Doctoral Thesis

Tracking Technologies for Interactive Tabletop Surfaces

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Tracking Technologies for Interactive Tabletop Surfaces

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presented by

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2011
TRACKING TECHNOLOGIES FOR INTERACTIVE TABLETOP SURFACES

Ramon Hofer Kraner
Summer 2011
I. ABSTRACT

In team meetings a high amount of creative work is done in an analog way. Although digital devices exist in every meeting room such as projectors or displays they often lack interactivity. Especially for groups it is difficult to use devices that were designed for single person use. Large projections do not offer intuitive interaction for multiple people. Only a few tracking technologies exist that can track multiple peoples’ input concurrently, but will fail if the interactive surface is used horizontally. Most tracking systems are designed for vertical use and fail when used on a table horizontally.

Although unnoticed, tables manifest a central part in everyday office work. Cooperative work often is performed around and on tables. Tables physically support work artifacts and enable people to work in an ergonomic position and allow even multiple people to share information on it. Integration of digital interactivity into the table seems promising and is subject of the research area tabletop interactive systems.

Many researchers have set up interactive systems for tabletop interaction. The various technical solutions to solve the issues connected with the use of interactive surfaces only fulfill fractions of requirements for tabletop interaction. For example it is essential that multiple devices can be tracked concurrently without influencing each other. Additionally arm and palm resting and material that is needed for team work such as laptops, drinks and snacks need not influence the reliability of the tracking system. Multiple additional requirements such as high sampling rate and unequivocal identification of the devices are needed in order to create an intuitive and reliable work place for several people. In the first chapters of this thesis this requirements for supporting people working digitally at tables are analyzed and explored.

In a second step current research prototypes and commercial products are presented and compared by using a dedicated classification system. This classification system was set up by using the requirements and input from other publications in Human Computer Interaction (HCI) research.

None of the research prototypes or commercial technologies found, provide a comprehensive requirement satisfaction. Especially the tracking of multiple objects or touch on the table top surface seems to be difficult. Even more challenging is the simultaneous detection and separation of touch and objects on the screen. Very demanding seems also robustness against foreign objects on the screen. Many tracking systems work on vertical screens, but fail when used horizontally since then irritation by additional objects that need not to be tracked is very likely.

In this thesis a system is developed enables intuitive interaction by providing:
Simultaneous tracking of multiple users’ interactions
Detection of multiple objects and multiple touch points simultaneously
Irritation-free tracking (not disturbed by non-system-inherent objects)
Ergonomic suitability for creative team work (integrated design, large surface)

Such a system combines the advantages of multiple tracking technologies and provides a new kind of user experience. By eliminating the need for a “turn taking”-behavior the system gains intuitiveness and provides an irritation-free environment for relaxed team work. An optimized form factor (slimness) also contributes significantly to a comfortable work environment and finally a responsive system (tracking rate and lag) leads to a positive user perception, which results in increased acceptance for digital enabled work environments.

The following three technologies have been developed within this work:

**MightyTrace** features a tracking technology that is integrated into the table or more precisely inside a LC-display. It can track more than 16 devices concurrently and outperforms most tracking systems presented by other researchers. For this special high speed read out, electronics were developed and optimized for usage in tabletop scenarios.

A next prototype bases on the same technology than MightyTrace but additionally integrates touch tracking. A dedicated touch overlay can be used with the same sensors already integrated in the MightyTrace display. Touch detection is a delicate issue in HCI (Human Computer Interaction) and has been extensively analyzed. Although a (in research) very popular finger tracking technology is used for this second prototype **touch’n’tangibles** still e few issues were analyzed that have not been reported in research yet. Occlusion of finger touches is an issue that was hardly noticed in camera based setups for example.

In a next step a third prototype is presented that combines the advantage of analog and digital work - the **Digisketch** prototype. A commercially available active pen is used which is called the Anoto pen. It can track its position on an almost invisible pattern printed on paper. The challenge with this tracking technology is to make it work on LC-displays. Special films were found to design an optimal solution that still ensured a good image on the display and also enabled a reliable tracking of the pen.

Finally the three prototypes were compared in their technical performance and by their ability of fulfilling the given requirements.
II. ZUSAMMENFASSUNG


Keiner der Forschungsprototypen oder der kommerziellen Technologien bietet eine umfassende Abdeckung der Anforderungen. Vor allem die Ortung von mehreren Objekten gleichzeitig oder mehreren Berührpunkten auf der Interaktionsfläche scheint schwierig zu sein. Eine noch größere Herausforderung ist die simultane Detektion und Separation von Berührung und Objekten. Sehr anspruchsvoll ist auch die Gewährleistung von Robustheit gegen Fremdkörper auf dem Bildschirm. Viele Ortungssysteme arbeiten
einwandfrei auf vertikalen Bildschirmen, aber scheitern bei horizontaler Verwendung, da hier die Irritation von zusätzlichen systemfremden Objekten wahrscheinlich ist.

In dieser Arbeit wurden Systeme entwickelt, die eine erfolgreiche Interaktion ermöglichen, indem:

- Gleichzeitig die Interaktion von mehreren Benutzern erfasst wird
- Die Erkennung von mehreren Objekten und mehreren Berührpunkte gleichzeitig ermöglicht wird
- Die Ortungstechnik nicht von systemfremden Objekten gestört wird
- Der Interaktionsschirm ergonomisch an die Bedürfnisse von Teamarbeit angepasst ist (Integriertes Design, grosse Oberfläche)


Die folgenden drei Technologien sind im Rahmen dieser Arbeit entwickelt worden:

Die **MightyTrace Tracking-Technologie** ist in eine Tischplatte integriert worden, bzw. in ein LC-Display. Die Technik ist in der Lage, mehr als 16 Geräte gleichzeitig zu verfolgen und übertrifft somit die meisten Tracking-Systeme welche von anderen Forschern vorgestellt wurden. Die dafür erforderliche Hochgeschwindigkeitsortung wurde speziell für den Einsatz in tischbasierten Systemen entwickelt.

Ein weiterer Prototyp basiert auf der gleichen Technologie wie MightyTrace, integriert aber zusätzlich eine Detektion von mehreren Berührungen gleichzeitig. Durch eine speziell entwickelte Berührungsdetektionsvorsatzscheibe kann mit der gleichen Technik wie MightyTrace auch noch Berührung geortet werden. Berührungserkennung ist ein hochaktuelles Thema in der HCI (Human Computer Interaction) -Forschung und wurde umfassend diskutiert. Obwohl eine (in der Forschung) sehr beliebte Fingerortungstechnologie für diesen zweiten Prototyp verwendet wird, zeigt **touch’n’tangibles** einige Aspekte die noch nicht in der Forschung veröffentlicht wurden. Z.B. führt Abschattung während bestimmten Szenarien zu Problemen, die kaum in Kamera-Setups bemerkt wurden.


Abschliessend wurden die drei Prototypen miteinander verglichen, um die Erfüllungen der gestellten Anforderungen aus der Forschung zu bewerten.
This work would not have been possible without the support and encouragement of my family, friends and colleagues. Thus I want to thank all who have supported and enabled my work for the last five years.

First of all I want to thank Prof. Dr. Konrad Wegener from the Institute of machine tools and manufacturing (IWF) of the ETH Zurich for giving me the opportunity to start my thesis at inspire AG and for being my primary PhD supervisor. I have never met a person who works as much, sleeps as less and still questions as challenging as Mr. Wegener. It is always surprising how fast he is able to see the tiny uncomfortable details in the big picture.

A great part of my thanks goes to PD. Dr. Habil. Andreas Kunz from the Innovation Center Virtual Reality (ICVR) who was my primary contact person and co-supervisor and became a very good colleague while I worked on my thesis. I well appreciated his transparent and amicable lead. He showed great interest in my work and was happy to share moments of success. He was always eager to provide substantial feedback. He supported my needs for hardware and run interference for me whenever I needed it, which is something one cannot expect from every supervisor. I liked his positive, free and open way of lead and learned a lot about how to handle delicate issues in research. He provided me with a work environment that let me work very self-determined and creatively. I want to thank him for the relaxed atmosphere and all the support of any kind.

Prof. Dr. Morten Fjeld was my second co-supervisor and provided me with a lot of background information concerning publications and social networking. I guess there is hardly any person in the HCI community Morten does not know. Whenever I was looking for a paper or somebody to cite Morten knew it.

The last of my supervisors is Prof. Dr. Pavel Hora who I want to thank for kindly agreeing to take over the missing second ETH approved supervisor position which was required by the ETH for external PhD students.

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- Thomas Nescher, internship, *Qualisys Camera Evaluation and Integration*, 2007
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<td>ADC</td>
<td>Analog Digital Converter / Conversion</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge Coupled Device</td>
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<tr>
<td>CSCW</td>
<td>Computer Supported Collaborative Work</td>
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<tr>
<td>CUI</td>
<td>Command Line User Interface</td>
</tr>
<tr>
<td>DPI</td>
<td>Dots Per Inch</td>
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<tr>
<td>FET</td>
<td>Field Effect Transistor</td>
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<tr>
<td>FTIR</td>
<td>Frustrated Total Internal Reflection</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
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<td>HCI</td>
<td>Human-Computer Interaction</td>
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<tr>
<td>IR</td>
<td>Infrared</td>
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<tr>
<td>LC</td>
<td>Liquid Crystal</td>
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<tr>
<td>LCD</td>
<td>Liquid Crystal Display</td>
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<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
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<tr>
<td>MCU</td>
<td>Master Control Unit</td>
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<tr>
<td>MS</td>
<td>Microsoft</td>
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<tr>
<td>MSPS</td>
<td>Mega Samples Per Second</td>
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<tr>
<td>MT</td>
<td>Multi Touch</td>
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<td>NOF</td>
<td>Number Of</td>
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<td>RGB</td>
<td>Red Green Blue</td>
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<td>SC</td>
<td>Surface Computing</td>
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<td>SDG</td>
<td>Single Display Group work</td>
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<tr>
<td>TUI</td>
<td>Tangible User Interface</td>
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<td>USB</td>
<td>Universal Serial Bus</td>
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<td>VR</td>
<td>Virtual Reality</td>
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<tr>
<td>WYSIWYG</td>
<td>What You See Is What You Get</td>
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<td>XML</td>
<td>Extensible Markup Language</td>
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1 INTRODUCTION

1.1 TABLETOPS: RECENT AND CURRENT CHALLENGES

Scott [B1] argues that for a long time traditional tables were the preferred work environment for many planar collaboration tasks such as planning, scheduling, brainstorming, design, and layout activities. These activities base on a high degree of interactivity between the participants. Concurrent interactions are dominant and fluid transition between modes of collaboration, such as discussion, visualization, negotiation, presentation and artefact manipulation. The size and orientation of tables enables collaborators to sit around, and to spread out and to spatially organize task-related artefacts. Especially tasks that require a high amount of creativity are performed in teams, in which the creative and innovative potential can be accessed more easily by mutual influence of the participants. The general advantage of tables over wall based interaction is that all participants are able to actively access and see the information on the surface (Figure 1).

As computers become omnipresent in corporate and educational settings, access to digital information also becomes more important during such collaboration tasks. Furthermore, collaboration gains importance in
industrial business processes and the requirements for team work have increased because products become more complex and integrated. This requires that people from very different fields of expertise have to find comprehensive solutions together.

Chia Shen [B10] states that tables are an important part of social group settings. But for a long time, access to digital data was reserved for single users, interacting with their personal computer. Thus, researchers begun to realize digital data access also in tabletop collaborations in order to equip the natural way of human collaboration with the right tool. Moving from a single vertical screen to a horizontal interactive surface leads to a new way of collaboration. People do no longer have to gather in front of a small screen (See Figure 2, left) while longing for their interactive slot and trying to see the information. A large central surface is visible and directly accessible to all participants at the same time and provides a non-prefering work environment. This possibility of such a paradigm shift inspired teams of researchers all over the world to present numerous concepts and solutions to tackle the various issues arising when moving interaction from small vertical screens to large horizontal interactive surfaces.

Figure 2: Paradigm shift from personal computer to the interactive tabletop system

In 1991, Wellner et al. [B68] introduce the concept of a digital tabletop interactive system called Digital Desk, which still followed the personal workspace metaphor, but enabled access to digital data through more intuitive interaction principles. By using fingers which were tracked by a computer system, the digital desk could detect touches on a relatively large surface. The Digital Desk Calculator was a milestone under two aspects: It decoupled the interaction with digital data from traditional mouse and keyboard, which was the case ever since the first trackball DATAR [B19] and Dough Engelbart’s [B47] early prototype of the mouse. Secondly, Digital Desk moved interaction with digital data to the horizontal workspace.

Researchers’ efforts in creating an intuitively usable interactive tabletop system resulted in a wide field of different technologies and setups, addressing one or more technical challenges occurring in tabletop designs. These technical challenges are described in the following chapters.

1.1.1 DIRECT INTERACTION

Tabletop interaction is intended to provide natural interaction for a group of co-located users. Obviously, mouse and keyboard are no longer the tools of choice for collaborative work, since every user should have direct access to data manipulation. Interaction devices such as mice or trackballs do not provide a general input interface, but restrict usage to one user at a time, unless multiple mice are used. But since a mouse is
not directly linked to the curser on the screen only indirect control of the virtual representation is possible. Additionally, indirect manipulation breaks the physical link of real and virtual object movement, separating input and output channel which results in a sort of hidden, magical behavior. A touch enabled interface on the other side provides a direct experience and an intuitive and rich user experience. Other interfaces such as the commercially available Wacom [W15] pen tracking tablet, or the Mimio [W21] ultrasonic front projection tracking technology also provide means to couple input and output at the same location.

1.1.2 MULTI USER INTERACTION

Supporting simultaneous interaction for multiple users requires that the system can distinguish between different user inputs. It allows each participant to actively take part in the work process. This means that each user possesses the same amount of interaction rights and is not restricted in taking part in the process by waiting for his interactive timeslot or interaction device (turn taking). Resistive touch tracking technologies like the SmartBoard [W2] do not support multiuser interaction, since their resistive overlays will interpolate between multiple touch points. However, other products were developed out from research which support simultaneous interactions by using e.g. optical tracking technologies like the famous interactive table “Microsoft Surface” [W31].

Tracking of multiple concurrent inputs is not only required when multiple people access a digital surface, it is also needed when one user is using multiple fingers (multi touch) on a touch interface or is using several physical input devices simultaneously for a task. This can be the case when specific bi-manual gestures have to be performed such as scaling an item by moving two fingers close or away from each other.

1.1.3 HORIZONTAL SURFACES

Vertical tracking technologies have been developed mainly for single user operation, thus only able to track one input at a time. This is sufficient for most vertical use cases, since interaction is performed by standing or sitting in front of the device, activating its surface only by a single touch or interaction point. Vertical displays normally serve only as information displays such as white boards or presentation screens and do not need support for multiple user interaction, since no advanced and complex interactions are required. Typically no information editing is performed. But as soon as the interactive surface is aligned horizontally requirements change. Not only is the surface accessible from all sides which provides possible user interaction from multiple people, but also it uses the table metaphor.

Tables are used to arrange and place physical objects, to use arms, fists, fingers and elbows and to physically support any kind of object being placed on it, which leads to the fact that conventional tracking systems fail. Objects that are part of the system such as interaction devices (e.g. pens) must reliably and accurately be detected in position. But it is likely that additional objects like work artefacts, coffee mugs, ball pens, or laptops are placed on the interactive surface, although they are not part of the technical system. These objects can confuse the underlying tracking system and thus make interaction tracking difficult or even impossible. Many tracking systems that enabled an accurate interaction tracking in vertical position will fail when being placed horizontally, since the tracking technologies get disturbed by objects not intended for
use with the system. For example the Mimio [W21] ultrasonic based tracking will be influenced by objects on the screen, since the ultrasonic waves require a free line-of-sight and thus cannot propagate freely anymore. Or technologies such as projected capacitive sensing (Visual Planet [W38]) allow tracking of multiple touch points, but cannot distinguish between different objects with different dielectric constants that are misleadingly placed on the surface.

