Bachelor Thesis

SmartTabs - Design und Evaluation eines Systems für selbstangetriebene Displays

SmartTabs - Design and Evaluation of a System for Self-Actuated Displays

by
Leonard Krämer
Student ID 01/784596

at the

Universität Konstanz

Faculty of Sciences
Department of Computer and Information Science

1. Evaluated by Prof. Dr. Harald Reiterer
2. Evaluated by Jun.-Prof. Dr. Bela Gipp

Konstanz, 2016

Abstract

This work outlines the implementation of the SmartTab platform, a robot – tablet combination. SmartTabs aim to simplify concurrent handling of multiple tablets. SmartTabs can create multi-device-displays and adjust their position dynamically to multiple situations. SmartTabs also are a platform to evaluate interaction with self-actuated displays and their benefit to the user. In the second part of the work we conduct an experiment to evaluate the SmartTabs performance as a tool for dynamic peephole navigation. In the experiment we explored the question whether or not bodily movement leads to better performance in spatial navigation and memory tasks. We found no evidence for increased memory performance, but could confirm that the navigation performance is increased when users have to engage their whole body. We also discovered that the SmartTab is an appropriate tool for dynamic peephole exploration and increases the users comfort.

Abstract

Diese Arbeit beschreibt den Aufbau der SmartTab Plattform, einer Roboter – Tablet Kombination. SmartTabs zielen darauf ab die Handhabung mehrerer Tablets gleichzeitig zu erleichtern. SmartTabs können Multi-Device-Displays erstellen und ihre Position dynamisch an viele Situationen anpassen. SmartTabs sind außerdem eine Plattform um Interaktion zwischen Benutzern und selbstbewegten Displays zu erforschen und ihre Vorzüge aufzuzeigen. Im zweiten Teil dieser Arbeit führen wir ein Experiment durch um Leistung der SmartTabs bei dynamischer peephole Navigation zu evaluieren. In dem Experiment haben wir die Frage erforscht, ob körperliche Bewegung zu besseren Ergebnissen bei der räumlichen Gedächtnisfunktion führt. Wir haben keinen Beleg für erhöhte Gedächtnisleitung gefunden, konnten allerdings bestätigen, dass die Navigationsleistung durch einbinden des gesamten Körpers steigt. Außerdem haben wir entdeckt, dass das SmartTab ein geeignetes Werkzeug für dynamische peephole Navigation ist und den Komfort der Nutzer steigert.

Contents

Chapter 1

Introduction

> "It seems inevitable that robotics, embedded in our built environment, will support and augment everyday work, learning, healthcare, entertainment, and leisure activities." (Gross and Green 2012)

1.1 Motivation

Using robots to make life easier and to use them to carry out all tedious every day tasks has been a dream of mankind since their invention. Today most of our lives are centred around interacting with computers in different shapes and sizes, all with a different purpose. To use these computers to achieve our goals we often have to switch between devices, because telephone calls require the smartphone, writing documents requires a laptop and somehow tablets have become multi-purpose devices, often used for entertainment. Technologies like Handoff[1], Connichiwa (Schreiner and Rädle 2015) or HuddleLamp (Rädle, Jetter, Marquardt, et al. 2014) make it easy to connect multiple devices to use them as a unit. These connections increase the possibilities a user has without switching to a new device, by using the features of one device on another one, potentially increasing productivity. Also concepts have been developed that use the connected devices to create a combined, dynamic user interface. For example HuddleLamp and Connichiwa allow to create combined, tiled displays by putting several devices in a cluster. When a device is removed from the cluster it automatically changes its purpose to a contextually appropriate view. For example when removing one of the devices from a cluster showing a map it would act as a notepad or when removing one device from a cluster showing a video it will act as remote control.

> "If possible at all, the manual integration and configuration of devices is challenging for the users." - H.C. Jetter (Jetter and Reiterer 2013)

Applications like this have the potential to be very useful and create a natural way of interacting with device clusters. However when more and more devices enter the field, handling all of them becomes a tedious process. For example

[1] Apple Handoff - `https://www.apple.com/de/ios/whats-new/continuity/` - Online March 17, 2016

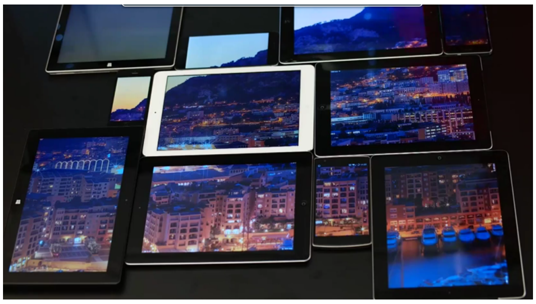

Figure 1.1: Many devices in complicated alignment form a connected display showing a dynamic high resolution image. Connected with Connichiwa. - Source: `https://youtu.be/FEzxv-CMsAs?t=1m44s`

aligning two tablets to a connected display takes only little time, but if four or more devices should be aligned to create a bigger surface (Fig. 1.1) it takes at least double the time. We figured that the solution to this problem is to equip the devices with the ability to move autonomously and automatically. This way the devices can find the perfect alignment by themselves and creating a large connected surface becomes as easy as flicking a finger.
Looking deeper into the matter revealed that self-actuated devices, especially displays, are not only useful when used in clusters, but that they already enable interesting usecases with just a single device. For example spatial peephole navigation can be hard when the data is very dense (Seifert et al. 2014), but becomes an easy task when using a robot to hold the peephole.
This work is about the design and evaluation of a system that tries to cover a wide variety of usecases by offering a flexible and extensible platform to develop applications for self-actuating devices.

> "Self-organization can be observed in many biological or natural systems and often leads to an almost magical and nearly optimal use of resources that is not result of an external ordering influence or a top-down design." - H.C. Jetter (Jetter and Reiterer 2013)

Chapter 2

Background and Related Work

This chapter highlights the works of different authors, which were the inspiration for this project.

2.1 Egocentric Peephole Navigation

> "Spatial memory is an important facet of human cognition – it allows users to learn the locations of items over time and retrieve them with little effort." – Joey Scarr (Scarr 2012)

Egocentric peephole navigation is a relatively new way to explore spatial data. It is enabled by the invention of portable computers like PDAs and later perfected on tablets.

Studies of dynamic-peephole-egocentric-navigation (Mueller et al. 2015) (Rädle, Jetter, Butscher, et al. 2013) have shown that this way of navigating large information spaces is superior to non-egocentric navigation concerning mental effort. Spindler *et al.*(Spindler and Schuessler 2014) found users can navigate data about 35% faster using a spatial navigation technique.

Spatial Memory One explanation why egocentric peephole navigation works so well is that it utilizes spatial memory. "Als rein räumliches Gedächtnis wird hier das Vermögen bezeichnet, sich örtliche Zusammenhänge einzuprägen, sich die Lage einzelner Objekte in ihrer Umgebung oder die räumliche Beziehung verschiedener Elemente zueinander zu merken." (Leifert 2013). This roughly translates to: Spatial memory is the ability to memorize local coherences, to remember the position of individual objects in their surroundings or to remember the local relationship of various objects to one another. The advantages of spatial memory are longevity (Czerwinski et al. 1999) and large capacity (Jiang et al. 2005).

The first techniques exploiting the spatial memory were developed by the ancient Greeks (Bower 1970) who tried to create an organized memory. The so called "method of loci". When using the method of loci things are memorized by linking them to a vivid mental picture and a sequence of locations. The locations must be well known and set in a known order, for example the locations the user encounters on his way to work. To recall the memorized things the user simply goes through the locations and at each location the memorized thought pops into his mind. Since the order of the sequence of locations is fixed also the order of the things remembered is fixed. The method of loci shows, that it makes sense to memorize things in a thing-location relation in the form of a mental picture. The second crucial factor to remembering when using the method of loci is that the user verbalizes the thing-location relation in his mind. Examinations of human brain activity while memorizing and recalling things using the method of loci have shown that the method of loci uses the part of the brain relevant for spatial memory (Maguire et al. 2003). The main limitation of the method of loci is that it does not perform well when the things to remember are not verbalized easily, like the different forms of snowflakes.

> "The longevity and success of the method of loci in particular may point to a natural human proclivity to use spatial context [...] as one of the most effective means to learn and recall information." (Maguire et al. 2003)

SmartTabs can use the spatial memory in two ways. The first effect is that the SmartTabs can facilitate recalling certain facts. For example the user can remember the position the SmartTab was in and therefore can remember what data has been shown. The other way is that the user sees the SmartTab driving to a certain position, recognizes the behaviour and therefore remembers. A different way to explore spatial data is to simply show everything at once in high resolution on a big (tiled) screen.

Müller *et al.* (Mueller et al. 2015) concluded that there is no difference in spacial memory performance whether the information is laid out vertically or horizontally. Despite the indifference for memory performance vertical navigation is perceived as more physically demanding than horizontal navigation while the perceived mental demand is lower for vertical navigation than for horizontal navigation. That the memory performance does not change despite that the physical demand changed leads to the hypothesis that the spacial memory performance of egocentric peephole navigation is independent from the actual physical movement of the user. Self-actuated displays have the natural characteristic that the physical demand for moving them is minimal. This makes them the ideal platform to test this hypothesis.

2.2 Tiled Display Systems

For a tiled display system multiple equal displays are set up next to each other to create a large display. One of the biggest challenges for tiled display systems is designing the system so that the display which often has over 100 mega-pixels can be supplied with dynamic content. Computer clusters, running special software (Krishnaprasad et al. 2004)(Johnson et al. 2012), are used to provide enough computational power for this demanding task. The biggest advantage of tiled displays is that much information can be shown at the same time to help the user understand big coherences. This characteristic can also be exploited with self adjusting devices aligning to form a tiled display. Even if the devices are arranged only loosely it often makes sense to form a group to appear as

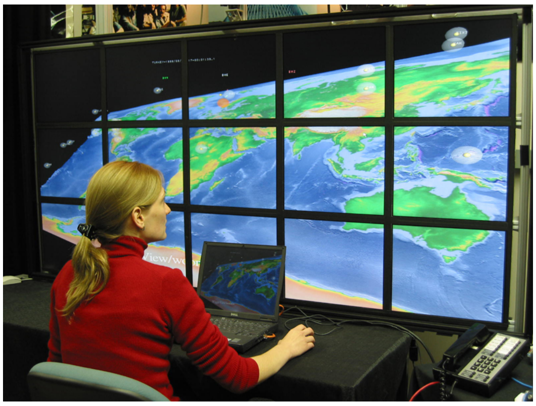

Figure 2.1: Tiled Display - Source: `https://www.evl.uic.edu/cavern/teravision/`

one big screen. It often is better to use every single device to display one part of the application, rather than creating one big screen. This way the spatial configuration of the devices can be used as additional input method or to display information in the most relevant way. For example display the controls near the user and the content that can not be manipulated on a device that is currently out of reach. This kind of applications is known as cross device applications.

2.3 Cross Device Applications

Handoff[1] by Apple demonstrates how useful and simple cross device applications can be. For example it allows to use the iPhones telephone functionality on a MacBook if the devices are in the same wireless network. Connichiwa (Schreiner and Rädle 2015) and HuddleLamp (Rädle, Jetter, Marquardt, et al. 2014) are two cross device web application frameworks. They focus on connecting tablets and smartphones to small clusters to display, transfer and manipulate data. This makes applications like a video player showing a video on the pooled display surface of all devices, or a painting software that uses one device as canvas and the other devices as paint pots possible. In order to function, HuddleLamp needs a unique setup with a RGB-D camera and a dedicated server to transfer data and to detect the devices on the camera picture. This makes integrating new devices incredibly easy since all it takes to add a new device to the 'huddle' is to navigate to the website and hold the device under the camera. In contrast to that Connichiwa uses one of the connected devices as server. This makes Connichiwa completely independent from additional hardware so that it can operate in remote places without internet connection. With an all overseeing camera HuddleLamp eliminates the need of additional sensors to enable position aware self adjusting devices. Since the devices are always tracked reliably and accurately by the camera, the self driving devices could be operated safely while keeping the devices simple and cheap. The use of web technology makes it possible to develop applications without being concerned about the underlying hardware, because web applications can be accessed from a wide variety of

[1]Apple Handoff - `https://www.apple.com/de/ios/whats-new/continuity/` - Online March 17, 2016

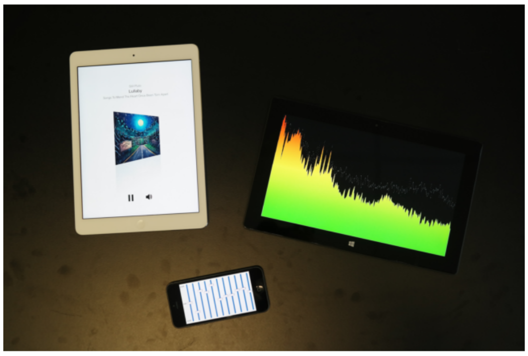

Figure 2.2: Cross Device Music Player with Connichiwa - Source: (Schreiner and Rädle 2015)

devices, namely every device that is able to run a suitable web browser. The combination of multiple self-adjusting devices and cross device web applications creates a powerful system. This system can change from a loose arrangement, where every device acts as one single part of an application, to a tiled display, offering a big connected surface when needed, in little time. The changing of positions offers the possibility to utilize the advantages of a loose arrangement of devices and a tiled display throughout the flow of an application.

In the context of a painting application that could mean that the devices offer flexibility in the creative phase of composing a picture and then seamlessly transition to a review phase where all devices together form a big screen. When the user is done reviewing the progress it is just as easy to resume to the creative process, because the devices are able to quickly resume their previous positions. The next section introduces systems that use moving elements and displays to interact with the users.

2.4 Self-Actuated Display Systems and Other Robots

Kinetic Sculptures (Fig. 2.3) are artistic installations that move. Some showcase a new kind of technology, but most exist just to be appealing and inspiring. While the first machines, for example from the famous artist Jean Tinguely[2], were mostly (electro-)mechanical, newer kinetic sculptures often use modern micro controllers to perform precise movements or other effects.
Kinetic Sculpture BMW[3] is a sculpture located in the BMW museum in Munich. It consists of a large array of spheres hanging from the ceiling on almost invisible thread. Over time the spheres move up and down and form different shapes. This way the threaded spheres form a large volumetric display where every single sphere represents a pixel. While most of the shapes appear random from time to time the sculpture shows recognizable images, like the silhouette of a BMW.

[2] Jean Tinguely - `https://en.wikipedia.org/w/index.php?title=Jean_Tinguely&oldid=687063127` - Online March 17, 2016

[3] Kinetic Sculpture BMW - `http://www.joachimsauter.com/en/work/bmwkinetic.html` - Online March 17, 2016

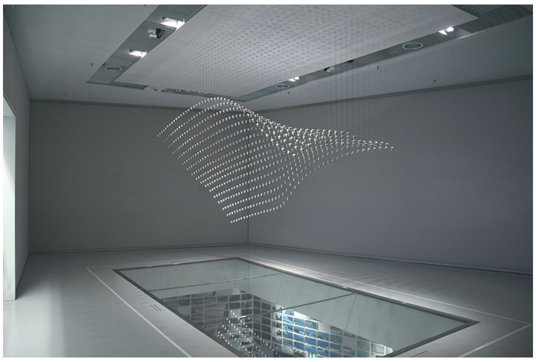

Figure 2.3: Kinetic Sculpture BMW - Source: http://www.joachimsauter.com/en/work/bmwkinetic.html

The ever changing shapes invite the observer to pause and study the graceful movement. The user is not intended to interact with the sculpture.

Aerial Tunes (Alrøe et al. 2012) (Fig. 2.4)on the other hand wants the user to interact with the sculpture. Aerial Tunes is an installation of fans and spheres. The light spheres are suspended in mid air by the fans creating a static upward airflow underneath each sphere. The oscillating movements of the spheres are measured and translated into a soundscape. The spheres can be lifted or lowered by hand to manipulate the sound. Aerial Tunes is special in the aspect that the state of the installation is both visual and audible at the same time.

Figure 2.4: Aerial Tunes - Source: http://interactiveinstallations-brodiet.blogspot.de/

Flyfire[4] (Fig. 2.5 and 2.6) by the SENSEable City Laboratory is a system of little drones carrying small RGB-LEDs. Together they form a self organizing volumetric display in mid air that can display digital information. Seen from afar the individual drones with their LEDs appear as one big screen. This big screen can ideally be used at large public places. Since the individual pixels can move Flyfire can display smooth transitions or create traces of light. Also the "display" is visible from all sides which lets it create different impressions, depending on the observers position. Although Flyfire only achieves decent resolutions when

[4] Flyfire website - http://senseable.mit.edu/flyfire - Online March 17, 2016

seen from afar the possibility of a flying 3-dimensional display in general is very inspiring.

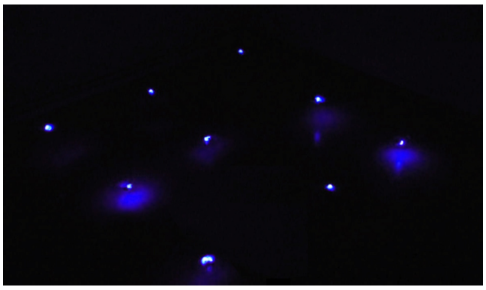

Figure 2.5: Flyfire drones in flight. Source: `http://portfolios.pratt.edu/gallery/1838375/Flyfire`

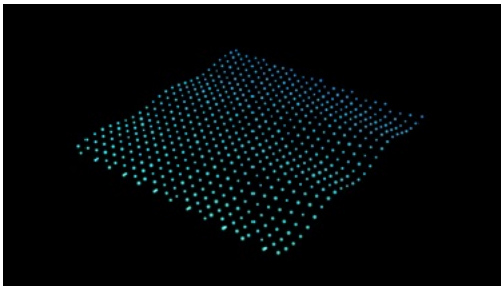

Figure 2.6: Flyfire Vision: many drones form a volumetric display - Source: `http://senseable.mit.edu/flyfire`

ZeroN by Jinha Lee *et al.* (Lee et al. 2011) (Fig. 2.7) is a system for "mid-air tangible interaction". This new way of interacting with tangibles is similar to tabletop tangible interaction, but extended to the space above the table. The main part of the system is contained in a box above the table. It contains a contraception resembling a plotter with a strong electro magnet and sensors attacked. While the plotter is in charge of horizontal movement, the magnet attracts a permanent magnet underneath. The electro magnet is controlled precisely to cancel out the gravitational force pulling the permanent magnet down, rendering it weightless. Not only is it possible to let the permanent magnet fly, but also the vertical position can be controlled. Additionally ZeroN has several beamers projecting pictures onto the scene. Cameras are used to track user input and the position of the permanent magnet, which is the centrepiece of the system. Lee *et al.* remark that the actual space that the system covers is very limited and that the magnet often oscillates around the stable position. Nevertheless the system is very impressive. Since the carrying capacity of ZeroN is limited to 100g the system would be able to carry a small OLED display and battery but it falls short when it comes to carrying a complete tablet. In his work Lee also describes interaction techniques and usecases which are relevant for SmartTabs.

