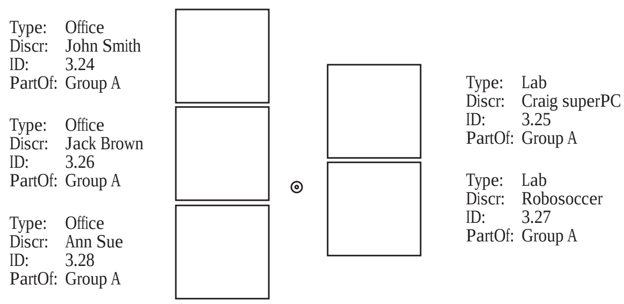
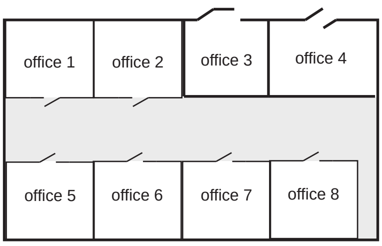


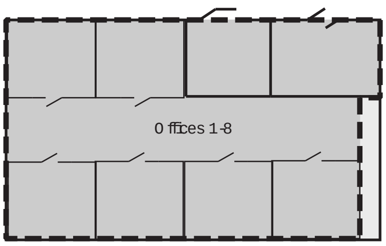
Figure 3.8: First layer of an academic environment.

Content To preserve the functional organization of the environment, only functional elements of the *same type* can be grouped together. Mixing elements of different types also mixes functionality, which is not desired for this abstraction level. ‘Part Of’ is the property that is used to identify similar functional elements, because it represents the organizational relation between the elements. This property reflects the organizational structure of the environment, often related to the necessity to exchange information in the environment. To create groups, functional elements of the same type *and* with the same ‘Part Of’ property are grouped together. However, to preserve a correct functional grouping and prevent cluttering of groups, these elements must be spatially connected or have a close spatial relation (they must be close). If elements within the same group cannot be reached without traversing through other groups, these elements do not belong to the same group. This is illustrated by Figure 3.9.

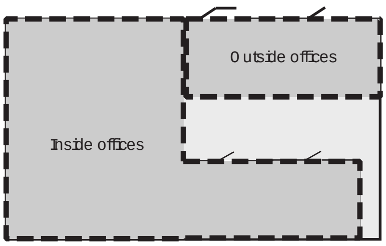
This layer still describes the environment from a functional perspective, however the elements are of bigger size. Instead of describing each functional element, similar functional elements are described as a zone. The difference between this layer and the previous one is that the detailed distinction between functional elements is not made any more. It is impossible to identify one particular functional element, but instead we have created a group in which all units offer the same functionality. So, not all functional elements are described. It is unclear which element exactly offers the functionality the user is looking for. However it is clear that the group offers the functionality and that the element is somewhere in this group.



(a) Office setting



(b) Incorrect grouping



(c) Correct grouping

Figure 3.9: Grouping of Spatial connected functional elements. Office 3 and 4 are not connected to the others (they don’t share the same hallway).

Example Figure 3.10 shows a graphical representation of this second layer. Compared to Figure 3.8 layer two describes the environment in a more general way. Instead of describing each functional element, groups of functional elements are described, introducing functional zones. A possible way of verbally describe the position, only using information from this second layer is 'Close to the labs of Group A and the offices of Group A. Slightly further ahead are the offices of Group B and the labs of Group B. Just behind are the Offices of Support'. This description is still detailed, but does not describe any functional element in particular. Only abstractions of functional elements are used.

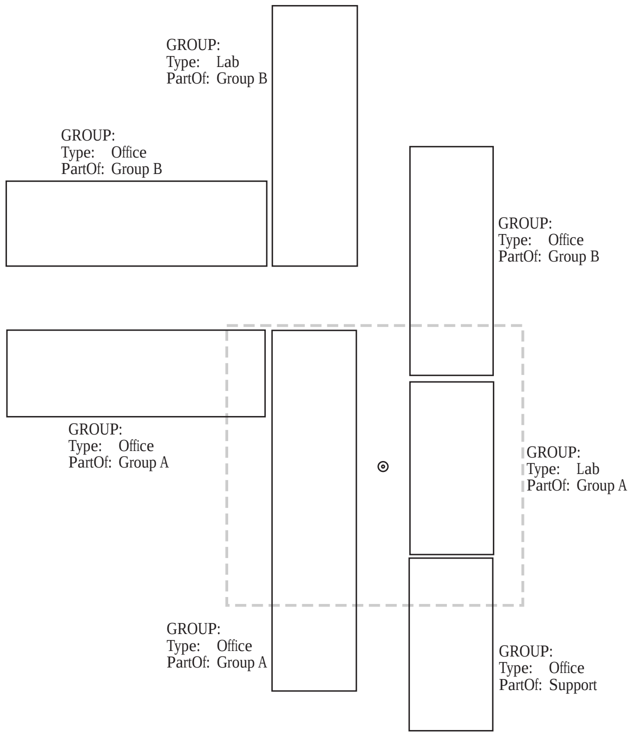


Figure 3.10: Second layer of an academic environment.
The grey dotted line is the surface area covered by layer one.

3.4.4 Third layer: destination zones

Goal & Scope For further abstractions, a distinction must be made between environments with a small amount of *types* of functional elements and environments which have many *types* of functional elements. The first environment provides many similar functions, the latter many different functions. For the creation of the third layer a distinction in the approach is made between these two environments.

Functional zones in layer two can span over small or large areas. With the 'Part Of' property, these similar functional elements form groups in layer two. However, only units of the same type are grouped. There is still a separation between different functional elements types and as such a functional distinction. If we try to 'zoom out' once more, there is a choice between two ways of grouping the functional elements. In the first option, all elements of the same type can be grouped (regardless of the 'Part Of' property). The second option is to group all elements with the same 'Part Of' property (regardless of the type of element). Although the first option seems fair in some cases (all check-in desks, all baggage claim belts), it has little value in other cases (all offices of a building, all tutorial rooms). The same goes for the second option, it can be favourable in some cases (everything of group X), but sometimes useless, as functional elements with the same 'Part Of' property can be spread over many physical locations (everything of KLM airlines at this airport).

This third layer will not always result in groups covering a substantially larger area than the groups from layer two. This will be particularly the case if the environment is extremely homogeneous, with only one type of functional element in it. In that case the groups of layer three will be the same as the groups of layer two.

The individual functional elements cannot be identified in this layer. In environments where the main task spans over more than two destinations pure destination zones are created. It is very clear which functionality is offered by the zone, but the differences whit in the zone cannot be identified. In the more homogeneous environments the organizational structure is used to create destination zones. It is not possible to identify the functionality that is offered by this zone, because it can incorporate many types of functional elements and hence many functions.

The goal of this layer is to be able to describe global destinations in an environment. In contrast to layer two, this layer describes the global context of a location.

Content The first option is the preferred method in environments where the main tasks span over many (more than two) functional elements. To create a further abstraction from this environment, *all functional elements of the same type* are grouped. Essentially this is just a different generalization from layer one, since it does not take the structure of layer two into account. However it will create a generalized zone of functional elements that all offer the same function. This creates a bigger functional zone. Again a constraint is that these units must still be connected or have a close spatial relation, but areas can be pretty big. It is possible to get similar zones at different locations, if the environment offers similar functionality at different positions.

The second option is the preferred method for environments that offer many similar functions (not many types of functional elements) and where the main tasks span over one or two destinations. A problem in these environments is that it is difficult to describe the environment only by functionality. Generalizing only in terms of functionality would create a too coarse layer of information. Moreover these environments are generally not characterized by functional structure, but by an organizational structure, based on the organization which occupies the environment. To capture this organizational structure *all functional elements that share the same 'Part Of'* are grouped together. In the previous layer we used the 'Part Of' property only to group functional elements *of the same types*. However, we can also use the 'Part Of' property to group any functional element that belongs to the same 'Part Of' category, regardless of the functionality. The resulting groups will have mixed functionality, but will reflect the organizational structure of the environment.

Example Figure 3.11 shows this for the academic building example, an environment with many similar functions. In this case the layer covers a larger area than layer two. Also the functional organization is vague, the distinction between offices and labs cannot be made based on information in this layer. An example of describing the environment verbally with information from layer three can be 'Current position is at Group A. Groups B and C are ahead, Support is back'.

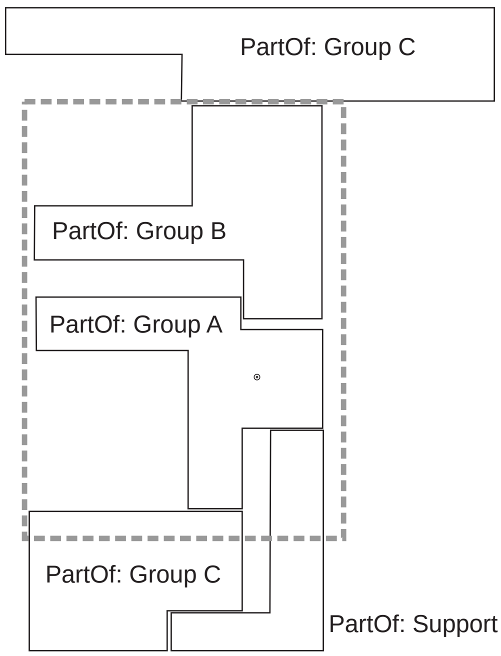


Figure 3.11: Third layer of an academic environment.
The grey dotted line is the surface area covered by layer two.

3.4.5 Fourth layer: main purpose

Goal & Scope The most rough way of organizing an environment is by describing it by the main purpose. Analysis of the environment already identified the main tasks and users. These tasks were broken up in pieces, functional elements, for detailed description of environments. Further generalizations created further levels of abstractions. For this fourth and final layer of abstraction, we go back to this tasks and describe the environment as spaces where people can accomplish this overall goal. However, we do not look into detail how or where they accomplish the task or any subtask. This layer divides the environment in a few main areas. The functionality of the environment can be deducted from the main task. It identifies the spaces where the main tasks are accomplished. It identifies main areas in which 'somewhere' the task can be accomplished. It gives an overall description and tries to capture the idea or main purpose of the environment. Although it is a very rough abstraction, using this layer makes it instantly clear what kind of functionality is offered. For example 'everything to attend a lecture'.

The goal of this layer is to be able to describe the main functional distinctions in the environment. It provides a rough understanding of the context of a location in relation to the other functions of the environment.

Content To describe the environment by main tasks, all functional elements that are involved in the same main task are grouped together. Regardless of functional element type or any of the properties, functional elements that are a destination in the same main task are grouped together.

Example Figure 3.12 shows a graphical representation of this layer for the academic environment example. It shows that the environment is used for two purposes: 'going to work' and 'attending a lecture'. The elements we saw as example for the previous layers are all part of the main task 'going to work'. As can be seen the area covered by this layer is substantially larger than the area covered by layer three. An example of a verbal description of the position with information from this fourth layer is 'In the area where people go to work. The area for attending lectures is West of the current position'.

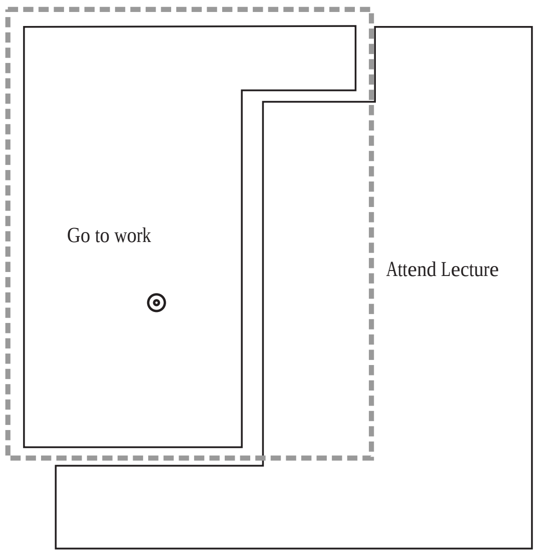


Figure 3.12: Fourth layer of an academic environment.
The grey dotted line is the surface area covered by layer three.

3.4.6 Layered model

The four layers of abstraction provide a structure to describe the immediate surroundings of a position, the bigger context and the global context of the position. To describe a location (or place), detailed information on its immediate surroundings can be given, less detailed information on the elements that are further away and eventually the global context is given. Figure 3.13 illustrates the level of abstraction of environmental information in relation to the distance from a position.

The further away a functional element from a certain position is, the less important a detailed description of this element becomes. However, to still be able to describe the functional element the abstraction of this element is used, which also contains other functional elements. An example of a description of a location, using information from several layers of abstraction is 'In the part of the building were people go to work, in the area where Group A houses. Offices of group B are close. You are now near the office of Jack Brown and the office of Ann Sue. Also near the lab of Robosoccer and the lab of Craig superPC.' Table 3.17 summarizes the four layers and their purpose.

Layer	Relation
First layer: Local view	Local descriptions; immediate surroundings, allows for local orientation and wayfinding.
Second layer: Functional zones	Local functional distinctions; local context, allows for understanding of nearby functionality.
Third layer: Destination zones	Global functional distinctions; global destinations, allows for understanding the global functionality.
Fourth layer: Main tasks	Rough functional distinctions; Divides the environment in a few areas, allows for understanding of the functions of the environment.

Table 3.17: Summary of layers of abstraction

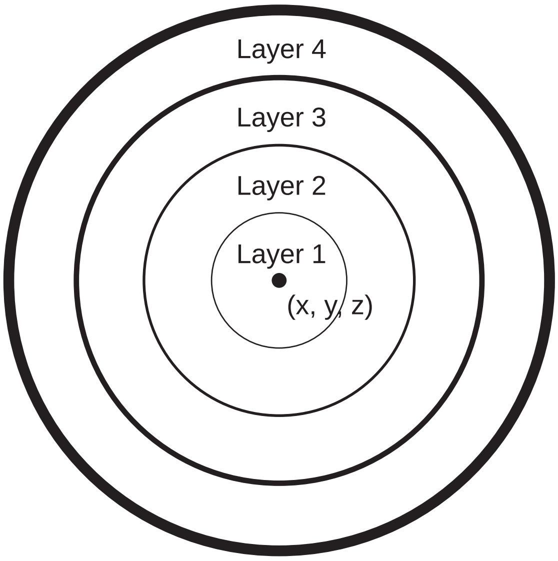


Figure 3.13: Each layer of information covers a wider area.

3.4.7 Points of Interest

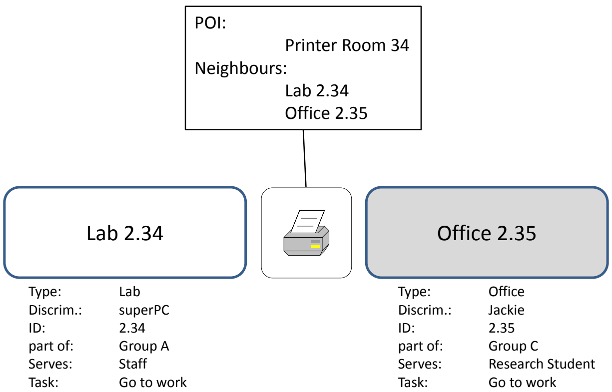
Points of Interest (POI) are locations in a building providing *special services* to any type of user, that this user *may* or *may not* find interesting. Consequently there are points that are only relevant to certain types of users or a certain part of the user base. Points of Interest are not the main reason why a user visits the building, but they have a supporting role to the user in accomplishing his goal. For example, an ATM in a shopping centre enables the user to obtain cash, which can be used to purchase goods. However, some users will already have cash on them and will find information on the location of the ATM not useful, whereas users that run out of cash while shopping are interested in the location of the ATM. But, few users will visit the shopping centre *just* for getting cash out of the ATM, so it will not be identified as a destination in the model. The same goes for locations like toilets, information desks, meeting points and help phones. It depends on the environment if something has to be modelled as a POI or functional element. Take the ATM example, in a bank building, the ATM will be a functional element because many users visit the bank, just to withdrawal cash out of an ATM.

Besides points of interest, landmarks are also important in wayfinding. Landmarks are points in an environment, which are generally used to give users orientation and bearing (as reference point that is visible from a large part of the environment; for example the Eiffel tower in Paris) and in wayfinding instructions to denote a point. In the latter case it is used by the user to check the validity of the route he is travelling ('You pass the water fountain at your right') or as a reference to an upcoming decision point in his route ('Directly after the fountain, turn right'). In this research a landmark is considered a Point of Interest that already has been defined. Landmarks are not being identified, but some external source defines the landmarks. The identification of landmarks is in itself a separate research area, but important in wayfinding (Raubal & Winter 2002).

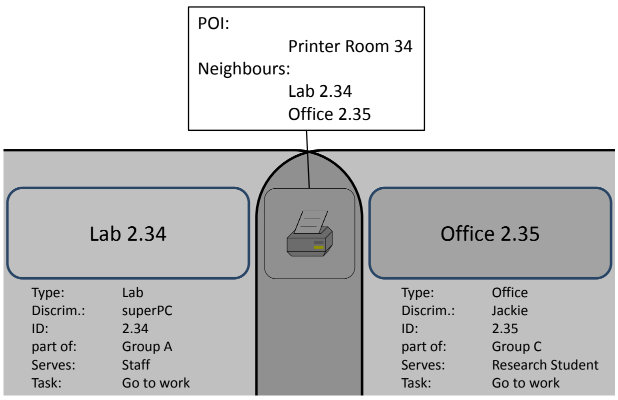
Incorporating Points of Interest in the layered structure is not straightforward. POI are important information at any level of granularity, but their exact location is only important at the lowest level of granularity (in the local view). However, they cannot be omitted in higher levels of granularity, because then important information on the indoor environment is lost. But, for the other levels of granularity it will however be sufficient to just state that a number of Points of Interest of a particular type are 'somewhere' in this zone. It can even be sufficient to know that there is 'at least one' Point of Interest of a type in the zone. In fact we cannot identify POI in just one layer, because they will get lost in abstractions. On the other hand they way of grouping the functional units (by their properties) leaves little room to incorporate POI, because their functionality is substantially different from the functional elements that are near to it.

An approach which on one side respects the layered structure of functional abstractions and on the other hand allows for propagation of the Points of Interest through all layers, is to associate a Point of Interest with neighbouring functional elements. The propagation through all layers is accomplished by including them in the functional groups of which these neighbours are also members. Suppose that the POIs are externally defined and their position is known. It can be determined which functional elements are neighbours of each POI. If information about the neighbouring functional elements is associated with the POI, POIs can be included in the abstraction approach. A POI is included in the groups to which their neighbours also belong. In theory a POI can be a member of more than one group in a layer of abstraction, this will be the case if a POI has neighbours of a different type or part of property.

As a result Points of Interest are included throughout the layered structure and available at every layer of abstraction. The exact position of the Point of Interest in a zone is not known, the only certainty is that it is somewhere in this zone, it may be on the edge or in the middle.



(a) Point of Interest with two neigbours



(b) Point of Interest is member of two abstraction zones

Figure 3.14: Points of Interest and their relation to abstraction layers

The example in Figure 3.14 illustrates the incorporation of Points of Interest in the layered structure. The printer room is located between Lab 2.34 (part of Group A) and Office 2.35 (part of Group C). As a consequence the printer room will be a member of any group Lab 2.34 belongs to *and* a member of any group Office 2.35 belongs to, in all the abstraction layers.

3.5 Evaluation

This sections provides an evaluation of the structure and the way it is developed. It gives the initial impetus to the discussion and conclusions on this approach in later Chapters.

3.5.1 Methodology summarized

To summarize the methodology outlined in this Chapter, the approach described in the previous sections can be summarized in the following eight steps:

1. Create usage tables of the environment, based on the types of users, their goals and destinations.
2. Deduct the main functions of the environment.
3. Define functional element types and properties, based on the destinations of the users.
4. Define instances of functional elements and start creating abstraction layers.
5. The first layer identifies all functional elements and their connection. It incorporates all points where functionality is offered.
6. The second layer identifies functional zones, which is an area in which 'somewhere' the functionality is offered. It is based on the 'Part Of' property and types of functional elements.
7. The third layer has only information about groups of functional elements, which belong to the same organizational unit.
8. The fourth layer identifies the locations in the environment where the main functions are offered.

3.5.2 Use in different environments

Many indoor environments will offer essentially the same functionality, but have a different physical layout. For example airports all offer the same functionalities, but all in a different configuration. Knowing your way at Melbourne airport does not mean you can navigate your way flawless at Amsterdam airport as well. However, similar functional elements exist in both environments and similar groupings can be made in both environments. This means it is possible to re-use functional elements of this method in other environments. Arthur & Passini (1992) defined the four functional settings for indoor environments: Travel setting, work setting, retail setting and recreational settings. We evaluate the spatial structure for each of these environments. The aspect of reusability is also evaluated.

Travel setting

In travel settings it is often clear at which points in the environment functionality is offered. The environment is designed to provided travel services and the physical layout often groups similar functionality. Also the actions a user has to take to accomplish his task, departing or leaving, are clear. Supporting services, like ticketing, are part of the optional destinations and as such identified as functional element and included in the structure. The travel setting is typical setting in which the environment offers many different function, incorporating many types of functional elements.

Advantage of environments in the travel setting is that they are similar in many cases. For example, applying this method at different airports will probably result in finding the same types of functional elements. The same goes for railway stations, subway stations, ferry terminals, etc. Therefore it is possible to create a set of functional elements types for each particular travel environment as minimal set of functional elements for these environments.