May it be the limited capability to track multiple inputs at a time, the unhandled influence from objects lying on the screen, or the limited physical strength implied by the table metaphor only few tracking systems exist that support horizontal operation.

1.1.4 DISPLAY SIZE

Tabletop displays have to be large enough to accommodate several people around the interactive table. Each participant must have access to the areas that are relevant to the interaction. Many state-of-the-art tabletop systems use back- or front-projections, since their size to price ratio is still unbeatable for diagonals above 40 inches. In the recent years, also Liquid Crystal Displays (LCD) became better in terms of size and resolution and the price went down to the range of high-end projections. Currently, up to 102” (2.7m² display area [W1]) displays are available.

1.1.5 IMAGE QUALITY

A sharp, high resolution, bright and contrast rich image supports the natural impression of the interactive surface. Projections need darkened rooms in order to provide best image quality and suffer from inadequate calibration. Recent commercially available flat panel displays provide excellent image quality and brightness that even perform well in sunny lit rooms. The flat constructions and uncomplicated usage without any need for calibration make it the display devices of the future.

1.1.6 FORM FACTOR

Many tabletop systems use optical elements like small webcams that are mounted underneath or above the screen in combination with a projector that is generating the image. But this possibility for an easy setup has its drawbacks especially for tabletop interaction. Front projections cast shadows on the surface when users are interacting. Unnatural and irritating visual feedback is the result. Back projections on the other hand provide a clear image without any interference with objects above the surface. But unfortunately the space behind the screens is reserved for the light path, which results in bulky tabletop systems that cannot comfortably seat users, since feet and legs would enter the projection pyramid.

The table height, room for legs and display size defines the ergonomic impact on the user and will significantly influence interaction experience. Especially for group work it is important that users will have access to the interactive surface without the need to stand or sit uncomfortably all the time.
1.1.7 ORIENTATION

Kruger et al. [B11] intensively analyzed the influence of rotation in tabletop collaboration. In order to not exclude users from accessing information on the screen, data has to be visible and editable from arbitrary positions around the screen. If this is not the case, some of the users are privileged with respect to interaction priority. Also the interfaces need to be recognizable in all orientations in order to give all participants a clear view of the current work focus.

1.2 RESEARCH POSITIONING

It is important to situate the field of tabletop interaction systems within current well-established research fields. The history of tabletop research is well presented by Kunz et al. [B89] and Müller-Tomfelde et al. [B7]. Figure 4 shows how this thesis fits into the broad context of human computer interaction (HCI). Within HCI, this work is part of the field of computer supported collaborative work (CSCW), in which technologies are placed that support groups of people working together. The work can further be focused on a scenario, in which people work in the same place at the same time and physically close to each other, using a common display and multiple input devices: Single display groupware (SDG). The term was initially introduced by Stewart et al. [B8] in 1999. A further refinement can be done by restricting the field to horizontal surfaces, which then would be defined by the term tabletop interactive systems. The term tabletop follows the tradition of earlier terms, such as desktop and laptop, highlighting the location of the computer or display. It was first defined in research by Dietz and Leigh [B75] and Tandler et al. [B9].
1.3 WORK SEQUENCE

The area of interactive tabletop systems focuses on the impact of tabletop interactive technology on human behavior and how this technology can be designed accordingly. The goal of this dissertation is the design of new tabletop systems. For this current state of the art interaction systems are analyzed and requirements are defined for a next generation tabletop interactive system. The development of such a tabletop system closes the gap between existing research and the next stage vision.

Four sequential stages can be identified in this thesis, earlier stages inform later ones:

- **Identification of the challenges and requirements in a tabletop system:**
  Since the challenges for tabletop systems are different from vertical interactive systems, these differences are analyzed in detail. As a result, parameters for the classification of tabletop systems are defined. Also requirements for a vertical interactive system are given.

- **Analysis of current and past technologies and products that enable tabletop interaction:**
  A comprehensive literature research exposes the whole width of available tracking and display technologies used in tabletop research with their individual working principles. This catalogue of technologies is clustered and evaluated in respect to the parameters determined before. By comparing the found technologies, the gap between a solution that fulfills all requirements found in the first stage and the current best practice is identified, which defines the area of possible improvements.

- **Development of next generation interactive tabletop systems:**
  The core of this thesis is the innovation, design and construction of new interactive systems for tabletop applications that close the gap between best practice and vision. The focus of the three developed systems lies on an integrated design approach. In fact, LC-displays are used as displaying devices and the interaction tracking system is integrated into the display in order to create a highly compact and high performing system with respect to the defined parameters. The second system is an extension to the first one and also incorporates touch detection, by using the same base electronics. Finally, a third system is developed that incorporates the tracking in the interaction device itself. In total, three new systems MightyTrace, TNT and Digisketch are presented.

- **Technical comparison of the developed systems:**
  The systems are finally compared with respect to their technical performance and parameters.
1.4 CONTRIBUTION TO RESEARCH

This dissertation contributes to the field of tabletop interaction in the following three ways:

- **Classification system for tabletop interactive systems:**
  A lot of research has been done in the field of tabletop interaction. Many different systems have been built in order to enable certain interactive work on tabletop surfaces. Some systems emerged to a commercial status, while other technologies were not introduced in research but started directly as products. By setting up a classification system, this wide field of technologies becomes more structured and the capabilities with respect to an application in tabletop surfaces are instantly accessible.

- **Hardware oriented approach for tabletop interaction:**
  In this work, a bottom-up strategy is used to build interactive systems that outperform existing hardware in the various aspects of tabletop requirements. Analyzing the requirements and the existing product properties, recommendations can be defined in order to generally improve existing designs and to a large extent independent of the application area.

- **Three state-of-the-art prototypes:**
  Each of the three prototypes developed and presented in this thesis sets a new international level in interactive tabletop systems. The prototypes’ design principles and capabilities were presented to the HCI community on international conferences in several papers, each having passed peer reviewed processes. At the time of writing, no comparable system was available with respect to the technical capabilities, neither as a commercial product nor as a research prototype.

1.5 DISSERTATION STRUCTURE

**BACKGROUND**

This thesis starts with a discussion about the background of the interactive principles concerning tabletop interaction. It is clarified how teamwork is preferably done at tables and how this can be supported by providing intuitive interaction. Different technical aspects are presented that influence intuition. Multiple concepts are presented that are relevant primarily for the realization of technical systems.

**REQUIREMENTS**

The requirements chapter focuses on facts that define a state-of-the-art interactive tabletop system. This chapter concludes with a table that defines the requirements for the development of the prototypes.

**TABLETOP TRACKING TECHNOLOGIES**
In this chapter, related work in research as well as commercial products are presented that enable tracking of user input. In the last section, the presented technologies are opposed to each other in a classification system that allows comparing the solutions under different important aspects. The chapter concludes with an analysis of the comparison and demonstrates what can be improved in the current systems. In the end, an overview about the following research prototypes is given.

MIGHTYTRACE PROTOTYPE

The development of MightyTrace will be described. This system constitutes the basis of this thesis and will be presented in detail. MightyTrace uses the fact that standard LC-displays are transparent to infrared light. Active interaction devices were developed that can be tracked in position and orientation on the surface of the LC display. Components were evaluated that allow transmission and reception of IR light through the display matrix. A lot of work was spent in designing high speed data acquisition in order to fulfill requirements for natural interaction. The final system was integrated into a 40” LC-display. Its components are presented in detail and performance results are shown. A demonstrator software was implemented to show the basic functionalities of the system.

TNT: TOUCH’N’TANGIBLES ON LC-Displays

TNT is an extension to the MightyTrace interaction system. TNT additionally allows to track multiple touch points on the surface by overlaying a touch-sensitive-IR-emissive layer. Information about the principle called FTIR is presented and the impact on the tracking quality of different parameters such as finger pressure and inclination and size of the overlay is analyzed. The analysis also served as a base to determine the optimal sensor arrangement of the MightyTrace system, thus leading to an adjusted sensor alignment of the original MightyTrace. A small prototype was developed showing the feasibility of the technology.

DIGISKETCH

Digisketch bases on a commercially available tracking technology that was developed by Anoto. In this chapter the theory of operation is presented and analyzed in details. The technology needs a compatible surface in order to track positions properly. Thus in a next step an LC-display was adapted to enable a tracking. The method leads to a good performance but also to a decrease in image quality. The effect is analyzed and discussed. A small demonstrator application is implemented using an existing framework.

1.6 DISSEMINATION

The material in this dissertation and related work of it also appears in a number of peer-reviewed papers.

1.6.1 CONFERENCE PAPERS


3) R. Hofer, T. Nescher, A. Kunz, QualiTrack: Highspeed TUI Tracking for Tabletop Applications, Interact 2009, Uppsala, Sweden, Band LNCS 5727, Nr. II, Pages 332--335,


6) C. Ganser Schwab, A. Steinemann, R. Hofer, A. Kunz, InfrActables: Supporting Collocated Group Work by Combining Pen-Based and Tangible Interaction, Proceedings of Tabletop 2007, Newport, Rhode Island, USA


1.6.2 PATENT

2 BACKGROUND

2.1 TABLES AND TEAM WORK

Tables are a central part of our everyday’s work environment. Team work is preferably performed around tables because:

- Spreading and spatial organization of task artefacts [B1] and more generally physical objects, is intuitively and easily possible because of the planar space provided. Task artefact grouping [B3] like piles and geometrical alignment [B2] is possible.
- Tables support individual work and group work; switching between these two modes is possible at any time [B4].
- At tables, task-related objects (e.g. notebooks, design plans) and non-task-related objects (e.g. beverages, mobile phones) can be used concurrently.
- Tables provide an informal and relaxed atmosphere.
- Tables offer an ergonomic and comfortable seating of multiple collaborators

Figure 5: Two persons working at a table using all sorts of additional task artefacts to organize and execute their task.
Tables support collaborative work, because they generally enable organization and distribution of resources by providing a large stable surface for artefact distribution. Collaborative work allows people to develop more complex and larger-scale solutions and provides settings, in which people can find help, support, and inspiration. For collaborative designers, sharing a work surface can enhance the design process [B5].

### 2.2 Enabling Digital Access on Tabletop Surfaces

Since the first computer was available for the public, the only possible place for digital data access was in front of a personal computer workstation. As the name indicates, this access was designed for one person only, interacting indirectly with a small vertical screen. A shift to horizontal multi-user collaborative systems is required in order to support the requirements for collaborative work in the future. From a technical point of view this shift from vertical to horizontal interaction is not only a physical one. Many challenges have to be mastered to enable collaborative work in the horizontal layer. Beside a paradigm shift from serial to parallel work, it requires that the interactive horizontal space lives up to users expectations. That is, after decades of collaboration around regular tables, people have developed and partly standardized human communication skills, gestures, turn-taking and object manipulation on and around such tables. When integrating computer technology into tables, designers must make sure to support such work modes.

Tabletop surfaces need to be equipped with digital data access in order to support team work in the future. In the next chapters, different aspects of how to achieve such digital surfaces that support intuitive multiuser interaction are illuminated.

According to Scott et al. [B12], the tabletop research area can be divided in four distinct groups of digital tabletop systems:

- **Digital desks**: Replacement for individual’s traditional desks.
- **Work benches**: Semi-immersive virtual reality environments above the table surface.
- **Drafting tables**: Inclined surface as a digital drafters or artist’s table.
- **Collaboration tables**: Support small group collaborative activities, such as design reviews, planning or similar.

This thesis focuses on the latter of the above groups; collaborative tables.

### 2.3 Direct Manipulation

What is today considered to be self-evident in HCI, was not in the mid 1980ies. Computer systems were used by text entry on a console invoking an action; this was called the CUI (Command Line User Interface). Shneiderman [B39] later described the natural approach of direct manipulation, in which a physical action has direct impact on the output at the same location and time. Control over the computer is performed directly, while CUIs for example require a relatively high level of abstraction and learning.
The term “direct manipulation” was coined by Shneiderman in 1982. He defined direct manipulation as a style of interaction characterized by the following properties according to Frohlich [B40]:

1. Continuous representation of the object of interest,
2. Physical actions or labeled buttons instead of complex syntax, and
3. Rapid incremental reversible operations, whose impact on the object of interest is immediately visible.

Summarizing the above three stage definition it can be stated that:

- **Direct manipulation is input, generating output at the same time and place.**

The Wacom tablet [W15] is a good example on a direct manipulation device. It mimics analogue pen and paper interaction by tracking a pen’s position, pressure and inclination directly on a high resolution LC-display (see Figure 6).

![Figure 6: Wacom Cintiq high-resolution tablet for direct manipulation [F6]](image)

The mouse on the contrary is an example for an indirect manipulation. A mouse will not provide coinciding action-perception spaces. While relative input is done by relative motion on a small area, the resulting feedback is visually rendered on a screen in absolute coordinates separated from the input location. Hence, the mouse’s physical housing is separated from the virtual representation. In spite of most users’ long experience with the mouse, this separation remains noticeable when the mouse is used for drawing or handwriting. Then, the effect becomes visible that the action-perception space is completely separated from the input space.

Fishkin et al. [B38] proposed devices that provide “really direct manipulation”. Handheld devices such as PDAs were used to show direct manipulation techniques. For example, the turning of pages in the physical space is done by flipping over the pages. By slightly tilting the PDA towards the desired direction of navigation in the book, it will turn over the virtual page on the PDAs display. Today, such interaction principles have already been implemented in games running on commercially available devices like the Apple iPhone [W19]. There, a marble can be controlled through a labyrinth by tilting and rolling the entire device.
2.3.1 TANGIBILITY

FROM CUIS TO TUIS

In the very early days of computing, users had to interact with computers by entering text into a command line. In 1973, Xerox PARC [W1] developed the Alto personal computer, thereby providing the first graphical user interface (GUI). More than ten years later, Macintosh released its first commercially successful product to use a GUI. The desktop metaphor was used to spatially organize and align documents and files on the screen. Apple defined the "What You See Is What You Get" (WYSIWYG) paradigm, documented in their "Human Interface Guidelines" [B45]. Although GUIs mark a significant improvement over the command line interfaces (CUI) in transcending from textual language to symbolic language, thereby supporting user input as a visual manipulative activity. Still though, GUIs are isolated from the physical or tangible world. GUIs only trigger the visual channel making the interface to the computer primarily a visual medium. The virtual desktop is a representation of artefacts in the real office workplace [B46]. Virtual documents and folders are used as containers for information like real papers and books.

Users may find an interface very intuitive\(^1\) if it calls upon usage patterns similar to those we already know and master. Intuitive interactions are often based on decisions that do not require reasoning. Writing with the mouse will not be very intuitive since it is not designed and used for writing, while using a pen will be highly intuitive to most users. Also a pen will reveal its function instantly by its shape. Everyday tools such as mugs or scissors are recognized by their shape and will express their inherent function by their shape. Interactive systems can be designed similarly to this principle. By designing the system in such a way that users can mainly rely on learned experienced patterns, it becomes more intuitive. New interaction paradigms will have to base to a large extend on known patterns in order to be intuitive to users.

Of course, specialized input devices that only serve one function are not universally usable. There is always a tradeoff between intuition and universality of an input device. A mouse is one of the most universally usable devices. Its design is optimized for just one purpose: ergonomic usability. Its shape has no meaning, it only serves as a comfortable physical hand rest, but its function can be very different.