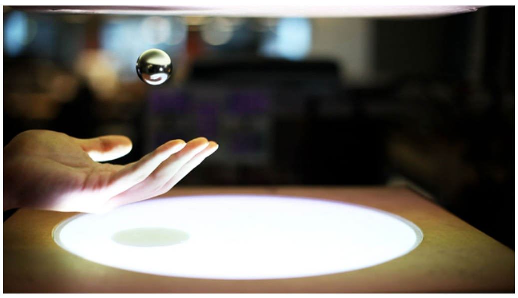

Figure 2.7: ZeroN - Source: `http://leejinha.com/ZeroN`

Figure 2.8: A BitDrone acts as a remote presence robot - Source: `https://www.youtube.com/watch?v=hHBYMWc3ux8`

BitDrones by Rubens *et al.* (Rubens et al. n.d.) (Fig. 2.8) takes the ideas of ZeroN and Flyfire and combines them to a functional system. To make the flying drones, with their fast spinning rotors, more approachable the rotors are kept in cages preventing collisions and harm. On the other hand Rubens *et al.* also use drones without a protective cage when the drone has to carry a larger weight which makes the drones less approachable but enables them to carry a high resolution display. The drones which do not feature a protective cage are not used for prolonged interaction but rather for precise inputs. The drones with a protective cage allow longer and more involved interaction, since the user is not at risk of harming himself. The drones with a protective cage can be used for visual and haptic building of 3D models and allow gestures like resizing or rotating the model through multi device gestures, where the user moves two BitDrones and the other drones follow the movement. Drones with a high resolution display are used as telepresence devices allowing free movement in the whole room for the remote user. While BitDrones presents new usecases for interacting with drones and other tangible-mid-air user interfaces it is strongly limited by the low weight the drones can support. This forces BitDrones to resort to a resolution of one, maybe few, pixel(s) per drone, if close and prolonged interaction is wanted. To overcome these limitations BitDrones will have to become smaller, so that every pixel takes up less space or the drones capacity for lifting weight must be increased, so that each drone is capable of carrying a high resolution display along with a protective cage. Both possibilities appear very hard to achieve. Also BitDrones are limited by the power of the battery they carry, which can be compensated by having multiple drones and cycling through them with some of them reloading and the others acting as a display.

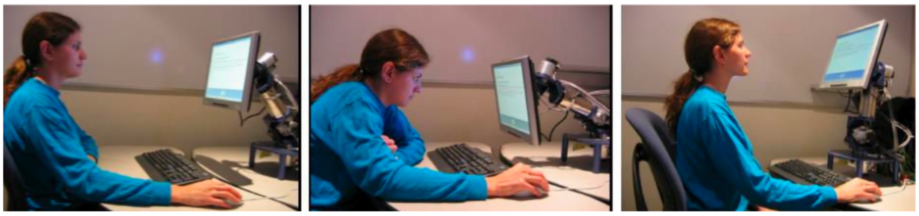

Figure 2.9: Roco mimics the users posture - Quelle: (Breazeal et al. 2007)

Figure 2.10: Animated Work Environment - Source: `http://workgroups.clemson.edu/AAH0503_ANIMATED_ARCH/research-AWE.html`

Roco by Cynthia Breazeal and Rosalind Picard[5] (Fig. 2.9) is a system where a display is mounted on a stationary robot arm. The system tracks the user with a camera and the robot mimics the users posture. It displays the advantages and disadvantages of a robot arm nicely. The arm is able to mimic the user fast and precisely, but the robot arms reach is very limited. Cynthia Breazeal *et al.*(Breazeal et al. 2007) conducted a study which indicates that the self-actuated display mimicking the users posture has positive effects on the users comfort and persistence.

Animated Work Environment (Green et al. 2005) (short AWE) by Green *et al.* combines digital technology with an actuated wall. The wall is able to take in predefined positions for specific tasks. When the user chooses from one of the predefined activities, like 'collaboration' or 'play', AWE will take in an appropriate position. Like Roco AWE interacts with the user by changing its position. This way it does not only provide the perfect work environment, but also does the arrangement of its elements influence the users mindset towards the specific task. AWE does not only adjust the alignments and positions of the displays but also of the other elements which can act as dividers. The classification of positions into tasks makes handling the AWE easier.

KUKA youBot[6] (Fig. 2.11) is an omnidirectional mobile robot platform with mecanum wheels and robot arm attachments. For autonomous operation it features an on-board PC and a powerful battery. The youBot has several

[5]ROCO website - `http://robotic.media.mit.edu/portfolio/roco-2/` - Online March 17, 2016

[6]KUKA youBot website - `http://www.youbot-store.com/youbots/youbots` - Online March 17, 2016

Figure 2.11: A youBot with a robot arm attachment - Source: `http://www.youbot-store.com/youbots/youbots`

attachments that reach from laser sensors over cameras to robot arms and fork lifts. The youBot is 580 mm long and 360 mm wide. It can carry up to 20 kg (Bischoff 2011). Multiple youBots were successfully used to assemble parts of an IKEA table in coordination with each other (Dogar et al. 2016).

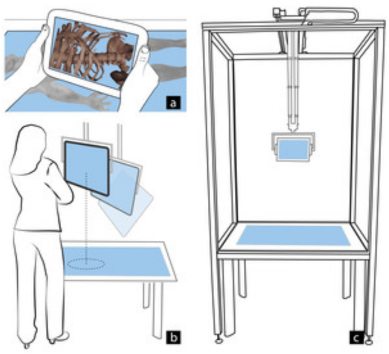

Figure 2.12: Hoverpad - Source: `http://www.uni-ulm.de/in/mi/mi-forschung/mi-forschung-rukzio/projects/hoverpad.html`

Hoverpad by Seifert *et al.* (Seifert et al. 2014) (Fig. 2.12) is a flexible system for exploring virtual information spaces in real space. It was developed to help handling digital peepholes in situations where the user is incapable of handling the peephole. These cases include tasks where the handling of the peephole has to be so exact that the trembling of the user becomes an issue. Also the system can offer greater reach than the users arms and the user does not fatigue from holding the tablet in place. Another advantage is that the peephole is capable of autonomous movement. This enables applications where the peephole navigates

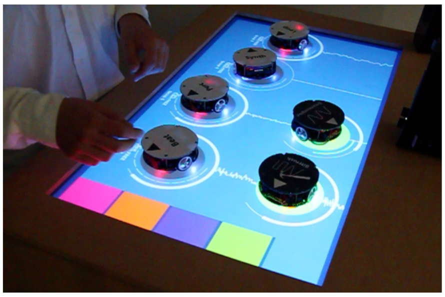

Figure 2.13: TangibleBots on top of a multitouch-table visualize a music mixer - Source: (Pedersen and Hornbæk 2011)

towards interesting points in the data on its own to simplify searching. Hoverpad is made of a large frame surrounding the whole active surface. On top of the frame a plotter-like contraception moves a telescopic arm. The telescopic arm extends downwards and can move up and down. At the end of the telescopic arm is the tablet mount, which has several motors which can adjust the yaw, pitch and roll of the tablet. With this setup Hoverpad is able to move the tablet in almost every position at almost every possible alignment inside of the metal frame. The sophisticated design also allows using the tablet from all sides. Additional to the tablet the Hoverpad also has an interactive table display with multitouch capabilities. The combination of the flat, stationary and the actuated display makes hybrid views like a 2D-3D combination where the table display shows a map and the tablet displays 3D models of buildings and topography shown on the map.

The tablet display can be controlled very precisely. It allows indirect manipulation of the tablets position through gestures or through controls displayed on the multitouch table as well as direct manipulation through buttons on the tablet mount. Seifert at al. created five demo applications showcasing the automatic movement, hands-free interaction and the visual stability of the system. In contrast to AWE Hoverpad does not aim to replace the traditional workspace, but it is intended to support certain specific tasks.

Tangible Bots (Pedersen and Hornbæk 2011) (Fig. 2.13) by Pedersen and Hornbæk are active and motorized tangibles for the use on a multitouch-table. The tangible bots can reflect changes in the digital model, provide haptic feedback and compensate errors. They can be manipulated either directly by hand or indirectly through controls on the multitouch-table or by using another tangible as control. Additionally it is possible to form groups of tangible bots which then can be controlled jointly by manipulating just one tangible bot and the others will follow the command uniformly. In two studies Pedersen and Hornbæk (Pedersen and Hornbæk 2011) have shown that changes of the tangibles rotations can be completed faster when the tangibles can be joined in groups and then rotated simultaneously than when the tangibles are not motorized and have to be moved by individually hand. Their results also indicate that the time saved increases with higher numbers of tangibles and also the tangibles speed.

Robot Soccer (Fig. 2.15)is the exiting realisation of the team sport football for mobile robots. [7]." The games are carried out in different classes of robots, which focus on different aspects of football. While the matches with wheeled robots focus on tactics and have fast paced games the main challenges in matches in the humanoid league[8] are tracking the ball and shooting in the intended direction. Since the humanoid robots are prone to tripping and falling over the general speed in this league is much slower.

> "By the middle of the 21st century, a team of fully autonomous humanoid robot soccer players shall win a soccer game, complying with the official rules of FIFA, against the winner of the most recent World Cup." – Motto of the RoboCup[9]

Figure 2.14: Humanoid robots play football
Source: http://www.ais.uni-bonn.de/robocup.de/news.html

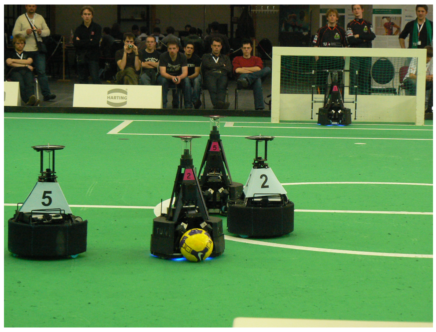

Figure 2.15: Wheeled robots playing football - Source: http://heise.de/-979934

As the motto of the RoboCup states the goal of robot football is as much winning against the other teams as pushing the state-of-the-art of robotics forward. Besides improving the software and algorithms the teams are encouraged to develop new, better hardware to gain an edge over their opponents. Superficially the main reason why the wheeled robots operate much faster than their legged counterparts is that they can not fall over, but at a close look more simplifications quickly reveal. Firstly, the holonomic drive lets the robots change directions quickly without the need to turn first. Secondly, the wheeled robots have omnidirectional cameras (to see at the winner of the Robocup 2010[10]) which offer a 360° view of the surroundings. Thirdly, some wheeled robots are allowed to use a centralized server for some processing. These three simplifications allow for the teams to concentrate on fast and effective tactics for offence and defence.

[7]Wikipedia: Roboterfußball - http://de.wikipedia.org/w/index.php?title=Roboterfußball&oldid=134662001 - Online March 17, 2016

[8]Humanoid League - http://wiki.robocup.org/index.php?title=Humanoid_League&oldid=3249 - Online March 17, 2016

[9]RoboCup: Objective - http://www.robocup.org/about-robocup/objective/ - Online March 17, 2016

[10]RoboCup German Open: Tech United gewinnt souverän das Middle-Size-Finale - http://heise.de/-980069 - Online March 17, 2016

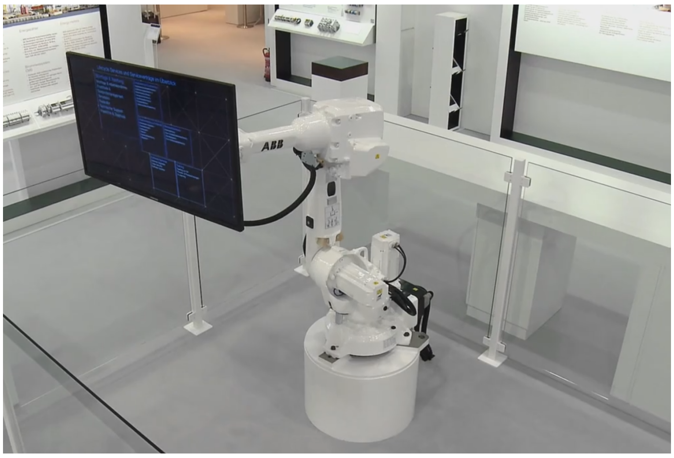

Figure 2.16: An industrial robot carries a large display. Source: Product video at: http://www.meso.net/ABB%20HMI13

Industrial Robots ABB Kinetic cube shaped displays[11] and ABB Service Exhibit[12] (Fig. 2.16)are installations by the MESO Digital Interiors GmbH. They display how fast and precise powerful industrial robots can move and how this can be used to move large displays freely. Unfortunately, the industrial robots are so powerful that they can seriously harm humans that stand in their way so that MESO's installations can only operate behind a fence, disallowing direct interaction with the system.

Tablebots[13] (Fig. 2.17) is a prototype of a system to make handling multiple tablets at the desktop less inconvenient. The prototype is made from LEGO and uses several cameras and AR markers to track the robots. The main interaction is carried out with identification cards which trigger autonomous movement of the robots, depending on the position of the card on the table. The system is able to detect how much display surface a user needs and automatically provides the correct number of displays. Every Tablebot is able to move autonomously and can also react to certain triggers. For example when a user is called via Skype a new Tablebot will approach and offer the opportunity to take the call without interrupting the workflow on the other devices. Alternatively the Tablebots can be controlled semi-automatically with the identification cards whose position and alignment the robots follow. This makes it possible that a user can change his position during a meeting by just taking a new seat and putting down his identification card. Direct manipulation also is supported. The robots register when they are moved and remember the new position. Additionally the robots can support the user at certain scenarios. One usecase is saving and recalling positions, such as the robots remember their positions when a user leaves and then later can recall the exact configuration for the user to pick up right where he left. The interaction techniques used with the Tablebots were created using

[11] ABB Kinetic cube shaped displays - http://www.meso.net/ABB-CubeDisplay - Online March 17, 2016

[12] ABB Service Exhibit - http://www.meso.net/ABB%20HMI13 - Online March 17, 2016

[13] Tablebot Video - https://www.youtube.com/watch?v=PRkuGkY3buE - Online March 17, 2016

Figure 2.17: Two Tablebots create a connected display

Blended Interaction (Jetter, Geyer, et al. 2012), a framework for interaction design that tries to leverage the interaction principles which are already in our heads. For SmartTabs this approach is expanded and refined. One of the main flaws in Tablebots is that the positioning of the Tablebots is not precise enough to create tight alignments of the displays. This is partly due to the kind of drive chosen and partly due to the tracking system's inaccuracy. In addition the tablets pitch on the Tablebots is fixed which limits the effective operating range of the Tablebots. At close proximity the tablet should lie flat on the robot, further away the tablet must be positioned more upright to provide the best viewing angle. Also touch interaction is most accurate when the users finger and the device form a right angle. The SmartTab has its roots in this project.

Chapter 3

The SmartTab

This chapter outlines the main idea behind the SmartTabs' creation and then gives a short overview over the SmartTabs development.
This chapter is a summary of the main development steps. For more details about building the SmartTab robot, the software design and the design decisions please see the project paper which is provided digitally with this work or contact leonard.kraemer@uni-konstanz.de to receive a free digital copy. The idea of the SmartTab is to enrich a standard tablet with the ability to change its position autonomously. This feature frees the user from the burden of rearranging his devices for different tasks and allows to use the same device, a high-definition touchscreen device, in different positions easily. This can be especially useful when using multiple tablets in a connected cross-device application where the spatial layout of the devices defines the functionality, like in the demo of HuddleLamp (Rädle, Jetter, Marquardt, et al. 2014). Apart from easing the users physical strain when rearranging his work environment the SmartTab also supports the user in other physically demanding tasks like holding the tablet still over a prolonged period of time when exploring high definition spatial data and searching in this type of data in a dynamic peephole setting. The word SmartTab is used for the conjunction of the SmartTab robot and a tablet.

3.1 Building the Robot

Building the actual SmartTab robot was a process that took about half a year and was divided into three main phases. The first step to building the robot was to elicit requirements the robot had to match, to guide the development in the desired direction. The second step was selecting a suitable hardware platform to create the prototype. The third step was to build the first prototypes and from that point on all changes were iterative improvements based on the experience with the prototypes. Throughout the process of building hardware prototypes the SmartTab robots firmware and the software for the tablets was created and improved.

3.1.1 Requirements

The requirements (see table 3.1) are based on usecases derived from the related work on cross-device applications and moving displays, for a system operating in a tabletop environment, supporting the user in everyday tasks (see 5). "Usability" means that the robot should not look intimidating or fragile in any way, so that the user does not fear interacting with the robot in a direct way, like pushing it away. This facilitates close range interaction and is necessary if the robot and the user want to coexist on the same desk. "Usability" in this case is not used in the meaning commonly used in HCI[1], which would be an aggregated value of all these characteristics, combined with characteristics from the specific application the SmartTab runs, but rather in an ergonomic sense. "Accuracy" is a very necessary attribute that, on the one hand ensures the safe operation of the robot, for example it does not fall off the table or bump into the user accidentally. On the other hand high accuracy also opens up new usecases like exploring high density spatial data (see 5). "Speed" is a variable that should be as high as possible, but also not exceed an upper bound, because high speeds are unsafe and can also frighten the user. "Stiffness" is a crucial feature for the look and feel of the SmartTab. To be able to compete with traditional displays for the space on the desk it is clear that the footprint of the SmartTab should be reduced so that it only takes up the absolute minimal "Space" possible while maximising the display surface. "Extensibility" must be given to account for the smaller displays, compared to regular monitors. Reducing the "Sound"-level of the SmartTab facilitates the use in quiet environments like offices. The system should also feature "Mobility" to easily transfer it to an new place and to ensure that the system works in different environments. "Adaptability" and "Cost" are two characteristics that mostly matter in the context of prototyping the system fast and applying it to different usecases easily to explore possible applications with low effort. The tabular 3.1 lists all requirements and what the SmartTab must achieve to meet the requirement.