Work setting

In work settings the organizational structure is an important aspect of the layout of the environment. Therefore the biggest challenge in the office setting is to choose the right 'Part Of' property. Sometimes this is a department, sometimes a research group or another group from the organization. The work setting is a typical setting in which the environment offers many similar functions, incorporating few types of functional units. Often many instances of a functional element type exists.

Work setting environments in general will share the same set of types of functional elements, like offices, meeting rooms and laboratories. Therefore a basic set of types of functional elements can be defined to apply this method to offices. Similarly to the educational building from the example, health-care facilities, offices and industrial buildings can be analysed and structured.

Retail setting

The retail setting can be divided into two general environments: the indoor shopping mall (large environment with many stores) and the department store (one store, many products). The layout of an indoor shopping mall is in general chaotic and shops are not part of a bigger whole or organizational structure . Take for example the Melbourne Central Shopping Mall. A map of level 2 can be seen in Figure 3.15. The shops have no relation to each other at all and their position in the environment is chaotic. Electronics stores are located next to designer shops, outdoor stores or the hairdresser. Only the food shops are located together in the food court (on the top right). It is impossible to generalize the environment by functionality. Often a location is described by its physical position 'On the third floor in the south west corner'. These type of descriptions cannot be generated with the current method. For indoor shopping malls, this methodology cannot be used.

In contrast a big department store like the Australian 'Meyer' and the Dutch equivalent 'Bijenkorf' are organized by type of products and as such have a structure. Suppose a shelve is defined as functional element (for example a shelve with electronic products of the brand Philips), then the shelves can be organized in a structure of type of product (electronics) and/or brand (Philips). Concluding, for the case of bigger department stores this approach to structure and describe indoor environments can be used. In this case the environment will offer many similar functions (things to buy, check outs) and have little different types of functional elements.

In terms of functional element reusablility, the organization of department stores is similar, all locate similar products together and create departments which sell these products. Therefore the approach to functionally structure one department store will be very similar to the approach to structure another. Functional elements can be reused, as well as the way of grouping them.

Recreational setting

Most environments in a recreational setting are outdoor and therefore not in the scope of this methodology. For example, zoos, parks and theme parks are a challenge to describe, but are outdoors. Stadiums, cinemas and concert halls are examples of indoor recreational environments. However these environments offer the same function at many different positions: a seat to watch the entertainment, possibly supported by food and drink stalls. Breakng down the environment by functionality is hard, because the functionality is the same. For these type of environments it is possible to apply the methodology, by defining seats and the other destinations as functional elements. However, the way to group them is not functional, but just how it is currently done, by physical position: by stands and rows.

3.5.3 Shortcomings

Environment limitations As already could be anticipated from the previous section, the method does not work in extremely unstructured environments or extremely homogeneous environments. This is due to the nature of the functional elements, on which everything is based. In extremely unstructured environments it is simply not possible to find a structure and create generalization of the environment, because there is not any. For extremely homogeneous environments it is also very difficult to create generalizations, because the only difference between functional elements is their physical position, for example the seats in a cinema. In both cases there is a lack of organizational structure to support the environment.

Physical properties As a consequence of strictly describing the environment by its functional properties, the physical and geographic properties of the environment are not exploited. For example, this method does not identify locations such as 'The west wing' or 'Offices overlooking the park', unless explicitly defined. Also terms used to informally describe a location are not captured, but could be added as an additional property to functional elements.

Effort to create a structure The effort required to create a structure based on functionality can be considerable. After identifying the types of functional elements actually defining them for the entire building can be a big effort. For each instance of a functional element the properties have to be defined. However, it might be possible to automate this process using existing (digital) maps of the building. This has not been researched, due to time limitations.

3.5.4 Number of layers

Currently four layers of granularity are used. These are based on the functional and organizational structure of the environment. The current structure is based on the minimal properties that can be defined for any functional unit in an environment. Every functional unit is part of a main task and every functional unit is part of a organizational structure. Using these two properties and the different type of functions, it is possible to create these four layers. Each layer spans over a larger area and generalizes the previous one.

It can be argued to use less than four layers. As a result less abstractions can be made. For small environments this might be useful and may be automatically introduced by similar results in grouping functional elements for layers two and three. This shows that the method automatically copes with this, because similar levels of abstraction are obtained. Finally, the goal of functionally describing small environments at different layers of abstraction can be argued itself. An office building which only has 10 offices can accurately and efficiently be described by just using one layer of information, the local view of layer one. However, for larger environments abstraction layers are required.

Also it can be argued to use more layers. This will particularly be applicable to very large environments, which also have a lot of functionality or a complex organizational structure. Essentially this will create opportunities to introduce additional 'Part Of' properties, for example one for the direct organizational parent and one for the parent of that parent. Suppose a multinational company houses all its departments in one massive building. Then for a functional unit of the type office more than one 'Part Of' property can be defined; one for the section it belongs to (eg. 'Sales') and one for the department it belongs to (eg. 'Asia-Pacific operations').

3.5.5 Real world implementation

The concept of defining spaces in a building as elements for wayfinding is not new. However, the functional approach presented here has not been followed before. Implementations of classic (outdoor and indoor) wayfinding are based on a weighted cost-graph, where nodes are destinations and edges are paths (or spatial relations). The cost to travel along such a path is a representation of the effort to travel over that edge. This can be the distance in time, space or the physical effort needed, for example the difference between stairs and elevators. In an implementation the destinations are defined in terms of polygons describing the physical boundaries of the destination. Lorenz & Ohlbach (2006) define open spaces, bounded by walls, as nodes (Figure 3.16). Then they connect these nodes with edges and also add additional information to nodes, which stores information about the direction and orientation of edges, allowing angular descriptions in wayfinding (turn right/left). Also an approach to generalize the environment is tried, but this is again an ad hoc solution. What is lacking in their approach is the functional aspect of the space. The analysis of the environment is strictly physical, dividing the space into rooms, corridors, wings and storeys without knowledge of the function of these space.

Moreover Franz, Mallot & Wiener (2005) analyse the use of graphs in exactly this area of research: the cognitive *and* architectural science. Especially the representation of the influence of the environment on wayfinding in graphs remains a problem. For navigation in unfamiliar environments this is the biggest problem, because graphs only capture a very coarse representation of the environment. But they conclude representing this type of information in graphs is still the best option, which might need some refinement, especially by capturing the behaviourally relevant aspects of the environment. The methodology we presented before is an attempt to describe nodes with functional and relevant information.

Both studies show that it is possible to link a conceptual idea of destinations and paths to a usable implementation for wayfinding purposes. The same could be done for the methodology described in this thesis, but was not done due to time considerations.

3.5.6 Applications

One obvious application of this methodology is in 'where-am-I' applications or digital 'you-are-here' maps. A position can be described in several ways and more importantly be placed in context. The environment of a functional element can be described into detail and at the same time abstracted information can be used. Current applications are only able to describe a position in one way, mostly without describing the context of the position. It adds more useful information about a location.

Current	Enhanced
'Third floor, room 3.43'	'Room 3.43 of Jack Johnson, at the IT department.'

Turn-by-turn instructions are still the most useful way to guide someone to a position. But turn-by-turn instructions are abstract and the user is not aware of its surroundings. Using these layers of functional information about the environment, location awareness can be enhanced.

Current	Enhanced
Turn left at third corner	Turn left at the third corner, entering the IT department.
Continue ahead	Continue ahead, passing Check-In area and heading to Arrivals.

Lastly this method allows to cope with position uncertainty. Many outdoor and indoor positioning technology is not 100% accurate, but often error margins are known. These are often in the form of 'Within a range of 7 metres of this point'. Problem with these uncertainties is that it is difficult to accurately describe the location if the position is not exactly known. However, with the model with different layers of granularity this becomes easier.

If a position is known with little uncertainty, then the location can be described in detail, using layer one. But if there is some uncertainty (eg. whit in 20 metres of a point), it is impossible to describe the location in detail. Instead a description based on the information in layer two can be used to accurately describe the location.

The next chapter will elaborate on positioning techniques and the accuracy. They will be evaluated and see what level of environmental descriptions can be reached with these technologies. Chapter 6 will relate these technologies to the structure just described.

3.6 Summary

This Chapter introduced a method to develop the spatial structure of indoor environment. From a user perspective view, the environment is analysed and functional elements can be identified. Mapping properties on these functional elements allows for generalization of the elements, based on shared properties. Besides one basic layer of functional elements, three other layers of generalization are defined. The local view is the most detailed representation of the environment and describes all functionality that exists. Functional zones are groups of functional elements that share a common property and are generally close to each other. A functional zone is a part of the environment which provides similar functionality. A further generalization from functional zones are destination zones. These destination zones represent areas in the environment that do not necessarily have to provide a similar function, but the functional elements in these destination zones have a close relation based on the organizational structure. Finally the most coarse view of the environment is based on the main tasks that users execute in the environment. It divides the environment is few zones, clearly representing the locations in the environment where *all* functionality to execute a task is located.

These four layers of granularity can be used to describe a point in the environment at different layers of abstraction. Various applications can be thought of that will use this structure. For example, to describe environments from the perspective of the current position, elements close can be described in detail, whereas elements further away are described at a more general layer.

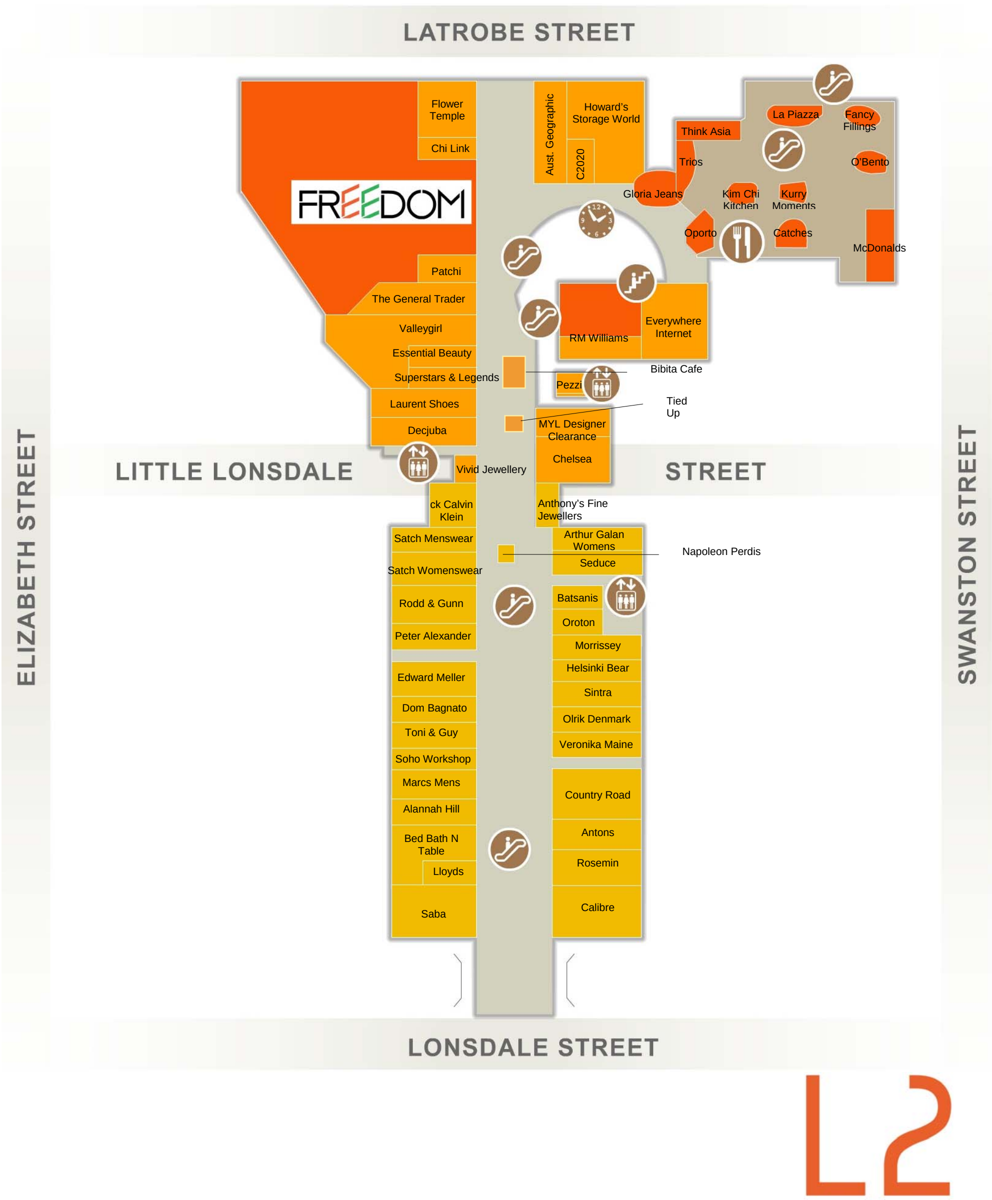


Figure 3.15: Level 2 of Melbourne Central shopping mall; a chaotic environment

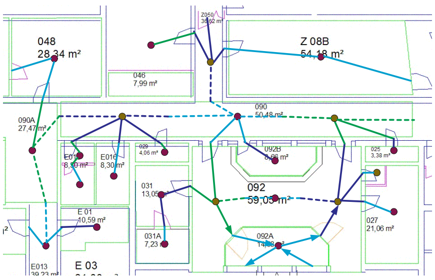


Figure 3.16: The method of Lorenz & Ohlbach (2006):
Identifying spaces (nodes) and paths (edges)

Chapter 4

Indoor positioning technology

To address the second part of the research questions, the technology part, this Chapter presents an overview and review of wireless indoor positioning technologies. The characteristics, like accuracy, cost and infrastructure, of each technology are addressed. Several existing applications that assist in wayfinding, using one of these technologies, are also reviewed, providing a context of the current state of research on wayfinding with wireless technology. Lastly, a focus on systems that assist visually impaired people are considered, to address the last research question.

Considerable research in assisting visually impaired persons with wayfinding tasks has been done. Although most researchers focus on the development of an outdoor navigation system, there are examples of research in indoor navigation systems. This section provides an overview of indoor and outdoor navigation and locationing systems that use wireless communication technology. Not all are specifically designed for use by visually impaired users. However, concepts for positioning are general and can be applied to any positioning system. Hightower & Borriello (2001) and Chen & Kotz (2000) give a good introduction and overview of current location systems. Liu, Darabi, Banerjee & Liu (2007) do this as well with an in depth analysis of indoor positioning technology. This section provides an overview of the research that has already been done in the area of indoor location systems. It does not intend to be complete, however, the intention is to cover most technologies with one example.

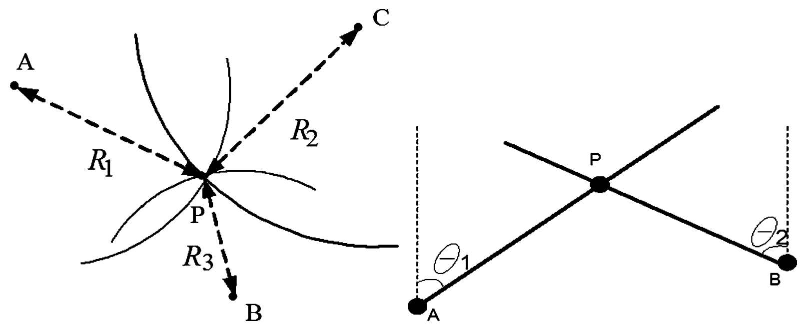
4.1 Wireless indoor positioning technologies

4.1.1 Principles

Three approaches to determine an indoor position can be identified: proximity, triangulation and scene analysis. Many different technologies can be used for each approach, but positioning systems always use at least one of these methods.

First, with the *proximity* approach, the environment is equipped with a grid of base stations. For each base station the exact position is known. When the target detects a base station (or the base station detects the target, this is an implementation decision) it is considered close to this base station. In case two base stations are detected, the one with the strongest signal is considered closest. Because the exact location of each base station is known, the target must be 'near' the base station, hence the term proximity.

Next, the *triangulation* approach works by calculating a position out of information from at least three reference points, often signal transmitting base stations, using the geometric properties of triangles. Lateration is the principle of locating a target based on the distance from these reference stations. Angulation estimates the position of the target by computing angles relative to these reference points. Several methods of measuring distance and angles exists, which will be introduced when discussing the technology that uses them.



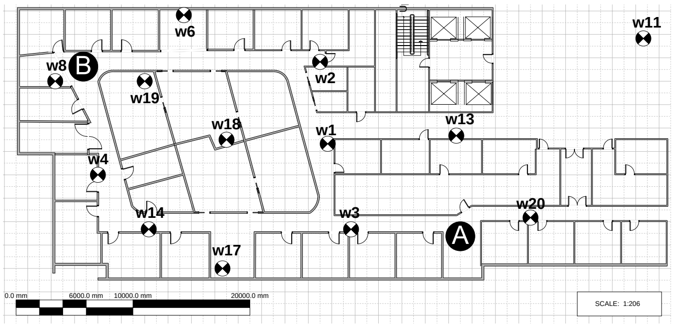
(a) Lateration (b) Angulation

Figure 4.1: Triangulation approaches (images from Liu et al. (2007))

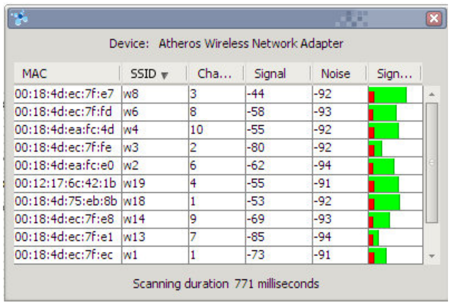
Finally, *scene analysis* is also known as *fingerprinting*. This approach first collects features (fingerprint) of the environment and then calculates the position of the target by comparing live measurements with the collected fingerprints. A common way of collecting fingerprints is by collecting signal characteristics for various points in the environment. During the collection of fingerprints (offline phase) coordinates (and/or other labels) and the respective signal characteristic of nearby base stations is collected. In the online phase the received signals are compared against the previously collected signals. Various algorithms that determine the position from this information exist, needed to cope with the problem of RF-signal absorption, reflection and scatter. The two most common algorithms are k-nearest-neighbour (kNN) and the probabilistic method. The kNN algorithm matches the received signal characteristics to k close matches in the database. Averaging, either weighted or unweighed, these k location matches gives an estimate for the current position. The probabilistic algorithm matches the observed signal characteristics (s) to one of the collected positions (M_i). The problem then becomes a classification problem, which can be mathematically represented as $P(M_i|s) > P(M_j|s)$ for $i, j = 1, 2, 3, \ldots, n$ and $i \neq j$. In other words the algorithm determines the position of the target by finding the collected position candidate where the target is most likely at the moment, given the signal characteristics that are being received by the target. Other algorithms to solve the indoor positioning problem with fingerprinting are neural networks, support vector machine (SVM), and smallest M-vertex polygon (SMP) (Liu et al. 2007).

Example: Fingerprinting

Figure 4.2(a) shows a building structure with WLAN access points at 13 positions. Bob is standing in the corner of the building (top left, marked B) and Alice is standing in the middle of the building (marked A). Both have a WLAN receiver and receive signals from the access points. Bob receives the signals listed in Figure4.2(b) and Alice receives the signals listed in Figure 4.2(c). Bob receives a very strong signals from w8, because he is standing next to the access point. But Alice does not receive any signal from w8 at all, there is too much interference between her position and that of w8 to receive a signal. The pattern of all signals together is called the *fingerprint* of the location.



(a) Bob (B) and Alice (A) in the ICT building, with the WLAN access points.

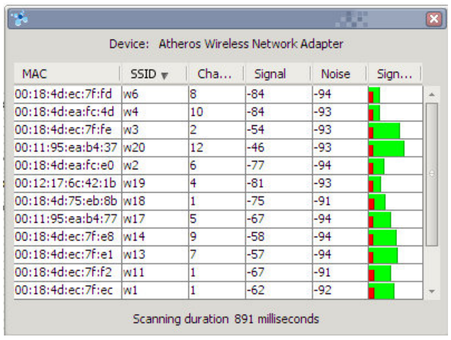


Device: Atheros Wireless Network Adapter

MAC	SSID	Cha...	Signal	Noise	Sign...
00:18:4d:ec:7f:e7	w8	3	-44	-92	
00:18:4d:ec:7f:fd	w6	8	-58	-93	
00:18:4d:ea:fc:4d	w4	10	-55	-92	
00:18:4d:ec:7f:fe	w3	2	-80	-92	
00:18:4d:ea:fc:e0	w2	6	-62	-94	
00:12:17:6c:42:1b	w19	4	-55	-91	
00:18:4d:75:eb:8b	w18	1	-53	-92	
00:18:4d:ec:7f:e8	w14	9	-69	-93	
00:18:4d:ec:7f:e1	w13	7	-85	-94	
00:18:4d:ec:7f:ec	w1	1	-73	-91	

Scanning duration 771 milliseconds

(b) Signal levels at Bob's location.



Device: Atheros Wireless Network Adapter

MAC	SSID	Cha...	Signal	Noise	Sign...
00:18:4d:ec:7f:fd	w6	8	-84	-94	
00:18:4d:ea:fc:4d	w4	10	-84	-93	
00:18:4d:ec:7f:fe	w3	2	-54	-93	
00:11:95:ea:b4:37	w20	12	-46	-93	
00:18:4d:ea:fc:e0	w2	6	-77	-94	
00:12:17:6c:42:1b	w19	4	-81	-93	
00:18:4d:75:eb:8b	w18	1	-75	-91	
00:11:95:ea:b4:77	w17	5	-67	-94	
00:18:4d:ec:7f:e8	w14	9	-58	-94	
00:18:4d:ec:7f:e1	w13	7	-57	-94	
00:18:4d:ec:7f:f2	w11	1	-67	-91	
00:18:4d:ec:7f:ec	w1	1	-62	-92	

Scanning duration 891 milliseconds

(c) Signal levels at Alice's location.