Research into more intuitive and direct interaction with computers has led to a field called tangible user interfaces (TUI). Since the invention of Durell Bishop’s marble answering machine (MAM) [B33], TUIs have become an important field in HCI research. MAM uses marbles as message storage elements. Marbles are associated with single messages left on the answering machine – by dropping the desired marble into a bowl, associated messages can be played back or the caller is called back. This instantiation of a message into a marble enables a graspable access to digital information. According to Ishii, TUIs are user interfaces that “augment the real physical world by coupling digital information to everyday physical objects and environments” [B34], and in a more recent work: “A Tangible User Interface gives physical form to digital information and computation” [B35].

The background for using tangible user interfaces stems from the observation that mankind has ever since developed skills for sensing and manipulating their physical environment. Tangibility helps to understand the world and its content. Experience patterns and the feedback through the body’s senses determine

\(^1\) According to the Oxford English Dictionary: “Intuition is the apparent ability to acquire knowledge without inference or the use of reason”

\(^2\) Another framework that is not discussed here was presented by Hornecker et al. in 2006 [B36]
information such as weight, shape, structure, consistency, hardness, dynamic behavior or temperature of an object very fast. TUIs take advantage of such skills in order to connect the digital and the real world through the graspability of digital information.

Many researchers described and developed TUIs in their work. Among them, Fishkin [B42] developed a taxonomy for the characterization of TUIs and also proposed a very broad three state characterization for TUIs²:

1. An input event occurs in the form of a physical manipulation, such as tilting, shaking, squeezing, pushing, or, most often, moving.

2. A computer system senses this input event, and alters its state.

3. The system provides feedback: It alters its display surface, grows, shrinks, makes a sound, gives haptic feedback, etc.

To visualize this sequence of action involved in TUI handling, a work from Underkoffler et al.[B37] is cited here: The authors built Urp (Urban Planning Workstation) which used scaled physical buildings to configure and control an urban simulation of lights, shadows, wind flow etc. A clock TUI represented the position of the sun, while a material wand was used to change the building’s surface. An anemometer and a wind tool could be used to measure and adjust wind speed and direction. The shadows and wind flows around the buildings would be computed by the system according to the measured input of rotation and translation of the TUIs. Finally, the winds and shadows were projected onto the table to visualize their intensity and direction. None of the TUIs was meant to influence something else as what it was designed for. Their inherent function was defined by their representation. These TUIs were used in a very specific way since their physical shape was designed accordingly.

In contrast to a very unspecific mouse, TUIs are not universally usable since they were only designed for specific functions. In setups where TUIs are misused as a general input device for functions they are not intended for, the usage of more general but less intuitive devices must be considered. Often a pen is used as a cursor replacement, but this disturbs the association of writing and the shape of the pen.

In conclusion, TUIs can take on any shape that serves a particular usage in the interactive system. In general, TUIs provide a physical interface to a specific function of a system. Even buttons and switches can be considered as a tangible interface. According to this view, also pen input devices are considered as tangible user interfaces.

**TOUCH**

Touch is very intuitive to us. People use pointing and touching a lot in daily work. Touch technology has been developed since the early 1970ies, when the PLATO IV touch-screen terminal was presented. It included a 16-by-16 grid infrared touch panel allowing students to answer questions by touching anywhere on the screen. It was able to detect one touch point at a time resulting from direct interaction on the screen. Also at this time, one of the first patents mentioning touch detection was issued to Sam Hurst, who patented the Elograph [B114]. In the 1980ies, touch became more popular when the Sensor Frame [B113]

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² Another frame work that is not discussed here was presented by Hornecker et al. in 2006 [B36]
was presented which could also detect finger inclination angles when entering the screen. Also within this time, one of the first multi touch sensing devices was developed by Lee et al. [B67]. It could only be used indirectly by touching a pad, generating output on a separate screen. At the same time, Kasday [B115] enabled direct multi touch on CRT-displays. These devices were far before their time and were not successfully commercialized. This was also due to lacks in supporting software and operating systems that were not able to integrate multi-touch paradigms in their usability concepts. In 2005, Han [B86] presented a way of easily detecting multi-touch by using the well-known phenomenon of frustrated total internal reflection. Since then multi-touch detection has gathered a large community and many systems have been presented using different detection technologies.

The touch detection systems can be distinguished into single- and multi-touch. Single-touch systems can only detect one input location at a time. Multiple touch points on single-touch systems are either detected as one touch point or confuse the system or are interpolated in some sort of way depending on the technology.

Multi-touch systems can detect multiple synchronous touch points, whereas the resolution of the tracking defines its accuracy and ability to distinguish between close touch points. Multi-touch technologies incorporate several design challenges because of the plurality of concurrent input. Since multi-touch systems extend the interactivity, more complex interactions are possible. Gestures can be performed and bimanual input can generate totally new interactive paradigms. For example, it is not only important to know where a touch occurred, but also to which hand the touch belongs and which fingers are used. Path tracking algorithms make sure each finger is identified for the time it is interacting. Furthermore, it becomes challenging to prevent the system from detecting palm resting as input. It is demanding to detect palms reliably and distinguish their input from intentional pointing or develop a touch technology that only reacts on finger tips. The challenges here are shifted more towards the interpretation algorithms than to the hardware.

Figure 7: Multi-touch screen [F7]
TAXONOMY FOR INTERACTION DEVICES

In order to characterize and classify tangible user interfaces in general, Fishkin [B42] proposed a taxonomy based on the parameters ‘metaphor’ and ‘embodiment’.

Figure 8: Examples arranged in the taxonomy space for TUIs. The area where direct manipulation is allocated is marked.

Embodiment characterizes the degree of merging input and output in a user interface. A question to this according to Fishkin is: “To what extent does the user think of the state of computation as being embodied within a particular physical housing?” The author divided the embodiment axis into four intervals (1-4):

1. **Full**: The output device is the input device. Example: The iPhone [W19] with its inclination sensor will control a virtual ball on the screen if the user tilts and rolls the whole mobile phone, which itself is the output screen.

2. **Nearby**: The output takes place near the input. The output is tightly coupled to the focus of the input. Here, most of the classical TUI applications are located, like the above mentioned Urp [B37] or photo cube [B43], in which users can access particular web pages by placing a cube onto the screen with the corresponding link picture exposed on top.

3. **Environmental**: The output is around the user. A typical interface would be audio signals upon user input.

4. **Distant**: The output is over there, on another screen. An example is the cube interface by Block et al. [B44], which a user can turn and move to select content on a TV screen.

The other axis is slightly more abstract and defines levels of metaphors for a TUI. A TUI can invoke different metaphorical links to a user by means of shape, size, color, weight, smell, and texture. The links can in total

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3Metaphor (Oxford dictionary): A figure of speech in which a word or phrase is applied to something to which it is not literally applicable (e.g. food for thought)
provide a certain level of metaphors that can be divided in the following five intervals (1-5) along the metaphor axis:

1. **None**: No metaphorical links available. Example: Virtual pictures can be resized and enlarged, while real pictures do not scale.

2. **Noun**: The shape / physical properties of the object. An "X" in the system is like an "X" in the real world. Example: real and virtual dictionary.

3. **Verb**: The motion of the object. "X"-ing an "A" in our system is like "X"-ing something “A-ish” in the real world.

4. **Noun and Verb**: Motion and shape match. Example: Urp [B37]

5. **Full**: The virtual system is the physical system. Example: iPhone or “really direct manipulation” [B38] of a PDA like input device.

This broad space of classification gives a bird’s eye perspective of physical and tangible interaction. Based on this classification Figure 8 offers a few examples of areas with their expected potential. Additionally, the area is marked where direct manipulation is defined. Below that area, input and output are separated. Output is no longer displayed or generated on the tangible user interface itself but is generated in a distance. Direct manipulation can be placed in the metaphor - embodiment space as the area including all metaphor domains that lie within the nearby and full embodiment.

### 2.3.2 SAMPLING RATE AND LAG

Human computer interaction works in a two way manner. Users are bound in the closed-loop system of input and output and actions based on subsequent inputs. Performance is unsurprisingly influenced by system lags. In scenarios of text editing or curser movement in word processing, lags are of minor importance. In applications, in which real time responses are required such as graphic feedback, lags can considerably affect performance. Especially in direct manipulation setups, lag and sampling rate can affect the usability of a system considerably. More precisely, lag can even be considered as a degree of directness of the particular system. Card et al. [B60] as well as Ware et al. [B61] showed that lags should preferably be smaller than 50 ms for virtual reality setups, where head movement had to be in synchronization with interaction. According to MacKenzie et al., it should even be around 25 ms in order to almost not be perceivable. At 75 ms the effect of a slight performance decrease can be shown. Above 100 ms, users’ error rates will increase substantially - for example by 214 % at 225 ms. Thus, for a direct manipulation system, the maximum value of 100 ms for lag is the absolute maximal threshold and essential for quasi-natural perception. Note, that for vibro-tactile perception this value decreases down to only a few milliseconds [B63].

In contrast to the lag, the sampling rate will determine the number of updated positions and state information per time (see Figure 9). If the sampling rate is too low, the user’s performance will also decrease because the movement cannot be mapped to the virtual world correctly anymore. In other words, sampling
rate defines the degree of movement mapping. MacKenzie et al. [B64] state that typical sampling rates should lie preferably above 20 Hz. High end systems for tabletop interaction track up to 280 samples per second. Such a system was presented by Hofer et. al in [OP3]. The system builds up on the InfrActables framework [OP6] and is able to identifying multiple interaction devices, while also detecting their position, orientation and status at this sample rate.

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Concluding, the following two statements can be made:

- **Sampling rate** = Degree of mapping
- **Lag** = Lack of direct coupling

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### 2.3.3 TRACKING AND DISPLAY RESOLUTION, ACCURACY

Resolution in tabletop systems can be an issue if high precision tasks have to be performed. Depending on the display resolution, it can become very tedious to select very small targets, especially if the display resolution is higher than the tracking resolution. In general it can be said that the two resolutions should be in the same range. There exists no literature, and further research has to be done to exactly determine the amount of needed accuracy for a special task.

For current products one end of the scale are high precision tracking devices like the Wacom tablet, which features up to 508 dpi resolution, while on the other end of the scale systems like the VIP interactive foil [W38] exist, which only features touch detection resolutions of 8.4 dpi.
2.3.4 DETECTION MODALITIES

THREE STATE MODEL

Direct input from the user can be divided into several different distinct states. Bill Buxton [B27] defined a three-state model for input devices. This model is still valid although it was designed back in 1990. He defined three basic states for input devices:

1) **Out of Range**: Input is not detected by the system because the device or the user is not in the range of detection.

2) **Tracking**: Tracking is the state in which the input is detected and its motion and location can be determined. It becomes more apparent if the term hovering is used, since in most input devices tracking will be the state in which the device hovers closely above the screen without touching the surface. The position information is available to the system. This state can even be extended by taking height information into account allowing the system to distinguish between different tracking/hovering states. The hovering state is used to feedback the current position detection of the system to the user, e.g. by displaying the cursor underneath the device’s position. Grossman et al. [B28] propose Hover Widgets to use the tracking state for an extended interaction. Also Fitzmaurice et al. propose “Tracking menus” for an extended interaction using the tracking state extensively [B29]. Hinckley et al. [B30] on the other side presented a combined interaction by using a touchpad and a Wacom tablet pen to design specific hovering interaction. By mapping a distinct touch pressure to the tracking state, Benko et al. [B31] realized a multi-touch tracking system that emulated the tracking state.

3) **Dragging**: When being in dragging state, the user activates the input device in order to drag or select objects on the screen. Clicking is likely to be considered as an own state, but the state dragging does not depend on the movement but only on the activation of the input device, thus also including a click. Dragging activates the device’s associated function like drawing or picking up information.
Not every input device provides the full set of these three states. In Table 1, some state model examples are shown for different common input devices.

<table>
<thead>
<tr>
<th>State model</th>
<th>Input device and its behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mouse</strong></td>
<td>A single button mouse will basically toggle between two states of input. When the mouse is moved, it always determines its relative motion and delivers this data to the system. Thus, the system is always capable of determining a position remaining in tracking state. As soon as the button is clicked the mouse state is changed to dragging.</td>
</tr>
<tr>
<td><strong>Touch screen</strong></td>
<td>Touch screens are basically not able to provide any tracking state detection. A touch of the user will directly cause a transition from out of range to dragging state.</td>
</tr>
<tr>
<td><strong>Tablet Stylus</strong></td>
<td>A tablet PC stylus will incorporate three states, since its position can be detected even if the pen is hovering above the surface, in the tracking state. Only moving the stylus out of the detection area or clicking the tip will leave the tracking state.</td>
</tr>
</tbody>
</table>

**Table 1**: Examples of state models for different input devices according to Buxton [B27]

**ADDITIONAL INHERENT INPUT ON THE INTERACTION DEVICE**

Additional modalities are possible for more advanced direct manipulation systems. Within the above state models, additional inputs on the interaction device itself are not comprehended. If users can press for example buttons on the device, they will alter its inherent state. The above three state model can be extended by a state number four “+Input” that monitors input on the device, thus enabling additional input on the device. As an example, the notepad tool from the InfrActables [OP6] is shown in Figure 10. A user is expanding a note stored “inside” the notepad by clicking its button on the side.
IDENTIFICATION OF THE INTERACTION DEVICE

Some systems allow the identification of the interaction device. This is important for multi-device interactive surfaces. Accurate mapping of the devices to their individual virtual representation have to be made in order to allow intuitive interaction. It has to be made sure that a color storing ring (see Figure 11) for example always represents its function by displaying the current color inside the ring. If this is confounded with a representation of another tool like a notepad (see Figure 10) that displays a note, the system becomes meaningless. Another example of unequivocal identification is that users have to be sure that the red pen is always the red pen.

ORIENTATION OF THE INTERACTION DEVICE

The last modality for tracking user input will describe the orientation of the input device. Orientation is important in multiuser environments, since the users are positioned around the interactive surface and need to recognize interacting devices and their function from any angle of view. For this, the devices need to be rotated, which also means that their virtual representation needs to follow this rotation. This is only possible by tracking the orientation of a device and mapping the virtual representation correctly to the physical alignment.
SUMMARY OF DETECTION MODALITIES

In this thesis, the following naming scheme for different detection modalities is used (see Table 2):

<table>
<thead>
<tr>
<th>Keyword</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track state</td>
<td>Position tracking when hovering</td>
</tr>
<tr>
<td>Drag state</td>
<td>Position tracking when touching</td>
</tr>
<tr>
<td>+ Input</td>
<td>Inherent input, additional input on the device</td>
</tr>
<tr>
<td>Identification</td>
<td>unambiguous identification</td>
</tr>
<tr>
<td>Orientation</td>
<td>Tracking of orientation</td>
</tr>
</tbody>
</table>

Table 2: Naming convention for the different modalities

2.3.5 METHOD FOR THE TAXONOMY OF DEVICE MODALITIES

Card et al [B41] developed a taxonomy for input devices. It is based on a technical approach. The authors define several physical properties that can be detected by sensors in order to allow humans to generate physical input on a computer system. Position, rotation, force, and torque are used to span a multi-domain space (Figure 13). Each physical movement can be separated into its direction and coordinates in space, and into the resolution that can be detected. An input device is integrated using several circles that mark properties in the particular domain and in the provided resolution. The connections among the circles define the input device’s composition. If the connection is a dotted line, it defines an attached property such as a button on the mouse.

Card’s model is capable of mapping the **track and the drag state** by indicating the system’s ability to detect positions in the z direction. For a binary behavior like a resistive touch screen, the user’s finger is either detected in the drag state or is out of range - there will be no indication on the z axis. For a Wacom™ tablet the pen’s hovering capability is indicated in the z domain. Also an **inherent state** detection can be mapped by layout compositions including buttons, which has been done for the mouse and its three buttons in Figure 13. **Orientation** sensing can be identified by marks in the rotary domain. However, the capability of
identifying the TUI cannot be used within this taxonomy. Figure 13 shows the allocation with respect to the taxonomy of Card for different common interaction devices.