3.1.2 Building the Robot

The chosen hardware platform is the LEGO NXT platform, which was chosen, because it is created to be sturdy, easy to integrate and features a wide variety of different motors, sensors and other attachments. Also the LEGO NXT brick, which is the heart of the SmartTab robot, can be programmed in different programming languages. The robot was developed using multiple prototypes, the first ones were made from LEGO and then refined with the help of Sven Schöller of the "Wissenschafftliche Werkstätten" of the university of constance. The first three prototypes explored two different types of holonomic drive (mecanum wheels and omni-wheels) and the lifting arm. Then the heart of the robot, namely the NXT and the motors, was modelled in Autodesk to model an aluminium frame that would provide the necessary stability to support the weight of the robot and a tablet. Also the aluminium frame takes up much less space than the LEGO structure needed to support the weight.

[1]Human Computer Interaction

Table 3.1: The initial requirements for the SmartTab

Usability	There should be nothing keeping the user from interacting with the SmartTab. Also it should provide the possibilities of direct and indirect manipulation.
Accuracy	Accurate positioning of the SmartTab to given coordinates. Error < 1 cm.
Speed	To reduce waiting times the display should move fast. Desired top speed: $1\frac{m}{s}$, since higher speeds yield higher risk. Karwowski (Karwowski and Rahimi 1991) found that speeds up to $0.64\frac{m}{s}$ are perceived as safe.
Stiffness	To be able to use the tablet it must not shift if the user touches it.
Space	Little structure should be able to move a big screen. Ideally the contraception disappears behind the tablet.
Extensibility	It should be possible to use multiple SmartTabs at a time.
Sound	There should be as little operating noise as possible
Mobility	It should be possible to use the system in different locations.
Adaptability	It should be possible to adapt the system easily to new ideas.
Cost	Low cost.

3.1.3 Version 1 - LEGO prototype

The first version of the robot was three different robots, each testing one specific feature. The first two, versions 1a and 1b, were concerned with the drive, exploring the properties of mecanum-wheels (Fig. 3.1) and omni-wheels (Fig. 3.2 and 3.3). The third prototype (version 1c) showcased the performance of a LEGO compatible linear actuator, which was used to power the lifting arm mechanism which is used to adjust the pitch of the tablet (Fig. 3.4).

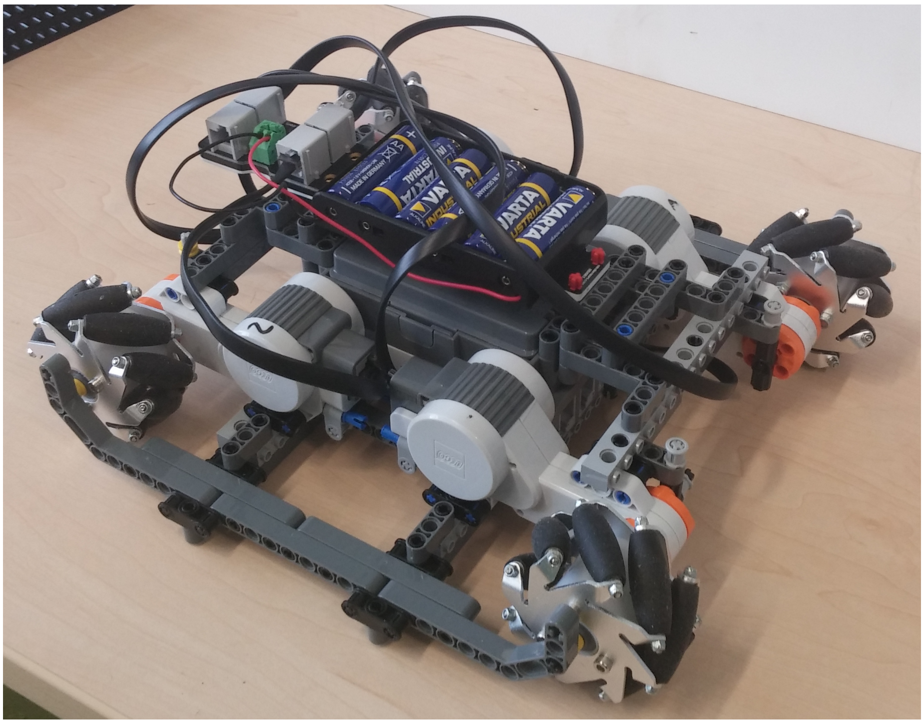

Figure 3.1: Bird view of version 1a with the mecanum wheels.

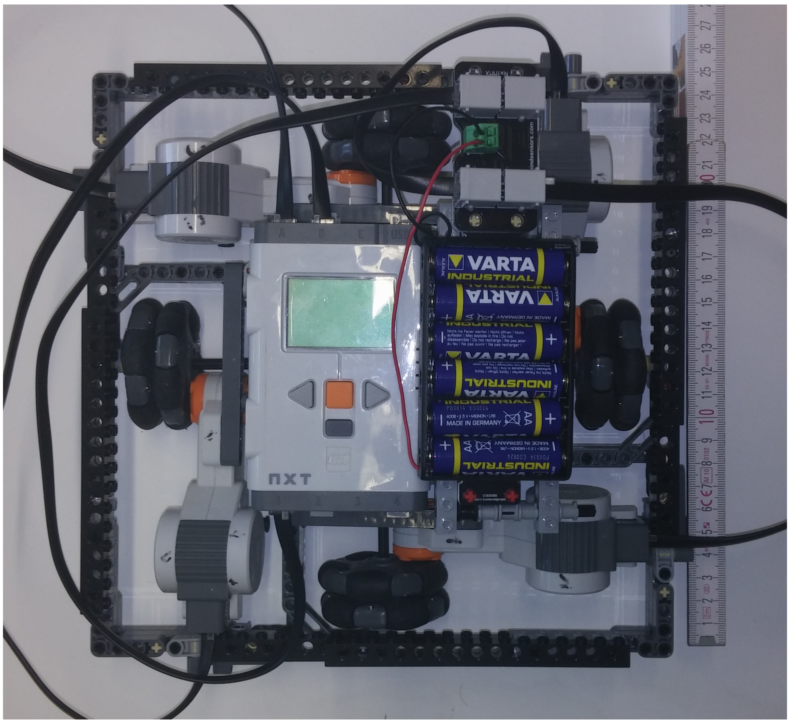

Figure 3.2: Top view of version 1b 14:20 sowing the general layout of version 1b and 1b 14:20

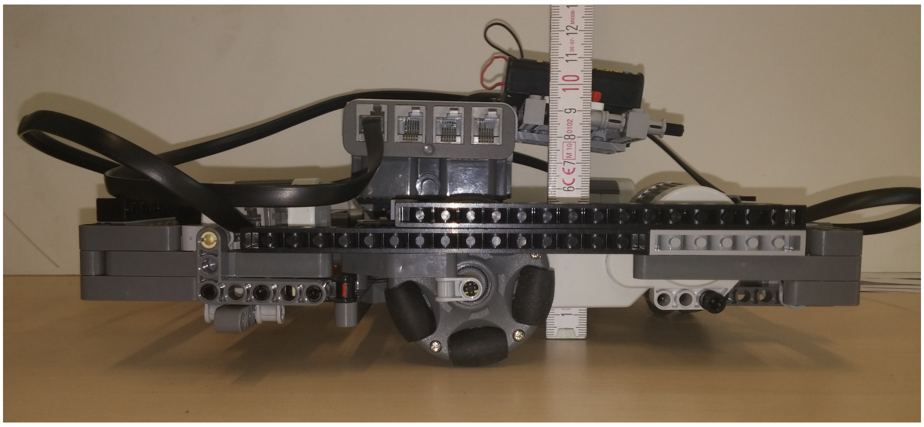

Figure 3.3: Side view of version 1b 14:20 illustrating the almost seesaw like design of the onmi wheel drive.

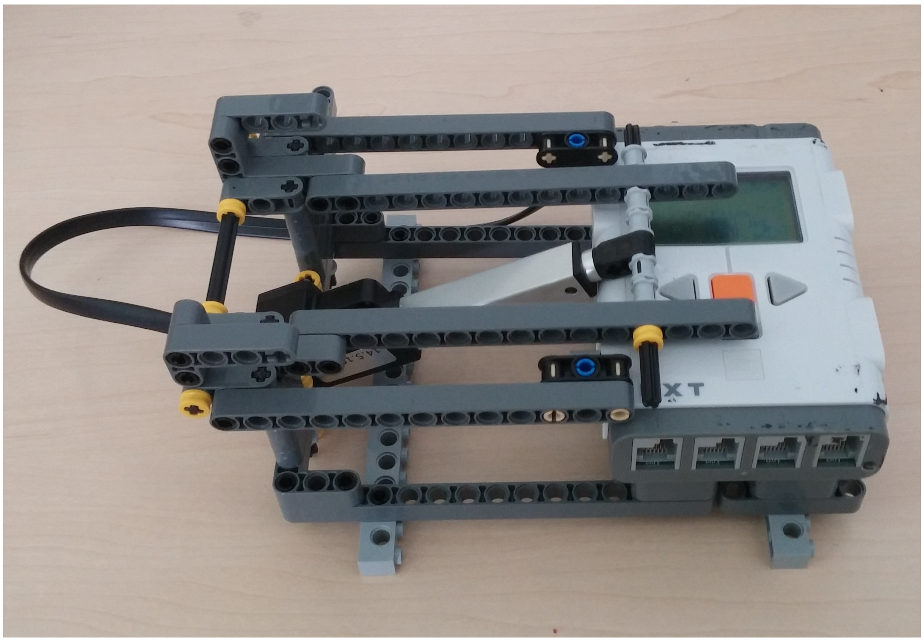

Figure 3.4: Display of version 1c without a tablet lying on it. The silver linear actuator is clearly visible in the middle of the lever.

3.1.4 Version 2 - Metal Frame

The first prototypes have shown, that a mecanum-wheels drive has superior characteristics compared to an omni-wheel drive. It has also shown, that the LEGO construction holding the robot together was bulky, but still weak. This lead to the decision to machine a metal frame to support the robots components (see Fig 3.5). Version 2 (see Fig. 3.6) was born. Unfortunately the first try of constructing a metal frame was not functional due to mechanical issues, which arose from machining errors. The axle mountings were warped and put too much strain on the axles. So we designed a new frame to accommodate for the mechanical imprecision. Also the frame was still a bit weak and warped under pressure.

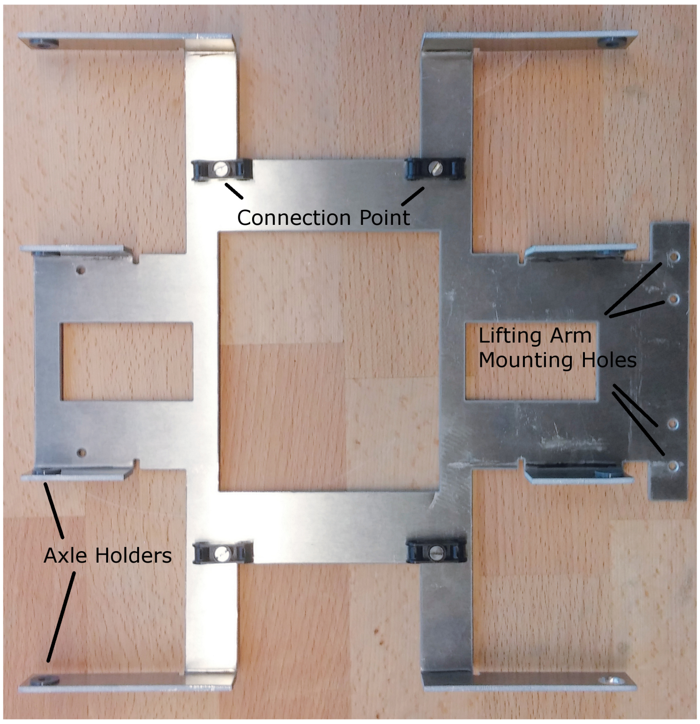

Figure 3.5: The bare aluminium frame. The four screwed on black Lego pieces connect the frame with the motors and the NXT.

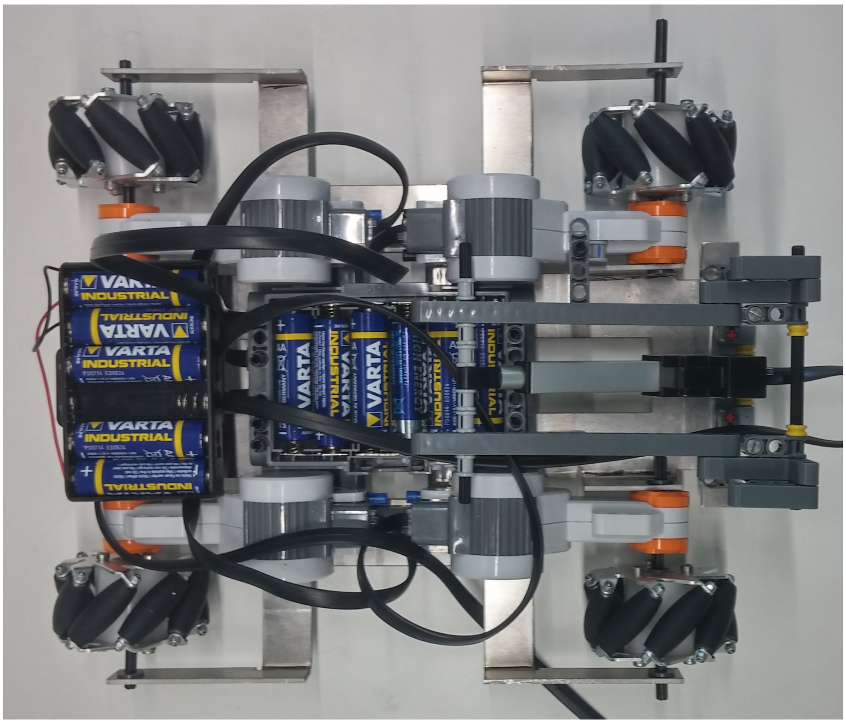

Figure 3.6: Top view of the fully assembled prototype 2. The long axles allow to chose the best position for the mecanum wheels.

3.1.5 Version 3 - Improved Metal Frame

With the insights gained from the second prototype the third prototype was constructed featuring adjustable axle mountings (Fig. 3.7) and a screw-on skeletal reinforcement (Fig. 3.8). The third main improvement over version 2 was that the lifting arm was reinforced (Fig. 3.9). The fourth improvement was a new tablet holder with a sticky pat to secure the tablet on the robot (Fig. 3.9). Finally we constructed a box made of black PVC to hide the robots internals from the user, protect the wheels and to give it a sturdy look (Fig. 3.10).

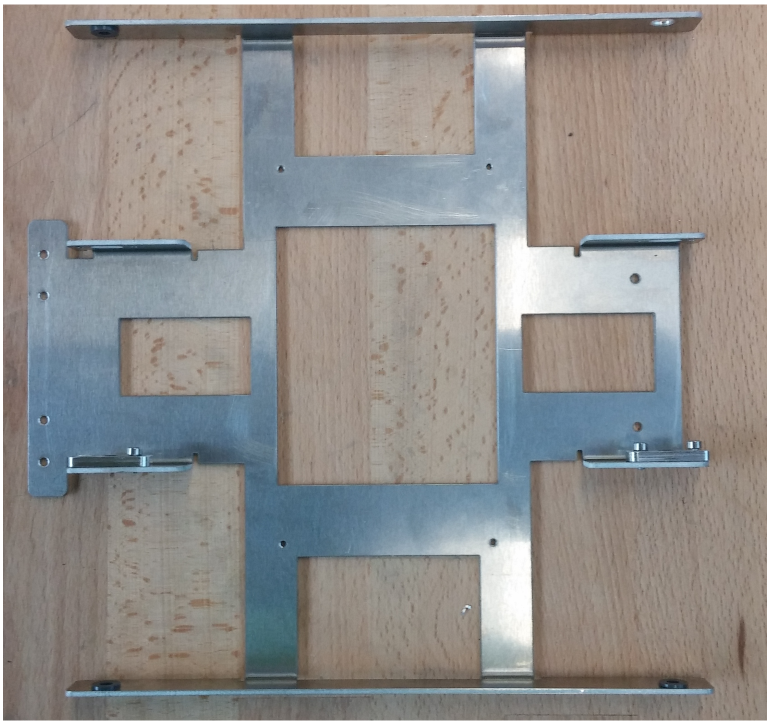

Figure 3.7: Improved frame. Showing the connected sides and rounded edges. Also two axle mountings are attached.

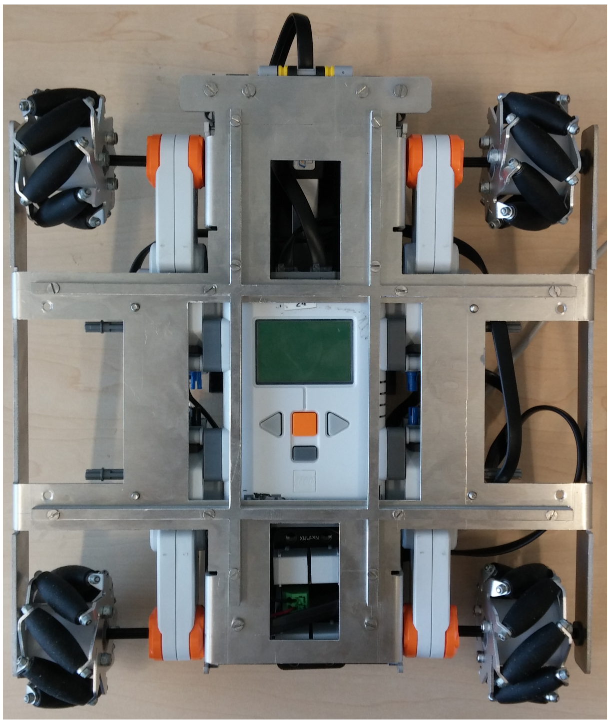

Figure 3.8: Bottom view showing the skeletal reinforcement structure.