Figure 4.2: WLAN signal fingerprinting.

4.1.2 Infrared

Infrared (IR) technology is used in a wide range of applications. IR is most famous for its use in remote controls for household devices such as TVs and Hi-Fi systems. It is also used to produce video images or photos at night, when using a conventional spotlight is not desired. Furthermore IR signals are used in creating thermal heat maps, in weather satellite imaging and many astrological and space applications (NASA 2008). However, the application that is of most interest here is the use of infrared for communication between devices. Phones, notebooks and computers have infrared receivers and transmitters which allows them to communicate and exchange messages, using the IrDA protocol.

Infrared technology consists of transmitters and receivers which are able to send, receive, modulate and demodulate light signals within the 1260 nm and 1675 nm range[1]. Light in this part of the light spectrum is invisible to humans (NASA 2008). An infrared transmitter is typically a Light Emitting Diode (LED), which can be anything smaller than a brown bean and is being mass produced. The infrared receiver consists of a photodiode, which is also small in size and being mass produced. A complete IR sender and receiver device including some logic can be very small, figure 4.3 shows an ultra-small IR transceiver.

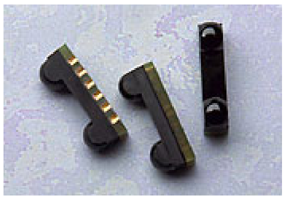


Figure 4.3: Avago IrDA transceiver (size: 1.60 x 7.00 x 2.73 mm)

Infrared technology is based on light, which has the main disadvantage the signal can easily be blocked or distorted by almost anything. Line-of-sight visibility is required for every form of interaction. Misalignment of transmitter and receiver can result in communication errors. Advantage is that IR communication chips are very cheap (less than US$1) and widely available.

In wayfinding systems infrared is basically used as a passive system, using the proximity approach. The transmitter is at at fixed position and associated with this position. The user will carry a receiver, detect the signal of the transmitter and deduct that it is close to the position of the transmitter, totally independent of the actual distance between the two. This idea is based on the property that IR signals do not propagate through walls and if the signal is received, the transmitter must be visible, thus the user must be near the transmitter. The signal can

[1]Infrared radiation covers the much larger spectrum of 750 nm to 1 mm, but the range of 1260–1675 nm is used in data communication

carry some additional information, such as transmitter ID or information about the location and environment of the transmitter.

Several location systems use IR, such as Active Badge (Want, Hopper, Falcão & Gibbons 1992), Cyber Crumbs (Ross 2004) and Talking Signs (Crandall et al. 2001). The accuracy of a system solely based on IR depends on the environment, but is generally 'room sized'. By associating the transmitter to a position one can tell someone is 'near' this position.

4.1.3 Ultrasound

With ultrasound sound waves which are not audible for humans are used (above 20 kHz). Several animals such as bats and whales use (ultra)sound for navigation, using echolocation. Probably the most well known use of ultrasound and echolocation is the sonar, used in naval applications to locate other vessels. In all these examples ultrasound is used as a reflective technology, based on the reflection pattern and speed, the distance and shape of an object can be calculated. Echolocation is also used in robotics to detect walls and objects (Wikipedia 2008).

However, for indoor positioning the use of ultrasound is slightly different. Ultrasound positioning uses the trilateration approach. In general the indoor environment is equipped with ultrasound transmitters, typically three or more at the ceiling in each space. These transmitters are synchronized and each transmit a different modulated signal. The user of a system is equipped with a receiver, which receives the signals of the transmitters. Because the signals are synchronized, the receiver can observe time differences in the signals received. Based on these time differences, the receiver calculates its distance from each receiver and deducts its position.

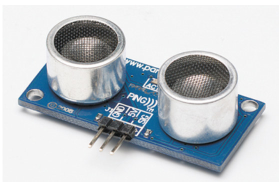


Figure 4.4: Ultrasound transmitter and receiver.

As with IR, ultrasound transmitters and receivers are small and widely available, but they are more expensive at approximately US$35 for a transceiver. Figure 4.4 shows an ultrasound transmitter and receiver board. Also installation of the system requires careful placement of the transmitters. Furthermore to finally obtain the position, there must be a system that relates the distances between receivers to a position (eg. performs trilateration calculation).

The Active Bat system is an example of a positioning system using ultrasound (Harter, Hopper, Steggles, Ward & Webster 2002). Accuracy is reported up to 9 cm within the actual location in

95% of the readings. The system of Randell & Muller (2001), using a combination of ultrasound and RF signals called *low cost indoor positioning system*, is reported to have an accuracy of 10 to 25 cm.

4.1.4 RF signals

Radio Frequency signals are electromagnetic waves between 3 Hz up to 300 GHz that carry information on the modulated carrier. RF signals differ from ultrasound and IR signals in a sense that they can penetrate through walls, windows and other obstacles between transmitter and receiver. These signals are used for a wide range of applications, most well known for broadcasting radio and TV signals over the air and satellite communications. Information is contained in RF signals by modulating the carrier frequency by the sender and decoding this signal by the receiver. RF signals are used for one way communication (commercial radio broadcast) and two way communication (mobile phones).

A typical RF systems consists of a transmitter and a receiver, both equipped with an antenna to transmit and receive the wave. The transmitter contains a modulator and the receiver a demodulator. There can be many receivers of a signal from one transmitter. Communication can be secured by using a coding/modulation algorithm only known to one transmitter and receiver pair.

For positioning systems, RF signals can be used to determine ones position from the transmitter using the *wave propagation model*. Positioning is then based on the trilateration approach. The transmitter encodes a time signal in the wave, which is picked up by the receiver. Using the time-of-flight of the signal and the speed of light, the distance between transmitter and receiver can be calculated. Consequently if the receiver picks up signals from three or more transmitters, it can calculate it's own position using triangulation strategies. However, RF signals can propagate through walls, they are attenuated by this and other factors in the environment, making the distance calculations less reliable in indoor environments.

Priyantha, Chakraborty & Balakrishnan (2000) developed a location system based on ultrasound and RF signals. In the *Cricket* system a device determines its position by associating itself with a beacon, thus providing room size granularity. Beacons are placed in every room and along some other strategic points, to prevent too much interference. Cricket is a decentralized system, the beacons are not interconnected. Each beacon consists of an RF transmitter and an ultrasound transmitters. Beacons transmit a RF signal containing a string of information. After a pre-determined amount of time this is followed by an ultrasound signal. RF signals propagate much faster than sound over the air, which allows the receiver to calculate its distance from the beacon, using time of arrival differences. Furthermore algorithms are used to avoid collisions and determine the location of the nearest beacon in case of interference. The receiver device does all the computations and positions are note maintained in a central system.

4.1.5 Short range wireless

There are many short range wireless technologies. Most commonly known is *Bluetooth*, which has a less known competitor *ZigBee* (both are IEEE standards) (Bluetooth SIG 2007, Zigbee Alliance 2007). A recently introduced short range wireless standard is *Wireless USB* (USB Implementers Forum 2007). These technologies are all developed for short range communication between computer devices. The range is typically around 10 metres, but can go up to 100 metres depending on the implementation and environment. Bluetooth focuses more on portable devices which form ad hoc networks, such as mobile phones and headsets. ZigBee is more developed for wireless sensor networks, because of its low power consumption, with a more fixed nature. Wireless USB is designed for communication between between computer devices, which are traditionally connected with a (USB) cable, offering much higher data transfer speeds than the other two technologies.

Research into using these technologies for wireless positioning has mainly focused on Bluetooth, but the concepts are applicable to all three. The environment is equipped with Bluetooth transceivers which broadcast some information. The user carries a transceiver as well, which receives all the signals from the installed transmitters. Basically two approaches are used here. First, based on the proximity approach. Because the range of Bluetooth is 10 metres, one can be sure to be somewhere within 10 metres of the transmitter. In the second approach, using the trilateration approach, information from more than one signal is used and by means of multilateration the position of the user is calculated. This position is more precise than the first method, but harder to calculate and validate.

Several attempts have been made to make Bluetooth positioning more accurate by incorporating received signal strength indications (RSSI) into positioning calculations. However, this has been proven a difficult job, because RSSI values are not defined by the Bluetooth standard and differ from manufacturer to manufacturer. Furthermore some studies have found there was a weak relation between distance and RSSI for Bluetooth devices, making this an unreliable technology to use for trilateration.

Advantage of Bluetooth and other short range wireless technologies is that the equipment is small, widely available and relatively cheap. Also Bluetooth is incorporated in many devices which users of a system already might have, such as mobile phones or PDA's. Also the signals can penetrate through walls and obstacles. Disadvantage is the range, scalability and inaccuracy of positioning measurements.

Thapa & Case (2003) and Vetere, Nolan & Raman (2006) use the approach described above for Bluetooth positioning. Both conclude Bluetooth can be useful for positioning applications which do not require accurate positioning. Hallberg, Nilsson & Synnes (2003) use a distributed network of Bluetooth nodes, which also use the position of other (mobile) nodes to calculate their own position. This results in a slightly improved accuracy, but the time needed to enquire other peers for their position was quite long.

4.1.6 Wireless LAN

Wireless LAN (WLAN), also well known as Wireless Fidelity (WiFi), is an RF technology providing wireless connectivity to local computer networks. It is widely spread, available in almost every notebook computer, in many palmtops, PDA's and some mobile phones. Many buildings have WLAN installed, allowing visitor or employees to access the company network (and often the Internet) from anywhere in the building. WLAN is not limited to indoor use, for example the entire University of Twente campus has indoor and outdoor coverage over 140 hectares, dubbed Europe's largest wireless hotspot in 2003 (CTIT 2003).

Since the emerging popularity of wireless networks, especially IEEE 802.11 based, research interest has been focused on using these network infrastructures for indoor positioning. Low cost equipment and already installed infrastructure are the main advantages. The basics and one commercially available product will be described.

RADAR

Bahl & Padmanabhan (2000) were one of the first to propose an indoor position tracking system based on radio-frequency technology using scene analysis. They equipped a floor of a building with three wireless LAN access points and used a conventional laptop as to-be-tracked device. By surveying the building recorded signal and noise levels are assigned to a position. The base stations receive packets from the device and measure the signal strength and noise level. This is compared to the recorded data and a 'smart' algorithm is used to calculate the position of a device. Accuracy was between 2 and 4 metres was achieved. Later on several enhancements to this approach were published, based on the extensive analysis and discussion in the initial paper.

Ekahau

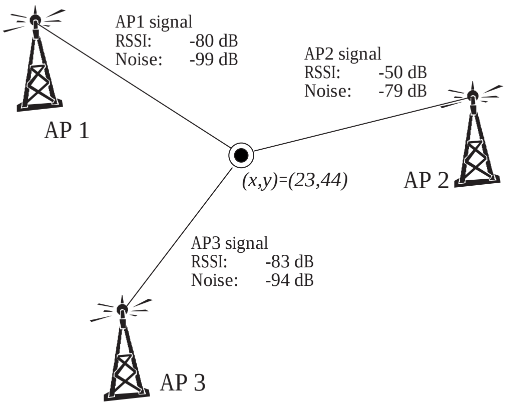
Ekahau is a commercially available product which offers indoor positioning, by tracking WLAN signals (802.11a/b/g) using the scene analysis approach. The system is designed to track devices like notebooks and PDAs, which have a built-in WLAN device. Additionally Ekahau developed a hardware tag, which is a small device that can receive and transmit WLAN signals. These tags can be used to track objects that are not capable of connecting to a WLAN network by themselves.

As with RADAR the area the system operates in has to be surveyed, before the positioning system can be used. This is typically done with a WiFi enabled device, running Ekahau software, and walking a route that is recorded by the surveyor. The software records signal and noise levels in the environment and associates this with a position. Creating a model of the environment in the Ekahau software will enhance performance, because it will use the information about hallways and rooms in its calculations. Basically the software tracks the WLAN signals, compares this to the information collected during the site survey and uses fingerprinting to determine its position. In areas with a proper network coverage, accuracy can be between 1 and 3 metres (Ekahau, Inc. 2007). Devices record the signal and noise levels of base stations and calculate their position based on this (stand-alone or with the help of a location service/database).

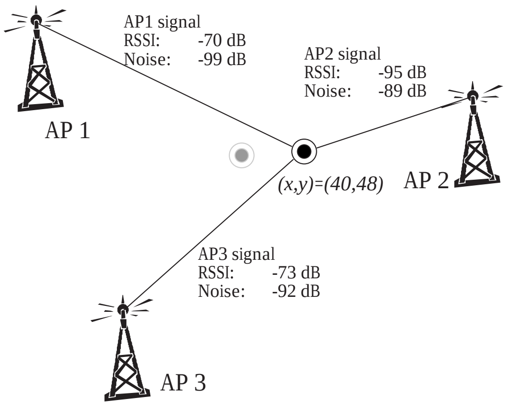
The Ekahau positioning engine works according to the *WLAN fingerprinting* principle. WLAN signals are RF signals that are emitted by each access point (AP), providing the network connectivity. The strength of this signal (RSSI[2]) differs for each point in a building, due to the distance from the AP and the interference from the environment. Often more than one AP is available in the environment. The set of signals at a position uniquely identifies that position. This is illustrated by Figure 4.5: at the position $(x, y) = (23, 44)$ three WLAN signals are received, from AP 1, 2 and 3. Now if the receiver moves to a different position, the strengths and noise levels of the three signals change (Bahl & Padmanabhan 2000).

The Ekahau positioning engine associates a position with signal strengths. First an environment has to be surveyed to record signal strengths and noise levels at many (known) points in the environment, which are then stored in a database (Figure 4.6(a)). Now to determine the position of a device, it works the other way around. The signal levels that are received are checked against the values in the database and the point that has the closest match to the signal values is returned as position (Figure 4.6(b)). To augment the positioning, techniques like map matching can be enabled. Using this technique, paths and spaces in the environment are modelled and used in calculations of the position. Rules like ‘It is impossible to go through a wall’ and snapping the position to a path reduce the positioning errors.

[2]Received Signal Strength Indication

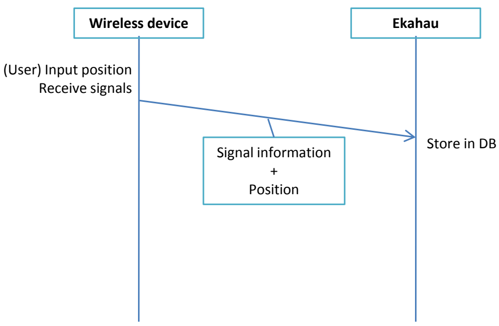


(a) Signal levels received at location (23,44)

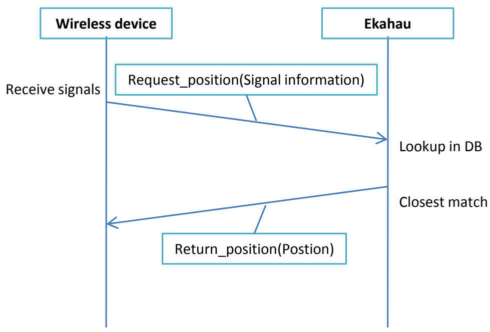


(b) Signal levels received at location (40,48)

Figure 4.5: WLAN signals have different characteristics at different positions.



(a) Surveying the environment; recording information



(b) Looking up a position.

Figure 4.6: Ekahau positioning engine, surveying and position lookup.

4.1.7 Indoor GPS

As mentioned in Chapter 1, the Global Positioning System is the main technology used for outdoor positioning. It consists of 32 satellites which orbit the earth and requires a receiver at the user side. The satellite signals contain information about the satellites orbit and location and time of transmission of the signal, that is processed by the receiver. If the receiver receives signals from at least three satellites, it can calculate its position on the earth. Initially developed by the United States *Department of Defence* it now offers up to several metres accuracy for positioning all over the world. Using this accurate positioning many applications have been developed, mainly navigation assistants. Biggest problem for using this technology indoors is the lack of sky view in indoor environments. GPS signals are already weak outdoors and have problems penetrating roofs, walls and windows because of signal attenuation.

GPS is based on trilateration. Receivers acquire and track signals from satellites in the sky. Each signal contains information on the position of the satellite as a function of the time. Based on this information and the timing differences between three or more signals the receivers are able to calculate their position on the earth. Basically the receiver calculates its distance from each satellite, for which the position is known because it is encoded in the signal from the satellite. Then using the principle of resection the position of the receiver is calculated (El-Rabbany 2002). This is also shown in Figure 4.7. Obviously, good reception of the satellite signals is a key issue in this positioning system.

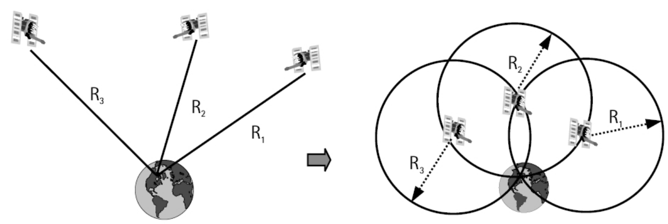


Figure 4.7: Basic idea of GPS (El-Rabbany 2002)

Several technologies augment the performance of GPS by adding extra signals, either via stations on the ground or other satellites orbiting the earth. The goal of both augmentation systems is to eliminate timing errors of the GPS satellites which are mainly caused by atmospheric interference when the signals travel to the Earth's surface. A set of base stations, for which the position is exactly known, monitors the GPS signals and inaccuracies. The information about these inaccuracies is then broadcast (via RF or satellite) and can be picked up and used in position calculations by enabled receivers.

An augmentation system based on ground stations is called *Ground Based Augmentation System (GBAS)*. *Differential GPS (DGPS)* is the most used GBAS, mainly provided for maritime usage and with RF beacons, transmitting GPS inaccuracy information, located along coastlines. These beacons cover a limited area and are mainly used in professional surveying. DGPS signals are freely broadcast by some coast guards (such as US Coast Guard) or commercially available from other providers (McNamara 2004).

An augmentation system using satellites to broadcast error information is called a *Satellite Based Augmentation System (SBAS)*. These systems are often regionally implemented and cover more countries or parts of a continent. The three major SBAS are: *the Wide Area Augmentation System (WAAS)*, covering North America and operated by United States Federal Aviation Administration (FAA); *the European Geostationary Navigation Overlay Service (EGNOS)*, covering Europe and operated by the European Space Agency (ESA); *the Multi-functional Satellite Augmentation System (MSAS)*, covering parts of Asia and the Pacific, including Japan, and is operated by Japan's Ministry of Land, Infrastructure and Transport (JCAB) (El-Rabbany 2002). Besides these three free SBAS, there are several commercial and military augmentation systems that are not free to the public. Note that there is no Australian Augmentation System yet and SBAS functionality of the receivers cannot be tested, since the experiments took place in Australia.

Recently more sensitive GPS receivers have become available on the market, which are advertised as indoor receivers. Typically they will receiver signals up to -160 dBm, to overcome the attenuation problems encountered indoors. However, a big problem with these receivers is that even if a signal is received, it is affected by a lot more factors than outdoor. Multipath effects and shadowing will be bigger by far. During research two high sensitive GPS receivers were tested, see Chapter 5.

The biggest advantage of indoor GPS would be that no infrastructure at all has to be installed in the environment.

4.1.8 RFID

RFID is the abbreviation of Radio Frequency identification. This technology makes it possible to store and remotely retrieve information from small electronic circuits, called tags. The technology is relatively new and is intended for a various range of applications. It can be used to replace conventional barcodes, use it for inventory tracking or personal identification (incorporated into passports). Basically a tag, which is a low cost electrical circuit in mostly in the form of a small sticker, can be placed on anything. The tag consists of two parts, a storage part which contains some information and a transceiver and modulation/demodulation part. Tags can be powered by a battery (active) or without internal power supply (passive). In the latter case electrical induction from the reader is used to power the tag. The information capabilities of RFID tags are small, they provide storage space up to a few kilobytes. Information on a tag can be retrieved by a reader, which is a powered device with a transmitter, receiver and an antenna, capable of modulating and demodulating signals.

For positioning systems RFID tags can be used to sense the position of a person, based on the proximity approach. Because the read range of a tag is limited, typically tag and reader can be only several centimetres from each other, positioning is accurate. Tags can contain some information on their position (in terms of a reference framework) or information on the environment. Another approach is to use tags with unique identifiers, which are related to a position by a central system.

4.1.9 Inertial Sensors

Inertial sensors are sensors that can sense orientation and acceleration. When accumulating the distance and direction travelled from a known starting point this can be used for positioning. Neither of the three approaches for positioning are used, because this system does not rely on wireless technology for positioning. Yeh, Chang, Wu, Chu & Hsu (2007) combines these two technologies. They use traditional Japanese *Geta sandals*, with embedded technology to track a users location. The idea behind the research is to provide positioning without a wireless infrastructure and with a wearable location tracking system.

The basic idea is to calculate the displacement vector after each step, update the location with this vector, starting from a known position. A pair of sandals is equipped with force sensors to detect a step, ultrasound transmitters and receivers, accelerometer, 3D orientation sensor and RFID reader. Two methods are developed to determine the displacement vector. One based on the distance between the two sandals, measured using ultra-sound. This distance is calculated by time-of-flight signal differences and triangulation in the ultra-sound signal transmitted by one sandal and received by two receivers on the other sandal. The other based on information from the accelerometer and 3D orientation sensor, which is converted to a displacement vector. The accelerometer method is inaccurate and will only be used if the ultra-sound method fails.