<table>
<thead>
<tr>
<th>Linear</th>
<th>Rotary</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>rX</td>
</tr>
<tr>
<td>Y</td>
<td>rY</td>
</tr>
<tr>
<td>Z</td>
<td>rZ</td>
</tr>
</tbody>
</table>

Position
- Wacom tablet
- Touch screen
- InfrActables notepad TUI

Rotation
- Joystick
- Button
- Button

Relative position
- Mouse

Relative rotation
- Force
- Torque

Relative force
- Force
- Torque

1 10 100 inf 1 10 100 inf 1 10 100 inf 1 10 100 inf 1 10 100 inf 1 10 100 inf

Figure 13: Input device taxonomy according to [B41]. Upper horizontal scale shows degrees of freedom (DOF) in interaction in x, y, z and rotation around x-, y-, z-axis; each of the six bottom sub-scales indicates the number of values that are sensed per DOF. The left-hand scale shows transfer functions for x, y, z, taking absolute position, relative position, absolute force, or relative force as input. The right-hand scale shows transfer functions for rotation around x-, y, z-axis, taking absolute rotation, relative rotation, absolute torque, or relative torque as input. In bold, the allocation of an InfrActables tangible user interface (TUI) presented in [OP6]
At this stage requirements for a tabletop interactive system are selected. The requirements are collected out from research publications presented before and from standards recorded in the ISO standards (International Organization for Standardization) collections. At the end of the chapter a table will give an overview about the selected requirements and their sources.

### 3.1 SYSTEM FOCUS

This thesis will focus on enabling technologies for interactive tabletop systems. The goal is to develop a visionary system that incorporates requirements and suggestions of current research works.

In order to position the content of this thesis, the metaphor-embodiment space of the “Fishkin device taxonomy space” is used. Tabletop interactive systems will only cover a fraction of the metaphor-embodiment space in Figure 14.

![Figure 14: Classification of this thesis according to the taxonomy presented by Fishkin [B42] and some examples placed on the map.](image)
Tabletop interactive surfaces will show output as a response to a user input on the interactive surface. The interactive surface is an input element itself, thus providing output that is nearby the input of the user.

In order to describe each envisioned area of this thesis, the four crossings in the embodiment-metaphor space that lie within the area of the thesis are described and examples are given:

- **Metaphors in the noun domain** crossing the nearby area will manifest in having the shape of tools that are used in real world but are not used like such in the virtual world.
  Example: A physical key is used as a drawing tool, but the key is normally used for locking and unlocking.

- **Metaphors in the verb domain** will use motion of real world objects transferred to virtual objects.
  Example: The rotation of an arbitrarily shaped object (e.g. a cube) adjusts the color intensity of a virtual object, e.g. an image.

- **Metaphors in the noun and verb domain** will combine both properties.
  Example: A wheel is used for changing the rotation of a virtual object (e.g. a bike's wheel).

- **Metaphors in the full domain** will react holistically.
  Example: A wheel shaped dial changes the rotation of its virtual wheel representation by rotation.

### 3.2 SYSTEM REQUIREMENTS

1) **Real time capability and tracking**

The requirement for supporting direct manipulation is implicitly comprised in tabletop interaction. Müller-Tomfelde et al. [B7] propose a “reliable real-time multi-user capability” for direct manipulation systems. Requirements for direct manipulation from the previous chapter are repeated to specify the above statement:

- R1: The sampling rate should be above 20 Hz
- R2: The lag should not exceed 50 ms
- R3: Interaction devices have to be unambiguously identifiable
- R4: Interaction devices have to be tracked in position
- R5: Dragging and tracking state should be identified

1990 Scott et al. [B12] identified eight essential issues that are important to consider when designing tabletop interactive systems. The authors analyzed various papers published in this area to find the following guidelines. Deviated from these guidelines, requirements for this thesis are generated. Also Fjeld et al. [B13] defined similar guidelines later in 2002, which include to a large extent similar findings to Scott. Even in the ISO 9241-16 [B24] standard for direct manipulation devices, some of these aspects were assimilated.
2) **Support interpersonal interaction**

Beside Scott et al. also Elwarts-Keys et al. [B14] state that technology must not disturb interpersonal contact and shouldn’t hinder conversation. Projection systems often require users to stand or sit non-ergonomically for longer periods of time, potentially impacting the comfort level of users and the naturalness of the interactions. Also Müller-Tomfelde et al. [B7] propose to consider “low spatial requirements when integrating direct-interaction devices into displays”. Thus space requirements of the interactive system have to be chosen in such a manner, that the users are not constrained in their ergonomic needs. In other words space for legs when seated at the table has to be large enough, which is defined in the ISO standards.

**Requirements derived:**

- **R6:** Provide comfortable seating as defined in the DIN EN 527-1 [B24]:
  
  - Standard table height: 740 ± 20 mm
  - Space for legs: minimal 620 mm
  - Depth of interactive surface: 120 ± 20 mm

3) **Support fluid transitions between activities**

Technology should not impose excessive overhead on switching between activities performed on a table, such as writing, drawing and manipulating artifacts. For example, paint programs often distinguish between text editing and graphical input, forcing the user to explicitly indicate his intention to write or draw. Studies of traditional tabletop design sessions [B15] revealed that people do not make this distinction and that they rapidly transition back and forth between writing and drawing. Technologies that support rapid and intuitive switching between activities are preferred. On one side this can be realized by designing applications that do not require explicit indication of a change of activities. On the other side this can be done by providing hardware in the case of TUIs that enable detecting and switching activities by sensors that are related to the activity. An example is the pen. As soon as the pen is pressed onto the surface it starts writing. Otherwise it is used for pointing.

**Requirements derived:**

- **R7:** Provide the possibility for inherent function change (state change on the device)

4) **Support transitions between personal and group work**

Possibilities for partitioning the workspace into areas of collaboration and of personal task editing like work on a laptop or sketching in a notebook is important.

**Requirements derived:**

- **R8:** Provide space for additional task artefacts, by enlarging the interactive surface. In DIN EN 527-1 [B24] recommendations for standard work environments are defined:
  
  - Standard table length: 1600 mm
  - Table width: 800 mm
5) **Support transitions between tabletop collaboration and external work**

Users of a tabletop system should be able to incorporate work that has been done outside the tabletop system. Accessing and retrieving files and other digital data from an external device is often cumbersome. Importing and exporting data should be designed intuitively, allowing a fast and direct data transfer. Off-the-shelf software is preferred. According to [W54] the Windows operating system (OS) covers 89% of OS usage (Windows 7 (17%), XP (49%), Vista (19%)).

**Requirements derived:**

- R9: Use off-the-shelf software if possible
- R10: Compatible with Microsoft Windows

6) **Support the use of physical objects**

Tabletop systems must support the familiar practices of using any physical object that is either task related or not. Identification of the object inherent function (when being used as an interaction device) is envisioned. But at the same time, the system must allow user to interact with objects that are not interpreted by the system (e.g. notebooks, coffee mugs, paper markers...)

**Requirements derived:**

- R11: Provide specialized input devices with their inherent functions easily identifiable by their shapes: Use tangible user interfaces (TUI) instead of GUIs.
- R12: Provide system’s immunity against tracking of non task-related objects

7) **Provide shared access to physical and digital objects**

All physical and digital task artefacts have to be accessible for all group members. Orientation and occlusion can become an issue. While orientation can penalize individual participants while trying to read text upside down, occlusion can even block people from seeing information since a collaborator is casting a shadow onto the surface of a front projection.

**Requirements derived:**

- R13: Use thin display devices. Do not use projections.
- R14: Provide orientation independent user interfaces (track orientation of interaction).

8) **Consider the appropriate arrangements of users**

People typically have various “distance zones” at which they interact comfortably with others [B6]. Interaction at “intimate” distances for prolonged periods will often feel socially awkward. People generally feel comfortable working at “arm’s length” since this preserves their personal space. Müller-Tomfelde et al. argue that display diagonals for tabletop interaction should lie above 40 inches (1020 mm). Again, orientation becomes an issue when users have to enter the “intimate” space of another user to recognize and access an object or information on the table.
### Requirements derived:

- **R15**: Provide a surface large enough for the supported group size (min. 40"
- **R16**: Allow users to access every area of the interactive surface
- **R17**: Allow the tracking of orientation of interaction devices or allow variable virtual interface element rotation.

### 9) Support simultaneous user actions

In systems, in which no simultaneous interaction is possible, people are forced to stick to the turn-taking paradigm which evolved out from the personal computing environment, in which users had to share a single interaction device. Systems designed for collaboration should enable simultaneous interaction and parallel work by allowing concurrent inputs. But concurrent input is also generated when interaction devices are not currently used but still lie on the surface, being tracked by the system.

### Deviated requirements:

- **R18**: Allow multiple concurrent user input
- **R19**: Allow multiple concurrent device input
- **R20**: Allow multiple concurrent touch input

### 3.3 REQUIREMENTS SUMMARY

In Table 3, the gathered requirements are shown together with their values and sources.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>R4, R18, R20</td>
<td>Touch tracking</td>
<td>Multi-touch up to 40 blobs</td>
<td>4 users each 10 fingers</td>
</tr>
<tr>
<td>R4, R11, R19</td>
<td>Device tracking</td>
<td>&gt; 6 devices simultaneously</td>
<td>4 users plus two extra devices</td>
</tr>
<tr>
<td>R3, R4, R5, R7, R17, R14</td>
<td>Tracking modalities</td>
<td>Track, drag, orientation, inherent state, ID</td>
<td>Three States: Bill Buxton et al. [B27] Orientation: Kruger et al. [B11] Inherent state, ID: [OP6], [OP3]</td>
</tr>
<tr>
<td>R12</td>
<td>Immunity</td>
<td>Foreign objects, physical impact</td>
<td>Scott, S. D et al. [B12]</td>
</tr>
<tr>
<td>R6, R13</td>
<td>Integrated design</td>
<td>System depth (table thickness) &lt; 120 ± 20 mm → Space for legs minimal 620 mm</td>
<td>DIN EN 527-1:2009-01 [B25]</td>
</tr>
<tr>
<td>R6, R8, R16</td>
<td>Table design</td>
<td>1600 x 800 mm, Height 740 ± 20 mm</td>
<td>DIN EN 527-1:2009-01 [B25]</td>
</tr>
<tr>
<td>R15</td>
<td>Interactive surface diagonal</td>
<td>&gt; 40&quot; (1020 mm)</td>
<td>Müller-Tomfelde et al. [B7]</td>
</tr>
<tr>
<td>R1</td>
<td>Sampling rate</td>
<td>&gt; 20 Hz</td>
<td>MacKenzie et al. [B59]</td>
</tr>
<tr>
<td>R2</td>
<td>Lag</td>
<td>&lt; 100 ms</td>
<td>Card et al.[B60], Ware et al.[B61] and MacKenzie et al. [B59]</td>
</tr>
<tr>
<td>R7, R8</td>
<td>Platform</td>
<td>X86</td>
<td>[W54]</td>
</tr>
</tbody>
</table>

Table 3: From all of the requirements (R1-R18), some of them can be expressed with explicit recommended values.
In this chapter, commercial display and tracking technologies are presented that enable direct interaction on tabletop interactive surfaces. Also systems are shown that were presented in other research work.

Today, there exists a wide range of products and different technologies that enable tracking of direct manipulation on interactive surfaces. In a first step, only the working principles are described - without any further classification. In a second step, the systems are classified by their abilities to track input in several configurations, by different input methods, and by multi-object tracking capabilities.

4.1 DISPLAY TECHNOLOGIES

4.1.1 PROJECTIONS

In traditional tabletop systems, projections are used because they offer a good price to image size ratio. A projection can be scaled up to almost any size. Only requirements for resolution, brightness and focus capabilities are limiting the scalability. Beside the scalability, a projector can be used on almost any surface, converting it into a display. Researchers even designed projections for non-planar and arbitrary shaped surfaces by using special calibration techniques [B21].

Although projection systems are widely applicable, they have two significant drawbacks:

- **Shadow casting:** Interactions on systems that use front projection can be quite demanding. The users will always cast a shadow onto the interaction surface. This is especially cumbersome when regions of interest are occluded by the shadows (Figure 15).
Space requirements: Both, back and front projection systems need a lot of space in front or behind the interactive surface for the projection cone. In the case of a front projection, the space is also for the users; while in a back projection setup, the space behind the screen is lost. Particularly in tabletop setups, back projection raises another problem: People sitting or even standing at a back projection table can disturb the projection by wrong leg and foot placement, also casting shadows on to the screen (Figure 16). In setups where the space for the back projection is physically protected against intrusion, people will take on ergonomic seating positions see (Figure 3).

4.1.2 LC-DISPLAYS

Liquid crystal displays (LCD) have become important displaying devices nowadays. Due to their bright and high-contrast screens and their small construction depths, they are suitable for a wide range of different applications in entertainment and professional environments. The LC-display technology is described in detail, since all prototypes developed in this thesis base on this promising technology. Other technologies like plasma, OLED and LED displays are not described. OLED will be discussed in the outlook chapter as a potential candidate for better and more flexible image displays.
THE LC-CELL PRINCIPLE

The core material used in LC-displays is liquid crystal. Liquid Crystals are a material that has properties between solid and liquid crystal. A liquid crystal may flow like a liquid, but its molecules are oriented in a crystal like manner. In a liquid crystal display, this “between the states” property is used to realize a light shutter. The basic setup of a liquid crystal display device consists of two conductive coatings evaporated on glass plates. A liquid crystal layer is placed between them. The LC-molecules align to a predefined direction, which is parallel to a polyimide coated surface that is brushed in a preferential direction. Light passing through this setup follows the helix alignment of the liquid crystals. This setup is also referred to as a Twisted Nematic (TN) cell and was first presented by Helfrich and Schadt [B1] in 1970. Light polarizing filters are mounted on each side of this cell and align the entering and exiting light according to the liquid crystal orientation. As soon as a voltage is applied to the electrodes, the orientation of the crystals changes according to the voltage level, and the molecules are aligned in parallel. The light’s polarization is no longer turned by 90 degrees. It is blocked by the exiting polarizer preventing the LC-cell from letting light pass through. Thus, TN cells are the smallest functional element in a LC-display device, allowing switching on and off light by applying voltage to electrodes.

![Figure 17: Liquid crystal principle. Left: plain cell, Right: activated cell](image)

FROM PASSIVE TO ACTIVE MATRIX LCDs

To implement screens that consist of thousands (today millions) of TN-cells, an intelligent system is necessary in order to individually drive each cell and switch it accurately to black, white or to a gray level. To ease the control, a passive matrix driving method is used. A grid of transparent electrical wires (commonly ITO, indium tin oxide) is used to address the cells by rows and columns. Using such a matrix driving method, the driving complexity can be reduced significantly for example by 98% for a 100 x 100 pixel display.
A major drawback of the passive matrix control technique is a phenomenon named cross-talk, which reduces contrast in the image. In order to eliminate this effect and to extend the number of addressable pixels in the image, a new technique was developed called active matrix driving. By mounting tiny transistors that switch the cells at each crossing, the cross-talk effect can be reduced or eliminated. The transistors are usually made up of deposited thin films, and are thus called thin-film transistors (TFTs).

**DISPLAYING COLORS**

Gray levels in a TFT matrix can be displayed by using one or a combination of the following techniques:

- **Spatial dithering**: The ratio of black and white pixels within a sub pixel defines its gray level.
- **Pulse width modulation**: The pixels are controlled by very short pulses that can be varied in length. The human eye integrates over a long time compared to the pulse length, thus interpreting these signals as grey shades.
- **Frame rate control**: The gray levels are obtained by turning pixels on and off during a period that spans multiple frames.