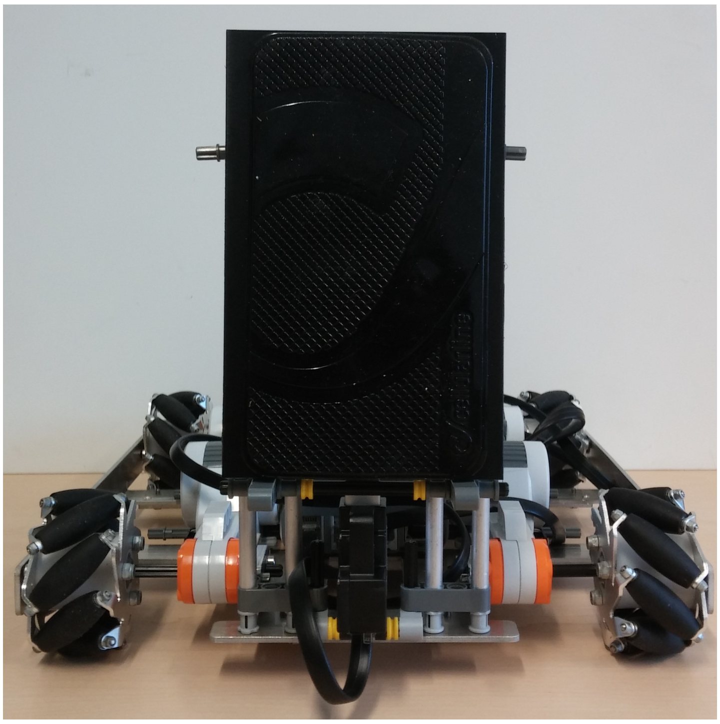

Figure 3.9: Front view showing the reinfoced lifting arm with the black anti-slip mat.

3.2 Final Assembly of the Robot as Presented at the End of the Bachelor Project

Figure 3.10: The SmartTab fully assembled with the black box and a Samsung Galaxy Tab S 10.5 mounted on the lifting arm.

Fully assembled the robot (Fig. 3.10) provides a powerful platform for the SmartTab. The lifting arm with the sticky pad offers tablet pitch angles from 0° to 90° while keeping the tablet safely secured to the robot without blocking any proportion of the tablets display or access to its buttons. The black box prevents injuries, offers stability and gives the robot a tough look. The mecanum wheels drive gives the rig the ability to move very precisely in every direction without having to turn first, making the movement of the robot very time efficient. But this is only a subjective view the next section will have a more objective look at the robots design. Version 3 of the SmartTab robot weighs 1.361 kg empty. With batteries the weight increases to about 1.64 kg. The black box weighs 723 grams. The fully equipped robot with batteries and the black box weighs 2.367 kg. For the complete weight of the SmartTab the weight of the tablet must be added.

3.3 Software Implementation

3.3.1 System Overview

The system overview (see figure 3.11) shows the combination of all SmartTab components. The user interacts with the SmartTab through direct or indirect

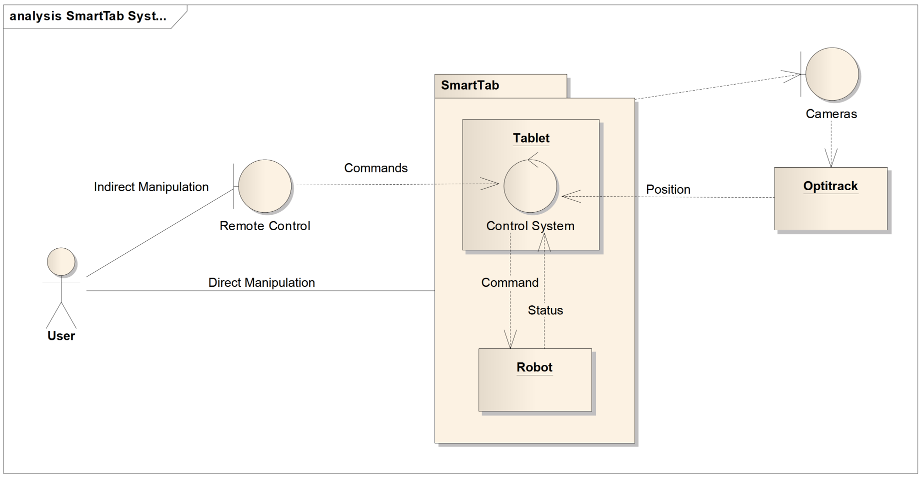

Figure 3.11: Overview of the SmartTab components and the flow of information. (Bigger picture in appendix 7.2)

methods and sees the content displayed on the tablet. The tracking system delivers accurate positional information to the tablet, to display location aware data and to control the SmartTabs movement safely. The tablet is the brain of the SmartTab. It is the point where all information flows together and is processed to create rich, location aware applications. This chapter outlines the main points of the Software implementation, for a detailed report on the SmartTabs software please see the project paper which is provided digitally with this work or contact leonard.kraemer@uni-konstanz.de to receive a free digital copy.

3.3.2 LeJOS Framework

As software framework for the NXT we chose LeJOS[2,3]. Apart from the ability to program the robot with Java, the highlights of LeJOS are, that the framework integrates classes intended to be used on the NXT and also classes for use on a PC or any other device running a JVM. This makes things like setting up a bluetooth connection with the robot a breeze. Also the remote debugging feature is really great for rapid prototyping. Another big plus is that the framework abstracts a lot of the actual hardware controlling away from the programmer and even offers out-of-the-box support for many third-party devices that can be attached to the NXT like the linear actuator and the motor-multiplexer, which is used to connect more than three motors to the NXT.

3.3.3 SmartTab Communication Protocol

The communication between the robot and the tablet is key for the operation, therefore we designed a protocol that fits the very special requirements of the SmartTab.

[2] LeJOS Website - `http://www.lejos.org/` - Online March 17, 2016

[3] LeJOS on Wikipedia - `https://en.wikipedia.org/w/index.php?title=LeJOS&oldid=668954221` - Online March 17, 2016

Requirements of the Communication Protocol

Many key problems of the data transfer, like addressing, routing and loss of information are already taken care of by bluetooth, so we can build on that and focus on more general requirements.

Speed The incoming data must be processed as fast as possible, so that every command is executed almost instantly to increase the rate at which the tablet can update the command. We must ensure that events are processed fast enough so that there is no build up of unprocessed incoming commands.

Latency The latency must be low, meaning that the time between sending a command to the robot and the robots answer must be small.

Accuracy It must be possible to control the robot with the highest possible accuracy.

Extensibility It must be possible to extend the protocol in the future. I.e. if the robot gains new features in the future it must be possible to extend the protocol so that these can be controlled too.

To fulfil these requirements Java serialisation is to bulky, so we created our own binary data transfer protocol. For convenience we encapsulated the protocol handling in a Java library that can be used in future projects with ease. The special part of the protocol is that it supports bi-directional communication and that the same library is used on the robot and the tablet. Figure 3.12 shows the inheritance structure of the protocol. The main class of the protocol library is the `ProtocolReaderWriter`-class which takes care of sending and receiving `ICodeHolder`-subclasses, for example the `DriveCommand`, from standard Java `DataInputStream`s and to `DataOutputstream`s.

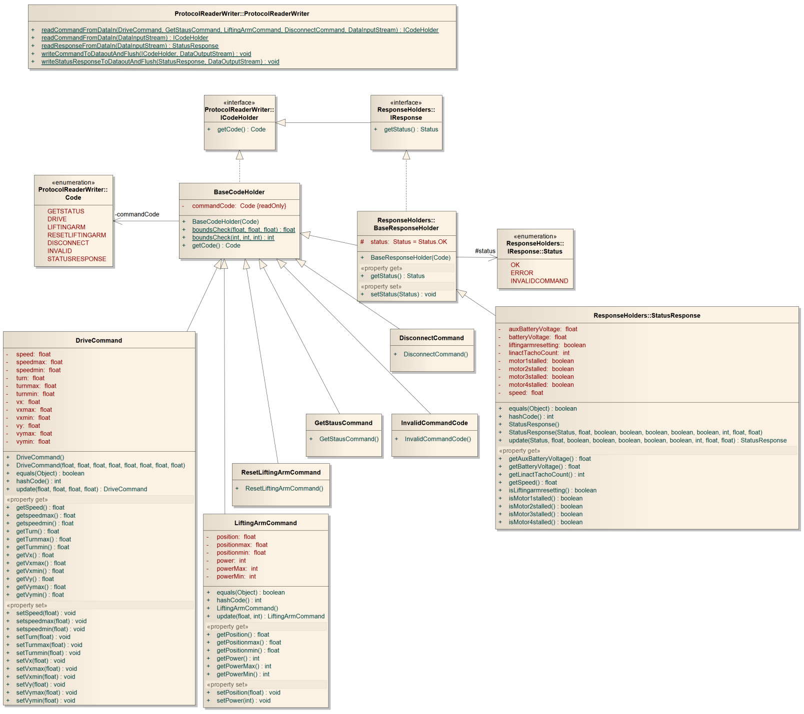

Figure 3.12: Inheritance structure of the protocol. (Bigger picture in appendix 7.1)

3.4 Discussion of the Robot

Based on the following requirements we can evaluate whether or not the design is a success.

All in all the design of the robot is a success. The two requirements that were not met perfectly, namely the noisy nature of the sound and the speed, come from the motors and can be be solved my using different motors. This would mean to develop a whole new custom combination of motor, gear, encoder and motor control system. Since these motors are already one of the most powerful Lego motors it would probably mean to ditch the Lego platform and all of its benefits. But since this system is a prototype and the desired speed of $1\frac{m}{s}$ is not based on usability tests it is very acceptable to trade off a bit of speed to ease the development and increase the adaptability of the system. The stiffness can be increased by introducing a second linear actuator to provide additional support for the tablet in every position.

In order to evaluate the performance of the robot further we used the SmartTab in one of its application domains, the aided exploration of spatial data. We created an experiment and implemented software to answer the question, whether or not a users body movement has an impact on the memory performance using a dynamic peephole egocentric navigation system.

Usability	green	The black box hides all potentially dangerous elements from the user and is sturdy enough to withstand a users pulls and pushes. Although the tablet looks lose it is strongly connected to the robot.
Accuracy	green	The platform provides highly accurate movement and has almost no backlash.
Speed	yellow	The speed of the platform is approximately $0.4\frac{m}{s}$ which is below the desired speed but still offers enough speed to travel the whole width of a standard table with about 2 meters in less than 5 seconds.
Stiffness	yellow	Using the tablet on the robot at low angles feels almost like using a tablet on a non motorized stand. At angles above 45° the tablet starts to give in when pressured and swings a bit if the user makes intense taps. Although this is noticeable at normal usage it does not hinder accurate input.
Space	green	The black box is about the same width as the tablet is and becomes almost invisible at the right angle.
Extensibility	green	Since there are no protruding structures on the robot it should be easy to operate several SmartTabs at the same time.
Sound	yellow	The mecanum wheels and the motors produce some noise. This might be disturbing, if the robot moves continuously.
Mobility	green	To ensure optimal operation the mecanum wheels need a flat surface. The ground clearance of about 1 cm allows to drive over small objects.
Adaptability	green	The integrated fully design prohibits fast changes, nevertheless modifications to the box are thinkable and there is plenty of room inside the box to add additional functionality like sensors.
Cost	green	It has low cost. One unit can be built with less than 1000€ enabling the production of several units to form clusters of SmartTabs working together.

Table 3.2: (green) Meets requirements. (yellow) Below desired quality but acceptable. (black) Does not meet requirements.

Chapter 4

Does full body movement lead to superior memory performance when using an egocentric peephole user interface? - A Study

This study is an adoption of the studies conducted in (Rädle, Jetter, Butscher, et al. 2013) and (Mueller et al. 2015) and focuses on the aspect of how much the extend of the bodily movement in an egocentric user interface influences the users performance. Thus the study setting, the tasks and the evaluation follow a similar pattern. As pointed out by Raedle *et al.* (Rädle, Jetter, Butscher, et al. 2013) dynamic peepholes offer a performance advantage over stationary systems in terms of long term memory and navigation performance. In order to explore the research question we had to create a study setting where the participants had to use their full body to navigate the peephole in one condition and the second condition should limit the body movement to the absolute minimum, without limiting the users ability to control the peephole. So for the first condition, with much bodily movement, we decided that the participants would have to move the peephole manually with their hands, a direct manipulation method. For the second condition, in order to reduce the bodily movement, the participants would control the peephole by simple directional inputs on a gamepad, an indirect manipulation method.

4.1 Hypothesis

To operationalize the research question we formulate the following hypotheses, based on (Rädle, Jetter, Butscher, et al. 2013):

H0 The actual type movement of the body does not affect the performance.

H1 *Spatial Memory* Moving the peephole directly with the hands has a measurable effect on the memory performance.

H2 *Subjective Workload* Moving the peephole indirectly with the gamepad instead of by hand yields a different subjective workload.

H3 *Navigation Performance* Users perform better in navigation tasks within a spatial user interface when using a direct input method and engaging the whole body.

4.2 Experiment

The experiment compares the effects of two different input methods on dynamic peephole navigation. In order to test H1, H2 and H3 the participants had the task to navigate a virtual surface to find symbols (see 4.2.1). Then a short distraction task followed (see 4.2.2). In the second main task, they had to place the symbols they had to find in the first task onto the empty canvas (see 4.2.3). Each participant had to carry out these tasks twice, once in the direct manipulation condition (see 4.2.4) and once in the indirect manipulation condition (see 4.4).

The experimental setting is derived from the usecase of exploring a map, for example a hiking map, with a dynamic peephole to explore a circular hiking route. This is an application of the sample task of finding paths between items in 2-dimensional data (Shneiderman and Shneiderman 1996). To increase the internal validity we chose to create a more abstract, generic task instead of a real-world application.

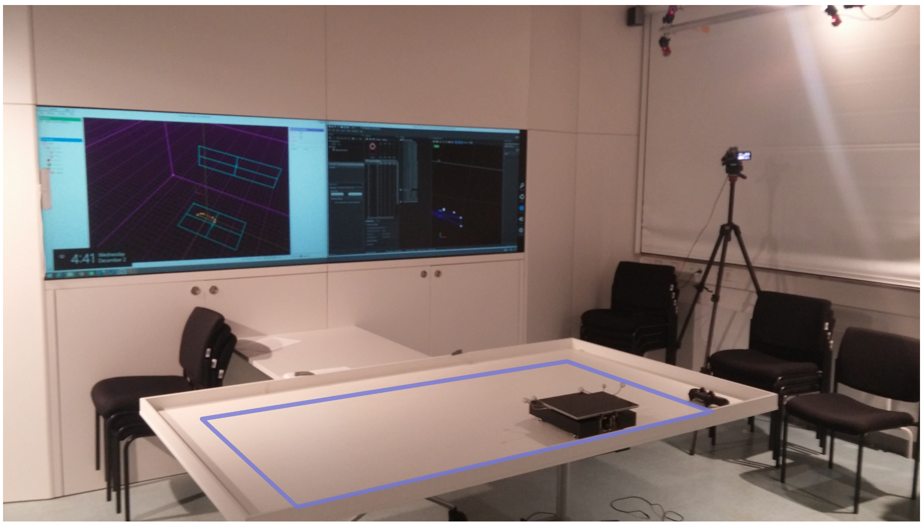

Figure 4.1: The experimental setting in the lab with the SmartTab sitting on the desk with the border. The blue outline indicates the approximate size of the virtual display.

4.2.1 Navigation Task.

In the navigation task the participants were presented with a symbol in the center of the peepholes display and had to move the peephole in order to match this small symbol with a larger version of the same symbol on the virtual display. The virtual display was laid out horizontally on a table. In contrast to (Rädle, Jetter, Butscher, et al. 2013), where the user was once directly in front of the canvas (egocentric navigation) and once sitting at a distance (pinch-and-drag), in this study the user had a similar position, directly in front of the desk, in both conditions. Then they could confirm the match by tapping the peepholes display in the direct condition or by clicking the ×-button on the gamepad. If the target and the symbol did not match a red outline would surround the symbol for a short time to give feedback. After hitting a symbol correctly the user had to decide whether or not he knew where the next symbol was by choosing "yes" or "no". The request to press "yes" or "no" was displayed on the tablet with additional symbols for the corresponding buttons on the gamepad. In the direct manipulation task the participant had to click a button on the touchscreen, in the indirect manipulation this function was mapped to × for "yes" an o for "no" (see Fig. 4.4).

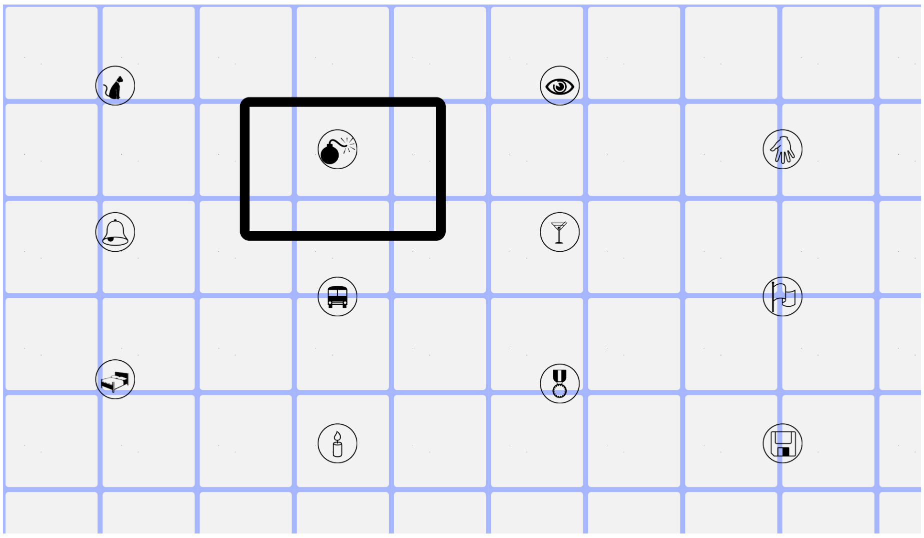

Figure 4.2: Visualisation of the contents of the virtual display. The black frame symbolizes the peephole. The participants could only see the portion of the virtual inside of the peephole at a time.

After going through eight different symbols this way the process would repeat, six times in total, before moving on to the next phase of the study (8 symbols × 6 repetitions = 48 trials). Four additional symbols acted as distractors. The order in which the participants had to go through the symbols was always the same as in the first pass through the eight symbols. The total number of trials was 1536 (8 symbols × 6 repetitions × 2 conditions × 16 participants). Due to the size constraints for the virtual display in the direct manipulation condition (see 4.2.4) and the requirement that it would not be possible to see two symbols at once the maximum amount of symbols on the virtual display was limited.

With circle packing[1] we were able to fit a total amount of 12 symbols (see Fig. 4.2).

4.2.2 Distraction Task.

After the navigation task the participants were asked to fill out a questionnaire and then had to solve paper mazes for five minutes. This task was designed to distract the participant from the previous task to push the items positions out of the short term memory.