The biggest problem of this approach is the accumulation of errors. To overcome this problem an RFID reader was added. Passive RFID tags are placed on strategic positions, which contain information about their position. Once a sandal reads an RFID tag, it updates its position based on this information. Then calculated position based on the displacement vectors is discarded and updated by the location obtained from the RFID tag.

4.2 Assisting visually impaired

Besides just locating a person or object, several systems try to add useful information about the environment, route or current position to this location. The focus in this section is on systems that are being developed for visually impaired people. The solutions in this section are not commercially available and most are only evaluated in a controlled environment. Commercially available systems are discussed in section 4.3.

4.2.1 Cyber Crumbs

Ross (2004) developed *Cyber Crumbs*, an indoor orientation and wayfinding system, especially designed for use by visually impaired people. This system provides visually impaired with step-by-step instructions from the entrance of a building to their destination, which is typically a room or a landmark.

An important motivation of the research was to create an inexpensive, easy to install and maintenance free system. The user wears a headset connected to a badge, which contains a voice synthesizer, infrared communication (IrDA) and some memory. The building is equipped with *Crumbs*, small devices with a unique ID that consist of IrDA communication, memory and a battery (solar power is proposed for next versions). These Crumbs are places at strategic locations along paths and destinations, such as critical junctions, stairs, office doors and rest rooms. Crumbs are in a semi-sleep mode by default.

When the user enters the building he collects his badge at the information kiosk and selects his desired destination. The kiosk computes the shortest route and programs the badge with a sequence of Crumb IDs and directions, starting with its own. The user can listen to all this directions or choose to get directions as he walks. While walking the badge transmits a signal each second. When this signal is detected by a Crumb, it will wake up and respond by transmitting its ID and associated landmark, until the badge is out of range. The badge detects this and the voice synthesizer will voice relevant information. The range of a Crumb is approximately 3.5 metres.

Evaluation of Cyber Crumbs showed a significant increase in performance in wayfinding by visually impaired. The distances travelled decreased (indicating less detours and more efficient navigation) and the speed of travel increased (Ross, Lightman & Henderson 2005). It is proposed to add more information about the environment to the text the Crumbs transmit. Since they only transmit text, this can be easily added and synthesized by the badge.

The advantage of this system is that it is lightweight to wear and requires no maintenance. Crumbs are relatively cheap when produced in large quantities (US$ 5 each for 100,000), but the badge is more expensive (US$ 600 each). All users who tested the system were enthusiastic about the system.

A few problems were found during the experiments. The system is unreliable in some cases due to reflections, causing confusion for the user. When users search for a Crumb and sweep the space too quick, the Crumb would not be located, because the badge transmits only every second and must be facing the Crumb. Another disadvantage is that the user has to program its badge upon entry of the building and can only travel along a fixed path. If he decides to go to another destination later on, he has to return to the entry to reprogram the badge.

4.2.2 Talking Signs

The goal of *Talking Signs* is to make everyday signs and Braille signs remotely readable. It does not provide the user with step-by-step directions to a destination, but gives users a spoken description of a sign. The system has been installed in several cities in the USA, but is most present in San Francisco with approximately 1,000 installed signs (Crandall et al. 2001).

Talking Signs consists of a small hand-held box, that is carried by the user. The box contains of a photo detector, FM discriminator, amplifier, internal speaker and a push button. Transmitters (placed in the environment) send out spoken messages (FM modulated human speech) on a infrared beam. These beams can be adjusted to change coverage of a certain area. The spoken messages contain information about the environment. If the user points its hand-held in the direction of a transmitter and pushes the button, the speech message will be played. For example, a sign above the entrance of the restrooms will say 'Restroom Entrance'. Because the user has to point his hand-held towards the transmitter, he knows the direction of the restroom. Users have to scan the environment for signs to orientate themselves and then decide which way they want to go.

This system has been installed in a transit station in San Francisco. Approximately 100 transmitters were placed and programmed in the station, labelling locations like shop entrances, agent booths, faregates, telephones and corridors. Visually impaired people were given a hand-held and ordered to complete a route. After the experiment they were encouraged to use the hand-held in daily use of the transit station. Training in the use of the system was an important factor for successfull use of the system. All participants were enthusiastic about the system. It gave them more confidence and enabled them to travel in the station independently, whereas they would have to rely on assistance of other people without the system.

Similar experiments were conducted in an outdoor environment to locate bus stops and give information about the bus timetables. Another experiment assisted visually impaired when crossing streets by providing information about the state of the traffic light and prevent the user from veering while crossing the street. This proves Talking Signs can be used for more than wayfinding only.

The advantage of Talking Signs is that once installed there is low maintenance of the system. The transmitters have no battery and operate on the mains power supply. The three experiments show that any type of information can be transmitted. The hand-held just plays the message it receives. This makes Talking Signs suitable for almost any application. Transmitters can be configured to transmit flexible messages (for example the bus timetable might be different in rush hours or weekends), which makes the system more flexible than Braille signs.

Installation and configuration of the system requires quite some work. The transmitters require continuous power, because they transmit their message all the time. This makes installation harder and more expensive. Also operation is not energy efficient. For each sign a message has to be recorded. Because no text-to-speech algorithm is used, this can be time consuming. Also it makes updating the information more cumbersome. Information send by the transmitters is relatively static, it cannot adept to the needs of the user. Experienced users have different information needs than beginners.

4.2.3 Digital Sign System

Tjan, Beckmann, Roy, Giudice & Legge (2005) propose a system that also makes signs available to visually impaired people. The goal is to assist the user and not to think for the user. It provides no step-by-step navigation instructions. Instead of using wireless communication technology to detect the location or signs the system uses -like tags. It is called the *Digital Sign System* (DSS), which is part of the bigger *Indoor Guidance System* (IGS).

The DSS consists of three components: passive retro-reflective tags, a hand-held device (the Magic Flashlight) and machine-vision software for identification of the tags. Tags are credit-card sized and consist of a pattern printed on a retro-reflective tag, which comes in many colors. The pattern is comparable to a barcode and is able to represent a 16-bits number. In order to locate a tag, the visually impaired user sweeps an area with its Flashlight, which emits infrared light from its transmitters. With the IR detectors and a camera, the Flashlight uses a tone varying in intensity and pitch to represent the amount of IR light that is reflected, allowing the user to point the Flashlight to a tag. When the Flashlight spots a tag, the camera is used to take a snapshot and the image is processed to identify the number of the tag. This number can then be used to lookup the associated verbal message in a database (part of the bigger IGS). The IGS basically consists of a spatial database of the building, a database of the tags and logic for describing spatial structures.

In experiments the tag identification system worked well in various types of situations and proved robust. Very bright sunlight is a problem, because this contains much IR signals, interfering with the system. The overall IGS system mainly supports visually impaired in wayfinding by providing information about the detected sign.

The main disadvantage is that barcodes are static and only provide a 16-bits identifier. Another system linking this code to valuable information must be present at all times and this will require an additional communication infrastructure.

4.2.4 RFID based infogrid

A system solely based on RFID tags, without the need for any wireless communication or central database is proposed by Willis & Helal (2005). It will not provide step-by-step navigation, but rather provide an advanced way of signage.

The basis of the system is a grid of passive RFID tags, which are placed under the carpet (indoors) or along paths (outdoors). The idea is that the RFID tags are installed and then programmed with their location and some information about their surroundings. Depending on this location information about the path (in hallways) or the environment (in case of a room) is programmed in the tag. Tags can carry any type of information about the environment encoded in a compressed XML based format, to optimize storage and provide interoperability. RFID readers are integrated in the walking cane and shoe of the user. To accommodate visually impaired users even more, the so called *NAVCOM belt* is provided. This belt consists of a set of ultra-sonic distance sensors and vibration motors. The closer a user moves to an object, the more the belt will vibrate.

The reading of RFID tags while walking is a problem, but this can be reduced by choosing the right tags and readers. The solution is cheap, for a resolution of 1 foot, it will cost US$ 1 per square foot (one dollar for each tag). There are no experimental results with visually impaired people or with people using the system for navigation.

4.2.5 Drishti

A system for both outdoor and indoor navigation is proposed by Ran, Helal & Moore (2004). The system combines DGPS and ultrasound technology in a wearable device, which weighs approximately 3.5 kg. The primary goal of the system is to provide a visually impaired user with routing and 'where-am-I' information. The system consists of a wearable computer, differential GPS receiver, wireless network (802.11b) interface and two ultra-sound receivers (beacons). Software components provide routing algorithms, a spatial database, voice synthesizer and analyser and indoor location service. The user interacts with the system via a set of voice commands and headphones for feedback from the system.

Outdoors differential GPS is used to determine the position of the user. Using voice commands the user can request more information about the surroundings or choose alternative routes. When entering an indoor environment, the user can switch the system to indoor navigation by a simple voice command. Ultra-sound transmitters are placed at known locations in the building. The two receivers are used to determine orientation and calculate position, based on time-of-arrival differences of signals from at least two beacons. The spatial database and routing service is used to guide a user indoors.

Using DGPS for outdoor positioning provides good accuracy. The indoor positioning technique is not expensive. Accuracy was within 22 centimetres in the experiment. Although ultra-sound can be reflected and will have some dead-spots in buildings (the signal may be blocked), adding more transmitters will reduce this problem. Because the small cost of a transmitter, this is a practical expansion.

Disadvantage is the gear for differential GPS reception is bulky, especially the antenna is not comfortable to carry. The user also has to wear headphones and use voice commands to control the system. Headphones may block valuable sounds for visually impaired and there are no test results how the system performs in noisy environments. Also there are no results from experiments where users actually navigate indoors using this system.

4.2.6 Robot Guide

All previous systems require the user to carry or wear a part of the system. This might be inconvenient. Based on this Kulyukin, Gharpure, Sute, De Graw. & Nicholson (2004) propose a indoor navigation robot to guide visually impaired. The *Robot Guide* (RG) enables the user to use its normal aids, like a cane, and does not limit the hardware as wearable systems do. Robots can carry larger hardware and better (heavier) batteries. The robot is intended for use in specific locations, for example airports.

The Robot Guide consists of three wheels, a laptop with wireless network connectivity (802.11), a (large) RFID reader and a laser range finder. RFID tags can be read when they are within a range of 1.5 metres of the robot. The laptop runs a spatial information system, speech recognition and synthesizing software and path planning software. Speech messages and audio icons (eg. sound of water bubbles when passing water cooler) are used to guide the user. Information on the RFID tags is associated with robot actions. This must be done manually. The robot navigates based on information from it's sensors and RFID information.

An experiment with visually impaired showed they appreciated the system. Especially the fact that they did not have to give up their (own) cane or guide dog assistance was appreciated. The navigation itself was not a problem. An advantage is that passive RFID tags are cheap and can be read from 1.5 metres with the antenna mounted on the robot.

The robot was rather slow and speech recognition could be better. For example when users started having a conversation, the robot is not supposed to act on this speech.

4.2.7 Personal Guidance System

The most research on wayfinding assistance has been done in the *Personal Guidance System* project at the University of California (in cooperation with other institutes). This project focuses on several aspects for an outdoor wayfinding system for visually impaired. Primary it is focused on user interface, how spatial information should be displayed for visually impaired. It is described in numerous publications (Loomis, Klatzky & Golledge 2001, Marston, Loomis, Klatzky, Golledge & Smith 2006, Golledge et al. 2004).

Differential GPS is used to determine the position outdoors and a portable computer carries the GIS information. The nature of the research is to experiment with user interfaces. Therefore the interface to the user is the changing factor in the research. Experiments with three-dimensional sounds (Loomis et al. 2001) and pointer interfaces (Marston et al. 2006) are reported. The system generally gives turn-by-turn instructions to the destination of the user.

4.3 Commercially available

At the time of writing this report (June 2008) there are three products in the market, which assist visually impaired with *outdoor* wayfinding. Most can be used in major cities around the world or at other places for which digital maps are provided. This section will only provide a quick survey of these products. Note that VisuAide (the developer of Trekker) and Sendero Group (the developer of BrailleNote GPS) have merged into Humanware in 2005. A review of all three systems can be found in the February 2006 issue of Braille Monitor (NFB's Access Technology Staff 2006).

4.3.1 Trekker

Trekker is developed by Humanware, a New Zealand based company (Humanware 2007*b*). The system consists of a PDA with a tactile keyboard, DGPS receiver (connects via Bluetooth to the PDA), speaker or headphones and a set of digital maps. The tactile keyboard is placed over the PDA, such that the touch-screen is completely covered by the keyboard. The system can provide the user with a wide range of information, such as 'Where am I?' information, route/navigation instructions, intersection detection and point of interest detection. Maps are stored on a memory card and can be changed, for example when the user moves to another city. The system is small, the PDA can be easily carried in one hand and the wireless GPS device can be placed in a backpack or attached to for example a belt. There is no need for wearing large gears or strange suits to carry the navigation system. Figure 4.8(a) shows a man using Trekker.

4.3.2 BrailleNote GPS

test BrailleNote GPS is also developed by Humanware (Humanware 2007*a*). The system consists of two main components, a DGPS receiver and a BrailleNote input device developed by Sendero Group (Sendero Group 2007). The GPS receiver is the size of a cell phone which is able to calculate routes and can relay this information to the BrailleNote (or VoiceNote) device. BrailleNote and VoiceNote are products which can be used as interface for various products, using a Braille display and several buttons. It can for example interface with Windows and Internet Explorer, allowing a visually impaired user to browse the Internet. In case of navigation the BrailleNote device is carried by the user and connected with a wire to the GPS device. The GPS device is worn at the shoulder of the user. It can provide information about points of interest, calculate routes, assist in navigation and provide information about speed, heading, etc. Figure 4.8(b) shows a woman using BrailleNote GPS.

For a review of and comparison between Trekker and BrailleNote GPS read the article of Denham, Leventhal & McComas (2004). It must be noted that Trekker is promoted as the main product for navigation by Humanware.

4.3.3 StreetTalk

StreetTalk is developed by Freedom Scientific, a US based company which has a wide range of products for the visually impaired. StreetTalk consists StreetTalk software and a PAC Mate, which is a product of Freedom Scientific. Many (Bluetooth) GPS receivers can be used to determine the position of the user. PAC Mate is the brand name of a series of portable products which provide input and output options to visually impaired, such as Braille display, speech-unit or QWERTY-keyboard. StreetTalk thus can provide information via Braille or speech. It can provide information such as route planning, step-by-step directions, where am I, nearest address and points of interest. An interesting feature is the planning mode, in which the device plots the route without moving, allowing a user to explore the route before actually leaving. There also is some integration with PAC Mate functionality (navigate to addresses in address book). Figure 4.9 shows two PAC Mate models (Freedom Scientific 2007).

(a) Trekker (b) BrailleNote GPS

Figure 4.8: Humanware products
(source: `www.humanware.ca`)

Figure 4.9: Two models of PAC Mate (GPS not pictured)
(source: `www.freedomscientific.com`)

4.4 Summary

Based on this literature study we can draw some conclusions on the characteristics of these indoor positioning technologies. The overall usability of a positioning system is a combination of three factors. First, the accuracy of the positioning technology is of the most importance, since this is the fundamental motivation for a positioning technology, obtaining the current position. But accuracy often comes at a cost and depends on the infrastructure that can be used by the technology, which is the second factor. Lastly the work the user has to do to obtain a position estimate is evaluated, which includes the size and limitations of the gear.

Best by accuracy and precision

Most accurate positioning technology is the ultrasound positioning system of Section 4.1.3. The included example of the Active Bat system provided an accuracy up to 9 centimetres. However, ultrasound signals can not penetrate walls and other objects, putting a constraint on the infrastructure. To successfully obtain an accurate position, at each point in the environment at least three ultrasound transmitters must be in line-of-sight. In practise this means that each room has to be equipped with at least three transmitters and hallways have to be equipped with strategically placed transmitters. Even more these transmitters must be mounted at exactly known locations, increasing the installation costs of the infrastructure.

RFID is also a very accurate positioning technology, but only when an RFID tag can be sensed. The range of passive RFID tags is in general not more than several centimetres, putting huge constraints on installation and maintenance costs, because an enormous grid of RFID tags has to be rolled out, for example under the carpet. Furthermore all these tags have to be programmed with their position. Even when RFID tags are cheap to produce and buy, the labour needed to get this system up and running dramatically increases the costs.

Best by infrastructure, scalability and costs

Judging technologies by infrastructure, scalability and costs indoor GPS is the best indoor positioning technology. No infrastructure is needed in the environment, reducing the infrastructure installation and maintenance costs to zero. The costs of the receivers are however considerable (several hundreds of dollars), but it is expected that the price of this technology drops. But even with this relatively expensive receivers, the absence of infrastructure costs still makes this overall a cheap technology to use.

WLAN positioning technology requires little installation costs, because the signals are surveyed after the equipment has been installed. Consequently the exact position of the transmitters does not have to be known, which allows for easy installation of the equipment. Moreover few transmitters are needed to cover a large area. The labour required to get the system up and running is considerable, because of the rough modelling of the environment and surveying it. However, compared to other technology, installation is easy and quick.

Chapter 5

Experiments

With information from the methodology derived in Chapter 3 it is possible to describe a position in a functional way. However, obtaining this position in indoor environments is not as easy as in outdoor environments. Interference from this indoor environment (the *built* environment) is one of the main difficulties in indoor positioning.

The experiments in this chapter will describe the characteristics of two indoor positioning techniques out of the techniques described in Chapter 4. Many of them require an infrastructure to be installed in the environment. For example sensors in every corner of the building. The two technologies evaluated here either use already installed infrastructure or require no infrastructure in the environment itself at all. .

5.1 Technology elicitation

Major problem for the deployment of indoor positioning systems are the costs and infrastructure requirements. Building managers do not want to install expensive infrastructure that solely can be used for indoor positioning. In most cases the costs and effort to install positioning systems are simply higher than to hire a person dedicated to assisting people in finding their way in the building.

Therefore in the elicitation of technologies to evaluate cost and infrastructure played a major role. First, indoor GPS positioning was selected as a promising technology. Being the main positioning technology outdoors the documentation of indoor GPS receivers promises good results indoors. Because this technology requires no infrastructure to be installed in the building at all, a major problem for not adopting indoor positioning technology has already been tackled. Second technology, WLAN positioning, is interesting for a different reason. It has requirements on the infrastructure that had to be installed in the building, but this infrastructure can be reused (at the same time) to provide wireless access to the Internet at the same time. Also WLAN infrastructures are already in place at buildings, which makes this technology useful for more than one purpose.

5.2 Test scenarios

The goal of the experiments is to measure the accuracy and positioning characteristics of the technologies. First we want to see if it is a feasible approach to use this technology and secondly we want to see how it performs under different circumstances.

To be able to evaluate and compare the technologies, two test scenarios have been developed. The first one is designed to measure and evaluate the accuracy of the technology when the target does not move. Ideally the reported position should not change and be correct, but most likely there will be some variations in the position. The second scenario looks at the performance when the target is moving.

5.2.1 Static indoor performance

The goal of this test is to evaluate the variation in accuracy in indoor environments, while the positioning device is not moving. Ideally the device should report a constant position, which is correct, and not deviate from it. This test can determine possible errors in positioning with this technology.

The positioning device was placed on a table indoors and was not moved for at least 20 minutes. Most factors in the environment remained stable, except for the people moving around in the office or other normal behaviour in the environment. This test gives an idea on the performance and positioning reliability of the technology. Accuracy, standard deviation from the actual position and variation in position are measured.

5.2.2 Moving indoor performance

The goal of this test is to test the performance of the positioning technology when the device is moving at walking pace speed. While devices may be accurate when they are static, moving performance may differ. For example it may take some time for a device to acquire or calculate its position or the changes in the environment can make the positioning unreliable. Sometime it might also take some time to adapt to the changed environment.

In this test a pre defined circular path of approximately 50 metres was walked indoor with the positioning device. The device was carried by a person at approximately 1.5 metres height and in most cases (depending on the technology) connected to a laptop computer. Errors in positioning and the update speed will be evaluated. For some technologies additional tests will be performed. The test environment was again the third floor of a six stories high building, but the path included several points where one could look outside through a window. This sky view is only important in the GPS tests and will probably not affect the other tests.

5.3 Indoor GPS

5.3.1 Equipment

The first technology to be evaluated are high sensitive GPS receivers, also known as *indoor GPS devices*. In the hypothesis of the research, it is assumed that the GPS positioning technology would not work indoors. However, during the project interesting products that claimed to use GPS for indoor positioning were discovered. With this promising outlook in mind, we were able to test two products. One receiver manufactured by *SiRF* and the second receiver manufactured by *u-blox*. SiRF is supplier of chipsets to many navigation systems manufacturers like TomTom and Garmin (SiRF Technologies 2008). Key difference between these (indoor) receivers and conventional (outdoor) receivers is that these indoor receivers are able to receive very weak signals, up to –160 dBm. Depending on the receiver there are also algorithms in place to minimize the multipath effects and signal shadowing. Both receivers still work in according to the general GPS principles, as described in section 4.1.7

Table 5.1 is a comparison of the documented features of both receivers. The receivers are both high sensitive and share quite some characteristics. The main difference are the number of signals that can be tracked, the ability to track DGPS and the physical dimensions. The receivers were connected to a notebook with the recommended support software installed. These evaluation receivers cannot be used as a stand-alone device.