By adding a color filter in front of each sub pixel of a triple of pixels, a matrix with additive color mixing capabilities can be constructed. See Figure 18 for details in layout and Figure 19 for a real close up screenshot.

![LC-matrix pixel layout](image1)

**Figure 18**: LC-matrix pixel layout. Three sub pixels define a pixel

![RGB](image2)

**Figure 19**: A close-up view of an LC-matrix [F1] as seen in front of an LC-display

Some important improvements of the original TN cells were developed by adjusting the LC crystal alignment. This led to better viewing angles and color reproduction. The different stages of improvements were called MVA (Multi-domain vertical alignment), PVA (Patterned vertical alignment), IPS (In plane switching) and S-IPS.
CONSTRUCTION

LC-displays do not differ much in construction. Nowadays, most of the displays use CCFL (cold cathode fluorescent lamp) to generate the background illumination. This is needed in order to see the picture displayed on the LC-matrix. Two CCFLs are mounted at opposing sides behind the LC-matrix. Several additional components are needed to distribute the light from the CCFL homogenously behind the LC-matrix surface. The acrylic light guide makes sure the light is directed from the CCFL source to the light guide surface. This is achieved by tiny light decoupling patterns on the light guide’s surface. A diffusion film above the light guide is used to further distribute the light homogenously towards the LC-matrix. By using prism films, a brightness enhancement is achieved. And finally reflective polarizer films recycle the polarized light that has been reflected by the LC-matrix because of the linear polarization of the entry side of the LC-cells, by changing the light’s polarization again. A reflector behind the light guide reflects light towards the LC-matrix boosting image brightness additionally.

Figure 20: The different components in an LC-display (cross-sectional view).

LED BACKLIGHT TECHNOLOGIES

As an alternative to CCFLs, LED backlights are becoming popular, mainly because of enhanced color representation and slightly reduced power consumption.

There are several types of LED backlighting methods. The cheapest is to use white LEDs instead of the CCFL lamps. But since these so-called pseudo-white LEDs are actually blue LEDs with yellow phosphor, the spectral curve lacks in green and red. Regarding color gamut, these LEDs do not have any advantages over CCFL.

New technologies use RGB (Red, Green, Blue) LEDs that consist of a red, a green and a blue LED and can be controlled to display different temperatures of white. By using these RGB LEDs, a display’s color gamut (the amount of displayable colors) can be increased drastically.

Switching to LED backlight also presents some severe drawbacks. Homogeneous light distribution is very difficult to achieve since the light sources are point-shaped. Additionally, each LED will age at a different rate and causing shifts in color reproduction. Finally, many first generation LED backlights are not as efficient as CCFL implementations, but are today as good as CCFL.

Other LED-based techniques were developed, which do not rely on the classic construction with sideward entering light, but the LEDs are mounted directly on the back plane behind the LC-matrix. Using such a construction, a technique called backlight dimming becomes possible. An image often contains areas where
darker colors or blacks are displayed. In conventional setups, black is displayed as a very dark gray, since the backlight always lights the whole display. Backlight dimming uses the fact, that the grid of LEDs behind the LC-matrix can locally be dimmed or switched off, such that black can be displayed a lot more realistically.

4.1.3 PLASMA DISPLAYS

WORKING PRINCIPLE

Plasma displays consist of an array of tiny cells that contain colored phosphor coatings. Each cell can be electrically addressed by a net of transparent display and address electrodes. The cells are positioned between two plates of glass (Figure 21). Selecting a cell is achieved by applying voltage at the display and the address electrodes. This creates a voltage difference between front and back of the cell causing the enclosed gas (Neon and Xeon) to ionize and form a plasma. Normally, pressure inside a cell is lower than normal air pressure because the VUV radiation (VUV: vacuum ultraviolet), which is not visible by the human eye, will only spread in vacuum. The fluorescent material in the cells is exposed to this VUV radiation and emits visible light according to the fluorescent material (green, red, blue). Different brightness levels are induced by triggering the cells for shorter or longer periods. With this active displaying method, very good contrast ratios can be achieved. Again, true black cannot be displayed because every cell has to be biased to be activated, which also leads to a certain amount of background radiation. However, contrast ratios are superior to LC displays and in the range of CRT monitors.

Thus advantages of plasma displays are their high brightness (active pixels), almost true black display, and superior contrast ratios. Also plasma displays have very wide viewing angles compared to LCDs. Since their invention in 1964 and the first color plasmas in 1992, plasma displays did not develop so much anymore apart from power saving issues and increasing sizes. LCD technologies started to compete with current plasma displays in size, price and electrical power consumption.

Figure 21: Construction of a plasma display [F2]
4.1.4 OLED DISPLAYS

OLED (Organic Light Emitting Diode) displays have been in the focus of research since 50 years. In the 1960’s, Martin Pope first made several observations on electroluminescence on a single crystal of anthracene. The first attempt to create a polymer LED was by Roger Partridge, who patented his findings in 1983. And finally, the first diode device was presented by Dr. Ching W. Tang and Steven Van Slyke in 1987 [B57], who started the current era of OLED device production and research.

OLEDs use an active light emitting technique, in which the material is self-emitting light – thus no backlight or illumination source is needed. OLED as used in everyday consumer products such as mobile phones and PDAs are made out of an emissive layer of organic compounds. This substance is deposited onto a suitable carrier material using a simple printing process.

For a proper function, several layers are needed for an OLED area. The anode is covered by a conductive layer that withdraws electrons from the emissive layer above. Finally, the cathode is mounted on top and provides electrons to the emissive layer. If a voltage is applied between cathode and anode, a current of electrons flows through the layers. The emissive layer becomes negatively charged while the conductive layer becomes positively charged. Close to the interconnection between conductive and emissive layer electrons and holes recombine, this causing a drop in energy levels of the electrons followed by radiation of the frequencies in the visible range. Normally, ITO is often used as anode material since it is transparent, while aluminum is used as cathode material.

4.1.5 LED DISPLAYS

LED displays also use a grid of electrodes to drive individual LEDs. One pixel of the screen comprises a red, a green and a blue LED, which are pulse width modulated (PWM) to achieve different brightness levels. At a sufficient distance, the human eye cannot distinguish anymore between individual LEDs and thus the three diodes seem to be one pixel with full color performance. Since every LED can achieve a relatively high brightness, LED displays are very powerful and can be used outdoors even in bright sunlight. Also the viewing angles are close to 180 degrees, depending on the used LED emission characteristics.
4.2 COMMERCIAL TRACKING TECHNOLOGIES

4.2.1 RESISTIVE SYSTEMS

Resistive tracking systems react upon pressure. Four-wire systems (for example by EloTouch [W10]) consist of two electrically conductive films of indium tin oxide (ITO) on the inner sides of the layers and silver bus bars along the edges. ITO can be 90% transparent for a single layer. The layers are separated by isolating spacer dots that are also almost invisible. By touching the surface, a user electrically connects these two layers. If a voltage is applied to the edges of one layer, a voltage gradient can be created. By pressing the other layer against the first, it probes the voltage present at the contact point. To determine a position of a touch, the following sequence is applied:

A unidirectional voltage gradient between Ux1 and Ux2 is applied (Figure 22). A touch will connect the upper and the lower layer. At the touch point, the voltage across Ux1 and Ux2 will be divided following the rules of voltage division. By measuring the voltages between Uy3 and Ux1 and Uy3 and Ux2, the ratio of the voltage divider can be determined and thus the position in X direction can be computed. To determine the position in the Y direction, voltage is applied between Uy3 and Uy4 and the above proceeding is repeated for this axis as well.

![Figure 22: Setup of a resistive touch tracking system [F8]](image)

Resistive touch screens have high resolutions of 4096 DPI or higher. Variations of the technology incorporate five, seven or eight wire setups. The five wire version works with a probing layer that only picks the voltage when pressed while the other 4 wires are connected to the corners of the underlying layer. This setup makes sure that in long term use common microscopic cracks in the ITO no longer cause non-linearities.

Due to their topology and detection algorithm, resistive tracking technologies are basically not capable of detecting multiple touch points. Multiple presses will be interpolated to a single touch by system inherent interpolation.

Recent research has used additional factors of standard resistive touch detection such as measuring the slight resistance change between the layer edges when applying multiple touches [B50]. The two conductive
layers are pressed together at several points, which reduce their resistance. This can be measured and enables some sort of multi touch detection on a system that has originally been designed for single touch detection.

A product called Lemur from Jazzmutant [W4] has a resistive multi-touch screen with an LC-panel, but is limited to applications requiring low precision. One of the newest breakthroughs in resistive touch detection were achieved by companies named Stantum [W5] and Sima [W7]. Their panels can detect unlimited touch points without interference, but are only manufactured for small mobile devices of up to 15.4” at the time of writing.

Having introduced the UnMousePad [B58] in 2009, the company TouchCo [W37] was founded, but has already ceased their business in 2010. The technology presented in the UnMousePad is called Interpolating Force Sensitive Resistance (IFSR) and enables multi touch by using two resistive layers and grids of electrodes. A vertical and horizontal array of electrodes with a resistive layer in between is used for sensing. Each group of four cells is read out by a special procedure that makes sure that the touch point can be interpolated correctly. The resistance between the vertical and the horizontal electrodes is measured at different nodes in order to interpolate the touch position.

Other applications of such resistive matrix pads are used in medical and dental pressure sensing devices, such as foot pressure scanners like Techscan [W9] shows in their portfolio. Xsensor technology corporation [W6] even sells pads that are able to detect multiple pressure input on an area as large as a 1 x 2 m but with a resolution of only 1.27 cm.

### 4.2.2 CAPACITIVE SYSTEMS

A simple capacitor has two electrodes separated by one or more dielectric layers. Capacitive sensing bases on the fact that changes in the capacitive field can be detected when inserting a dielectric object. The human finger behaves as a conductive electrolyte covered by a layer of skin, which behaves like a lossy dielectric. Also other conductive materials can be detected by capacitive sensing, such as metallic objects like keys or finger rings. If the finger is moved into the electrical field of a capacitor, the surplus of change in capacitance (although it is very small) can be determined. By mounting the two conductors on the same layer, the classic capacitor concept is stretched but its basic property to generate an electric field is still maintained. One way to determine a change in the field of a capacitor is to measure the delay time of a capacitor-resistor circuit. Even out of the box sensors exist that are used in projects like [B51].

There are several types of capacitive sensing methods for on-screen touch detection:

**PROJECTED CAPACITIVE TRACKING**

In April 1994, George Gerpheide proposed the shunt method and patented it [B51]. Layers of vertical and horizontal electrodes made out of ITO are separated by an isolating material. Each crossing of row and column is considered to be a single grid capacitor. A high frequency signal is applied to the electrodes. This signal causes the charges in the dielectric to continually reverse their orientation. The moving of the charges creates an alternating electric current which can be detected. This current is proportional to the capacitance of the electrode pair. If fingers are brought close to a node, its capacitance is changed since the finger is
seen by the electric field as a virtual ground thus changing the capacitance in that node. By evaluating each node individually, it is possible to interpolate between several nodes to extract the exact position of a touch. Several companies have slightly different implementations of this so-called projected capacitive tracking in their portfolio such as Synaptics [W12], Elo Touch [W10], Cirque [W3], Fingerworks [W8] or Touch International [W13]. Today’s state-of-the-art multi-touch capable mobile devices often use this kind of tracking technology. One of the first devices that used projected capacitive tracking to detect multi-touch input on a smartphone was the Apple iPhone [W19]. Its working principle is described in the corresponding patent [B54] and does include an array of small electrodes arranged in a grid behind the LC-screen components. Another company is N-trig, who has even combined multi-touch based on the projected capacitive technology with inductive pen tracking [W14].

Since even complete one chip solutions comprising the driving and control circuits for the electrostatic fields are available, this technology has gained large popularity. Even adhesive large sized foils are available from Visual Planet [W38] that can be mounted behind glass panels for interactive shop displays.

**SURFACE CAPACITIVE**

Surface capacitive touch panels consist of a layer of uniformly coated transparent conductive (mostly ITO) and a thin insulating top layer. An AC voltage is applied to the four corners of the conductive coating. If the conductive coating is touched by a finger, a very small current is drawn from each corner towards the point of contact. A controller measures the ratio of the current flow from each corner and calculates the touch location. This basic principle was extended by manufacturers like Wacom [W16], who do apply four instead of one differently ramped electrostatic field to further increase accuracy and reliability. This technology is called RRFC (Reversing Ramped Field Capacitive).

### 4.2.3 INDUCTIVE SYSTEMS

Electromagnetic induction originates along a conductor loop when a change of the magnetic flux is applied. In other words, if a conductive wire is moved within a magnetic field, a voltage can be measured at its ends. The voltage can be generated by moving the wire, or with every change in the electromagnetic field. This effect is used in transformers, electro motors and helped Wacom™ [W17] to implement one of the most advanced inductive pen tracking systems up to now. A large number of overlapping loop coils (antennas) is arranged in a matrix in a sensor board behind the LC-display components. The system discharges alternating current through these loops in a specific manner to generate electromagnetic fields. If the pen passes over these fields, it picks up energy in its resonant circuit. Thus, the pen is passive and does not require any battery, since it is powered by the electromagnetic fields. To track the pen, the system only determines the location roughly in a first step. For a more precise tracking, the pen generates also an electromagnetic field by using the stored energy picked up from the coils in the sensor board. At this time, the coils in the sensor board switch to receiving mode and record the currents induced by this pen signal. In a next step, the tracking is refined and only the coils close to the pen are switched on and off. The current sensing is then used to compute the location of the pen precisely. Even additional information such as pen tip pressure, inclination and a tool ID can be measured and transmitted with very high resolution using this procedure and an additional pressure sensor in the pen.
Other active induction based systems use wired pens or need batteries for the operation of the pen such as Scriptel [W20]. The first device that was able to detect a stylus on a tablet surface also used inductive tracking and was called Stylator [B55] and preceded the RAND [B56] tablet digitizer.

4.2.4 SOUND WAVE BASED SYSTEMS

The propagation speed of sound is relatively slow (343 m/s in air), which makes it a good choice for time of flight tracking since time can be measured with little effort (in the order of ms for normal screen widths).

PASSIVE OBJECTS TRACKING

ACOUSTIC PULSE RECOGNITION

Several piezoelectric transducers are attached to the edges of the back surface of a glass overlay. If an object touches the glass surface, it generates acoustic waves with very small amplitude. These waves travel through the glass with constant speed until they reach the transducers. They pick up the acoustic wave and convert it to an electronic signal. All the signals from the transducers are analyzed and compared to pre-recorded profiles, which base on the time of flight of the acoustic waves until they hit a transducer.

SURFACE ACOUSTIC WAVES (SAW)

Surface waves are generated by transducers in x and y direction and a special alignment of deflector arrays at two edges of the screen. Using this setup, sound waves can be generated, which cover the screen in a uniform pattern in x and y direction. On each opposing edge, a receiving transducer and its deflector arrays are mounted. In an untouched state, all the sound waves forming a grid above the screen are uninterrupted. As soon as an object (finger) touches the surface, some of the waves are interrupted which can be detected by the reception transducers. By knowing which wave lines are interrupted the exact position in x and y can be computed.

ACTIVE OBJECTS TRACKING

The above system is inversed when using active objects. In systems such as E-Beam™[W23] and Mimio™ [W21], an active pen is used. It emits ultra-sound waves that are not in the audible spectrum (40 kHz). At the side of the surface that has to be made interactive, two transducers are mounted in a small mobile housing and are attached to the surfaces in a fixed distance to each other. They receive the sound waves generated by the pen. Since light is by the factor $10^6$ faster than sound, it can be used for synchronization. Thus, an infrared synchronization pulse makes sure the transmitter and the receiver both know the start time of a sound wave. By comparing the arrival time at the different receivers and by using multilateration, the exact position of the pen can be calculated.
4.2.5 MECHANICALLY ACTIVATED SYSTEMS

FORCE SENSING

If a user touches a surface, he will apply a small force to the screen. By attaching force sensors at each corner of the interactive surface, the center of touch can be calculated by analyzing the individual forces present at each sensor. Vissumo [W24] takes also non-orthogonal forces into account, which produce very accurate positioning information.