4.2.3 Recall Task.

In the recall tasks the participants were presented with all previously searched symbols in a random order and an empty canvas. The participants tasks was to put all eight symbols back into the same spot as in the navigation task as accurately as possible. The participants could see all symbols at the same time and were also allowed to do as many corrections as they wanted.

The participants had to carry out these three tasks, navigation task, distraction task and recall task twice with different interaction methods in a within-subjects experiment.

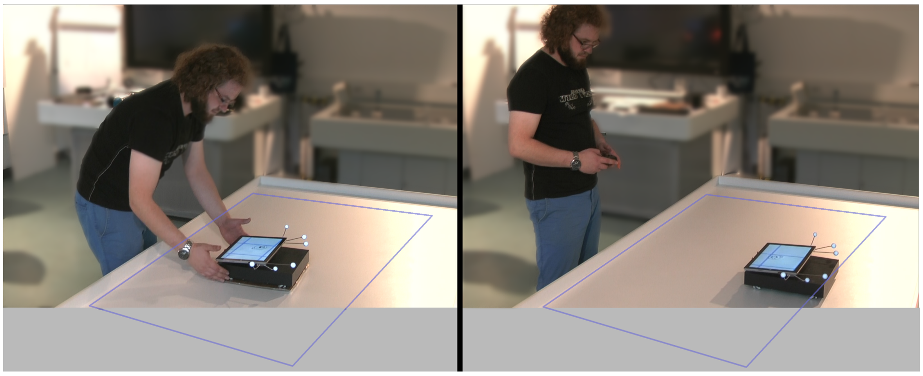

Figure 4.3: Left: A participant is navigating the virtual display by hand. Right: A participant is using a wireless controller to manipulate the peepholes position. The blue outline indicates the approximate size of the virtual display.

4.2.4 Direct interaction condition.

The first condition (see Fig. 4.3 left) is to move the dynamic peephole, which is sitting on a table, by hand, thus forcing the user to move his whole body to explore the virtual display through the peephole. In a small pretest with two participants the surface of the virtual display was limited from 80 cm × 140 cm, the size of a standard table, to 72 cm × 125 cm, so that every point of the surface is comfortably reachable for average sized adults. To be able to push the dynamic peephole easily the SmartTab was set on a sliding pad.

[1] Wikipedia: Circle Packing - `https://en.wikipedia.org/w/index.php?title=Circle_packing&oldid=688305561` - Online March 17, 2016

4.2.5 Indirect interaction condition.

In the second condition (see Fig. 4.3 right) the participant was equipped with a gamepad[2] (see Fig. 4.4) to steer a SmartTab, which moves the tablet for the participant. In the indirect manipulation condition the SmartTab was set on its wheels, using its holonomic drive to move the peephole according to the participants input. To provide a natural, easy to learn way of controlling the SmartTab with the gamepad we chose to fix the SmartTabs orientation to align the long side of the peephole with the long side of the table. This orientation can also be called 'landscape' orientation. This fixed orientation made it possible to create an easy to learn control scheme, by mapping the input direction on the left analog stick and the d-pad directly to a corresponding movement of the SmartTab. This means that pushing the analog stick to the right, or pressing the right button of the d-pad, makes the SmartTab move to the right, pushing it to the left makes the robot move to the left. Pushing the analog stick away from the user makes the robot move away, directly towards the far side of the table and pulling it towards ones self makes the robot move in towards the near side of the table. When using the d-pad it is possible to steer the SmartTab into eight possible directions, for example pressing the left and the away button simultaneously the SmartTab would move to the far left side of the virtual display. While pressing a button on the d-pad made the robot move at full speed, using the analog stick it was also possible to reduce the speed of the SmartTab by pushing the analog stick gently into the desired direction (see Fig. 4.5). The analog stick was set to have a dead zone[3], to make sure that the SmartTab would not move when the analog stick is in the neutral position. At the second technique the participant was asked to stand in one place, navigating the dynamic peephole using only the thumbs of both hands to control the SmartTab via the two joysticks and the buttons of the gamepad to limit the body movement to the absolute minimum.

[2] PlayStation 4 - DualShock 4 Wireless Controller

[3] Doing Thumbstick Deadzones Right - website - `http://www.third-helix.com/2013/04/12/doing-thumbstick-dead-zones-right.html` - Online March 17, 2016

Figure 4.4: The Dualshock 4 controller with indications of the finctions in the experiment.

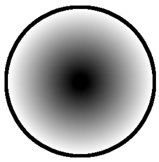

Figure 4.5: Illustration of the analog sticks gradual movement speed increase and deadzone. The brightness of the radial gradient symbolizes the speed the controller registers. In the dead center no input is registered, at the side of the cirle full speed in the specific direction is registered.

4.3 Method

We conducted a controlled lab experiment with 16 participants. The independent variables were the interaction method (d = direct interaction, i = indirect interaction), the symbol pool (pool 1 and pool 2) and the path through the symbols (path A and path B). Both paths were designed to have an equal optimal path length, i.e. they featured the same seven subpaths, but in different order and direction. The dependent variables were the navigation path length, the navigation time, the recall error and the participants subjective task load reports. The study was a within-subject design with repeated measures. The participants were randomly assigned to one of eight groups (i1A-d2B, i2A-d1B, i1B-d2A, i2B-d1A, d1A-i2B, d2A-i1B, d1B-i2A, d2B-i1A) to counterbalance all independent variables systematically. To eliminate the SmartTabs sound from the independent variables we asked all participants to wear earmuffs during all navigation and recall phases.

4.3.1 Participants

Of the sixteen participants nine were male and seven female. Their ages ranged from 19 to 60 years (M = 24.5, SD=10.1). No participant had visual impairments, apart from wearing glasses. The participants were all members of the university of constance, 14 students, one doctoral student and one staff member. Five participants stated that they have average or above abilities in using a gamepad, eleven expressed that they had below average or bad abilities.

4.3.2 Apparatus

The system used for the study was a SmartTab robot weighing 2367 grams and a Microsoft Surface Pro 3 tablet (12 Zoll ClearType Full HD+ Display, 17.0 cm×25.4 cm, 216 ppi, 85 pixel/cm²) with a 2160 pixel×1440 pixel resolution multi-touch screen at about 800 grams as peephole and control unit. For the indirect control by gamepad we chose a DualShock 4 Controller which weighs 210 g, has 6 axis motion sensing, 2 analog sticks, 2 analog triggers, 12 digital buttons, digital direction buttons (D-pad) and a capacitive 2 point touchpad. It is connected wirelessly to the surface via Bluetooth v2.1. For the direct interaction method a sliding pad made of cardboard and felt was used. It had a mass of about 50 grams. The combined weight of the SmartTab robot with the black box attached, the Surface Pro 3 and the passive markers was about 3.2 kg. Both conditions used an OptiTrack motion capture system by NaturalPoint with 24 cameras to track the position of the peephole. This system tracks motion with less than 0.5mm error at a sample rate of 100 Hz. With the ProximityToolkit (Marquardt et al. 2011) we defined a virtual display and one device to track the relation between the display and the device in order to display the contents of the virtual display on the peephole. The virtual displays dimensions were 72.0 cm × 125.0 cm resulting in a resolution of 6120 Pixel x 10625 Pixel (65.02 Megapixels). The software was implemented in .NET 4.0/WPF with C#for the study application and Java with the LeJOS framework for the communication with the robot. The .NET 4.0/WPF application used IKVM[4] to run the SmartTab communication library which communicated with the robot through a Java based proxy which handled the bluetooth connection to the NXT.

4.3.3 Procedure.

After welcoming the participants they were asked to fill out a consent form and a pre-questionnaire to gather demographic data and some data about the participants previous experience with touch devices, remote controlled vehicles and gamepads. The participants then were introduced to the first navigation technique. Before the actual exploration task began the participants were allowed to make themselves comfortable with the respective task and input technology until they felt comfortable. Then the study began. After the study the participants were asked to fill out a questionnaire about their experience

[4]IKVM website - `http://www.ikvm.net/` - Online March 17, 2016

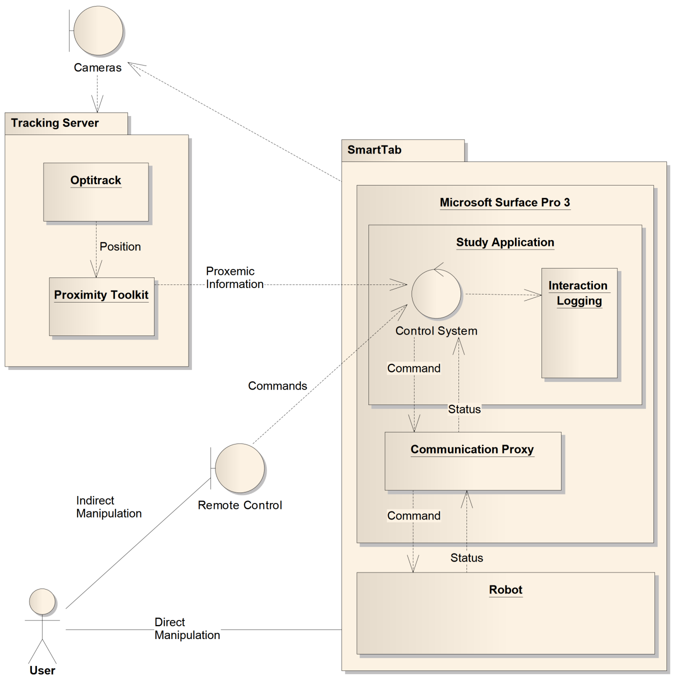

Figure 4.6: Overview of the study software architecture highlighting the main features. (Bigger picture in appendix 7.3)

with the system and then a short, semi-structured interview followed, going into more detail about the participants experiences.

4.4 Results

While the participant carried out the task we were logging the x- and y-position of the peephole in relation to the virtual display. Logging was carried out at 20Hz.

4.4.1 Navigation Performance

To evaluate the navigation performance we took the absolute path length for every trial into account. We did not consider the first run through the symbols in the evaluation, because the paths in this run were totally random, since the participants had not jet seen all symbol. The average path length for the direct manipulation by hand was 50923 pixels (5.99 m) and 65010 pixels (7.64 m) for the indirect manipulation of the peephole's position with the gamepad. A 2×5 (interaction method × runs) analysis of variance with repeated measures of the path lengths (ANOVA) has shown that the paths were significantly shorter when using the direct manipulation ($F = 18.62, p < .001, partial\mu^2 = .06$). On average the paths were 27.6% shorter when using the direct input, compared to the indirect manipulation. Thus we can accept Hypothesis H3.

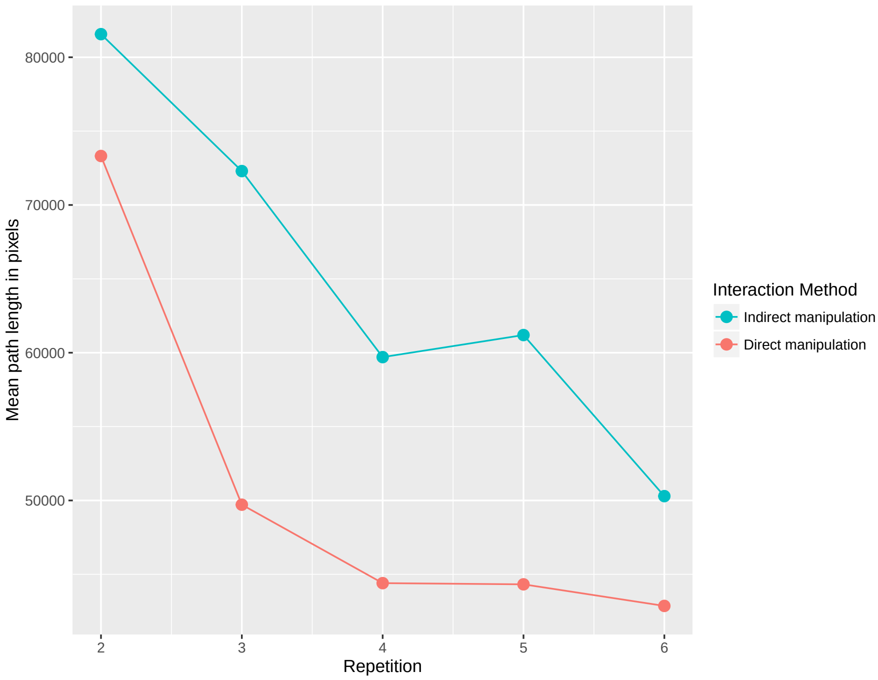

Figure 4.7: The average path lengths per run for runs 2 to 6.

Figure 4.7 illustrates this by showing the mean values of the path lengths in both conditions. We can see a learning effect in both conditions and also that the average path lengths for the indirect manipulation are longer than the ones for the direct manipulation. It also shows that the path lengths for the direct manipulation reaches a plateau after four runs and only declines marginally after that while the path lengths for the direct manipulation still decline.

4.4.2 Navigation Time

As for the navigation performance we also disregard the first run through the symbols, because the first run was completely random. The time measurement for each run started with completing the last symbol from the previous run and ended when the last symbol from the current run was found. The sample rate was also 20Hz. The mean navigation time for the direct manipulation was 59.89 seconds (SD = 30.20 seconds) and the mean navigation for the indirect manipulation was 67.40 seconds (SD = 23.38 seconds). A 2×5 (Interaction method × runs) analysis of variance with repeated measures of the navigation times (ANOVA) failed to reveal a statistically relevant effect ($F = 2.07, p = .17, partial\mu^2 = .02$) of the interaction method to the navigation times. Nevertheless the navigation times for the direct interaction condition were 12.5% shorter. Figure 4.8 shows

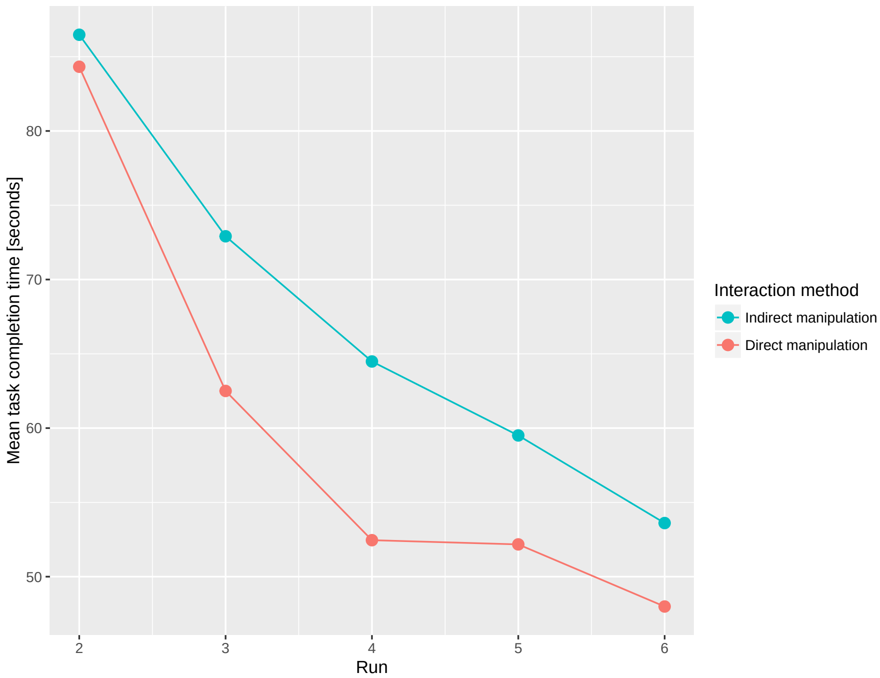

Figure 4.8: The average task completion time per run for runs 2 to 6.

the average task completion times for runs 2 to 6. It shows that the navigation times for both conditions improved with every subsequent run, because the participants learned the symbols positions.

4.4.3 Navigation Speed

Since of the circumstance that the navigation times for the direct manipulation were less smaller than the difference in path length would imply we also took a look at the navigation speed. The navigation speed is calculated by dividing

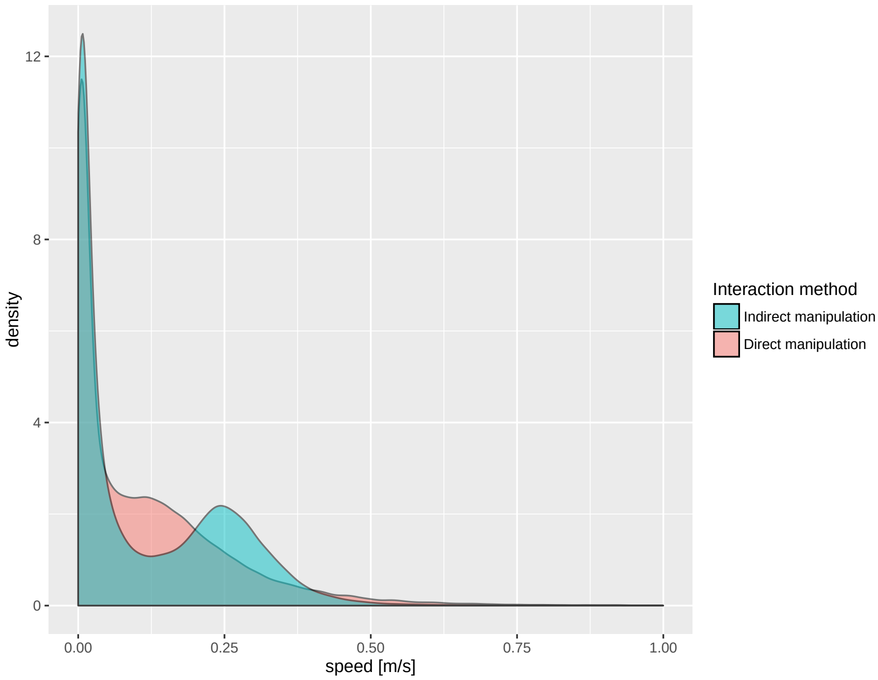

Figure 4.9: Graph of the estimated kernel densities of the speed, grouped by interaction method. Indicates that the speed for the indirect condition was higher.

the distance travelled between two sample points by the time in between their respective timestamps. The navigation speed for the direct interaction is 0.113 $\frac{m}{s}$ (SD $= 0.137\frac{m}{s}$) and $0.121\frac{m}{s}$ (SD $= 0.132\frac{m}{s}$) for the indirect interaction. A test for statistical significance (ANOVA: $F = 170.9, p < 2e-16$, Paired, two-tailed t-test $t = 13.028, df = 219580, p < 2.2e-16$) significantly different navigation speeds. Averaged over all measurements the speeds measured in the indirect interaction method condition were 6% higher than in the direct manipulation condition. Figure 4.9 shows the estimated kernel densities for each speed; The estimated kernel density are a measure for how long the peephole was moving with the specific speed. The high density for the low values shows that over the course of the task the peephole often stood still or was accelerating/decelerating from/to still stand. The two other interesting spots are at speed ≈ 0.125, where the direct interaction has a local maximum for the kernel density and speed ≈ 0.25 where the indirect movement has a local maximum in the kernel density. This illustrates the previously shown correlation between the speed and the interaction method. Although the navigation speed for the indirect manipulation was faster than the speed for the direct manipulation no participant reported that it was hard to read the contents of the peephole because of the speed.