SiRF GSC3f/LP

For this evaluation the SiRF evaluation kit of the *GSC3f/LP chipset* is used. This comes as a small boxed chipset, with two RS232 ports and a USB port for connectivity to a PC. The device is powered by net power or by the internal battery which lasts for 14 hours. The SiRF receiver has an extra feature called *dead reckoning*. This is a filter that extrapolates the receivers position in case the GPS signal is temporary lost. Receivers without dead reckoning would just stop giving positioning information. The receiver is able to track 12 GPS and/or SBAS signals. It cannot receive and use DGPS signals. It comes with a few software tools for configuring the device and reading the output, of which *SiRFdemo* is the most powerful.

u-blox SuperSense

This evaluation kit has the ANTARIS *LEA-4H chipset* as core. The technology to track very weak signals is called SuperSense. The evaluation kit comes as a tiny boxed chip with only an USB port for connectivity to PC. The device is powered by the power supplied by the USB port of the computer. It has no internal battery and is considerably smaller in size than the SiRF receiver. The u-blox receiver is able to track 16 GPS and/or SBAS signals and is capable of decoding DGPS signals. The device comes with u-blox' *u-center software* to configure the device and process the output. See Figure 5.1.

Figure 5.1: u-Blox AEK-4H evaluation receiver package with external antenna

Both receivers can output the data as NMEA data stream, which is protocol for interfacing with marine electronic devices developed by the National Marine Electronics Association (NMEA). Many types of information can be exchanged with this protocol, for example water depth, heading, bearing and current position. NMEA protocol stream are typically transmitted at 4,800 bps and consist of ASCII protocol commands and responses (El-Rabbany 2002). The NMEA protocol output is used, because it allows for easier comparison between the receivers, using the same tools.

5.3.2 Environment and configuration

Initially the same environment as with WLAN experiments was chosen as target environment for the experiments. However, it turned out that indoor GPS is not as promising as it looks like on paper. Eventually the environment for the static indoor experiment consisted of an apartment on the ground floor of a three storey high apartment block. The GPS receivers and antennas were placed at approximately 50 centimetres from a window (with closed blinds).

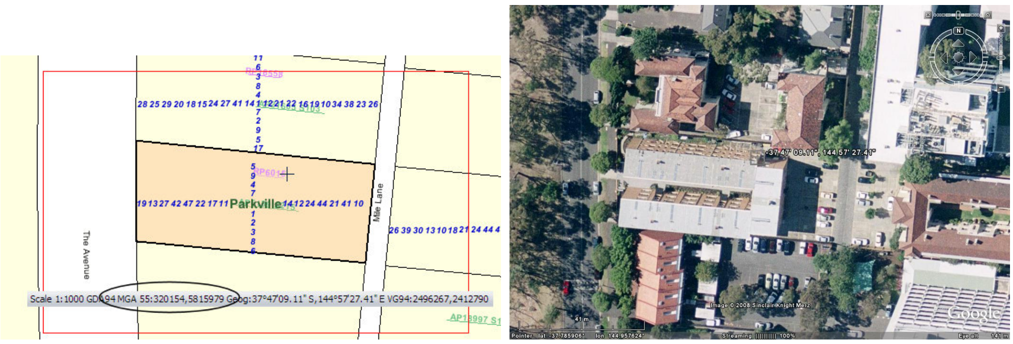
For the moving indoor experiment the environment eventually consisted of a ground floor shopping centre, consisting of two supermarkets and some smaller convenience stores. The dimensions of this test environment were approximately 400 by 200 metres.

Both receivers used the same configuration; no SBAS information was allowed to be used (this would probably increase the positioning error, since Japanese MSAS satellites could be received, but these correct the GPS signal for the Eastern Asia region only), and all available channels could be used for GPS satellites tracking. Dead reckoning and DGPS were enabled.

5.3.3 Results

Method of analysis

GPS devices output coordinates in the WGS84 geocentric system. Coordinates of this system uniquely identify a position on *the sphere* of the Earth. However, calculations with these coordinates are elaborate, because the curve of the Earth's surface has to be taken into account (particularly in distance calculations). To perform calculations, these coordinates are first converted to the Universal Transverse Mercator coordinate system (UTM). In the UTM system calculation of distances between points can be done more easily by using the Pythagorean theorem, because the influence of the curve of the Eath's surface is minimal (El-Rabbany 2002, chapter 4). Additional advantage is that the UTM projection is the same as the datum used in Australia, GDA. The transformation from WGS84 to UTM can be found in (National Geospatial-Intelligence Agency 1990) and is performed for our data files by the software tool GPSBabel[1]. The result of this transformation is to obtain coordinates in the UTM 55(H) zone reference frame, representing the distance in metres from the origin. The actual position was determined by looking up the location in the geographic surveying system of the Government of Victoria[2] and verifying it visually in Google Earth, as shown in Figure 5.2.



(a) Using LASSI (b) Verification in Google Earth

Figure 5.2: Position of the receivers

[1] http://www.gpsbabel.org/
[2] LASSI: http://services.land.vic.gov.au/maps/lassi.jsp

Results Static Indoor

Both receivers were unable to acquire any signal on the third floor of the ICT building, probably because of the complete lack of sky view (no windows). Rarely just one signal was picked up, but this was not enough for the GPS device to calculate a position. This cannot be supported by any graphs or data, because the devices simply generate ‘no fix’ data, which means that no position is calculated. It is suspected that due to the construction of the building the GPS signals are too weak. There are three more floors of reinforced concrete above the level where the test was conducted, also little skyview through windows is available in the hallways.

Using an empirical approach it was concluded that in order to at least get the devices to output positioning information, a window with some sky view must be near. As a result the static indoor test was executed on the ground floor of an two stories high apartment block, near a window. See Figure 5.3 for a picture of the test setup. After the initial initialization and signal acquisition times, both receivers were able to estimate a position. For approximately 1.5 hours data was collected, without moving the antennas. The environment did not change, except for people moving around in the apartment and adjoining apartments.

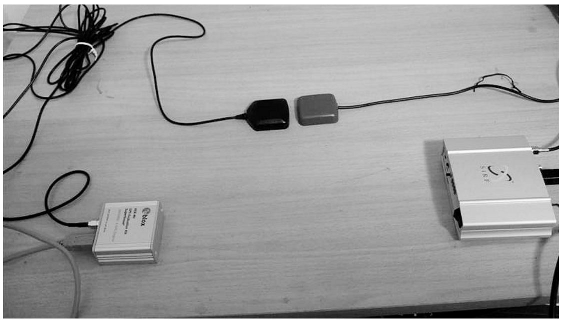


Figure 5.3: GPS setup

The results are represented in Table 5.3 (SiRF receiver) and Table 5.2 (u-blox receiver). Additionally Figures 5.5 and 5.4 show the location estimates in various ways. The scale of the graphs is different, in Figure 5.5 a square on the floor of the graph measures 25 by 25 metres. In Figure 5.4 these squares measue 5 by 5 metres.

u-blox SuperSense The average error of the position estimates was just less than 16 metres. Only for 5.63% of the estimates the error was less than 4 metres. Where 62% of the estimates is within the 16 metres error range, more than 10% of the estimates have an error of more than 32 metres, with a maximum of almost 63 metres. The errors can be explained by signal reflection and attenuation of the building and adjoining buildings, however these are exactly the kind of problems this ‘indoor’ receiver should be able to cope with.

SiRF The performance of the SiRF receiver is much worse than the performance of the u-blox receiver. On average the error measures more than 221 metres, having estimated the position correct a few times and with a maximum error of over 1.7 kilometres! Just over 55% of the estimates is within 100 metres of the actual position, and more than 31% has an error greater than 200 metres. From this results it can already be concluded that this receiver is worthless for indoor positioning, because positioning errors of magnitudes of hundreds of metres are unacceptable for indoor positoning.

Results Moving Indoor

As noted above, the standard moving indoor test in the ICT building did not work. Probably because of the interference and signal blocking of the building construction. Therefore the experiment was repeated in a shopping mall which was completely on the ground floor, without anything stories on top of it. According to the user manuals of the receivers, the main advantage of indoor receivers should be that they work in situations like this, compared to conventional GPS receivers.

The test was slightly adapted. Both receivers were taken at walking speed to the tram stop. From there they were moving with the speed of the tram, which can reach up to 50 km/h. At and in the shopping centre, the receivers moved at walking speed. The results are not as easy to present in numbers as with the static test, because the receivers were constantly moving. Figures 5.6 and 5.7 show the actual path in the shopping centre and the GPS fixes from the receiver. Interestingly, but not surprising, the receivers are very accurate outdoors. The approach to and departure from the shopping centre from the West is accurately recorded. Then in the first part (indicated by character A) there is a small covered area, with windows at the front and back. Here the receivers still generate position fixes, but the errors increase (although still within several metres). Then there is a short (10 metres) covered walk outdoor (indicated by character B). After this outdoor part, when the main part of the shopping centre is entered, the accuracy of the GPS decreases rapidly, and eventually both receivers are unable to calculate position fixes. Occasionally a position is calculated, but there are may misplaced fixes, as can be seen in the bottom left corner of figure 5.7. The shopping centre also has a small pyramid of glass, which is covering the food court (indicated by character C). Both receivers started to report position information once they were moved into this area. The boundaries of the environment are accentuated by the white lines.

Property	SiRF	u-blox
Core chipset	SiRFstarIII GSC3f/LP	ANTARIS4 LEA-4H
Number of Channels	12	16
GPS signal tracking	L1, C/A code	L1, C/A code
Tracking Sensitivity	–159 dBm	–158 dBm
Acquisition Sensitivity	–142 dBm	–148 dBm
DGPS	No	Yes, DGPS
SBAS	WAAS, EGNOS	WAAS, EGNOS, MSAS
Accuracy	2.5 metres	2.5 metres
Augmented accuracy	2.0 m	2.0 m
Connections	2×RS232 & 1×USB	1×USB
Protocols supported	AI3/F, SiRF Binary, NMEA	u-blox Binary, NMEA
Dead Reckoning	Yes	No
External Antenna	Yes, active	Yes, active
Power source	External or battery	USB powered

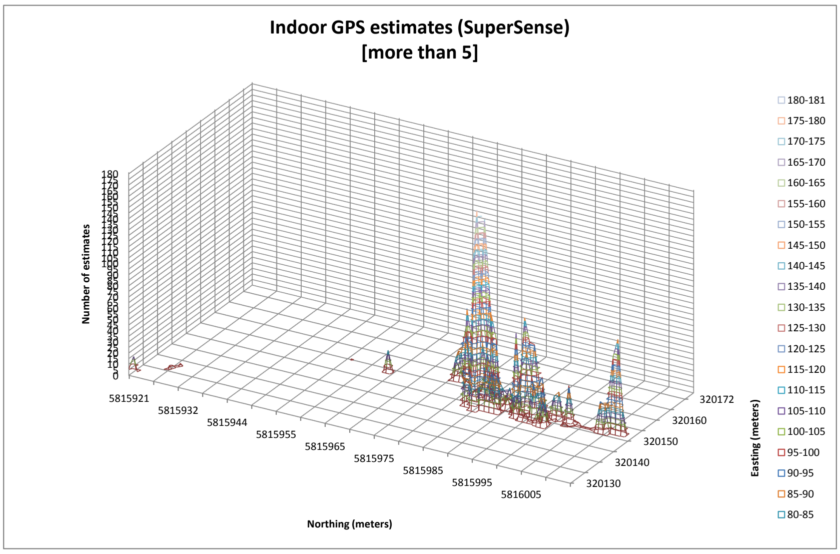
Table 5.1: GPS receivers and core features compared

Samples	3515
Average error	15.67 m
St.dev.	*10.35*
Minimal error	0 m
Maximal error	62.77 m
Within 2 m	1.28 %
Within 4 m	5.63 %
Within 8 m	13.14 %
Within 16 m	62.36 %
Within 32 m	89.93 %
More than 32 m	10.07 %

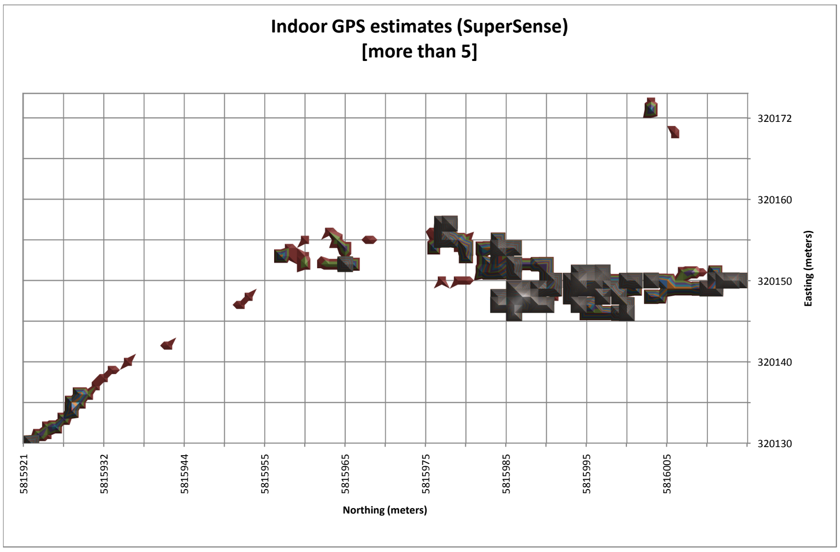
Table 5.2: Static indoor using u-blox receiver

Samples	2388
Average error	221.11 m
St.dev.	*310.49*
Minimal error	0 m
Maximal error	1778.5 m
Within 12.5 m	10.77 %
Within 25 m	18.14 %
Within 50 m	36.61 %
Within 100 m	55.22 %
Within 200 m	68.08 %
More than 200 m	31.92 %

Table 5.3: Static indoor using SiRF receiver

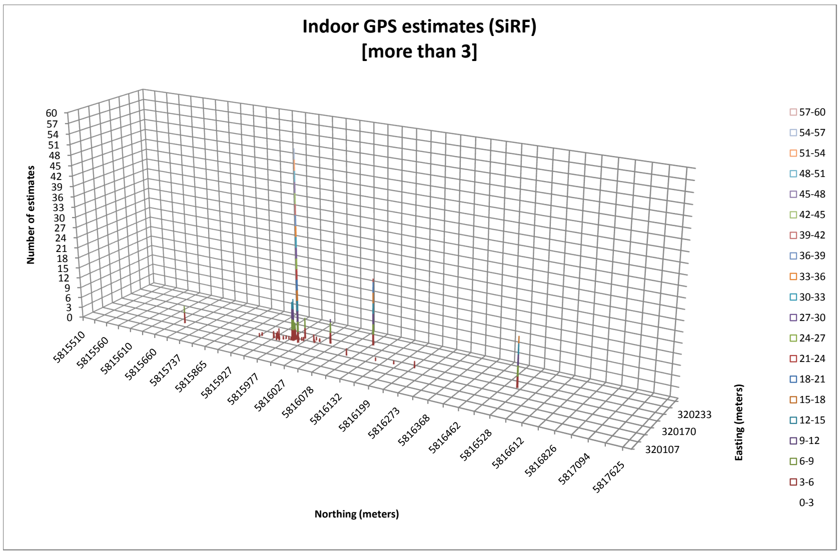


(a) 3D plot

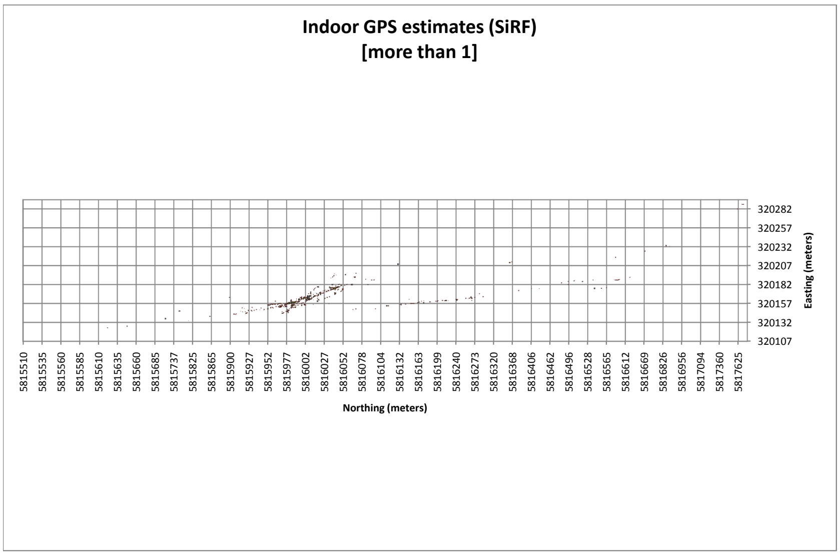


(b) Contour map

Figure 5.4: GPS estimates during static indoor (u-blox), only shows estimates that occurred more than 5 times.



(a) 3D plot



(b) Contour map

Figure 5.5: GPS estimates during static indoor (SiRF), only shows estimates that occurred more than 2 times.

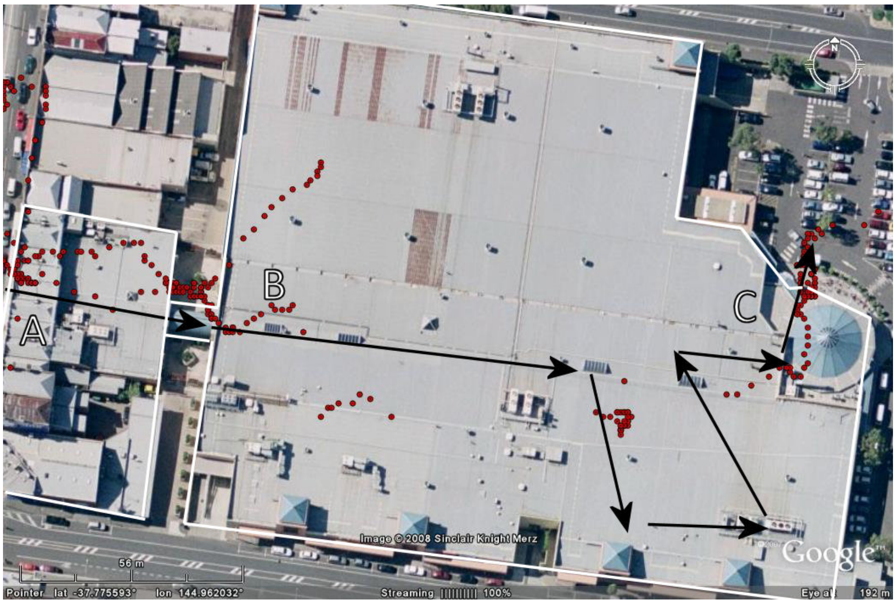


Figure 5.6: SuperSense Receiver valid fixes in the shopping centre. The red dots are fixes, the arrows are the actual path walked.

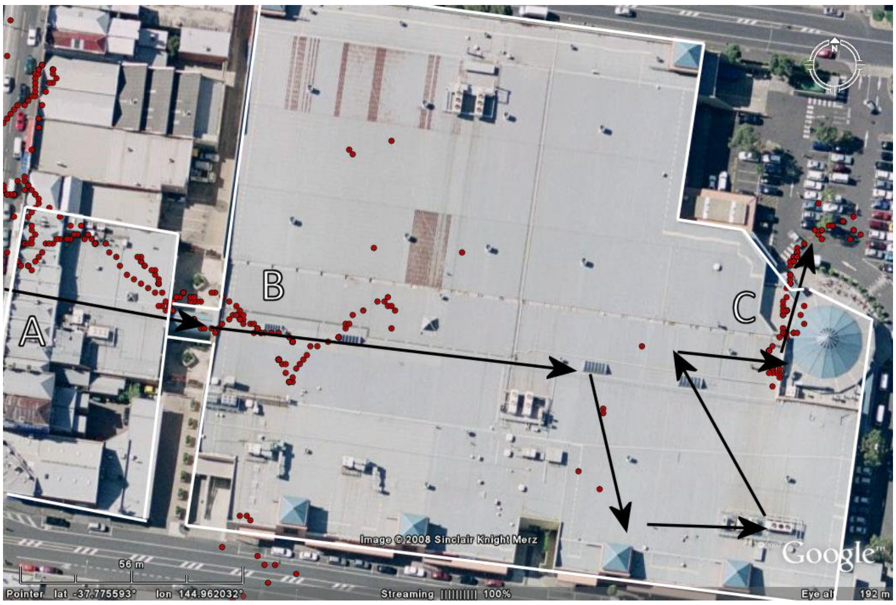


Figure 5.7: SiRF Receiver valid fixes in the shopping centre. The red dots are fixes, the the arrows are the actual path walked.

5.4 Wireless LAN

5.4.1 Equipment

Section 4.1.6 already elaborated on the principles of WLAN positioning and the software solution of Ekahau. For this experiment the off-the-shelve solution of the Ekahau [3] positioning engine was used. This is a software based solution, which can be installed on any laptop with an Atheros wireless chipset.

An evaluation version (4.0.18, build 16346) of Ekahau Location Survey was used in this experiment. It was installed according to the documentation on a HP laptop, with a recommended wireless network card. The test environment consisted of a floor of the ICT building of the University of Melbourne. Two AP of the MUWIRELESS[4] are located on this floor and signals from APs on other floors can be received as well. Additionally experiments with strategically placed access points were conducted. These additional access points consisted of normal personal computers with wireless network cards also with an Atheros chipset. These computers are configured to act as access point (without actually providing network connectivity), advertising their SSID. All were placed on the floor, with the network card antenna approximately 40 centimetres above ground level.

5.4.2 Environment and configuration

The test environment consisted of the third floor of the ICT building of the University Of Melbourne. This is a six storey high building, equipped with WLAN access points to the MUWIRELESS. The location of these access points is shown in Figure 5.9(a). To train the Ekahau Location Suite, the floor was surveyed in an afternoon, by walking the paths as shown in Figure 5.8.