DISPERSE SIGNAL TECHNOLOGY (DST)

The MicroTouch™ tracking technology invented by 3M [W25] probably has the most demanding processing algorithms. It is able to detect even slight touches on a glass plate by measuring the vibration they cause in the glass. Sensors are mounted in each corner and measure the vibration energy in the plate. A touch on the plate will generate bending waves that propagate through the material and spread out over time. Because of dispersion these waves propagate out to the edges at different speeds, reflect and interfere with one another. A highly complex wave formation over time is the result. By using appropriate algorithms, it is possible to reconstruct the original wave center, thus detecting the touch center.

4.2.6 OPTICAL SYSTEMS

LIGHT GRID

A grid of small light bars is generated above the screen by attaching arrays of acute-angle emitting light diodes on the x and y side of the screen. On each opposite side, an array of light sensors is mounted. Every sensor is activated by a LED. As soon as a user touches the surface, some of the light paths are interrupted and the corresponding location can be determined. Usually, infrared light is used since its wavelength is invisible to the human eye. This technology is one of the oldest used for large screen touch detection. Today, Craftdata [W26] or IRtouch [W27] still produce such panel overlays.

CORNER-MOUNTED CAMERAS

Infrared-sensitive surface cameras are mounted in the corners of the screen, taking images of roughly the first few millimeters of the space above the surface. The cameras are basically line-cameras since their chip was cut down to only a few pixels of height while the width still has the original resolution. In the frame around the screen, infrared light bars are mounted. These light bars are only visible to the infrared cameras. In an untouched state, every camera will record a continuous strip of light. As soon as an object is entering the camera’s field of view, it interrupts the strip at that location. By analyzing the visible segments in the images of at least two cameras, the exact touch point can be determined. Smart Technologies [W28] sells a system called DIV-IT™, which has become quite popular in class rooms as a replacement for whiteboards. The versions equipped with more than two cameras are able to detect two synchronous touch points, whereas the Nextwindow [W29] technology can provide two finger tracking by using two cameras only.
BEHIND SCREEN CAMERAS

There are many different products on the market that track user input on a screen with a camera being located behind the screen. One of such a product is the Microsoft (MS) Surface Table [W31], which was preceded by earlier prototypes such as PlayAnywhere [B66]. The principle is slightly different from system to system, but basically visual information is acquired by seeing through the interactive screen from behind. MS Surface also uses infrared emitters also placed behind the screen to illuminate objects in front of the screen such as fingers, or objects like mobile phones, cups and so on. The illuminated objects are seen by the camera and the visual data is interpreted by segmentation algorithms to extract user input data. Several cameras (for increased resolution) inside Surface acquire the images, which are analyzed by special multi-touch algorithms to determining position of touches and orientation and identification of objects. Surface uses projectors inside the box to generate an image on the interactive surface. Another product that uses the same kind of principle is the MultitouchCell [W30], which is a stackable multi touch capable box. Other companies such as Evoluce [W34] use LC-panels (which are partly transparent to IR light) to display the image, while cameras are acquiring touch information from behind. Various methods for multi-touch detection are used today, see [W55] for details:

- Diffuse Illumination (DI)
- Diffused Surface Illumination (DSI)
- Frustrated Total Internal Reflection (FTIR)
- Laser Light Plane (LLP) and LED Light Plane (LED-LP)

However, only a few of these prototypes made it to a commercial product, although there exist some promising solution designs like Cubit [W36].

LIGHT SCATTERING

Tactex [W35] developed a unique way of using cellular foam and a light source for the detection of multiple touch inputs. Although they do not disclose the exact working principle on their website, the corresponding patent [B53] describes the following working principle: A compressible material is used that is able to scatter or diffuse light. Pairs of optical fibers are directed into the material and end at defined points in the material in such a way that the end points are aligned in a grid. At each end point (a cell), the pair of fibers provides a receiver and a transmitter fiber. Each cell can be illuminated by the transmitter fiber. A finger press will compress the material thus changing the light scattering inside the particular pressed cells and induce a change in the received light intensity that can be detected through the receiver fiber.
4.3 RELATED RESEARCH WORK

4.3.1 MULTI-TOUCH THREE DIMENSIONAL TABLET - 1985

Already back in 1985, Lee et al [B67] introduced a multi-touch sensitive tablet. It was capable of detecting several touch points simultaneously. Additionally, it was even capable of sensing the pressure of each contact point accounting for the third dimension sensitivity.

The hardware consisted of a matrix of metal plates, which enabled capacitance sensing between the plate and the fingertips. 2048 (64 x 32) metal sensors were used and addressed using row and column selecting circuits. A CPU (10 MHz) controlled the selection timings and read the sensor values from the analog to digital converters. In order to achieve update rates of around 20 Hz for multiple touch points, a special recursive readout algorithm was used. This could reduce the sensor scanning times by one order of magnitude.

To read out the capacitance change when fingertips cover the sensor plates, the following circuit was used:

![Figure 23: Readout schematic for the capacitive multi-touch sensitive tablet](image)

A charging diode (CD) is used to charge the sensors in one row by applying a voltage to the row line controlled by a microcontroller. The CD also prevents the sensors from discharging when the row line is switched back to ground. The column selection switch is closed when the corresponding sensor is read out. The sensor (capacitor) is then discharged via the timing resistor associated with each selection switch. The discharging diode also blocks charge flow from the selected sensors to the unselected. By analog multiplexing the column lines to an operation amplifier, the discharging time can be measured for each sensor, which depends on objects in front of the sensor plates. Since fingers spread a tiny bit if pressure is increased they will cover more sensors. This can be registered and interpreted, too.
### 4.3.2 Digital Desk – 1991

In 1991, Wellner [B68] created a very advanced digital desk for its time, which was capable of reliably detecting hands, fingers and pens. It also incorporated means to detect paper documents on the desk. The system consisted of a normal desk that uses a front-projection as well as a front image acquisition system. Digital documents can be mixed with analog documents on the same surface which was an innovative combination of paradigms. Wellner found that paper is very well accepted since its tangibility and high resolution print make it easy to handle. On the other hand, electronic documents have the advantages that they can be copied, edited, shared and filed well, and provide search ability or instant calculations. In DigitalDesk, these advantages were combined by giving the computer access to the printed paper. Hence, users perceived interaction as natural both with digital and printed documents.

The DigitalDesk used a camera to acquire images which were then processed by the computer. The algorithm was also able to detect moving objects on the screen. By analyzing the shape of a moving hand, it could detect a finger’s position on the desk. Still the visual system was unable to detect if a finger touched the desk’s surface. Therefore a microphone was attached to the desk and used to “hear” touches of fingers. By synchronizing visual analysis and audio signal, touch points could be located. Dragging was not supported.

While a low-resolution camera was used for the detection of hand interactions, a second camera incorporated zoom optics that was directed to a small area on the desk. In this area, the system was able to recognize text and numbers on a paper document. In the presented application “DigitalDesk Calculator”, users of the system could use their fingers to do calculations on a projected calculator. Additionally, the system could take numbers from paper documents as input. By pointing at a number on a paper, the system projected a rectangle around the detected number. With a short tap, the number was entered into the virtual calculator to be used in further calculations.

### 4.3.3 ActiveDesk – 1995

In 1995, Fitzmaurice et al. [B69] introduced ActiveDesk, which only allowed interacting with dedicated interaction devices, so-called Bricks. The ActiveDesk used a back-projected interaction surface that was inclined by 30 degrees to follow the design of a drafting table. Fitzmaurice introduced the term “graspable user interface” for his bricks, which depicted a physical representation of the graphical user interface. In some initial observations with Lego™ bricks concerning manual object sorting, Fitzmaurice observed that tasks were often performed in parallel, and bimanual work was efficient. In a second step, physical and virtual object manipulation was analyzed. Users had to fit a stretchable square to predefined positions, rotations and scale factors. The same task was performed in a virtual setup using a drawing application. The comparison revealed that task completion time differed by an order of magnitude. Physical manipulation was faster and more accessible for the test subjects.

Basing on these observations, Fitzmaurice et al. proposed a system that combined the physical and virtual world. In the proposed application called “GraspDraw”, users were able to create objects such as lines, rectangles and circles by using bimanual brick input. A button on the bricks provided an additional input for the creation of shapes. An object could be scaled, rotated and moved by placing the receivers upon it, much like grasping. To release a grasp, the bricks had to be lifted from the surface for about 2 cm. In order to
associate different functions to the bricks, a physical tray supporting the ink metaphor was used. By dipping the interaction devices into a compartment in the tray, a particular tool could be selected. An audio feedback was generated to inform the user of the tool change.

An off-the-shelf electromagnetic tracking system called Flock of Birds 6D from Ascension [W33] was used to track different bricks. Today this tracking system features accuracies of ±0.25 mm and update rates of 190 Hz and is able to track position and orientation in all degrees of freedom of multiple receiving devices [W18]. The emitter generates relatively strong electromagnetic fields that can easily be disturbed by metallic objects, while the receivers (bricks) are cable bound.

### 4.3.4 THE METADESK – 1997

In 1997, metaDESK was introduced by Ullmer et al. [B70]. The metaDESK incorporated more advanced graspable user interfaces. Unlike the interfaces in the ActiveDesk prototype, they provided more physical information about their inherent function. The shapes of the graspable user interfaces represented clues to their function they were associated to. They were designed in a more specific and intuitive way, which leads the authors to a new name for this kind of interfaces: The term Tangible User Interface (TUI) was introduced, which indicates the alliance to the virtual graphical user interface (GUI).

Ullmer et al. presented a system that consisted of an interactive surface in the design of the ActiveDesk with an inclined surface incorporating a back-projection system. The elaborated TUIs were tracked using two different tracking technologies. One group of TUIs, the active lens and the passive lens, were tracked by an Ascension Flock of Birds 6D [W33] electromagnetic tracking system. The other group of TUIs was tracked using passive infrared tracking. An IR-emitter behind the projection display emitted IR-light that was reflected by these specially designed TUIs on the surface. Several passive TUIs were designed. One of these was called the Dome and consisted of transparent material that was reflective in the infrared spectrum. In their proposed application Geospace, the Dome served as a pinning tool, which was used to move the virtual map around when dragged. A second Dome was used to support bimanual zooming and rotation of the map, by moving the two domes relatively to each other. A second rotation and zooming tool was introduced that offered less physical freedom by restricting the relative rotation between two puck-like handles.

The active lens, a moveable LC-display, provided an adapted 3D-view of the virtual map in real time. By moving the active lens, the three dimensional view onto the map could be adjusted. By using the passive lens directly on the screen, an area on the map could be enlarged.

The system offers a 7 Hz tracking rate for the infrared tracked devices and uses a sophisticated synchronized system of three PCs to handle all user input and render the output on the two screens. A tray at the upper edge of the screen was used to hold all IR-reflective devices. The system distinguished between devices by detecting which one was actually lifted off the tray. Thus, only one passive device could be tracked at once.
4.3.5 THE BUILD-IT SYSTEM – 1998

The BUILD-IT system was introduced in 1998 by Fjeld et al. [B71]. BUILD-IT picked up the brick metaphor from ActiveDesk, in which the whole interaction is based on brick shaped interaction devices. The system consists of a tabletop front-projection that uses IR-emitters above the table to illuminate the interaction area. The bricks incorporate an IR-reflective film, while a camera mounted above the interactive surface detects the reflected IR-radiation. The bricks can be detected in position and orientation. Functions can be associated to any brick by placing the brick onto a particular function symbol. The brick will be associated to this function instantly. To decouple a function from the brick, the user simply interrupts the free line-of-sight between the brick and the camera, so that the system no longer detects the device. Many intuitive functions like zooming, rotation, scaling and point of view adjustment were designed using intuitive bimanual interaction paradigms.

Figure 24: BUILD-IT system. Bricks are used to navigate and edit a virtual environment on a two dimensional front-projection while a three dimensional side view will provide spatial feedback.

Like metaDESK, the BUILD-IT system also offers a quasi-3D view on a vertical screen beside the tabletop projection, allowing a perspective view of a 3D scene. Although BUILD-IT has a low device tracking rate and a high lag, it still sets a mark in the long list of tabletop interactive systems, since its dynamically configurable universal user interface was one of the first to merge 2D and 3D in such an accessible multiuser environment.

4.3.6 SENSETABLE - 2001

SenseTable was presented by Patten et al. [B74] in 2001. The system used two Wacom® Intuos [W15] tablets, which allow inductive sensing. The two tablets covered an area of 52 x 77 cm and detected objects with a resolution of up to 1000 dpi. In the original state, the tablets detected only two objects at a time. To increase this number of detectable interaction devices, the coils inside each device were randomly switched on and off. A random number generator made sure that each device was turned on around one third of the time. This concept yielded a major drawback: The update rate was reduced from 130 Hz down to about one detection per second. In order to increase this sample rate again, an additional circuit was installed that sensed if a device was touched. A touched devices would turn on its coils 100% of the time and therefore be sampled at rates equal to that of an unmodified Wacom® board.
The system used a front-projection and two vertical screens to display extra information. Interactive content was partly visible on the surface of the so-called pucks. This allowed a clear identification of a puck’s functionality, since this cannot be derived from its shape. The pucks were dynamically associated to virtual objects by placing the puck next to it. The object is released again by shaking the puck or removing it from the interactive surface. Additionally, each puck could be extended by adding a dial that allowed the user to enter extra input on the device, for example adjusting a value.

4.3.7 DIAMONDTOUCH – 2001

Few systems dealt with new principles of touch detection since the multi touch detection system by Lee et al [B67] in 1985. More than 15 years later, DiamondTouch was introduced by Dietz et al. [B75]. It features a new way of detecting multi-touch input from multiple persons by incorporating a technology that made it possible to distinguish between touch inputs from different users. A touch was no longer a position on the surface, but also had an identity. This was possible by a capacitive coupling of the input signals through the users. Antennas in the interactive surface transmit a high frequency signal. As soon as a user touches a spot on the table, the signals are coupled through the user and the chairs to the receivers, which identify the part of the table each user is touching. This is possible because the antennas underneath the surface are controlled via a time-division multiplexing, which makes sure each antenna is switched on only in its particular time slot. Using a 100 kHz square wave for the signal, DiamondTouch acquired and distinguished touches for all users with a 75 Hz overall sample rate, while objects on the surface do not interfere with normal operation.

Since the system is designed to detect multiple users’ touches, no additional tools are available (TUI) for the intuitive operation of more complex functions.

4.3.8 WORKPLACE TO SUPPORT THE TEAMWORK – 2002

Kunz et al. [B87] presented a workplace to support the teamwork in 2002. It consisted of a back projection table that could track at least three different pens simultaneously. Differentiation between the inputs is done by color separation. Each pen incorporates a LED of different color. A webcam underneath the table is analyzing the image for the different colors. The system was not able of detecting the tracking state since the LED was only activated by pressing the pen onto the table surface. Five years later Ortholumen (see 4.3.18) used the same principle on a top projection surface.
4.3.9 SMARTSKIN – 2002

Rekimoto introduced SmartSkin in 2002 [B76]. Like Diamond Touch, it is a system that is able to detect multiple finger touches on a tabletop using capacitive sensing that is integrated into the interactive surface. The sensor only consists of copper wires that are aligned in a grid. The wires are divided into groups of transmitters (vertical) and receivers (horizontal). By applying sinusoidal signal to one of the transmitter wires, the receiver wires will pick up this signal because each crossing point acts as a very small capacitor. The amplitude of the received signal is proportional to the frequency and voltage of the transmitted signal. If a user approaches to the said crossing, the signal will be distorted or attenuated by the finger, because it is a grounded object. Thus proximity of hands and fingers can be measured by electronic circuits. By using time division multiplexing, each transmitter is switched on separately in order to properly detect multiple touches on the sensor array. To prevent the system from picking up noise of nearby electronic instruments, a technique called “lock-in-amplifier” is used.