4.4.4 Spatial Memory / Recall

Evaluating the results for the recall task did not yield a statistically significant effect ($F = 0.02, p = .887, partial\mu^2 = .00005$). The mean deviation from the actual positions of the symbols in the direct manipulation condition were 967.60 pixel (SD = 904.43 pixel) or 11.38 cm (SD = 10.64 cm). The mean deviation from the actual positions of the symbols in the indirect manipulation condition were 981.30 pixel (SD = 624.33 pixel) or 11.54 cm (SD = 7.345 cm). With this result we can reject H1.

4.4.5 Subjective Work Load / NASA TLX

To gather insight into the perceived task loads the participants had to rate their subjective task load with the NASA TLX at the end of each navigation task. When evaluating the overall results with a two-tailed, paired t-test no significant difference can be found ($t = -1.2032, df = 15, p = 0.2475$). Thus we can reject hypothesis H2.
When subjecting the subscales to two-tailed, paired t-test we find that only the physical demand subscale yields statistically relevant differences ($t = -3.3232, df = 15, p = 0.004633$) and indicates a significantly lower physical demand for the indirect manipulation of the peepholes position. This is a confirmation of the study setup which was intended to produce a low physical demand in the indirect manipulation condition. Figure 4.10 shows the subjective task load ratings for both

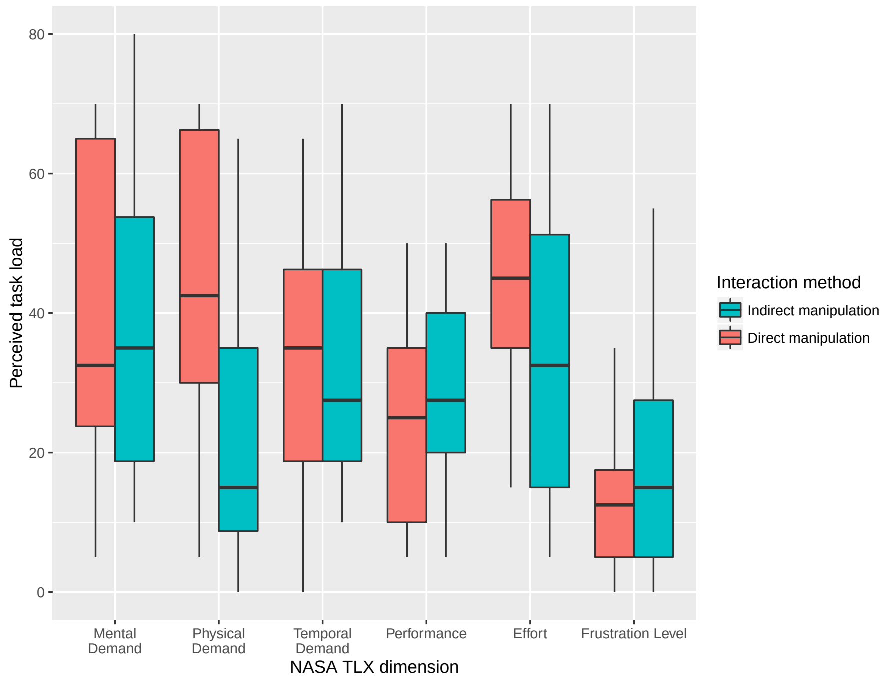

Figure 4.10: The subjective workloads ratings for every subscale of the NASA TLX. Pairwise comparison of both interaction methods.

tasks in a box and whiskers plot[5]. The coloured boxes illustrate the 25% and 75%

[5]Box and whiskers plot - `http://docs.ggplot2.org/current/geom_boxplot.html` - Online March 17, 2016

quantiles while the black line in the middle shows the mean subjective task load ratings for that condition and subscale. The whiskers indicate the total range of values. This plot illustrates nicely how the ratings for the different subscales differ by interaction method. Most interestingly there appears to be no correlation (Paired, two-tailed t-test: $t = 0.90736, df = 28.651, p - value = 0.3718$) between the mental demand and the interaction method.

4.4.6 Preferred Interaction Method

Seven of sixteen participants stated that they preferred the indirect interaction method over the direct interaction. Surprisingly only one of the participants with average or above gamepad experience preferred the indirect manipulation with the gamepad. Five participants preferring the indirect interaction with the gamepad stated that it was more fun, four stated it was more comfortable. Of the 9 participants preferring the manual, direct interaction six stated that they were more precise and three stated they were faster than with the gamepad.

4.5 Discussion of the Quantitative Study Results

The key finding of the experiment was, that the navigation paths were significantly shorter, often optimal (Fig. 4.11), when using direct manipulation instead of indirect manipulation of the peepholes position. The main limitation of this finding is that many participants complained about their mediocre precision when handling the SmartTab with the gamepad. The observations have shown that the participants often overshoot the target, when it was already on the screen of the peephole, several times and then doubled back to hit the target. This process of circling in on the symbols took several distinct, controlled movements. This phenomenon can be seen in the paths of every run, even the last. Figure 4.12 shows the path the peephole took at the indirect interaction method in the last navigation run of participant 5, who reported to be skilled handling gamepads. We can see that the participant had problems to position the SmartTab accurately at four targets and circled in on their positions.

The participants used the analog stick to navigate the canvas when in between targets at full speed. Then, to navigate in close range of the target, they stopped the SmartTab and tapped the analog stick softly so that the SmartTab would move a minimal distance at a time. This behaviour can be seen in figure 4.13; the smooth curves between the targets were achieved by pushing the analog stick all the way and the tight movements around the targets were done with the light taps.

That the navigation times did not yield a significant difference can be explained by the fact, that the navigation speed with the gamepad was significantly higher. The speed value is highly influenced by the weight, shape, size and sliding characteristics of the SmartTab in the manual condition and the set speed when operating the SmartTab with the gamepad.

To sum up the quantitative data analysis we can state that we found a significant difference in the navigation path lengths. This leads to the conclusion that the direct interaction method, with the high amount of bodily movement, is more accurate, easier to remember and incentives the participants to chose an

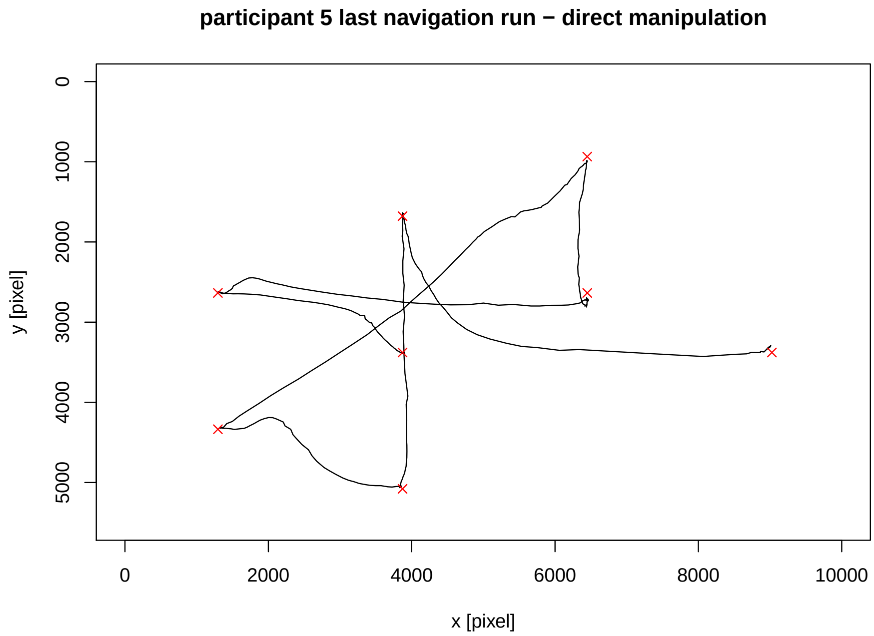

Figure 4.11: The navigation path of the last run of paticipant 5. The actual positions of the targes are marked in red. The image shows almost optimal paths for the direct manipulation task.

optimal path.
The discrepancy between the significantly shorter navigation paths and the fact that the navigation times were not significantly different lead to the discovery that the participants were able to manoeuvre the peephole faster when they were using the SmartTab to carry out their intended movements. Since this connection was found when evaluating the study a follow up study should be conducted out to confirm this finding.
The finding that the spatial memory performance was not affected by the interaction method indicates that the body movement is not the leading factor for spatial memory. One explanation for this finding can be found in the method of loci, where it is possible to remember many things for a long time by associating them with places (see 2.1).
The fact that many participants had problems steering the SmartTab accurately, so that they never had the exact same path to a symbol may be a factor that prevented the building up of motor memory, which was proposed as a possible additional memory source, aiding in the spatial memory task by Raedle *et al.* (Rädle, Jetter, Butscher, et al. 2013). For the direct interaction method the path lengths did not improve much after the fourth trial, which might be a possible case for the build up of motor memory. This situation suggests that motor memory plays only a minor part in the spatial memory, but the facts are too vague to make a clear statement about this.
The most fitting explanation for the lack in difference in the recall results is that the recall task was too easy, so that the participants had no problem remembering

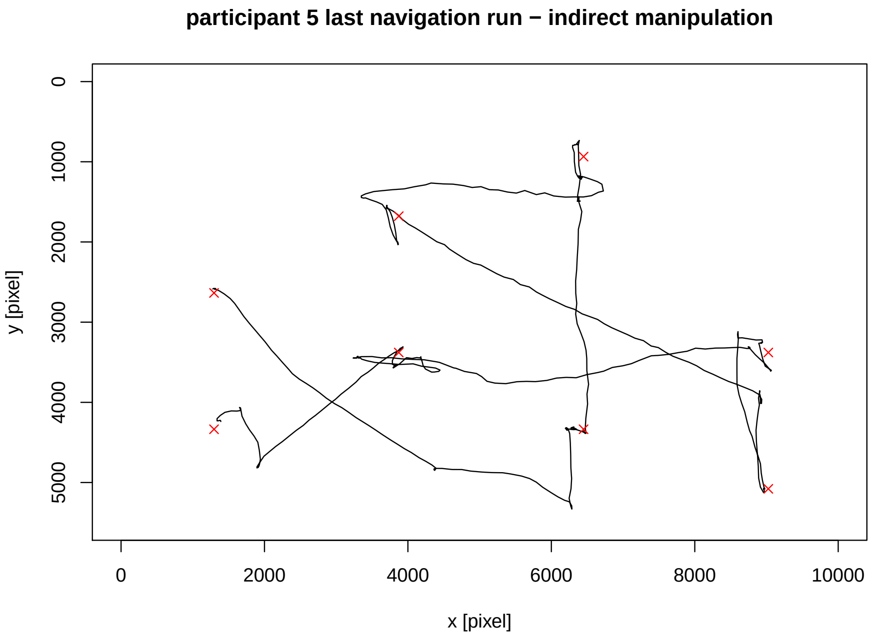

Figure 4.12: The navigation path of the last run of paticipant 5, a skilled gamepad user. The actual positions of the targes are marked in red. The Image shows that the participant overshot five targets. Apart from circling in on the targets the navigation path was almost optimal.

all positions. Factors helping the participants remember the positions were the frame of reference created by the table, the grid on the virtual display and the regular arrangement of the symbols due to the circle packing.
To explore the question whether or not the amount of bodily movement has an impact on the memory performance a new experiment should also feature a bigger virtual display and no alignment of the symbols so that the room for error is bigger.

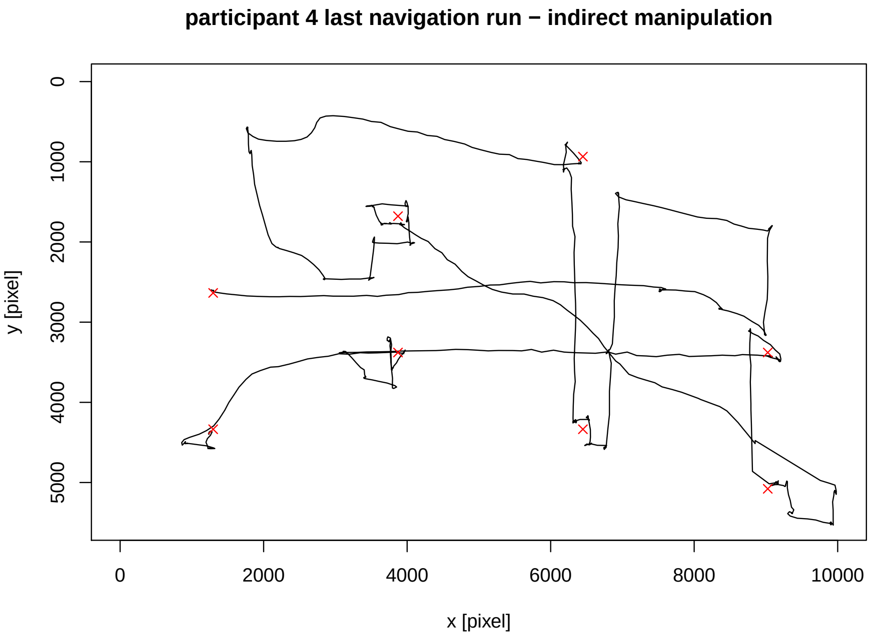

Figure 4.13: The navigation path of the last run of paticipant 4, a gamepad user with average experience. The actual positions of the targes are marked in red. The image shows how the user was circling in on the targets.

4.6 Results from the Qualitative Data

In the interviews we asked the participants questions about which condition they preferred and why. We also assessed for which interaction method they thought that they were faster and more precise. The third question was about the method they used to remember the symbols and their position and at last we asked them weather or not they felt that they had a better overview over the virtual display at any point.

With their answers they mostly confirmed the results of the quantitative analysis. For the first question the results were split, 9 participants preferred the method "by hand" and 7 preferred to use the gamepad. The reason they gave for preferring the manual condition was, because they felt it was more precise. Some said that they preferred it because they felt more involved with the direct manipulation and that this has helped them remember the symbols. For liking the indirect interaction method better the participants explained that it was more comfortable and more fun.

When asked at which condition they were faster most (eleven) participants stated that they were faster with their own hands, because it was more precise. Four said that the gamepad moved faster than they did. One was undecided.

The participants used different methods to remember the positions of the symbols. For the direct interaction some users tried to remember the distances between the symbols by moving the peephole repeatedly until it felt right, some used their position towards the table as clue and others used the provided grid. One

user created little stories, similar to the method of loci. In the indirect condition the users mostly used the grid and oriented themselves by the frame of reference, which the table formed.
For the question about the overview the common voice was that the interface was not overseeable or that it was the same for both conditions.
We also asked the last eight participants to evaluate their experience driving the robot on semantic scales with five response levels. On a scale from precise to imprecise the robots accuracy scored three points ($3, SD = 1.0$), which means that the control was neither precise nor imprecise.
When asked if the control was direct or indirect the participants also rated it as neither direct nor indirect, but right in the middle. ($3.1, SD = 3.1$)
On a scale from very slow to very fast the participants felt that they learned how to control the robot fast ($3.7, SD = 0.8$).
On a scale from too slow to too fast the robots movement was perceived as a bit too fast ($3.4, SD = 0.5$).
The volume of the robots movement was rated as above medium ($3.3, SD = 1.28$) on a scale from very silent to too loud.
The analysis of the video material shows that overall reception of the robot was good and no user was scared by the robot. While all participants handled the SmartTab with care when pushing it around they had no inhibition to do so in he first place. Some participants complained that the display could be fixed better, so that it does not shake when the robot moves. Two users wanted to take the SmartTab home.
A general problem of the motion tracking was that users would sometimes obstruct the cameras' view of the markers in areas with low coverage. This lead to hesitant updates of the peepholes screen.

4.7 Discussion of the Qualitative Results

The participants answers on which method they used to remember the positions of the symbols suggest that the direct manipulation supplies the user with additional information which can be used to restore the positions later on. Nevertheless almost half of the participants preferred the indirect manipulation. Apparently the higher comfort and the fun they had using the gamepad is highly valued.
The outcome of the evaluation of the robots control suggests that it was fast to learn to control the robot, but the control is far from perfect. Together with the observations during the experiment we conclude that a gamepad is not the optimal way to control a dynamic peephole for spatial exploration. While the directional input with a direct mapping between the controller and the robot was understood easily, controlling the robot's speed was a challenge. We suggest to use an input method that provides more haptic feedback and has a longer travel range from the neutral position to full speed. For example a joystick.
The perceived loudness of the SmartTab must be taken with a grain of salt, because the lab was not quiet and the participants were asked to wear earmuffs during the whole study but the exploration and the distraction phase.

4.8 Implications of the Study Results for the SmartTab

All in all the experiment was successful and has shown that the SmartTab can be used to explore spatial data effectively. The trade-off when using an indirect control to a direct control is the precision, but it also makes the exploration more comfortable and more fun. In addition to that the automatic drive offers a higher speed, which can help exploring large information spaces. How the speed of the SmartTab compares to a user using a system like the horizontal condition presented by Müller *et al.* (Mueller et al. 2015), where the user could walk around in an unobstructed area, is unclear.
To take care of the shaking display a second linear actuator can be used in a future model.
To overcome the problem of motion tracking we suggest implementing an odometry system to become less dependent on frequent updates of the absolute position.
With these results we can revisit the requirements assessment table: Most notably the previously yellow speed assessment is now green, because the speed is more than enough to fulfil one of the main usecases of the SmartTab.