A model of the building has to be constructed before surveying. This gives the Ekahau software a framework to work with. The model consists of spaces (open area's) and rails (paths). Rails are used to connect spaces to each other. Additionally zones can be defined, but these are only used to communicate human-understandable descriptions to the user. To train the model, the way to survey the environment is to walk at a steady pace and click on your location on a map. The software this location information and associates it with the received signal levels. The floor was surveyed by walking the routes two times in both directions, to minimize the effect of antenna alignment and signal absorption by the body of the surveyor.

For this test the entire floor was modelled as one 'big' open space, to test the performance of the software with minimal modelling.

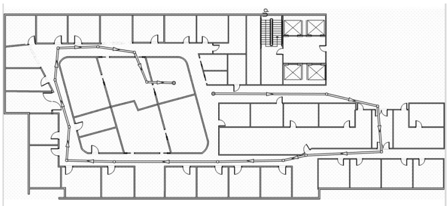
[3] `http://www.ekahau.com`

[4] WLAN network of the Melbourne University

Two test setups were tested. One with the existing WLAN infrastructure (2 WLAN AP's on the same floor) and another with an artificial new WLAN infrastructure, with 13 access points placed at positions throughout the environment (see Figure 5.9(b)).

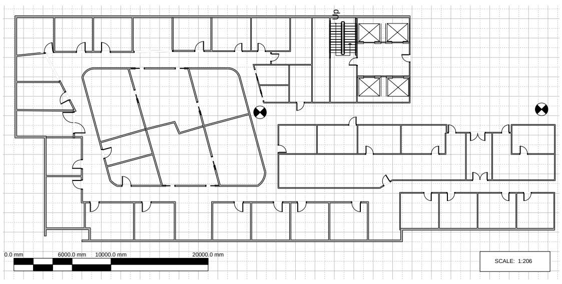
First the Ekahau suite was trained by surveying the building 3 times. A circular path was walked 2 times counter clockwise (Survey 1-5 and 11-15) and 1 time clockwise (Survey 6-10). The second time the path was walked counter clockwise, a more aggressive signal measurement algorithm was used, which may result in some signals not being detected at all. In the end several evaluation runs were done, to get the following results.

(a) Survey counter clockwise (b) Survey clockwise

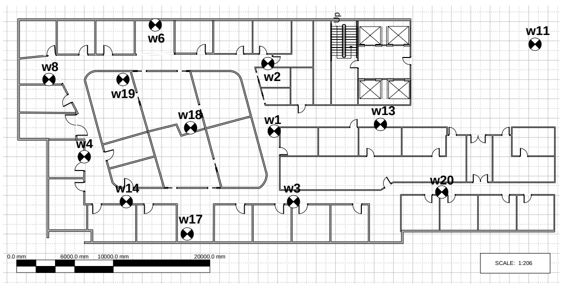


(c) Evaluation path

Figure 5.8: Ekahau training data and evaluation path.



(a) Existing infrastructure: WLAN access points.



(b) New infrastructure: more WLAN access points.

Figure 5.9: WLAN access points in the ICT building.

5.4.3 Results

Method of analysis

The problem with the evaluation version of Ekahau is that it can only output positioning information graphically on a map, as shown in Figure 5.11. There is no interface which outputs numerical values that can be used in analysis. However, for these results the image of the Ekahau window was recorded in a movie and later processed by a MATLAB script[5]. This script extracts the (green) dot from the image, determines the centre and returns the position as an (x, y)-value with the window as reference frame (Figure 5.11).

The moving indoor results are represented in a table, summarizing the most important statistics and a figure representing error vectors. The error vector represents the amount of error between the estimated position and the actual position. The end of the error vector with the dot is the actual position. The other end is the estimated position, calculated by Ekahau based on the observed signal characteristics. The statistics are obtained by measuring the error vectors.

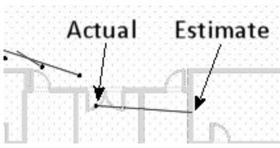


Figure 5.10: Error vector

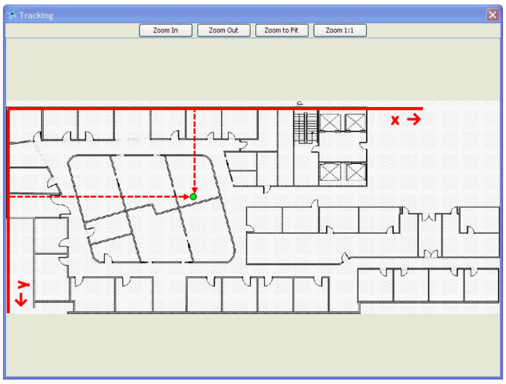


Figure 5.11: Position extraction from Ekahau location tracking window.

Static Indoor performance

During this test the laptop was not moved and the position was monitored for 20 minutes. The expected result is that the location is correct or only has a slight deviation from the actual

[5]Developed by Mauro Maiorca, masters student at University of Utrecht and University of Melbourne.

position. Ideally this deviation is small and constant. However it is expected that the position slightly varies because of the changing signal and noise levels due to changing interference from the environment, especially moving people and electronic equipment. Note that the building was surveyed during daytime and the test is also conducted during daytime.

Samples	3822
Average error	1.93 m
St.dev.	*0.51*
Minimal error	0.81 m
Maximal error	4.60 m
Within 1 m	0.92 %
Within 1.5 m	16.85 %
Within 2 m	62.76 %
Within 2.5 m	88.63 %
Within 3 m	96.75 %
More than 3 m	3.25 %

Table 5.4: Static WLAN results

These results show that the Ekahau WLAN positioning is accurate in static performance. Although the position was not once estimated without an error, all position measurements are within 4.5 metres (maximum error measured) of the actual position, and on average off by less than 2 metres. One reason of the constant error to the SSW can be the very short distance to one of the access points, causing to have one very strong signal.

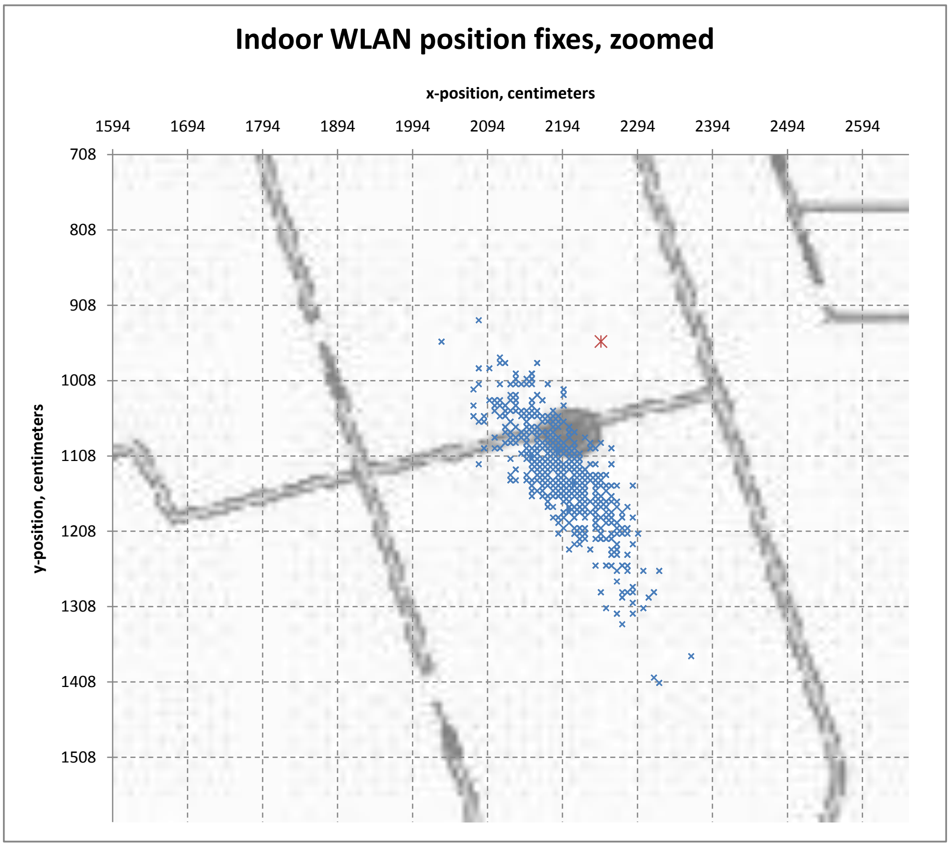


Figure 5.12: Detailed results of the WLAN static test. The grid line squares are 1 square metre. Red asterisk is the actual position, blue cross marks are measures positions. Note: the blue crosses do *not* indicate *how often* that position was measured.

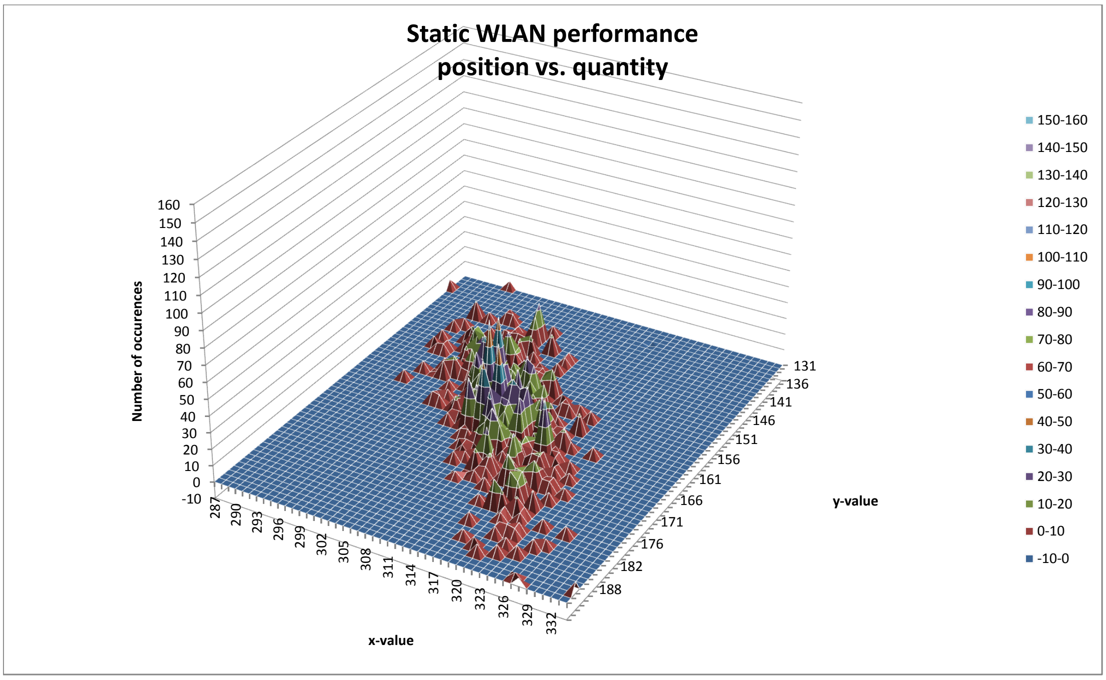


Figure 5.13: WLAN position measurements and number of occurrences.
Note: this graph uses pixels as units instead of centimetres (1 pixel equals 7 centimetres).

Moving indoor performance: Existing infrastructure

First the performance of Ekahau WLAN positioning engine was evaluated using the already existing WLAN infrastructure. The goal of this test is to evaluate performance without any adjustments to the infrastructure of the indoor environment (provided there is WLAN coverage). Signals from all WLAN access points of the MUWIRELESS network are used in positioning. This includes signals received from access points on other floors. Remember only two WLAN access points are available on the same floor. A sample set of 63 measurements was taken, walking at a normal steady pace. Figure 5.14 lists the results graphically and Table 5.5 shows the statistical evaluation of this test. The average positioning error is more than 10 metres, mostly directed to the core of the building. Almost 60% of the measured positions is within 8 metres of the actual position, but for the remaining 40% of the location estimates half has an error of more than 16 metres, with an error of more than 44 metres as maximum.

Samples	63
Average error	10.10 m
St.dev.	*9.63*
Minimal error	0.21 m
Maximal error	44.37 m
Within 1 m	3.13 %
Within 4 m	29.69 %
Within 8 m	59.38 %
Within 16 m	78.13 %
More than 16 m	20.31 %

Table 5.5: Existing infrastructure moving WLAN results

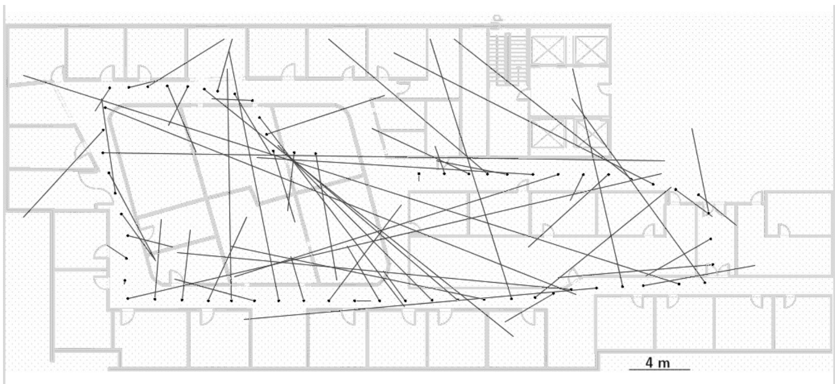


Figure 5.14: Existing infrastructure moving WLAN results

Moving indoor performance: 13 access points

This test evaluates the performance of Ekahau when the signals of 13 access points are being tracked and used for positioning. Thirteen access points for an area of roughly 1220 m^2 (52×23.5 m) is more than usually needed for WLAN coverage in a building. However, the expectation is to have very accurate positioning results, because at almost every location in the environment there is line-of-sight view of at least one access point. Figure 5.15 graphically shows the results of this test, whereas Table 5.6 shows the statistical analysis. Here the positioning estimate errors are on average 1.94 metres, not directed in a particular direction. Almost 60% of the estimates is within 2 metres of the actual position and even 95% is within 4 metres. The maximal measured error is less than 7 metres, far below the average error of the previous evaluation.

Samples	64
Average error	1.94 m
St.dev.	*1.06*
Minimal error	0.46 m
Maximal error	6.76 m
Within 1 m	23.44 %
Within 2 m	59.38 %
Within 3 m	84.38 %
Within 4 m	95.31 %
More than 4 m	4.69 %

Table 5.6: 'Benchmark' test, with all 13 AP's included.

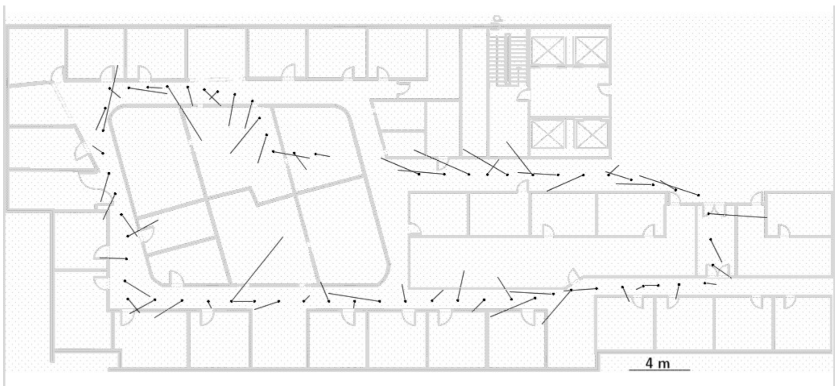


Figure 5.15: 'Benchmark' test, with all 13 AP's included.

Moving indoor performance: Four access points

Thirteen access points gave a satisfying performance. However combining the principles of triangulation and scene analysis, it is expected that using access points that are placed in corners (or on the edges) of the environment will provide a good infrastructure for WLAN positioning. To evaluate this expectation only signal information from access points w1, w6, w14 and w20 is used in the next test. Table 5.7 shows the statistical analysis of the results, Figure 5.16 the graphical representation. The average error of the position estimates is 2.65 metres, with a maximal measured error of 8.46 metres. The direction of the errors tends to follow the direction of the path walked. 45% of the estimates is within 2 metres of the actual location and 90% within 5 metres.

Samples	64
Average error	2.65 m
St.dev.	*1.54*
Minimal error	0.63 m
Maximal error	8.46 m
Within 1 m	9.38 %
Within 2 m	45.31 %
Within 3 m	75.00 %
Within 4 m	79.69 %
Within 5 m	89.06 %
More than 5 m	10.94 %

Table 5.7: Four access points at the edges (1, 6, 14, 20)

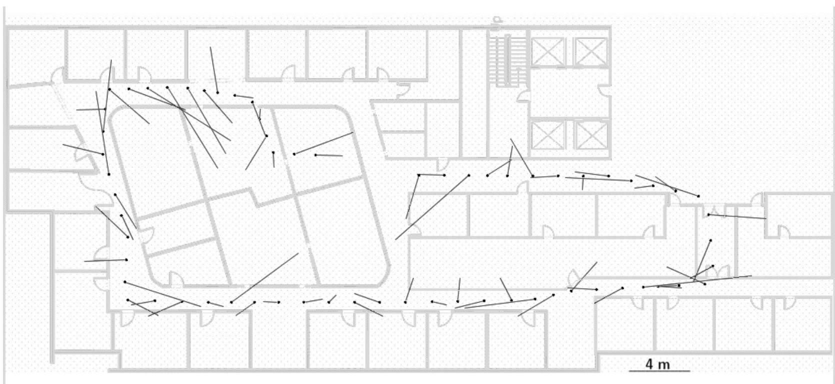


Figure 5.16: Four access points at the edges (1, 6, 14, 20).

Moving indoor performance: Five access points

Instead of only using signal information from access points on the edges of the environment, positioning may be enhanced by including signal information from an access point at a central location. To test this expectation only access points w2, w3, w6, w13 and w18 are used. The graphical results are shown in Figure 5.17, supported by the statistical analysis of Table 5.8.

Samples	64
Average error	2.52 m
St.dev.	*1.76*
Minimal error	0.29 m
Maximal error	9.17 m
Within 1 m	10.94 %
Within 2 m	51.56 %
Within 3 m	70.31 %
Within 4 m	79.69 %
Within 5 m	92.19 %
More than 5 m	7.81 %

Table 5.8: Five access points; at the edges and in the centre (2, 3, 6, 13, 18)

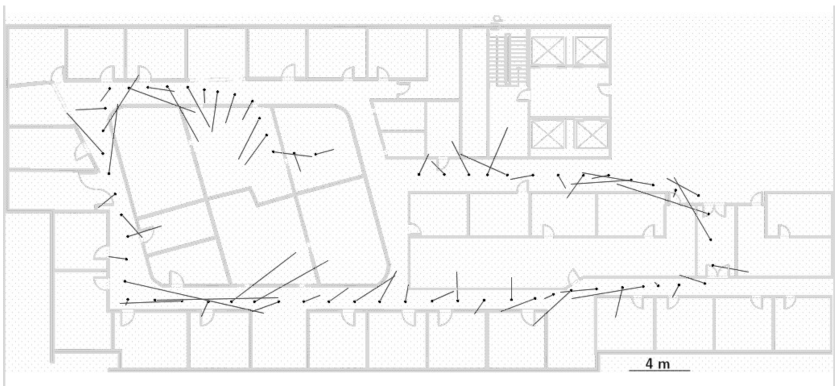


Figure 5.17: Five access points; at the edges and in the centre (2, 3, 6, 13, 18)

5.5 Summary

The experiments showed great variation in performance of the technology. To objectively evaluate the performance, several indicators are used. First the accuracy and precision of the technology is evaluated. Accuracy is measured as average error and standard deviation, precision is the amount of estimates that are within a certain interval. Second important aspect is the required infrastructure in the environment, including the scalability and costs of this infrastructure. Lastly the gear required by the user and the effort the user has to make to obtain a position estimate is evaluated. The combination of these factors determines if a technology can be used for indoor positioning. Also the claimed performance by the manufacturer and measured performance is evaluated.

5.5.1 Wireless LAN

Accuracy and precision

The accuracy and precision of WLAN varies, depending on the infrastructure and time spent to survey the environment. In the worst case scenario (using existing infrastructure) the accuracy was 10 metres with a standard deviation of 9.6. 78% of the estimates was within 16 metres. However, in the best case scenario the accuracy was 1.94 metres with a standard deviation of 1.06. Precision was high, 95% of the estimates was within 4 metres. Lastly the more realistic scenario's showed accuracy of 2.5 metres with standard deviation of 1.5–1.7 and a precision of 90% of the estimates within 5 metres. This last scenario shows that WLAN has an accuracy of 5 metres or better.

Infrastructure, scalability and costs

The infrastructure required by WLAN technology is easy to install and has low costs. WLAN access points do not have to be mounted exactly at a particular position, nor does the position of access points has to be known exactly. Once the access points are in place, the most effort is in surveying the environment. Although this can take considerable time, it is a one time effort that does not have to be repeated on a regular basis. Scalability of the system is high. If a new space is added to the building, only that space has to be equipped with access points and surveyed. Also if higher accuracy is needed in parts of the environment, adding an access point can solve this problem. But adding, removing or replacing access points does require re-calibration and consequently a new survey of the environment. Advantage of WLAN positioning is that the infrastructure can be used for another purpose: providing wireless network connectivity. Thus the infrastructure for positioning provides two services, dividing the infrastructure costs over this services. For good positioning it is however advised to use similar equipment at the client side (that measures the signals), because signal strengths and noise levels can be influenced by the antenna or chipset of the device. This imposes a limitation on the ease of adding new devices to the system.

User effort

The gear for WLAN positioning is small. A PDA with a wireless interface is sufficient, which is small, with little weight and easy to carry. No action by the user is required to obtain a position estimate, he does not have to point the device in a specific direction or align it with devices in the environment.