SmartSkin is able to detect positions of fingers, hands and even entire arms. Intelligent identification algorithms make sure that the fingers are properly separated and grouped by connected region analysis and template matching.

The image is front-projected onto the sensor surface. The team of Rekimoto constructed two prototypes. The large-sized model (80 x 90 cm) was able to detect finger touches with a resolution of 1 mm and had a sample rate of 30 Hz although the size of a grid cell was only 10 cm. The second prototype was a high resolution gesture recognition pad with a grid size of 1 cm.

So-called capacitive tags were also developed, which can be used much like TUIs in other systems. They consist of copper films attached to an object. SmartSkin only detects a TUI if a user touches it, since otherwise it is ungrounded. The layout of the copper plates defines the TUIs identity, its location and orientation. Thus SmartSkin was one of the first systems to combine touch and TUI input.

4.3.10 SENSEBOARD - 2002

In 2002, Jacob at al [B72] developed Senseboard, which consisted of a vertical front-projection and a rigid grid of cells (5.8 x 2.5 cm), in which magnetic tags (called Pucks) could be placed. Each puck was equipped with a Radio Frequency Identification (RFID) chip that could be detected by the Bannou Pro Intelligent White Board’s discreetly attached RFID readers. The authors modified the pucks in such a way that each puck’s surface could be pressed in order to send additional commands to the system. Special command pucks could be placed above normal pucks to initiate further functions like detailed viewing and grouping.

Senseboard was developed to collaboratively work at tasks that require a structured approach. They presented an application in which conference papers were sorted and clustered into a timetable. A user study showed that Senseboard could outperform a GUI based setup for the proposed specific sorting task.
4.3.11 THE MAGIC TABLE – 2003

Magic Table was introduced by Bérard [B73] in 2003. Magic Table is a front-projection tabletop interactive system. A whiteboard surface was used as an interactive surface. Therefore, standard whiteboard markers could be used to write and sketch on the surface. A camera mounted above the table detected strokes and two-handed gestures by multiple users around the table with 25 frames per second. Primarily, the whiteboard could be used as a standard whiteboard. The computer vision system provided the following additional features for interaction: Colored plastic tokens were used to select text or sketches on the whiteboard by using two tokens to define the corners of a virtual frame. The selected text or sketch was scanned by a second zoom camera in high resolution and overlaid onto the original one in the projected image. Now the text became virtual text, thus the original text could be erased. To position, rotate, scale and delete the virtual texts, special gestures with the tokens were used.

4.3.12 CARETTA – 2004

Caretta was designed in 2004 by Sugimoto et al [B77] to support personal and also collaborative work. A shared workspace was built consisting of 6 modules of each 10 x 8 grids comprising RFID tag readers in every cell. In total, 480 RFID readers are mounted behind an interactive surface. A front projection is used to display information on this surface. This collaborative space is used by groups of two to eight people to arrange tangibles that can be placed at discrete RFID tag locations. Manipulation of physical objects is possible, such as houses, stores, or office buildings, to redesign a town. Caretta identifies changes to the object arrangement at a sample rate of around 20 Hz. Tangible commands in the shared space or on PDAs start computer simulations, and update the simulation parameters and the visualization overlaid onto the space. Every participant of the group has the possibility to simulate personal arrangements on his own PDA that can be connected and synchronized with the Caretta system.

4.3.13 PLAYANYWHERE – 2005

In 2005, PlayAnywhere was introduced by Wilson [B84] and was the first step towards the commercial product Microsoft surface [W31]. Wilson used the newly introduced commercially available short throwing NEC WT600 DLP projector, which is able to project images of 40” from a distance of only 2.5” by using large-sized convex optical lenses. By taking advantage of this technology, he managed to create a very compact tabletop interactive system. The projector was placed right at the top edge of the interactive area and incorporated also a camera with a mounted IR-pass filter. The camera was equipped with a wide angle lens and obtained images of the whole interactive area. IR-emitters were also mounted on the projector in order to illuminate the surface. Objects that reflect IR-light were detected by the camera.

A lot of image processing was involved when tracking objects on the surface of PlayAnywhere. Distortion of the projector and the camera due to the wide angle optics had to be removed. Fingers touching or approaching the surface were detected by analyzing the shadow that was thrown onto the interactive area. If fingers were hovering (according to Buxton), their shadows would appear with a slight offset to the position of the real fingers. If fingers touched (drag) the surface, this offset is zero. In order to distinguish
between these two states, the size of the shadow at the fingertips was analyzed. Thus, PlayAnywhere was capable of determining the z-coordinate of the finger providing a full three state interaction. Accuracies of this tracking technique were around 3-4 mm. By analyzing the flow field of moving hands, the implementation of special gestures was possible, such as scaling and rotation of images. In order to track additional objects which were used as parts of a small gaming application, visual codes were attached to the pucks. Each puck could be identified in position, identity, and orientation and could be used to manipulate obstacles or a figure in a game. Additionally, PlayAnywhere was able to detect the outline and orientation of sheets of paper. The paper could also be used as an interaction device to rotate videos or images for example.

### 4.3.14 FTIR MULTI TOUCH – 2005

2005 was the birth of a rapid growing community of a cheap and easy to realize multi-touch technology first presented by Han [B85][B86], who spun off into a company named perceptive pixels [W32] in 2007. The system uses a back-projection to display images on a diffuse layer. In front of this diffuse layer, the core technology is mounted. It is called Frustrated Total Internal Reflection (FTIR) and consists of a 6.4mm thick sheet of acrylic as an optical waveguide, whose edges were polished clear. This sheet is edge-lit by high-power IR - LEDs, which are placed directly against the polished edges in order to maximize coupling into the acrylic. The rays are totally internally reflected within the acrylic as long as they are not frustrated by a touch of the fingers. Such a touch will decouple rays and scatter the light towards the back of the screen, where a camera equipped with a special IR pass filter detects this light and determines the position of the touch. This optical tracking only needs very few image processing steps to accurately compute the position of even multiple touches. With an update rate of 30 Hz and a resolution of 1 mm, the system is responsive and accurate enough even for fast interactions. In a more advanced prototype, Han reduces the contamination of the surface generated by oil and sweat of the fingers by the use of a special material called Rosco Gray #02105, which is itself a projection screen material. By using this material instead of acrylic, even different pressure forces can be detected. Since the material is not as rigid as acrylic, it will deform slightly under heavy pressure and needs up to a full second to eliminate any depression. Still the material is considered as suitable for HCI applications.

The main advantage of the FTIR based systems lies in its very simple scalability and tracking software implementation. Despite its simplicity, the technology cannot detect hovering and therefore only provides click and drag information. Due to the physical working principle, other objects on the tabletop’s surface cannot be detected unless they are coated with a coupling layer such as silicone or similar.

### 4.3.15 INFRACTABLES – 2005

In 2005, Ganser et al. [B90][OP6] proposed the InfrActables system. Within this system, all components were underneath the tabletop’s surface; it used back-projection as well as image acquisition from underneath.
The system was able to detect simultaneous TUI input on its surface up to 7 different devices. Each device provided the possibility to detect additional input from attached sensors (switches). This provided the ability to detect additional state changes. State change detection was not limited to one sensor per device, but could be extended to three binary inputs. Different examples of input devices were developed such as pens, a color tool, a notepad, and a ruler. The pens were used for writing, drawing and sketching. A tip switch in the pen detected a change from tracking operation (hovering) to dragging state. An additional switch at the side could be used as context menu pop up switch. All devices supported the three state input model found by Buxton. Thus, hovering of around 3 cm was also possible with all devices. A color tool was used to provide colors for the pen. By dipping the pen into the color tool, the color selected by the color tool’s rotation could be picked up. A ruler was used for measuring and navigation tasks. The notepad could be used to store notes much like with an analog Post-it™.

The system used active devices that were equipped with one or more IR-LEDs. An IR synchronization flash made sure that all devices were simultaneously emitting IR-light in synchronization with an IR-camera underneath the table. In order to distinguish unambiguously between devices, each device emitted a specific five-bit code that was transmitted over five camera frames and analyzed in the driver application. This means that the overall refresh rate is divided by the number of bits being used. This resulted in a final sample rate of around 12 Hz.

4.3.16 AUDIOPAD – 2006

Audiopad [B91] was introduced in 2006 by Patten et al. and is another TUI tracking top-projection based interactive system. Audiopad is based on a tabletop RF tracking system. Each of the tracked objects contains two LC-tags that resonate at a unique frequency. The position of the tag on the table is determined by measuring the resonance of the tag with several different antenna elements in the tabletop. Each tag can be tracked in position, orientation and identity, but determination of rotation is subject to drift. As the name of the system implies, Audiopad was mainly used to study new interaction concepts in collaborative audio application such as audio synthesizers. Interaction techniques included flow menus and one and two dimensional parameter adjustment using bimanual input techniques.
4.3.17 REACTABLE –2007

The reacTable is a comparatively long project, whose final system was presented by Jourdà et al. [B78] in 2007. An intermediate step towards reacTable was the so-called scoreTable [B79], which was presented in 2006. Like the SmartSkin system, reacTable is also capable of sensing simultaneous touch and TUI input at 60 Hz. In contrast to SmartSkin, reacTable uses back-projection, which eliminates the distracting shadowing effect of objects in front of the screen. Also TUIs on the reacTable are tracked at all times and do not need a user touching it.

reacTable uses an IR-emitter underneath the circular interaction area to illuminate objects on the surface. TUIs are equipped with special fiducials that show a unique black and white pattern. Since the white areas in the pattern reflect infrared light, a camera underneath the table can detect these patterns. The fiducials are called amoeba fiducials and are optimized for detection by a generic algorithm, incorporating a tree structure based layout [B80]. This tracking software together with the marker detection and also a robust multi-touch finger tracking was published in 2007 as the reacTIVision framework [B81]. The team around Kaltenbrunner also proposed a standardized interaction data protocol called TUIO [B82], which is integrated into the reacTIVision framework. The reacTIVision engine sends information about position and rotation of all interactive elements to a target application using the TUIO protocol. The protocol has become a widely accepted and a used tool for interactive systems in research and even in commercial systems. Meanwhile, many client implementations (C++, Java, C#, Processing, Flash, etc.) are available at the reacTIVision Homepage [W40] and further implementations and resources concerning the TUIO protocol can be acquired at the TUIO community site [W39]. The reacTIVision engine comes along with printable amoeba fiducials that can be applied to virtually any kind of TUI. The fiducials cannot be tracked in hovering mode. Fiducials are either active or not trackable. State detection is not supported, since fiducials cannot be altered when being in use. However, simple cubes can be used with several different fiducials on each side, each defining a distinct function.

The reacTable client application provides intuitive access to digital music creation and synthesizer functions by manipulation of the tangible objects on the screen. Its unusual round interactive surface and radial coordinate system can be used to place objects in relation to each other in order to adjust and alter digital sound samples.

4.3.18 ORTHOLUMEN – 2007

Ortholumen is a light pen based tabletop interaction system that can employ all the pen’s spatial degrees of freedom (DOF). The pen’s light is projected from above onto a horizontal translucent screen and tracked by a webcam sitting underneath, facing upwards. The system’s output is projected back onto the same screen. The elliptic light spot cast by the pen informs the system of pen position, orientation, and direction. While this adds up to six DOFs, Piazza et al. [B88] used up to four at a time.

In order to better separate input and output light, they employed polarizing filters on the webcam and the projector lens. Two applications, painting and map navigation, were presented. Ortholumen can be expanded to track multiple pens of the same or different colors. This enabled multi-pointer input, collaboration. Visible light, as opposed to infrared light or radio waves, may be perceived more directly by users. Ortholumen employs only low-cost parts, making the system affordable for home users.
4.3.19 INTOI – 2007

INTOI takes advantage of the Anoto Pen and Paper Technology. The pen devices keep track of their movements on special paper that contains a unique dot pattern almost invisible to the human eye. An infrared camera embedded in the wireless pen will process the images and a highly optimized integrated circuit will extract its position exactly from the images. The processed information is streamed to a computer via Bluetooth technology. The high resolution Anoto pattern is printed on a special back-light foil. The pens can be used as is on the proposed back projection hardware without any modifications.

INTOI is basically a multiuser interactive surface that features smart menu navigation. The pen can be used to pop up a circular menu that offers adjustment of properties such as color, line width, image loading and so forth. A clever interaction bases on drawing small circles inside the menu to adjust parameters. For example increasing a parameter would be realized by drawing a continuous circular shape in clockwise direction.

4.4 TECHNOLOGY CLASSIFICATION SYSTEM

Here, only technical aspects are used to classify the presented systems. This means that facts concerning software frameworks and capabilities were not taken into account.

PARAMETER GROUPS

Kunz et al. [B89] propose a classification system for tabletop interactive technologies, which separates the systems into systems that incorporate the tracking and display technology “above”, “in”, and “under” the actual interactive surface. They stress that for future systems it is important to integrate all components in the surface itself. This method of classification is used here as well. Kunz et al. also separate the systems into single touch, single TUI, multi touch and multi TUI. Here this separation is extended in such a way that also the amount of concurrent inputs is indicated, respectively how many touches and TUIs a system can detect. This classification group is called detection activation which can either be initiated by touch or TUI or both.

However five main groups of aspects of the systems were identified:

1) **Performance**: Performance is mainly defined by the tracking system’s update rate and resolution. For the update rate, 20 Hz or more have to be reached (following the requirement R1)

2) **Size**: Must be at least 40” as defined (following the requirement R15)

3) **Detection Modality**: The following detection modalities are possible. An ideal solution would cover all modalities.
   
   a. **Drag**: The input device has contact to the surface and is thus activating the dragging state (following the requirement R5).
b. **Track:** The input device is detected and the position can be determined without any contact to the surface. According to Buxton, this is the tracking state and can also be named as hovering (following the requirement R5).

c. **Identification:** Every input device is clearly identified and no confusion in device mapping can be made (following the requirement R3)

d. **+ Input:** Some input devices support additional inherent input. This may be buttons, rotational knobs, or other input elements on the device. The +Input condition is also fulfilled if the device is otherwise manipulated such as turned upside down in order to change an inherent input. (following the requirement R7)

e. **Orientation:** Orientation of the interaction devices can be tracked (following the requirement R14).

4) **Detection Activation:** Activation of the detection is made either by **touch** or **TUI** (following the requirement R11) Here, the amount of simultaneously trackable objects or touches is indicated as a number.

5) **Component Mount**

Components of a tabletop interactive system are its tracking (T) and its display (D).

a. **Above / Under:** The component is mounted above or underneath the interaction screen.

b. **Inside:** The component is integrated inside the interactive screen. Inside means that the dimensions in depths are significantly smaller than width and height of the screen.(following the requirement R13)
COLOR CODE

In order to visualize special capabilities of a system the following color codes are used:

- **Green**: indicates that this specific property fulfills the requirements set up in the requirements chapter.
- **Yellow**: Indicates that all properties of a specific aspect group are fulfilled. In other words if all properties in a group are marked green, they become yellow.