Usability	🟩	The SmartTab withstood the contact with the users undamaged. The users generally had a positive attitude towards the SmartTab.
Accuracy	🟩	The platform provides highly accurate movement and has almost no backlash. When using a remote control the control must offer the possibility to adjust the SmartTabs speed easily.
Speed	🟩	The speed of the platform is approximately $0.4\frac{m}{s}$. This speed is significantly higher than the speed at which users move the SmartTab when navigating a spatial user interface. The speed was rated as a bit higher than desired.
Stiffness	🟨	Using the tablet on the robot at low angles feels almost like using a tablet on a non motorized stand. At angles above 45° the tablet starts to give in when pressured and swings a bit if the user makes intense taps. Although this is noticeable at normal usage it does not hinder accurate input. The tablet trembles when the SmartTab is moving.
Space	🟩	The black box is about the same width as the tablet is and becomes almost invisible at the right angle.
Extensibility	🟩	Since there are no protruding structures on the robot it should be easy to operate several SmartTabs at the same time.
Sound	🟨	The mecanum wheels and the motors produce some noise. This might be disturbing in a silent environment.
Mobility	🟩	To ensure optimal operation the mecanum wheels need a flat surface. The ground clearance of about 1 cm allows to drive over small objects.
Adaptability	🟩	The integrated fully design prohibits fast changes, nevertheless modifications to the box are thinkable and there is plenty of room inside the box to add additional functionality like sensors. The software platform allowed for fast integration of the SmartTab into a system for dynamic peephole navigation.
Cost	🟩	It has low cost. One unit can be built with less than 1000€ enabling the production of several units to form clusters of SmartTabs working together.

Table 4.1: 🟩 Meets requirements. 🟨 Below desired quality but acceptable. ⬛ Does not meet requirements.

Chapter 5

Usecases for SmartTabs

SmartTabs enable many different scenarios which utilize the SmartTabs ability to move. This chapter will present these usecases. The usecases are derived from the related work and also two creativity workshop sessions with the Rack of Inspiration (Feyer 2015). Some of the usecases presented are not jet possible with the current version of the SmartTab and require additional sensors for example an optical sensor for autonomous location determination or a NFC-Tag reader. As pointed out in the section the SmartTab is a versatile platform, built to be modified and extended with with attachments and sensors.

5.1 Exploration of Spatial Data

Aided Navigation in Spatial Data The experiment conducted in this bachelor thesis has shown that controlling a dynamic peephole to navigate spatial data with an indirect interaction technique like a gamepad is hard. The main difficulty is to control the speed of the peephole not to overshoot targets. This task can be made easier with a method similar to the "snap to grid" functionality of many design tools. This functionality makes it easy for users to align objects with a grid system by automatically aligning items to the grid when they are dropped near the grid. The same principle can be applied to an autonomous, dynamic peephole. Interesting points in the spatial data are marked and when the peephole is near a point it will automatically move so that the nearest interesting point is in the middle of the screen. This eliminates the need of skill when steering the peephole. The user must only remember in which direction the next interesting point is and drive the peephole into its general direction. It should also be possible to toggle this "snap to POI" (point of interest) function on and off to enable free exploration of the data.

Search Spatial Data The automatic movement of the SmartTab enables the automatic search of spatial data with a dynamic peephole. Imagine the following scenario: In a crisis situation a group of first responders want to evaluate the situation and how to handle it properly. To decide quickly how to handle the situation they need the latest information about the location of the crisis visualized. One of the first responders brought his SmartTab and it is placed on the table. The SmartTab loads up a map of the crisis location which is enriched with the latest information. See how we imagine the first responders searching for a suitable airport in figures 5.1, 5.2 and 5.3.

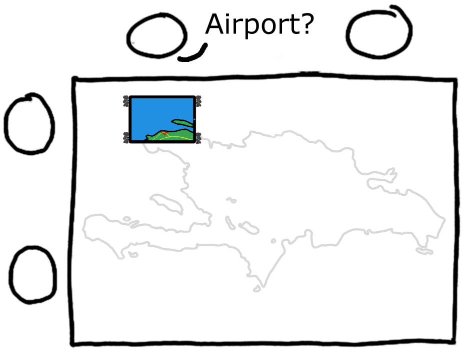

Figure 5.1: Four first responders must get a quick overview over the current situations and the airports. One issues the command to search for an airport and the SmartTab moves to its location.

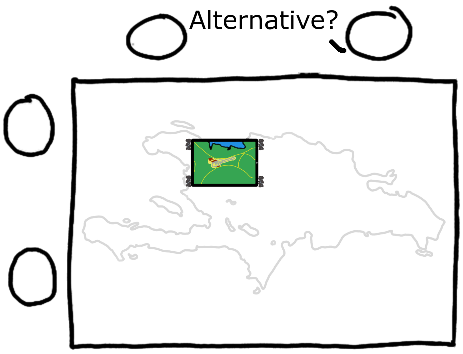

Figure 5.2: The SmartTab shows the airport that was nearest to its position. The helpers recognize the airports position and can immediately see that this airport must be affected by the catastrophe. They continue the search by issuing a second voice command.

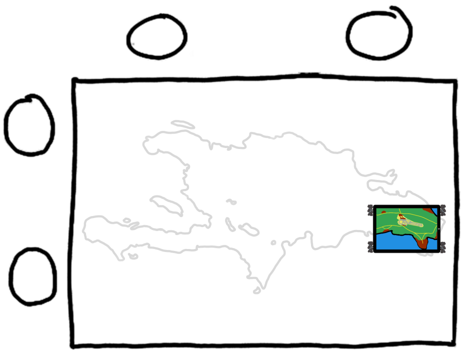

Figure 5.3: The SmartTab shows the alternative airport. Judging by its position in the spatial interface the first responders can intuitively estimate the distance to the center of the catastrophe and plan accordingly.

5.2 Enrich Real Objects with Digital Information

When a tablet with a camera is put onto the SmartTab robot the information of the camera can be used to create a mixed reality system to enrich real objects with digital information.

Presentation Like the Tablebots[1] this can be used to add additional digital information to brochures.

Enrich Map with Digital Data An more sophisticated scenario can play out as the following:
A tour operator presents a tour to his customers using a SmartTab which is driving on top of a map of a hiking route or a city. The SmartTab automatically moves along the travel route and while moving enriches the view of the underlying map with additional information corresponding to the position, like the travelled distance or sights. The customer gains a quick and memorable overview of the route. To travel the actual route the customer gets a paper version of the map, which is cheap, durable and independent from mobile network and power. With this map the user can easily remember the previously shown route, profiting from the longevity of spatial memory as shown by Czerwinski *et al.* (Czerwinski et al. 1999).

5.3 Adjustment of the Workplace to the Situation

Save and Restore In a multi purpose office SmartTabs allow to use one workspace for multiple users. For example in a company two employees work on creating a website. Employee A works only in the mornings, employee B works in the afternoon. Both work on the same project. In the morning A creates HTML templates for a website and when he leaves work the SmartTabs automatically save their arrangement and prepare the arrangement for employee B. In the afternoon employee B takes in the same spot employee A was in in the morning and starts creating the graphics needed for the website. This way both employees have a device arrangement that suits their needs while using only one workplace.

Floating Hardware In a time where more and more people work remotely and seldom come into the office a new kind of workspace, using the power of mobile devices can be designed. This new workspace is fully adjustable and follows the principle of 'floating licencing'[2], but applied to hardware. Similar to floating software licenses the company buys only a fraction of the amount of hardware needed for all employees in a traditional setting, because most of the employees work from home and don't come into the office regularly. The

[1] TableBot Video - `https://youtu.be/PRkuGkY3buE?t=5m28s` - Online March 17, 2016
[2] Wikipedia: floating licensing - `http://en.wikipedia.org/w/index.php?title=Floating_licensing&oldid=561962956` - Online March 17, 2016

available hardware, in the form of SmartTabs, is automatically assigned to the employees that are currently in the office. In practice the system could work like this: when an employee comes to the office to work he chooses one of the places on a long desk. The system recognizes the employee automatically and as many SmartTabs as he usually uses approach him, with his latest work loaded up so that he can start working straight away. If the employee brings his own hardware for example a laptop the SmartTabs will connect to it wireless and act as auxiliary displays. As more employees fill the office the amount of free SmartTabs will deplete and when there are no more free SmartTabs new users will get SmartTabs from the users who use the most resources. This way the resources are always used optimally.

While the previous example is quite extreme the following scenario is near real world. In offices employees often work in a face-to-face setting with two tables joined together to a big one. The employees are separated by a wall of displays. When these displays were self-actuated it would be easy for one employee to use all available displays, when the other one is absent. This can increase the utilisation of the available hardware and potentially increase the employees productivity.

Another perk in this scenario is that it would be very easy for the two co-workers to talk to each other across the SmartTabs, because the SmartTabs can adjust the pitch of the displays to let the users maintain eye contact. When the co-workers are done talking the SmartTabs will retake the upright position and block the view between them.

Switch Tasks Different tasks require different display configurations. For example for writing this work I used a traditional workplace with a keyboard and two vertical displays. To draw the graphics for this section I used a horizontal display and a stylus. Changing my workplace from the writing to the drawing configuration was a tedious task and took a lot of time. After I had finished drawing I had to reverse the process to include the graphics into this work. With SmartTabs I would have the possibility to let the robots do the work of arranging my workspace for me by giving them a simple command. This would not only save time but also give me the opportunity to switch between these two tasks in repeatedly to make adjustments to the pictures easily.

Automatic Adjustment to Users From a practical perspective a desirable feature is that displays always align with the viewers viewing angle. This can be particularly useful in scenarios where the user can not use his hands to adjust the position, either because he is out of reach, his hands are occupied by holding something else or because his hands are dirty. For example if the user works in a workshop and the display shows instructions or when a user is baking and it shows the recipe. It also makes a nice addition for entertainment when doing the chores. The self adjusting display would then always follow the user and play his preferred entertainment program. This way it is possible to clean the house while being entertained. To control the SmartTab voice commands would be used to keep the users hands free.

Automatic Creation and Adjustment of Tiled Displays When creating connected displays with Connichiwa (Schreiner and Rädle 2015) the user has

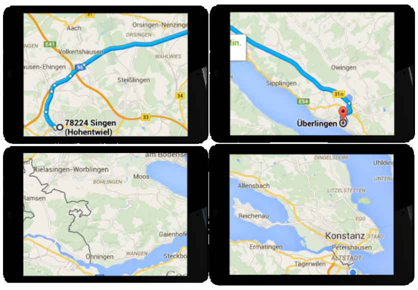

Figure 5.4: The path from Überlingen to Singen with a naive display alignment. It shows only little detail around the path.

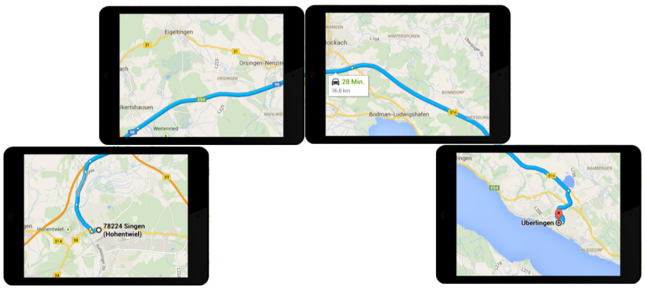

Figure 5.5: The SmartTabs automatically adjust the screens positions to account for the form of the path. This leads to a higher zoom level and therefore to a more detailed image of the route.

to place the devices next to each other and then perform a 'pinch' gesture to connect the. With SmartTabs this process becomes fully automated. The user performs a simple command and the SmartTabs automatically calculate the optimal positions and paths towards each other. Apart from the easing of the creation of tiled displays SmartTabs also can adjust their positions dynamically to the data. This feature is illustrated in figures 5.4 and 5.5.

5.4 Social Interaction

Turn Away When working on confidential information the goal is to keep this information safe when an unauthorized person enters the room. When using a laptop the natural reaction to hide the contents of the screen is often to tilt the screen down, this gesture is clearly visible to the intruder and he can react appropriately. This possibility is not given when using a desktop computer. A SmartTab can be able to detect intruders and when in 'private mode' automatically turn the screen away from the intruder so that he can not see the information. This simple social interaction lets the intruder recognize the situation naturally. After the intruder left the SmartTab automatically resumes into the previous position to let the user continue.

User Attention Control The experiments of Cynthia Breazeal *et al.* (Breazeal et al. 2007) have shown that the positioning of a display towards the user can have a effect on the attention and performance of users. This effect is easily exploitable with SmartTabs that feature repositioning the display as well as adjusting the pitch of the display.
Also movement can be used to attract the users attention to the contents on the SmartTabs display, similar to the way a waving hand in a crowd gains attention. Compared to using sound to gain the users attention movement is more subtle and does not disturb highly concentrated users. For example movement can be used to attract people to an exhibit in a museum.

> For example, a museum might learn over time how its inhabitants tend to use it and anticipate activities that it expects are about to happen. (Gross and Green 2012)

When using less subtle movements, like driving to the user from the edge of the table, the SmartTab can steer the users attention to an important event, like a video call.

Ambient Information A third way to utilize movement is to map information to the position of the SmartTab. Inspired by Ishii's "Ambient Room" (Ishii et al. 1998) the SmartTab can be used as a smart calendar. It shows the users appointments on the display and the position of the SmartTab is mapped to how far in the future the appointment is. This way an important appointment in the distance would not distract the user, because the SmartTab would be far away. When the appointment is near the SmartTab also is nearer to remind the user of the nearing appointment. Compared to a system without a display the main advantage is that the user can immediately grasp what appointment is nearing by just looking at the display, which shows the appointments data. To keep the users distraction at a minimum, when the appointment is far in the future a tablets front cameras image can be exploited to turn the display on, only when the user focusses the SmartTab. Another variable that can be mapped to the distance between the user and the SmartTab is the amount of e-mails in the inbox. When the inbox is empty the SmartTab is far away, the user does not need to bother with e-mail. And when there are many e-mails in the inbox the SmartTab is within the users reach, so that he can address the e-mails directly on the SmartTab.

Input Control A second usecase for self-actuated touch devices is input control. This means that the display actively drives out of the users reach, when no interaction is allowed and back, when the touch interface becomes active again. This interaction is a very natural and easy to understand way to interact with the user. This can be used in arcade game like machines, where the approaching screen creates affordance to interact with it.

Space Control When working together with self-adjusting devices one concern might be that the device makes an error and for example spills a glass of water that is standing on the table the SmartTab lives on. To prevent this from happening the user must be able to create areas where the SmartTab does not go. These areas could be defined with masking tape. It also would be desirable to be able to define a 'home-spot' for the SmartTab, where it rests when not needed.

Telepresence A SmartTab can also be used as a telepresence robot. The remote caller gets the control over the SmartTabs movements and he can see what the SmartTab sees through the front camera. The remote callers video feed is shown on the SmartTabs display. This was the remote user can look around in the room and for example in a meeting turn the device towards the talking person. This way the caller can see the facial expressions of every other participant and feels more involved than with a stationary display and camera.

5.5 Games

Seifert *et al.*'s implementation of a game for the Hoverpad (Seifert et al. 2014) shows impressively how self-actuated displays can be used to create mixed-reality games. These games blur the line between reality and the virtual game.

5.6 Intra Office Communication

A creativity workshop conducted with the Rack of Inspiration (Feyer 2015) has yielded the idea to use the SmartTab as a replacement for a tube-mail, to facilitate the exchange of small physical objects between offices.

Chapter 6

Conclusion

In this work we outlined the process of creating the SmartTab in a controlled manner, by repeated elicitation of requirements and testing the resulting build against these. For the latest test we conducted a successful experiment which has shown that the SmartTab is an appropriate tool for the suggested usecase. In the experiment we found no evidence for increased memory performance, but we could confirm that the navigation performance is increased when users have to engage their whole body. We also discovered that using an indirect control of the SmartTab to navigate the peephole increases the users comfort and makes spatial exploration more fun. Presenting the SmartTab to users evoked a generally positive reaction. While the experiment did not deliver groundbreaking results it opened up new questions and different viewing angles to the research question. We gave advice how to refine the study setup for future experiments to gather more profound insights.
The experiment results let us conclude that the SmartTab is an appropriate tool for spatial exploration, but the remote control still needs some polishing. Looking at the revisited requirements assessment (see 4.1) we can conclude that the SmartTab is on a good way towards more sophisticated usecases than dynamic peephole navigation. We could eliminate concerns about the insufficient speed of the SmartTab. The work done in this bachelor thesis lets us proceed with the development with confidence, towards the goal of handling multiple devices at once in a dynamic application. The usecases pictured in Chapter 5 will guide the further development of the SmartTabs.

6.1 Future Work

To elicit the necessary functions the SmartTab needs to fulfil a wide variety of usecases, we conducted another creativity workshop with the Rack of Inspiration (Feyer 2015) and concluded that the most pressing need is that the SmartTab must be able to locate itself autonomously. Therefore we will implement an odometry system using optical mice and add light sensors to the edges of the SmartTab to detect edges and changes in the surface material. This way the SmartTab is safe from dropping off the table and can distinguish between different surfaces, which allows to use masking tape to create different zones for the SmartTab. With the odometry system the SmartTab will be able to determine its relative location towards the last known position. In addition we plan on implementing an NFT-Tag reader, to mark create a low cost method for absolute localisation.