Overall

In general WLAN provides good accuracy indoors, the infrastructure is cheap and easy to install. There are some limitations on the types of devices that can be used on the client side, but these do not increase costs, only careful selection of the equipment has to be taken place. The technology is non-intrusive and requires little action and effort by the user.

The accuracy of 2-4 metres claimed by Ekahau was approached. With a few access points a very good resolution for indoor positioning using Ekahau can be established. The experiments showed that the performance using the existing infrastructure was much worse than the performance with the additional infrastructure. This is probably due to the fact that existing WLAN infrastructure is focused on optimal coverage with as less access points as possible. However a simple infrastructure with four access points already dramatically improved the accuracy. This could even be more improved by modelling the physical properties of the environment and take this into account in the position estimates.

5.5.2 Indoor GPS

Accuracy and precision

Indoor GPS proved to have a terrible accuracy indoors. The best case scenario in the static test showed an accuracy of almost 16 metres, with a precision of 62% of these estimates actually being within 16 metres (90% was within 32 metres). This test was conducted very close to a window, with sky view. The technology does not work when there is no sky view, as was proven by the experiment in the shopping centre. Consequently there is nothing that can be said about accuracy and precision indoors, other than that no estimates at all can be given. This makes the technology highly inaccurate.

Infrastructure, scalability and costs

Infrastructure required by indoor GPS is managed by the US Department of Defence. The use of GPS is free, so there are no installation costs of infrastructure in the environment. Drawback is that the infrastructure can not be enhanced or extended for a particular environment. The scalability of the system is unlimited, an unlimited amount of receivers could be added. The only costs imposed are the costs of the receivers.

User effort

The user effort to obtain a position estimate is low and the gear is small and easy to carry. While the evaluation receivers had to be connected to a computer, retail GPS receivers are of similar size as PDA's or mobile phones. It is expected that these receivers can be reduced to the same size. Possibly the antenna required to receive weak signals is bigger than with WLAN positioning.

Overall

These GPS evaluations show that it is not possible to use GPS for indoor positioning. In an office building the receiver did not work at all and in a simple shopping centre environment the performance was very poor. Also the static test shows that positions reported by the receivers are not necessarily correct. The tests show a continuous misplacement of the position and high error rates. The cause of all these performance issues is most likely the lack of sky view. We identified this already earlier as main problem for conventional GPS, but the problem persists also for indoor GPS. Concluding, indoor GPS performance is heavily depending on the environment. In general it is not very useful and less promising as expected. Sky view (either direct or indirect via windows) is needed. The claimed accuracy of 2.5 metres (both for the u-blox and SiRF receiver) can only be reached outdoors and certainly not indoors.

5.5.3 Combination of technology

Unfortunately it could not be verified if the combination of these two technologies creates an enhanced indoor positioning. Main reason is the complete failure of the indoor GPS technology in the environment. It was expected that indoor GPS would perform worse than WLAN positioning and that WLAN could be used to enhance the position estimated by the GPS device. However with no information at all, there is not much left to enhance.

WLAN positioning by itself proved to have a good accuracy. However, to be able to accurately estimate a position up to the level to a door entrance, the WLAN position technology has to be enhanced to overcome this 'last metre' problem. One other technology which can be used to improve the accuracy of WLAN is RFID. In the previous Chapter RFID was considered an expensive and infrastructure intensive technology. However RFID tags placed at strategic points can enhance the position estimate of the system. If, for example, at decision points in a building (a hallway crossing) accurate positioning is required, this can be provided locally by RFID by equipping only this area with RFID positioning. The installation costs of the RFID technology will be significantly lower than installing it in the entire environment. However, this will have impact on the gear the user carries, because it has to support both WLAN and RFID positioning.

This experiments and considerations make it clear, again, that the accuracy of an indoor positioning technology is highly influenced by the costs of the infrastructure for these technologies.

Chapter 6

Applicability of spatial structure

Having developed a spatial structure and having proved that indoor wireless technology can provide indoor position information, this Chapter provides a case of a wireless positioning system that uses the spatial structure. Does this spatial structure indeed prove the spatial awareness of humans with wireless positioning technology as underlying technology. The motivation for granular position descriptions becomes clear, as well as the limitations of the wireless positioning technology.

The spatial structure that is derived from an environment in the previous Chapter 3 can be used in various application. However it imposes requirements on the indoor positioning technology that is used. On the other hand the technology that is being used can also limit the functionality of the structure. With one (imaginary) applications the benefits of a spatial structure will be illustrated. At the same time the technology requirements from such applications will become clear.

6.1 Digital YAH for visually impaired

6.1.1 Application

A digital You-Are-Here (YAH) map is a replacement of the classic YAH map found in buildings, a map that describes your current position in relation to the environment you are in to support wayfinding decisions. The YAH map helps a user in understanding his location and supports his orientation. The YAH map transfers knowledge about the environment to the user. With this knowledge it is possible for a user to decide where to go next. A special case of the YAH map is the one that is used to represent the fastest way out of a building, the emergency YAH map. That special case is not considered here.

The digital YAH for visually impaired is a system that, on request of the user, gives a verbal description of the position where the user is at the moment. One one hand it requires the knowledge of it's current position and on the otehr hand it requires knowledge of the environment to give these kind of descriptions. A similar system can be developed for sighted persons, with a display displaying a map like image instead of just verbal descriptions.

Good classic YAH maps should conform to a set of guidelines (Klippel, Freksa & Winter 2006), most of these are useful for digital YAH maps as well. First criteria is *completeness*, all information that is necessary to complete a task (eg. navigate to another location, decide to go left or right) must be represented in the map. Secondly *(visual) clutter* should be minimized. To keep the map readable, the map must be easy to perceive and superfluous and irrelevant information should not be displayed. The next criteria is related to *semantic clarity*. The meaning of symbols should be clear, they must be non-ambiguous, consistent and clear signage must be used to avoid the necessity of a legend. Lastly the *correspondence* between map and environment must be clear. Information given in the map should correspondent to perceptible information, particularly through alignment with environment and picturing architectural cues. Guidelines for creator information and map placement are irrelevant for digital YAH maps.

6.1.2 Benefits of granular information

Probably the biggest challenge in describing environments is that the descriptions become cluttered because too much information is given. The possibility of describing a position at different levels of abstractions can prevent this clutter to occur. For example, suppose the position of the user is estimated with high accuracy (Figure 6.1(a)). Then the system knows the position of the user and can give a description of the position. Because the estimate is accurate, the system knows with high certainty where the user is and can describe the immediate position of the user in terms of functional elements (using the local view). For example 'Your current location is in the PhD office of Pedro' or 'Your current location is in PhD office 3.15b of Pedro', all being descriptions which strictly use information from the lowest layer (Figure 6.1(b)).

However in YAH maps also information related or close to the position in the environment are important. Suppose other functional elements that are close (defined to be within 7 metres) are also described. For example, 'Your current location is in PhD office 3.15b of Pedro, which is next to the office of Peter and next to the PhD office of Sylvia.' (Figure 6.1(c)). These descriptions at the lowest level give and accurate description of the environment. A user can map this information as shown in the figure. However, only giving information at this level of granularity will introduce clutter.

If a position and its surroundings are described by stating the 100 functional elements that are nearby, then the description becomes elaborate, unclear and cluttered with useless information.

Now the environment that is within 7 metres is described, suppose that this range is extended to 20 metres. But instead of describing the environment as functional elements, the first generalization is used: functional zones. Figure 6.1(d) shows the nearby functional zones. Now the description of the users position would become 'Your current location is in PhD office 3.15b of Pedro, which is next to the office of Peter and next to the PhD office of Sylvia. Within 20 metres also offices of supporting staff, dynamic fluids and laboratories of dynamic fluids are located.' Instead of using the description of the individual laboratories and offices, the first generalization is used.

Expanding the description even further, say to a range of 50 metres, descriptions of a higher layer are used; the destination zones. As Figure 6.1(e) shows, the description of the users position becomes 'Your current location is in PhD office 3.15b of Pedro, which is next to the office of Peter and next to the PhD office of Sylvia. Within 20 metres also offices of supporting staff, the dynamic fluids group and laboratories of the dynamic fluids group are located. Further down the hallway is the optical science group.'

Finally describing the general context of the position can be done by the highest level of granularity, from the perspective of the main tasks. As shown in Figure 6.1(f) the final description of the position of the user then could become 'Your current location is in PhD office 3.15b of Pedro, which is next to the office of Peter and next to the PhD office of Sylvia. Within 20 metres also offices of supporting staff, the dynamic fluids group and laboratories of the dynamic fluids group are located. Further down the hallway is the optical science group. In general you are in the workspace of the Physics department'.

The functional approach of the spatial structure does satisfy the completeness criteria for YAH maps. Because all locations that are necessary to complete a task are identified in the spatial structure as functional elements, it is possible to represent all information required to complete a task. Not all locations have to be represented as functional element, but can also be represented as a generalization.

The semantic clarity of these descriptions is also clear. Because grouping of functional elements in more general zones is done according to the same guidelines for every group, it is clear to a user what can be expected in these groups. At the same time functional grouping comes close to the users perception of the environment, thus increasing semantic clarity. However, a big part of the semantic clarity is reached by the description language itself and therefore not only related to the spatial structure. With the same information from Figure 6.1 a description like 'Your location is not in the Optical Sciences group, but in Pedro's PhD office' could be generated. However, this is obviously vague, but the spatial structure provides tools for generating semantically correct descriptions.

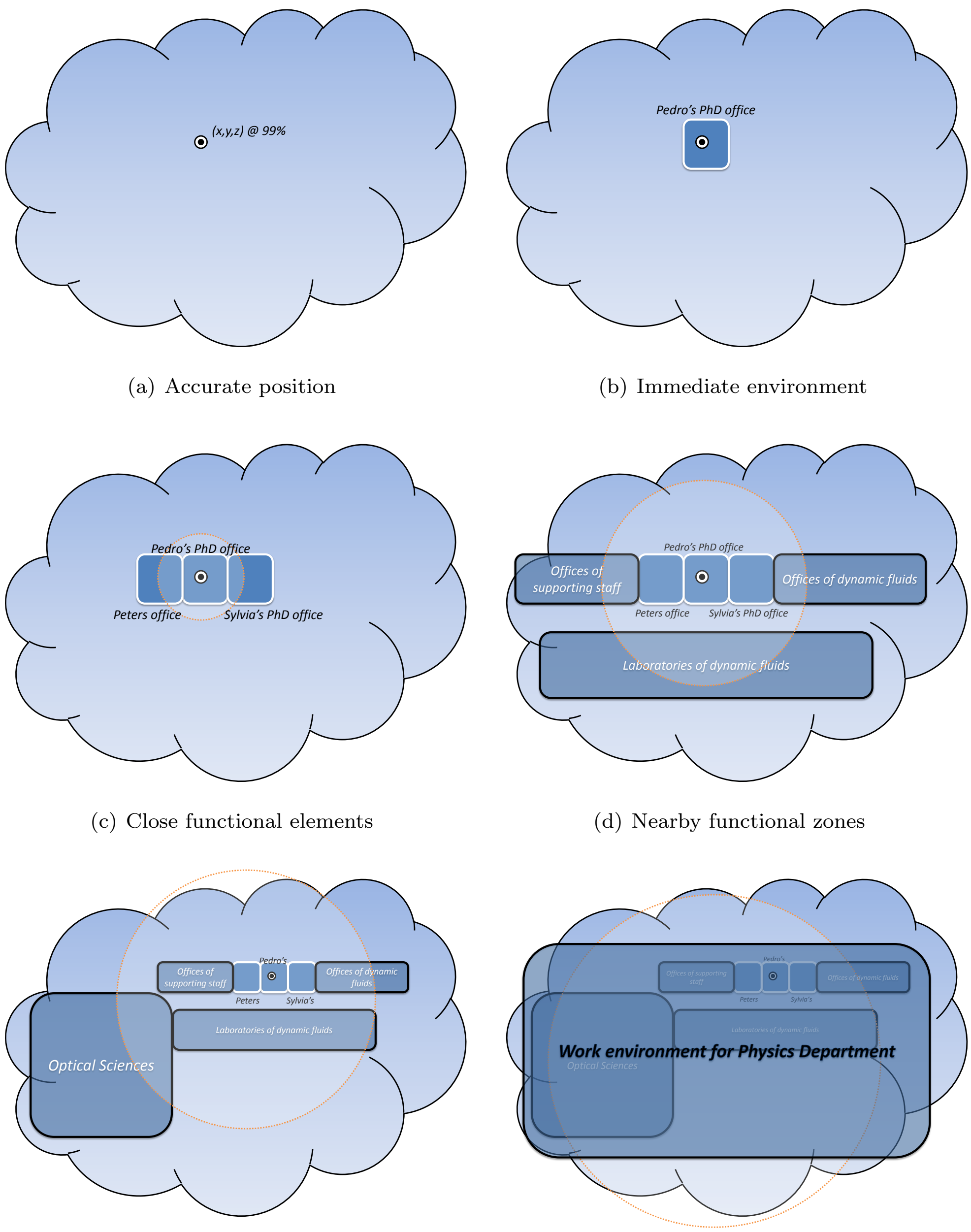
For correspondence between map, description and environment, the bearing of the user has to be known in addition to the position. Alignment of map and environment is very important in classic YAH maps. The spatial structure does not in itself provide information such as angles of directions between several functional elements or their generalizations. This depends on the implementation of the graph structure. Previously mentioned it is possible to store these kind of information in graph structures. Important aspect that is lacking in the spatial structure are architectural cues in the environment. Architectural cues are things like landmarks and distinctive objects in the environment that are important in wayfinding. Although not explicitly included or identified by the spatial structure, defined points in the environment can be defined as point of interest, which is then linked and included into the structure, based on the properties of neighbouring functional elements.

6.2 Technology considerations

The usability of the spatial structure depends on two aspects. First the accuracy of the positioning information and second on the availability (and accuracy) of the bearing of the user. With accurate positioning there is no uncertainty of the position of the user and bearings allow for relative directional information. It is obvious that when both are highly accurate the spatial structure can be used to it's full advantage, as described in the previous section. However, most indoor positioning system are not highly accurate and their accuracy is influenced by the infrastructure that is in place. Consequently indoor positioning systems can be highly accurate if there is an extensive infrastructure. For example if an environment is equipped with ultrasound sensors every 2 metres, the accuracy of the positioning technology is nearly perfect. However this extensive infrastructure comes at a cost, more equipment means more hardware, installation, configuration and maintenance costs. Therefore minimal requirements, particularly on the required accuracy, for the technology are drafted as a guideline.

Suppose the accuracy of a positioning technology is modelled by a circle. This circle surrounds the position estimate and has a radius of the accuracy. Consequently the circle represents the area where the user is (with a high confidence value). Say for example that a technology has an accuracy of 5 metres. Then the actual position of the user can be at any location within 5 metres; 5 metres (or less) to the left, right, front, back or any other direction. So the actual position is somewhere in a circle with 5 metre radius or, using the formula ($x = \pi \cdot r^2$) for calculating the surface area of circles, somewhere in an area of 79 square metres (this is a circle with diameter of 10 metres!).

Now, to be able to describe environments at the level of functional elements the positioning technology must be accurate enough to be able to estimate with certainty if a user is within one functional element or another. Consequently if the (average) physical size of functional elements



(a) Accurate position

(b) Immediate environment

(c) Close functional elements

(d) Nearby functional zones

(e) Further away; destination zones

(f) General: Task zone

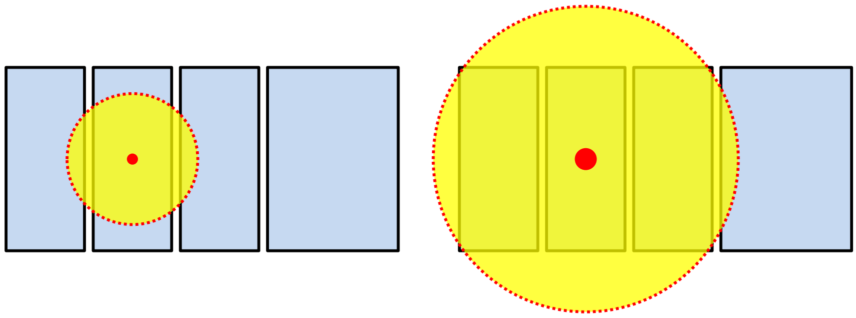
Figure 6.1: Different layers of granularity in the digital YAH map.

is big, the accuracy of the technology does not have to be high. Because functional elements are the smallest possible elements that are identified, it is sufficient to provide technology that is able to detect that the user is near on in the functional element. It is not required to know the position *within* the functional element. This observation suggest a relation between the (average) size of functional elements and the required accuracy of the technology.

Since accuracy of a position is measured by drawing a circle with a radius of this accuracy, this circle is the representation of the area of the user's actual position. To be able to accurately measure a position, the surface area of this circle must not cover a large part of other functional elements. Figure 6.2 shows the situation. Positioning technology in Figure 6.2(a) shows a position estimate with such an accuracy that there is high probability that the actual position in within the second functional element from the left. But the accuracy of the estimate in Figure 6.2(b) is too low. The probability that the actual position is within any of the small functional elements is equal. As such it cannot be determined in which functional element the actual position is and the positioning technology is too coarse.

Trying to get a more mathematical grip on this problem, we can use the mathematical formulas that define a circle. The surface area of a circle is $x = \pi \cdot r^2$ (and the circumference is $y = 2 \cdot \pi \cdot r$), where r is the accuracy of the positioning technology in metres. Suppose the average surface area of a functional element is 25 square metres (5×5), and assume that the ratio between length and width of the functional elements is not extremely biased. If there is a 1:1 relation between the accuracy and functional element size, let's calculate the radius of a circle with 25 m^2, which is $r = \sqrt{25/\pi} \approx 2.82$ metres. However, this means that only if the position estimate is in the centre of a functional element, the probability that the actual position is in this functional element is high. When the estimated position shifts to the edges of the functional element, the probability quickly decreases. Consequently if the position estimate is exactly on the edge of a functional element, the actual position can be away with a maximum distance of 2.82 metres. However, this distance (2.8) is 56% of the dimensions of the functional element (5.0).

If we decrease the radius of the circle by a factor C, the surface area decreases by a factor $2\dot{C}$. This implies that the accuracy of the positioning technology is better (a factor C better) and the chance of identifying a position within the correct functional element increases. The factor C is for most indoor wireless positioning technology a trade off between desired accuracy and costs. With an infinite sum of money, it is possible to create a perfect positioning system. We define C as a relative cost factor, so it is high when the accuracy is high (an most likely the costs as well). Resulting, as a guideline of accuracy $r = \frac{\sqrt{\chi/\pi}}{C}$ can be derived, where χ is the average surface area of a functional element and r is the accuracy of the technology in metres. In this case it becomes an optimization problem, rather than a mathematical problem. How much actually be spend to have optimal accuracy is up to the implementer. If this guideline for accuracy of the positioning technology is satisfied, then it is possible with the technology to describe environments at functional element level. Of course there is no 100% guarantuee that the position is correct, but at least there is a good chance of being right.



(a) Accuracy is good (b) Inaccuracy is too big

Figure 6.2: Positioning accuracy vs. Functional element size

6.2.1 High level descriptions with inaccurate positioning

Often a position estimated by a wireless technology has some inaccuracy. The previously introduced cost factor plays a big role in the magnitude of this inaccuracy, after the effect of the environment on the positioning accuracy. Some technologies, like GPS, also give an accuracy value with each estimate. This value represents the 'correctness' of the estimate. For example, if the accuracy value is 1, the positioning system is very sure of the position and if the value is 100, the estimate is not more than a 'best guess' among many other estimation candidates. Similarly the WLAN positioning technology we evaluated before can provide such accuracy values.

Now when it is known that an estimate is not accurate (or the positioning technology used is not accurate by nature) enough to identify a position within a functional element, we can choose not to describe the environment at the detailed level of layer one. If the accuracy of a position estimate spans an area covering many functional elements, then it cannot be determined with certainty in which functional element the user resides. Consequently, a detailed description of this environment cannot be given, because these descriptions have a close relation to an exact position.

However, if the accuracy of the position estimate spans over an area which is smaller or equal than a functional zone (basic layer two element) then it can be determined with considerable certainty in which functional zone the user resides. Consequently, descriptions that have the granularity of layer two (or higher) are still accurate for the position, even if the exact position is unknown.

Analogously if the position estimate is too inaccurate to determine the position of the user at a level of layer two, descriptions from layer three can be used and so on. This shows a very useful application of granular location descriptions, because indoor positioning technology can locally suffer from a increase in inaccuracy. Granular location descriptions then still allow for 'accurate' location descriptions. They do not leave the user without a clue of his location or render the positioning technology useless.

6.3 Benefits for visually impaired

Motivating goal for this research was the improvement of spatial awareness of indoor environment by visually impaired people with wireless technology. Previously the focus was not on visually impaired people and we only have literature research on visually impaired people. The intention at the start of this research was to have interviews or case studies with visually impaired people, to evaluate the research and get more insight in the needs of visually impaired people. Particularly, the potential effect of granular position descriptions on visually impaired people was of interest. However, due to unforeseen circumstances during the research it became clear that it would not be possible to conduct such case studies or interviews. The benefits for visually impaired people listed in this thesis are based on literature study and expectations derived from these studies.

First, visually impaired people will benefit because this is one of the first approaches to functionally describe environments at all. Previous attempts are often tailored turn-by-turn instruction systems, as described in Section 4.3. Instead of route knowledge, this allows a visually impaired person to acquire survey knowledge more easy, with relations between functional elements that are more clear, because of the way they are grouped together into bigger zones. Increasing both types of knowledge enhances the spatial awareness and wayfinding efficiency of people in environments.

Second, regardless of the position of the user, the model can be used to describe the contents of the indoor environment. By describing the environment at layer four or three the user can get an idea of the main functions of the environment and its contents. This is useful for the initial orientation in the environment.

Chapter 7

Conclusions

This thesis outlined that indoor wayfinding is a twofold problem, on one hand the technology used to estimate a users position has its limitations. On the other hand a way to describe this estimated position as a location in the environment provides a challenge. Both parts of this problem have been addressed and discussion points have been raised. This Chapter concludes the research and evaluates the indoor wayfinding problem in the context of the previously formulated research questions.

7.1 Spatial structure

How can the spatial properties of an indoor environment be organized into a usable structure for indoor location descriptions?

First aspect of this research question was the identification of elements in an indoor environment. For creating a functional description of the environment, functional elements are identified instead of physical elements (Chapter 3). Breaking down user behaviour in the environment reveals destinations and functional elements in the environment. Properties are then mapped onto each instance of a functional element, allowing for generalizations of the environment. Based on the organizational structure and the functional design, the environment can be divided into different zones, addressing the second aspect: structuring the elements of an indoor environment. These zones span over smaller and larger physical spaces, allowing descriptions of the environment at different levels of granularity. Eventually a hierarchical-like structure can be defined for the functional elements of the environment. In this structure all functional elements are defined, as well as more general concepts for describing any space in the environment.

Identifying the functional elements by analysing user behaviour introduces the risk of getting a biased view of the environment, especially when this analysis is done from the perspective of a specific user group or when user groups are not included in the analysis. This is both an advantage and a disadvantage of the approach. A benefit is that this approach structures the functions in the environment like this user perceives it. Drawback is the possibility of not covering all spaces (and having 'black spots') of the environment, particularly the spaces that are not of interest to the users included in the analysis. However, this does not implicate that analyses done without including all user groups are incorrect or impossible to use. As long as the target user groups are included, the obtained structure will still be valuable and useable, because all functionality required by these users is available in the structure. As such it will not give a complete view of the environment (not all areas will be covered), but it will give a view of the environment as the target user group perceives it.

Having organized the environment in a functional structure, generating descriptions at various levels of granularity becomes easier. Moreover the guidelines for generalizing the environment prevents the use of ad hoc generalizations, which are often used until now. A structured way to generalize an environment opens up the possibility of creating granular route descriptions or granular place descriptions that are proven valuable to enhance a humans understanding of the environment.

The developed structure does not provide room for vertical groups in indoor environments, that is the generalization of a part of the environment spanning over multiple floors. This is an issue to look into in the future and a difficult problem, because of the lack of interconnection between these functional elements. Often relatively long paths have to be travelled to get a vertical movement of several metres (via stairs or elevators). Consequently the relation between the functional elements at different floors is harder to detect.

Another issue is the effort required to analyse a building and create a structure. Considerable effort has to be made to correctly analyse an environment from a functional perspective. There is a set of minimal functional elements that can be defined for each type of building. However, each building is different and the functional elements may differ from environment to environment. Therefore the user analysis has to be repeated for each environment, although parts from previous analysis can be reused. Automatic creation of a functional structure from, for example, digital maps always requires user input, especially for defining properties. The time and effort required to create a structure could be an obstacle to efficiently deploy systems that use this structure, because of the labour costs to create it.

Concluding this structure provides a powerful framework for functional environment descriptions, but as discussed above there is still room for improvement. It provides a way to identify functional elements and structure these elements, thus structuring the indoor environment. Using this structure an environment can be described in a functional way. Moreover granular descriptions can be given from a position in an indoor environment. It opens the possibility to describe indoor environments in a general way and at the same time allows for detailed environment descriptions. This structure provides a structured approach to define and describe a place.

7.2 Technology

Which (characteristics of) wireless technologies are useful for indoor positioning and in what respect?

Experiments in Chapter 5 showed that with low cost equipment, the correct infrastructure and configuration an accuracy of 4 metres or better can be obtained with WLAN. On the other hand experiments showed that indoor GPS receivers, without adding infrastructure in the environment, are clearly not capable of reliable position estimation in indoor environments. Literature study and hands-on experience with other technology shows that the WLAN accuracy can be improved with additional technology when needed. In case a position estimate with high accuracy (within centimetres) is required RFID technology can be used to achieve this accuracy. However, this has implications on the infrastructure that is required for the positioning system to operate. Alternatively when orientation information is required, inertial sensors that sense direction can be used. These sensors require little infrastructure adjustments, but have an implication on the gear and processing power required by the user to carry with him.

Concluding, the most important characteristic of the wireless indoor positioning technology is a combination of the accuracy, the gear that must be carried and the required infrastructure. WLAN proves to be accurate up to several metres, has low requirements for the gear a user must carry and is easy in setting up infrastructure. Indoor GPS proves to be worthless inside buildings in terms of accuracy, has less infrastructure requirements than WLAN and the same kind of gear must be carried by the user. But bottom line, it is too inaccurate for indoor positioning. RFID requires more infrastructure than WLAN, the gear is similar, but the accuracy is much higher. However the effort to obtain a position estimate is also higher.

Can a combination of these technologies improve the performance of an indoor positioning system?

The (in)accuracy of WLAN positioning will not be a problem for sighted persons. They will be able to identify their position with the visual cues from the environment, even if a slightly incorrect description of the position is given. However for visually impaired persons this ‘last metres’ problem is a serious issue. Essentially this problem can be seen as a positioning problem in a very limited domain: within an area of 4 metres. To overcome this problem one can follow two approaches: First, improve the entire positioning system accuracy or second, implement a local positioning system using different technology . Advantage of the first approach is that it does not require the deployment of another positioning system, but probably it requires much more infrastructure for a relatively small improvement (as observed in the experiments with 13 access points and 4 access points). The second approach does require additional technology to be deployed, but provides a better resolution. Additionally this technology does not have to be installed in the entire environment, but only at positions where it is needed. Furthermore the technology is only needed to identify functional elements or access to functional elements, typically to identify doors. A candidate to provide this type of information is RFID technology.

Concluding that it is possible to provide indoor positioning with wireless technology. WLAN technology by means of the Ekahau positioning solution provides accuracy that is satisfying for indoor positioning.

7.3 Overall

How does an indoor wayfinding system provide useful information to visually impaired users?

Research has showed that in wayfinding performance sighted persons require the same information as visually impaired persons. In respect to the spatial awareness of visually impaired additional physical information about the environment has to be provided. Whereas for sighted persons it might be enhough to say 'the door is at your right', for visually impaired the absolute distance to that door is also valuable 'the door is 6 metres away, at your right'. This kind of physical information is typically not available in the functional structure of the environment. Therefore this structure mainly enhances classic turn-by-turn instruction systems, instead of replacing such systems. An actual guidance system will consist of many components, as laid out by Abowd, Atkeson, Hong, Long, Kooper & Pinkerton (1997), not just a positioning device and a translator that gives a nice description of this position. Especially for visually impaired users, possibly the user group that can have the greatest benefits of indoor navigation systems, the user interface is of utmost importance.

Lastly implementation of the indoor spatial structure and integration with a wireless indoor positioning system provides challenges. Implementation of the structure as a set of nodes and edges (as a graph) is an obvious choice and an already proven way of representing information for wayfinding purposes. However, the link between different layers of granularity and the decision at which level of granularity a point must be described will be a major challenge. The uncertainty of a position estimate will be the key decision factor, but cannot always be determined. However, Ekahau does provide some kind of quality filtering, but this functionality could not be evaluated due to license restrictions.

How can wireless indoor positioning technology improve the spatial awareness of humans in an an indoor environment?

The answer this question is twofold. First this wireless positioning technology must be accurate enough to provide good position estimates. Second, this position must be translated into human understandable language that describes the location. Even more, these descriptions must be structured in such a way that the spatial awareness that the user has of the environment increases. The literature study found that descriptions at different levels of granularity enhance the human understanding of the environment. With information about the environment structured in a way as described in this thesis it is possible to create these granular descriptions. Moreover this structure not just based on the physical structure of the environment, but on the functional aspect of indoor environments. With providing functional information at different levels of granularity, it is expected that the awareness of an environment that a user has will increase.

7.4 Future work

Already touched in this Chapter, main part of future work will be the implementation of a system that uses the structure presented in Chapter 3. Only then discussion points raised regarding the reusability and effort to create this structure can be evaluated. Major challenge for the implementation will be the representation of each layer as a graph and linking these layers together to provide an experience described in Chapter 3, with integrated descriptions of a location using information from the various layers of abstraction.

Combining more than one positioning technology into an usable integrated positioning system which provides high accuracy is also work that has to be done in the future. Although several researchers have tried to combine technologies, nobody has looked yet at the problem of providing highly accurate positioning at certain locations in an environment to overcome the 'last metre' problem. Highly accurate positioning is only needed during the final part of navigation.

If indoor positioning technology, combined with a structured way to functionally describe environment, really enhances the spatial awareness of humans has yet to be proven. Based on the literature it is expected that it will increase the awareness of the environment. With this increased spatial awareness of the indoor environment smarter turn-by-turn indoor navigation systems can be developed, as well as digital You-are-here map applications, that can be of great benefit to visually impaired people. This thesis has given an instrument to functionally describe environments and has proven that the technology for indoor positioning is currently available and mature.

Bibliography

Abowd, G. D., Atkeson, C. G., Hong, J., Long, S., Kooper, R. & Pinkerton, M. (1997), 'Cyberguide: A mobile context-aware tour guide', *Wireless Networks* **3**(5), 421–433.

Alexander, C., Ishikawa, S., Silversein, M., Jacobson, M., Fiksdahl-King, I. & Angel, S. (1977), *A Pattern Language: Towns, Buildings, Construction*, Oxford University Press, New York.

Apple Inc. (2008), 'iPhone 3G on Sale Tomorrow'. Press release, published: 10 July 2008; Online: `http://www.apple.com/pr/library/2008/07/10iphone.html`; Last accessed: 22 July 2008.

Arthur, P. & Passini, R. (1992), *Wayfinding: People, Signs, and Architecture*, McGraw-Hill Book Company, New York.

Associated Press Financial Wire (2007), 'TomTom says 1st-quarter profit rose 42 percent on increased market share', Newswire article from Associated Press Financial Wire. Published: 26 April 2007.

Bahl, P. & Padmanabhan, V. N. (2000), 'RADAR: An In-Building RF-based User Location and Tracking System', *INFOCOM 2000. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE* **2**, 775–784.

Bluetooth SIG (2007), 'The Official Bluetooth Technology Info Site'. Online: `http://www.bluetooth.org`; Last accessed: 18 September 2007.

Chen, G. & Kotz, D. (2000), A survey of Context-Aware Mobile Computing Research, Technical Report TR2000-381, Dartmouth College, Hanover.

Crandall, W., Bentzen, B. L., Meyers, L. & Brabyn, J. (2001), 'New orientation and accessibility option for persons with visual impairment: Transportation applications for remote infrared audible signage', *Clinical and Experimental Optometry* **84**(3), 120–131.

CTIT (2003), 'Europe's largest WLAN hotspot in Twente', Press Release. Online: `http://www.ctit.utwente.nl/news/archive/2003/jul03/wlan.doc/`; Last accessed: 2 October 2007.

Denham, J., Leventhal, J. & McComas, H. (2004), 'Getting from Point A to Point B: A Review of Two GPS Systems', *AFB AccessWorld* **5**(6). `http://www.afb.org/afbpress/pub.asp?DocID=aw050605` Last accessed: 12 June 2007.

Ekahau, Inc. (2007), 'Ekahau Real-Time Location System'. `http://www.ekahau.com/`. Last accessed: 3 September 2007.

El-Rabbany, A. (2002), *Introduction to GPS: The Global Positioning System*, Artech House.

Franz, G., Mallot, H. & Wiener, J. (2005), 'Graph-based models of space in architecture and cognitive science-a comparative analysis', *Proceedings of the 17th International Conference on Systems Research, Informatics and Cybernetics (InterSymp '2005), Architecture, Engineering and Construction of Built Environments* pp. 30–38.

Freedom Scientific (2007), 'StreetTalk GPS Solution'. `http://www.freedomscientific.com/fs_products/StreetTalk_info.asp`. Last accessed: 5 June 2007.

Golledge, R. G., Marston, J. R., Loomis, J. M. & Klatzky, R. L. (2004), 'Stated Preferences for Components of a Personal Guidance System for Nonvisual Navigation', *Journal of Visual Impairment & Blindness* **98**(3), 135–147.

Hallberg, J., Nilsson, M. & Synnes, K. (2003), Positioning with Bluetooth, *in* 'Telecommunications, 2003. ICT 2003. 10th International Conference on', Vol. 2, pp. 954–958 vol.2.

Harter, A., Hopper, A., Steggles, P., Ward, A. & Webster, P. (2002), 'The Anatomy of a Context-Aware Application', *Wireless Networks* **8**(2), 187–197.

Hightower, J. & Borriello, G. (2001), 'Location systems for ubiquitous computing', *Computer* **34**(8), 57–66.

Hillier, B. (1996), *Space is the machine: A configurational theory of architecture*, Cambridge University Press, Cambridge.

Hillier, B. (n.d.), 'The Common Language of Space: A way of looking at the social, economic and environmental functioning of cities on a common basis'. Online: `http://www.spacesyntax.org/publications/commonlang.html`; Last accessed: 10 September 2007.

Hölscher, C., Meilinger, T., Vrachliotis, G., Brösamle, M. & Knauff, M. (2004), 'Finding the Way Inside: Linking Architectural Design Analysis and Cognitive Processes', *Spatial Cognition IV-Reasoning, Action, Interaction. International Conference Spatial Cognition* **3343**, 1–23.

Humanware (2007*a*), 'BrailleNote GPS'. Online: `http://www.humanware.ca/web/en/p_DA_BrailleGPS.asp`. Last accessed: 12 June 2007.

Humanware (2007*b*), 'Trekker 3.0'. `http://www.humanware.ca/web/en/Trekker3.asp`. Last accessed: 31-May-2007.

Kitchin, R. M., Blades, M. & Golledge, R. G. (1997), 'Understanding spatial concepts at the geographic scale without the use of vision', *Progress in Human Geography* **21**(2), 225–242.

Klippel, A., Freksa, C. & Winter, S. (2006), 'You-Are-Here Maps in Emergencies — The Danger of Getting Lost', *Journal of Spatial Science* **51**(1), 117–131.

Kuipers, B. (2000), 'The Spatial Semantic Hierarchy', *Artificial Intelligence* **119**(1-2), 191–233.

Kulyukin, V., Gharpure, C., Sute, P., De Graw., N. & Nicholson, J. (2004), A Robotic Wayfinding System for the Visually Impaired, *in* 'To appear in Proceedings of the Sixteenth Innovative Applicationsof Artificial Intelligence Conference (IAAI-04)'.

Liu, H., Darabi, H., Banerjee, P. & Liu, J. (2007), 'Survey of Wireless Indoor Positioning Techniques and Systems', *Systems, Man and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on* **37**(6), 1067–1080.

Loomis, J. M., Klatzky, R. & Golledge, R. (2001), 'Navigating without Vision: Basic and Applied Research', *Optometry and vision science* **78**(5), 282–289.

Loomis, J. M., Klatzky, R. L., Golledge, R. G. & Philbeck, J. W. (1999), Human Navigation by Path Integration, *in* R. G. Golledge, ed., 'Wayfinding Behaviour: Cognitive Mapping and Other Spatial Processes', Johns Hopkins University Press, Baltimore, pp. 125–151.

Lorenz, B. & Ohlbach, H. J. (2006), 'A Hybrid Model for Indoor Spatial Reasoning', *Proceedings of First International Workshop on Mobile Geospatial Augmented Reality, Banff, Alberta, Canada (29th–30th May 2006)* .

Lynch, K. (1960), *The Image of the City*, The Technology Press & Harvard University Press, Cambridge.

Marston, J. R., Loomis, J. M., Klatzky, R. L., Golledge, R. G. & Smith, E. L. (2006), 'Evaluation of spatial displays for navigation without sight', *ACM Trans. Appl. Percept.* **3**(2), 110–124.

McNamara, J. (2004), *GPS For Dummies*, Hungry Minds Inc.

Meilinger, T., Holscher, C., Büchner, S. J. & Brösamle, M. (2006), 'How Much Information Do You Need? Schematic Maps in Wayfinding and Self Localisation'.

NASA (2008), 'Infrared Waves'. Online: `http://science.hq.nasa.gov/kids/imagers/ems/infrared.html`; Last accessed: 2 July 2008.

National Geospatial-Intelligence Agency (1990), 'Datums, ellipsoids and grid reference systems', *Defence Mapping Agency Technical Manual: TM 8358.1* . Online: `http://earth-info.nga.mil/GandG/publications/tm8358.1/toc.html`.

NFB's Access Technology Staff (2006), 'GPS Technology for the Blind, A Product Evaluation', *Braille Monitor* **49**(2). Online: `http://www.nfb.org/Images/nfb/Publications/bm/bm06/bm0602/bm060206.htm`. Last accessed: 12 June 2007.

Nikkei Weekly (2007), 'Daily life rewritten with IT tools: Portable GPS devices set cyclists free from maps, spawn innovative games', Newspaper publication in The Nikkei Weekly (Japan). Published: 2 April 2007.

Nokia (2007), 'Nokia 6110 Navigator hits the road (map included)', Press Release. published: 12 February 2007; Online: `http://www.nokia.com/A4136001?newsid=1104217`.

Noordzij, M. L., Zuidhoek, S. & Postma, A. (2006), 'The influence of visual experience on the ability to form spatial mental models based on route and survey descriptions', *Cognition* **100**(2), 321–342. TY - JOUR.

Passini, R. (1992), *Wayfinding in architecture*, Van Nostrand Reinhold, New York. 2nd Edition.

Priyantha, N. B., Chakraborty, A. & Balakrishnan, H. (2000), 'The Cricket location-support system', *Mobile computing and networking, Proceedings of the 6th annual international conference on* pp. 32–42.

Ran, L., Helal, S. & Moore, S. (2004), Drishti: An Integrated Indoor/Outdoor Blind Navigation System and Service, *in* 'Proceedings of the 2nd IEEE Pervasive Computing Conference', Orlando, Florida.

Randell, C. & Muller, H. (2001), Low Cost Indoor Positioning System, *in* 'UbiComp '01: Proceedings of the 3rd international conference on Ubiquitous Computing', Springer-Verlag, London, UK.

Raubal, M. & Winter, S. (2002), 'Enriching Wayfinding Instructions with Local Landmarks', *Proceedings of the Second International Conference on Geographic Information Science* pp. 243–259.

Ross, D. (2004), 'Cyber Crumbs for successful aging with vision loss', *Pervasive Computing, IEEE* **3**(2), 30–35.

Ross, D. A., Lightman, A. & Henderson, V. L. (2005), Cyber Crumbs: An Indoor Orientation and Wayfinding Infrastructure, *in* 'Proceedings of RESNA.', Atlanta, GA, USA.

Sendero Group (2007), 'Sendero GPS v3.5'. `http://www.senderogroup.com/shopgps.htm`. Last accessed: 5 May 2007.

SiRF Technologies (2008), 'Market Overview - Handheld GPS'. `http://www.sirf.com/about_sirf/market_overview5.html`; Last accessed: 10 June 2008.

Thapa, K. & Case, S. (2003), An Indoor Positioning Service for Bluetooth Ad Hoc Networks, *in* 'MICS 2003 Conference', Duluth, MN.

Tjan, B. S., Beckmann, P. J., Roy, R., Giudice, N. & Legge, G. E. (2005), Digital Sign System for Indoor Wayfinding for the Visually Impaired, *in* 'Proceedings of the 2005 IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR'05)', Vol. 3 of *Workshops*, IEEE Computer Society, p. 30.

Tolman, E. (1948), 'Cognitive maps in rats and man', *Psychological Review* **55**, 189–208.

Tomko, M. & Winter, S. (2006), 'Recursive Construction of Granular Route Directions', *Journal of Spatial Science* **51**(1), 101–115.

USB Implementers Forum (2007), 'Certified Wireless USB'. Online: `http://www.usb.org/developers/wusb`; Last accessed: 18 September 2007.

Vetere, F., Nolan, M. & Raman, R. (2006), Distributed hide-and-seek, *in* 'Proceedings of the 20th conference of the computer-human interaction special interest group (CHISIG) of Australia on Computer-human interaction: design: activities, artefacts and environments.', ACM Press New York, NY, USA, pp. 325–328.

Want, R., Hopper, A., Falcão, V. & Gibbons, J. (1992), 'The Active Badge location system', *ACM Trans. Inf. Syst.* **10**(1), 91–102.

Wikipedia (2008), 'Ultrasound'. Online: `http://en.wikipedia.org/wiki/Ultrasound`; Last accessed: 7 July 2008.

Willis, S. & Helal, S. (2005), RFID Information Grid and Wearable Computing Solution to the Problem of Wayfinding for the Blind User in a Campus Environment, *in* 'Proceedings of the ninth annual IEEE International Symposium on Wearable Computers', Osaka, Japan.

Yeh, S.-y., Chang, K.-h., Wu, C.-i., Chu, H.-h. & Hsu, J. (2007), GETA sandals: a footstep location tracking system. In Press.

Zigbee Alliance (2007), 'The Zigbee Alliance Website'. Online: `http://www.zigbee.org/en/`; Last accessed: 18 September 2007.