Chapter 7

Appendix

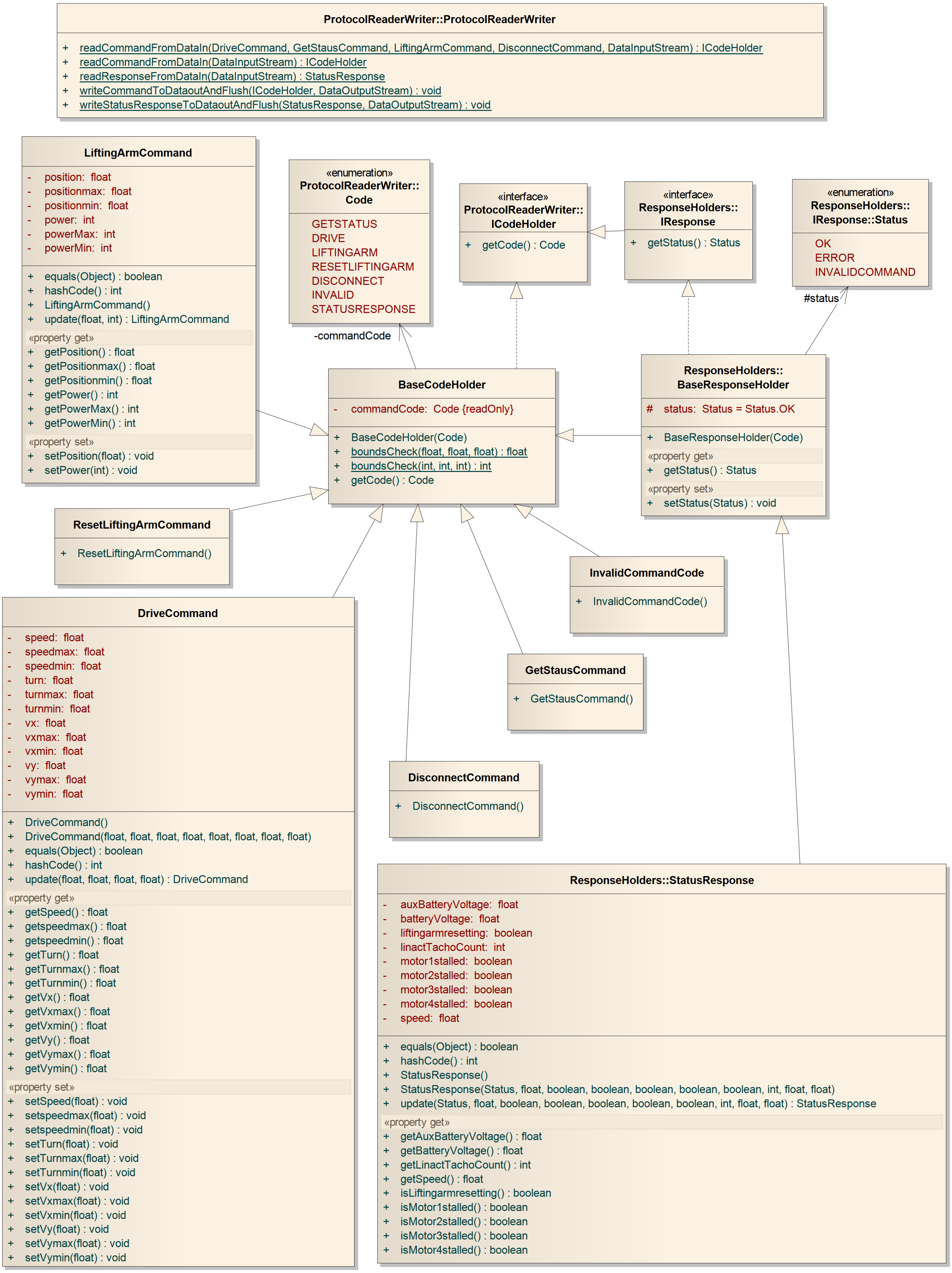

Figure 7.1: Inheritance structure of the protocol.

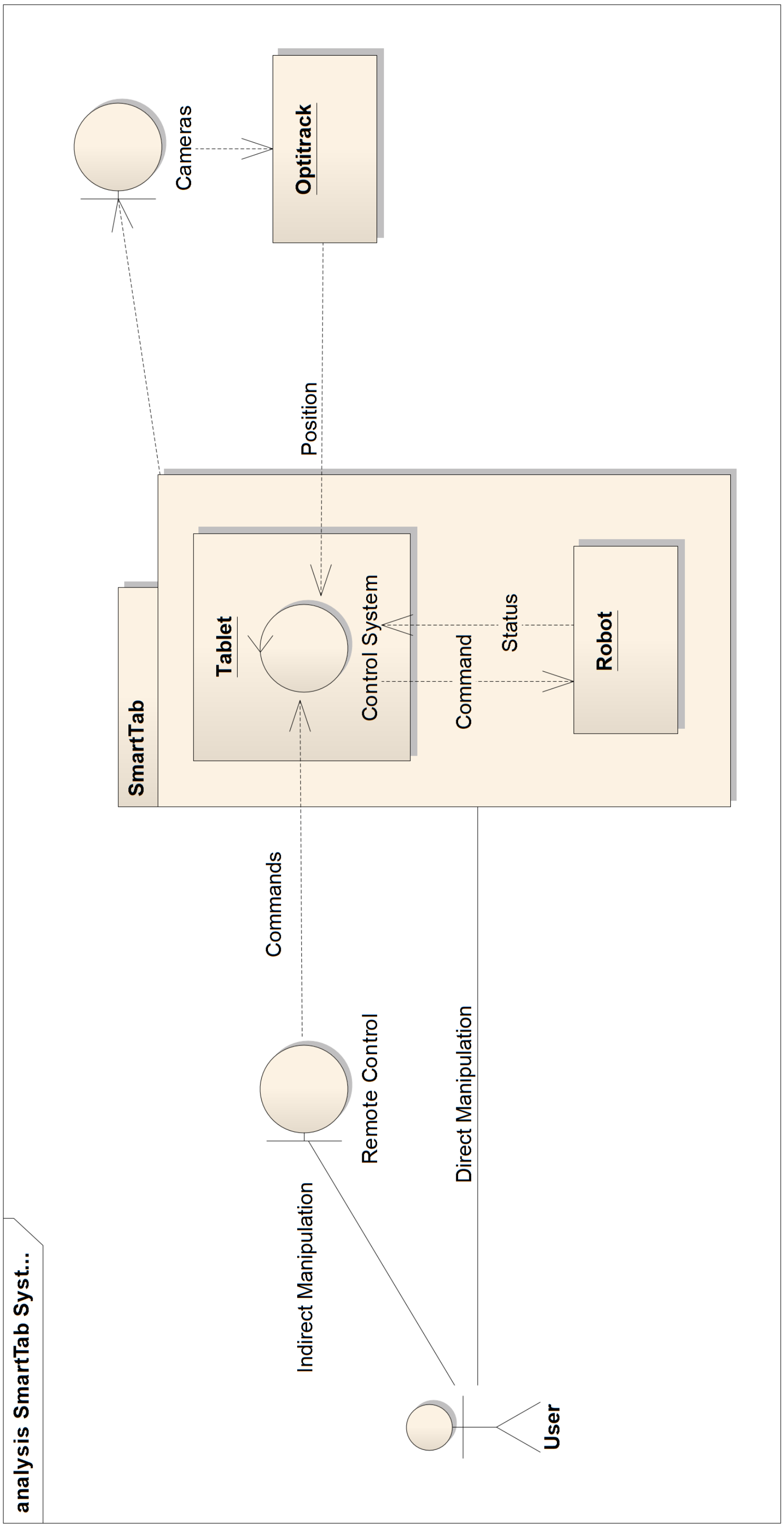

Figure 7.2: Overview of the SmartTab components and the flow of information.

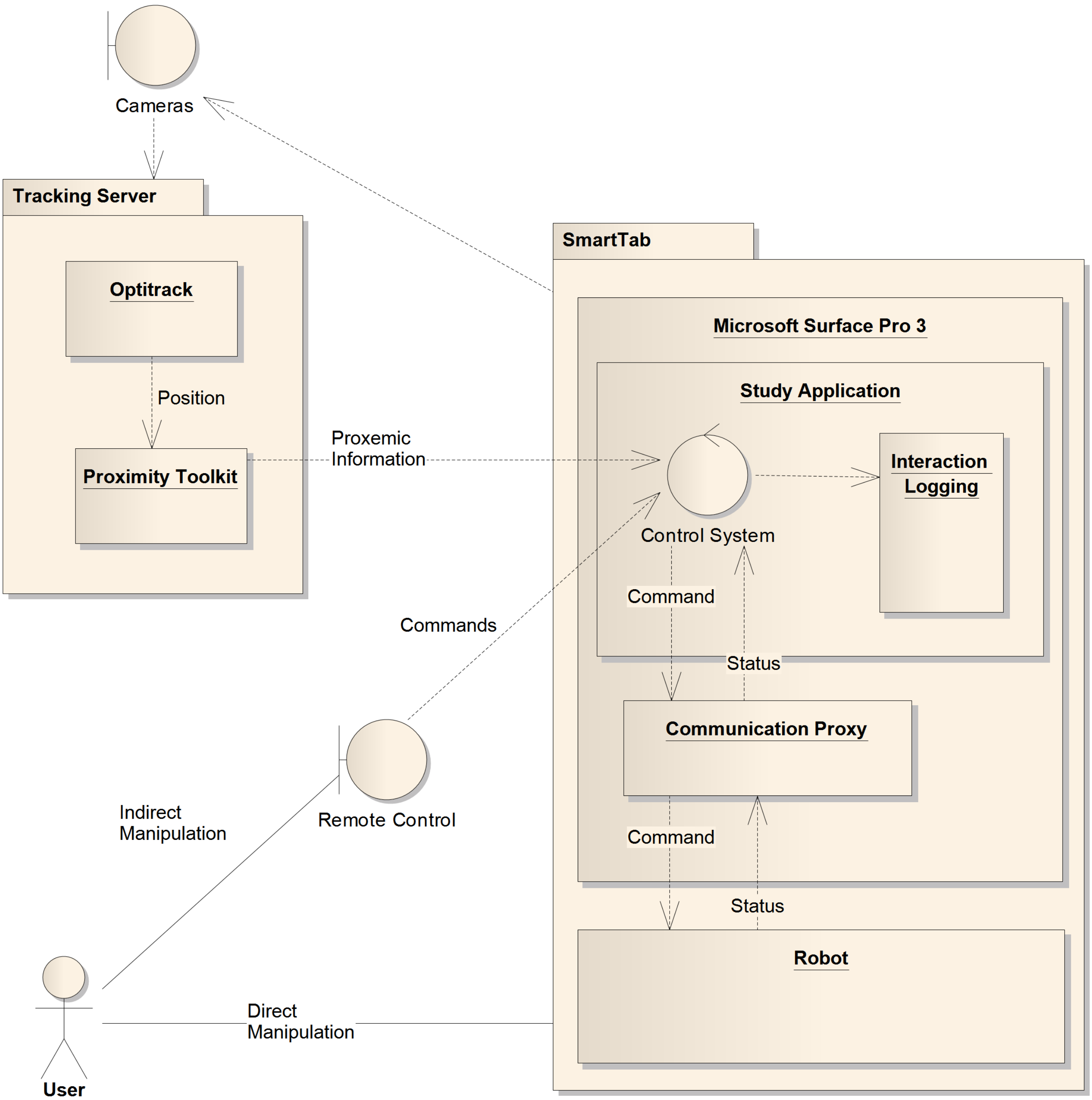

Figure 7.3: Overview of the study softwares components and the flow of information.

Bibliography

Alrøe, Tobias, Jonas Grann, Erik Grönvall, Marianne Graves Petersen, and Jesper L Rasmussen (2012). "Aerial tunes: exploring interaction qualities of mid-air displays". In: *Proceedings of the 7th Nordic Conference on Human-Computer Interaction: Making Sense Through Design*. ACM, pp. 514–523.

Bischoff, R (2011). "KUKA youBot – a milestone for education and research in mobile manipulation". In: May.

Bower, Gordon H (1970). "Analysis of a mnemonic device: Modern psychology uncovers the powerful components of an ancient system for improving memory". In: *American Scientist*, pp. 496–510.

Breazeal, Cynthia, Andrew Wang, and R Picard (2007). "Experiments with a robotic computer: body, affect and cognition interactions". In: *ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, pp. 153–160. ISSN: 2167-2121. DOI: 10.1145/1228716.1228737. URL: http://ieeexplore.ieee.org/xpls/abs%5C_all.jsp?arnumber=6251682.

Czerwinski, Mary P., Maarten van Dantzich, George Robertson, and Hunter Hoffman (1999). "The Contribution of Thumbnail Image, Mouse-over Text and Spatial Location Memory to Web Page Retrieval in 3D". In: *Press*, pp. 163–170. DOI: 10.1.1.33.774. URL: http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=94E9B4093AC910B2FD215A3EA65E04D8?doi=10.1.1.33.774%5C&rep=rep1%5C&type=pdf.

Dogar, Mehmet, Ross A Knepper, Andrew Spielberg, Changhyun Choi, Henrik I Christensen, and Daniela Rus (2016). "Towards coordinated precision assembly with robot teams". In: *Experimental Robotics*. Springer, pp. 655–669.

Feyer, Stefan (2015). *Rack of Inspiration – Design und Evaluation einer Toolbox zur Unterstützung des Inspiration Card Workshops.* bachelorsthesis.

Green, Keith Evan, L J Gugerty, I D Walker, and J C Witte (2005). "Awe (animated work environment): ambient intelligence in working life". In: *Architectura Zeitschrift Für Geschichte Der Baukunst.*

Gross, Mark D. and Keith Evan Green (2012). "Architectural robotics, inevitably". In: *Interactions* 19.1, p. 28. ISSN: 10725520. DOI: 10.1145/2065327.2065335.

Ishii, Hiroshi, Craig Wisneski, Scott Brave, Andrew Dahley, Matt Gorbet, Brygg Ullmer, and Paul Yarin (1998). "ambientROOM : Integrating Ambient Media with Architectural Space". In: pp. 1–2.

Jetter, Hans-Christian, Florian Geyer, Tobias Schwarz, and Harald Reiterer (2012). "Blended Interaction–Toward a Framework for the Design of Interactive Spaces". In: *Workshop DCIS*. Vol. 12. Citeseer.

Jetter, Hans-Christian and Harald Reiterer (2013). "Self-Organizing User Interfaces: Envisioning the Future of Ubicomp UIs". In: *Accepted paper at CHI '13 Workshop Blended Interaction.* URL: http://hci.uni-konstanz.de/blendedinteraction2013/.

Jiang, Yuhong, Joo-Hyun Song, and Amanda Rigas (2005). "High-capacity spatial contextual memory." In: *Psychonomic bulletin & review* 12.3, pp. 524–529. ISSN: 1069-9384. DOI: 10.3758/BF03193799.

Johnson, Gregory P., Gregory D. Abram, Brandt Westing, Paul Navrátil, and Kelly Gaither (2012). "DisplayCluster: An interactive visualization environment for tiled displays". In: *Proceedings - 2012 IEEE International Conference on Cluster Computing, CLUSTER 2012* Figure 1, pp. 239–247. DOI: 10.1109/CLUSTER.2012.78.

Karwowski, W and M Rahimi (1991). "Worker selection of safe speed and idle condition in simulated monitoring of two industrial robots." In: *Ergonomics* 34.March 2015, pp. 531–546. ISSN: 0014-0139. DOI: 10.1080/00140139108967335.

Krishnaprasad, Naveen K, Venkatram Vishwanath, Shalini Venkataraman, Arun G Rao, Luc Renambot, Jason Leigh, Andrew E Johnson, and Brian Davis (2004). "JuxtaView-a tool for interactive visualization of large imagery on scalable tiled displays". In: *Cluster Computing, 2004 IEEE International Conference on.* IEEE, pp. 411–420.

Lee, Jinha, Rehmi Post, and Hiroshi Ishii (2011). "ZeroN: mid-air tangible interaction enabled by computer controlled magnetic levitation". In: *Proceedings of the 24th annual ACM symposium on User interface software and technology.* ACM, pp. 327–336.

Leifert, Svenja (2013). *Theorie und experimentelle Untersuchung des Einflusses von Interaktionsdesign auf das räumliche und inhaltliche Gedächtnis.* Diplomarbeit.

Maguire, Eleanor a, Elizabeth R Valentine, John M Wilding, and Narinder Kapur (2003). "Routes to remembering: the brains behind superior memory." In: *Nature neuroscience* 6.1, pp. 90–95. ISSN: 10976256. DOI: 10.1038/nn988.

Marquardt, Nicolai, Robert Diaz-Marino, Sebastian Boring, and Saul Greenberg (2011). "The Proximity Toolkit: Prototyping Proxemic Interactions in Ubiquitous Computing Ecologies". In: *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology.* UIST '11. Santa Barbara, California, USA: ACM, pp. 315–326. ISBN: 978-1-4503-0716-1. DOI: 10.1145/2047196.2047238. URL: http://doi.acm.org/10.1145/2047196.2047238.

Mueller, Jens, Roman Rädle, Hans-Christian Jetter, and Reiterer Harald (2015). "An Experimental Comparison of Vertical and Horizontal Dynamic Peephole Navigation". In: *to appear in: Proceedings of the 33rd annual ACM conference on Human factors in computing systems (CHI '15).* ACM.

Pedersen, Esben Warming and Kasper Hornbæk (2011). "Tangible bots: Interaction with Active Tangibles in Tabletop Interfaces". In: *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI '11* 2011, p. 2975. DOI: 10.1145/1978942.1979384. URL: http://dl.acm.org/citation.cfm?id=1978942.1979384.

Rädle, Roman, Hans-Christian Jetter, Simon Butscher, and Harald Reiterer (2013). "The Effect of Egocentric Body Movements on Users' Navigation Performance and Spatial Memory in Zoomable User Interfaces". In: *In Proc.*

of ITS '13 ACM International Conference on Interactive Tabletops and Surfaces. ACM.

Rädle, Roman, Hans-Christian Jetter, Nicolai Marquardt, Harald Reiterer, and Yvonne Rogers (2014). "HuddleLamp : Spatially-Aware Mobile Displays for Ad-hoc Around-the-Table Collaboration". In:

Rubens, Calvin, Sean Braley, Antonio Gomes, Daniel Goc, Xujing Zhang, Juan-pablo Carrascal, and Roel Vertegaal. "BitDrones : + Towards + Self3Levitating + Programmable ++ Matter + Via + Interactive + 3D + Quadcopter + Displays ++". In: pp. 9–10.

Scarr, Joey (2012). *Supporting and exploiting spatial memory in user interfaces*. Vol. 6. 1, pp. 1–84. ISBN: 1100000046. DOI: 10.1561/1100000046. URL: http://www.nowpublishers.com/articles/foundations-and-trends-in-humancomputer-interaction/HCI-046.

Schreiner, Mario and Roman Rädle (2015). "Connichiwa – A Framework for Cross- Device Web Applications". In: *CHI'15 Extended Abstracts*.

Seifert, Juilan, Sebastian Boring, Christian Winkler, Florian Schaub, Fabian Schwab, Steffen Herrdum, Fabian Maier, Daniel Mayer, and Enrico Rukzio (2014). "Hover Pad : Interacting with Autonomous and Self-Actuated Displays in Space". In:

Shneiderman, Ben and Ben Shneiderman (1996). "The Eyes Have It : A Task by Data Type Taxonomy The Eyes Have It : A Task by Data Type Taxonomy for Information Visualizations". In:

Spindler, Martin and Martin Schuessler (2014). "Pinch-drag-flick vs. spatial input: rethinking zoom & pan on mobile displays". In: *Proceedings of the 32nd ...* v, pp. 1113–1122. DOI: 10.1145/2556288.2557028. URL: http://dl.acm.org/citation.cfm?id=2557028.