DATA CONSISTENCY

It must be noted that not all technical data of all systems were available. Researchers often do not provide extensive technical data such as scalability and update rate of a system, since the focus of the work was based on a specific part of the system. Commercial products on the other side will not declare the disadvantages of their systems properly. There might be systems that are disturbed by palm resting or object placement when used in horizontal position, which is not officially declared.
### COMPARISON OF PRODUCTS

<table>
<thead>
<tr>
<th>Category</th>
<th>Sub Category</th>
<th>Example product</th>
<th>Remarks</th>
<th>Year</th>
<th>Performance</th>
<th>Size</th>
<th>Detection Modality</th>
<th>Detection Activation</th>
<th>Component Mount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistive</td>
<td>4 wire resistive</td>
<td>Smart Board</td>
<td></td>
<td></td>
<td>Update rate [Hz]</td>
<td>Diagonal [inch]</td>
<td>Touch</td>
<td>TUI</td>
<td>Above</td>
</tr>
<tr>
<td>Resistive</td>
<td>Interpolating Force-Sensitive Resistance</td>
<td>TOUCHCO</td>
<td></td>
<td></td>
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<td>60 - 500</td>
<td>24</td>
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<td>2</td>
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<td>Surface capacitive</td>
<td>Elotech Surface Touch Technology</td>
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<td></td>
<td>186</td>
<td>22</td>
<td>1</td>
<td>D</td>
<td>T</td>
</tr>
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<td>Visual Planet Thru-window Touch (VPTouch)</td>
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<td></td>
<td>8.4</td>
<td>20</td>
<td>134</td>
<td>1</td>
<td>DT</td>
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<td>N-trig</td>
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<td>Wacom</td>
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<td>Acoustic Pulse recognition (APR)</td>
<td>Elotech APR</td>
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<td></td>
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<tr>
<td>Acoustic</td>
<td>Surface Acoustic Waves (SAW)</td>
<td>Elotech Secure Touch Surface Wave</td>
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<td></td>
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<td>32</td>
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<td>DT</td>
<td></td>
</tr>
<tr>
<td>Acoustic</td>
<td>Time of Flight</td>
<td>Mimio</td>
<td>Infrared sync signal</td>
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<td>87</td>
<td>85</td>
<td>4</td>
<td>DT</td>
</tr>
<tr>
<td>Inductive</td>
<td>Electro Magnetic Resonance (EMR)</td>
<td>ActiveBoard 300 Pro</td>
<td></td>
<td></td>
<td>Update rate [Hz]</td>
<td>Diagonal [inch]</td>
<td>Touch</td>
<td>TUI</td>
<td>Above</td>
</tr>
<tr>
<td>Mechanical</td>
<td>Dispersive Signal</td>
<td>3M MicroTouch System DST2700X</td>
<td></td>
<td></td>
<td>Update rate [Hz]</td>
<td>Diagonal [inch]</td>
<td>Touch</td>
<td>TUI</td>
<td>Above</td>
</tr>
<tr>
<td>Mechanical</td>
<td>Force sensing</td>
<td>Vissumo</td>
<td></td>
<td></td>
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<td>Diagonal [inch]</td>
<td>Touch</td>
<td>TUI</td>
<td>Above</td>
</tr>
<tr>
<td>Optical</td>
<td>Corner cameras</td>
<td>NextWindow, Smart Board DIVT</td>
<td></td>
<td></td>
<td>Update rate [Hz]</td>
<td>Diagonal [inch]</td>
<td>Touch</td>
<td>TUI</td>
<td>Above</td>
</tr>
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<td>Light grid</td>
<td>Craftdata</td>
<td></td>
<td></td>
<td>Update rate [Hz]</td>
<td>Diagonal [inch]</td>
<td>Touch</td>
<td>TUI</td>
<td>Above</td>
</tr>
<tr>
<td>Optical</td>
<td>Behind screen camera</td>
<td>Microsoft Surface</td>
<td>Integration of mobile phones</td>
<td></td>
<td>Update rate [Hz]</td>
<td>Diagonal [inch]</td>
<td>Touch</td>
<td>TUI</td>
<td>Above</td>
</tr>
</tbody>
</table>

Figure 26: Overview table of the tracking technologies on the market and their properties for different rating groups. Green fields mark that the particular property fulfills the requirements. Yellow boxes mark, that all properties of a requirements group are fulfilled. Inside the component mount group the letters indicate the position of the Display (D), Tracking (T) or of both (DT) in respect to the surface.

The above table reveals several facts:

**Component integration**

- Most of the systems integrate tracking and display components inside the interactive surface.

**Detection activation**

- Most systems only detect one or at maximum two touch points
- Only two systems can track touch and TUIs concurrently
Identification of objects or touch is mostly not possible

Detection modality

- The tracking state is only supported by a few systems.
- Orientation tracking is a very special feature.
- Additional state recognition and detection of the tracking state is difficult for most systems.
- Only two systems are capable of tracking all detection modalities, but are not available in sizes above 40 inch.

Size

- Most of the systems are available in sizes above 40 inch.

Performance

- Only about half of the systems do reach the required update rate of 20 Hz or more.

SUMMARY

All the presented commercial technologies span a wide field of options for specific applications. Each tracking technology has specific advantages and drawbacks. Only a few of the presented systems can be used in tabletop configurations fulfilling the requirements (R1 – R18) gathered in the previous chapter.

Resistive Films have the advantage of being very cheap and providing high sample rates, but they do not support palm rejection or multi-touch input if large screen sizes are envisioned. Only the very new TOUCHCO [W37] technology promises very accurate and suitable multi-touch and shape recognition, whereas its quality essentially depends on the software analysis algorithms that are implemented. Because of the layers in front of the screen that provide the needed resistive properties, the overlays are not 100% transparent. Some of the image brightness is lost in the polyester and glass layers - usually around 20%. One benefit of using a resistive display is that it can be accessed with a finger, pen, stylus, or any other solid object. But resistive displays are susceptible to scratches which degrade image clarity. Also a periodic recalibration is needed caused by tiny cracks in the layers of resistive film.

Capacitive sensing technologies on the other side offer very good image quality which is only slightly reduced by the ITO layer for the electrodes. On the other side, accuracy can drop to a low level if large interactive areas have to be made interactive. Since versions with transparent electrodes (ITO) are also available, capacitive sensing is not only restricted to LC-displays, but can also be used on back projection screens. Capacitive sensing has become very popular with the iPhone has become an everyday interaction device to users. It uses different configurations of projected capacitive sensing. One drawback may be that capacitive sensing does not support or at least limits work with gloved fingers, pens, stylus or hard objects with dielectric properties that cannot influence the capacity of the sensor.

Acoustic tracking of passive objects is able of tracking any single contact on the screen that can generate enough surface waves to trigger the sensors. Some of the technologies even implement palm rejection that especially makes sense in a horizontal layout. High accuracy and relatively large screen sizes are supported. When tracking active objects acoustic tracking, only physical objects emitting sound can be tracked. TUI interaction is possible with up to four tangibles, but no touch or hand will be detected. Also the tracking is
based on time of flight of the waves. It is obvious that occlusion of the line of sight will prevent the sensors from detecting correct positions, thus making a horizontal table based layout difficult.

Inductive tracking will actually outperform most of the tracking systems currently available. It’s very high sample rate, unachieved accuracy and additional features like pressure detection and dual pen mode do not leave room for competitors. Also the very clever idea of using an inductive field for energy transmission eliminates the need for batteries in the pen, which makes the interactive objects lighter and smaller. The interactive feeling is very close to a real pen on paper. Artists and designers love the tablet stylus that can be integrated in an LC-display for direct interaction. The technology is not able to track more than two devices simultaneously and will not scale easily to large sizes. Current tablets only provide pen tracking up to 21” image diagonal.

Mechanically activated tracking systems are not very common. They are robust systems due to their physical construction and will work under most extreme influences like vandalism, but still maintaining their high accuracy. However, their low sampling rate implies high requirements for the signal processing involved.

Finally, optical systems provide the most flexible way of detection. Processing the acquired images accordingly, virtually any object can be tracked in front of the camera. Only the power of the segmentation and interpretation algorithms defines the limit and quality of detection. Customized hardware like corner cameras can have higher sample rates than the usual 30 frames per second of standard CCD cameras. All variants have in common that line of sight is always needed. Occlusion of the camera-object path will irritate the system. Thus, most systems will be mounted either behind or at the side of the interactive surface. One of the most advanced tracking technologies is incorporated in Microsoft Surface. It will even track shapes of objects and can communicate optically with digital cameras or smart phones. One significant drawback of the optical path is the needed systems size. Another major drawback of all optical systems is their tendency to fail in bright sunlight due to infrared and visible radiation.

In conclusion, none of the above-mentioned systems provides sufficient means to track physical objects on a horizontal surface as desired. Although there are some technologies that track pens very accurately or even shapes and visual codes, some very incisive drawbacks like the extra space for light paths, limited size, the lack of suitability for horizontal use or the low update rate limit the usage in tangible HCI applications.
### COMPARISON OF RESEARCH PROTOTYPES

<table>
<thead>
<tr>
<th>Category</th>
<th>Sub category</th>
<th>Example product</th>
<th>Remarks</th>
<th>Year</th>
<th>Performance [m/s]</th>
<th>Size [mm]</th>
<th>Detection Modality</th>
<th>Detection Activation</th>
<th>Component Mount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitive</td>
<td>Projected</td>
<td>Multi touch three dimensional tablet</td>
<td></td>
<td>1983</td>
<td>20</td>
<td>30</td>
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<td></td>
<td>D T</td>
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<td>40</td>
<td></td>
<td></td>
<td>1 1 DT</td>
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<td>Inductive</td>
<td>Flock of Birds</td>
<td>Active Desk</td>
<td></td>
<td>1995</td>
<td>50</td>
<td>55</td>
<td></td>
<td></td>
<td>6 D T</td>
</tr>
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<td>MetaDesk</td>
<td></td>
<td>1997</td>
<td>7</td>
<td>55</td>
<td></td>
<td></td>
<td>6 D T</td>
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<td>Build-it</td>
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<td></td>
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<td>10 15 DT</td>
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<td>Optical</td>
<td>Color tracking</td>
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<td>&gt;42</td>
<td></td>
<td></td>
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<td></td>
<td>2 D T</td>
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<td>Diamondtouch DT 107</td>
<td>User identification</td>
<td>2001</td>
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<td>42</td>
<td></td>
<td></td>
<td>8 D T</td>
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<td>Color tracking support Teamwork</td>
<td>Workplace</td>
<td></td>
<td>2002</td>
<td>15</td>
<td>44</td>
<td></td>
<td></td>
<td>15 44 DT</td>
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<td>30</td>
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<td>RFID</td>
<td>Senseboard</td>
<td>Discrete cells</td>
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<td>1 55 DT</td>
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<td>Color tracking</td>
<td>Magic Table</td>
<td></td>
<td>2003</td>
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<td>&gt;42</td>
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<td>Cenetta</td>
<td>Discrete cells</td>
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<td>20</td>
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<td>Thow throw proj.</td>
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<td>Audiopad</td>
<td>Wacom techn.</td>
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<td>Reactive</td>
<td>Round projection</td>
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<td>32</td>
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<td></td>
<td>10 &lt;42 DT</td>
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<td>250</td>
<td>75</td>
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<td>250 75 DT</td>
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</tbody>
</table>

Figure 27: Overview table of the tracking technologies in research and their properties for different rating groups. Green fields mark that the particular property fulfills the requirements. Yellow boxes mark, that all properties of a requirements group are fulfilled. Inside the component mount group the letters indicate the position of the Display (D), Tracking (T) or of both (DT) in respect to the surface.

The above table reveals several facts:

**Component integration**
- No system integrates tracking and display components inside the interactive surface.
- The systems will integrate their tracking components above or under the interactive surface. This is mostly due to the use of optical, camera-based tracking systems.

**Detection activation**
- The combination of touch and TUI tracking is very rare, but if both activations are supported, the systems will track virtually unlimited touch points and TUIs.
- Apart from the DigitalDesk, systems which detect touch input also support multi-touch input

**Detection modality**
- The tracking state is only supported by a few systems.
- Identification seems common.
• Orientation tracking seems to be less difficult than detecting the tracking state.
• Additional state recognition is only possible within two systems.
• Only two systems (Wacom, InfrActables) are capable of tracking all detection modalities, but their components cannot be integrated in the screen. And vice versa if the components are integrated into the screen, some of the detection modalities are not supported.

Size

• Since most of the systems are based on optical tracking, the size can virtually be scaled to any size

Performance

• Only about half of the systems do reach the required update rate of 20 Hz or more

SUMMARY

In research, it is very common to use optical tracking systems to track touch, TUI or both, because it is very easy to realize. Although the software processing involves some serious challenges (calibration, object identification, filtering, transformation, path following, etc...) it offers the most flexibility and often existing frameworks can be used for the integration into new research projects. Optical systems also have the advantage that the image size can be scaled almost unlimitedly.

Other technologies such as capacitive or inductive tracking need a lot of implementation effort, since the solutions have to be built from scratch and are thus built for a specific application case only.

4.5 NEED FOR ACTION

In the previous chapters, the current system landscape was analyzed. It reveals that there exists no system that fulfills all of the requirements that were determined to be necessary for an intuitive tabletop system. Neither research prototypes nor commercial technologies provide a comprehensive requirement satisfaction. Especially the tracking of multiple objects or touch on the surface seems to be difficult. Even more challenging is the simultaneous detection and separation of touch and objects on the screen. Very demanding seems also robustness against foreign objects on the screen. Many tracking systems work on vertical screens, but fail when used horizontally since then irritation by additional objects that need not to be tracked is very likely.

Thus a system has to be designed that enables successful interaction by enabling:

• Simultaneous tracking of multiple users’ interactions
• Detection of multiple objects and multiple touch points simultaneously (satisfying the requirements for fast update rates)
• Irritation-free tracking (not disturbed by non-system-inherent objects)
• Ergonomic suitability for creative team work (integrated design, large surface, ...)

Such a system combines the advantages of multiple tracking technologies and provides a new kind of user experience. By eliminating the need for a “turn taking”-behavior the system gains intuitiveness and provides an irritation-free environment for relaxed team work. An optimized form factor (slimness) also contributes significantly to a comfortable work environment and finally a responsive system (tracking rate and lag) leads to a positive user perception, which results in increased acceptance for digital enabled work environments.

4.5.1 CHOICE FOR LC-DISPLAY TECHNOLOGY

Projection systems like Microsoft’s Surface are the systems that come closest to what is searched, but lack scalability and integrated design. Besides projection technologies other displaying technologies are widely used today such as LC-displays, Plasma screens, OLEDs, and LED displays. All of these provide a very slim display form factor.

In terms of flexibility of construction, OLEDs provide the best possibilities since the imaging layer is self light emitting. Large OLED-displays are very expensive and still tend to fail when being used for longer periods.

LED displays are very bright, but cannot be used for tabletop sized displays, because their pixel pitch of 1 – 5 mm is very large and would display a low quality image.

Plasma displays on the other side do not provide any flexibility in terms of components placing, since the cells have to be exactly aligned and maintained sealed.

LC-displays provide easy deconstruction where parts can be exchanged or removed without affecting other components (e.g. the backlight). Additionally, the LC-matrix is relatively robust and can be used as a standalone component that just needs a backlight of any kind in the visible spectrum. The decision for using the LC-matrix is particularly reached by discovering the fact that the LC-matrix is transparent to infrared light which is being analyzed in the following chapters.
4.5.2 OVERVIEW OF DEVELOPED SYSTEMS

Within the next chapters, the following systems based on LC-displays are developed and described in detail.

**MIGHTYTRACE**

In a first step, a prototype is developed that supports the tracking of TUIs on an LC-display (fulfilling the ergonomic requirements). This system is called MightyTrace and fulfills all requirements concerning TUI tracking (Detection of all modalities).

**TNT**

TNT (Touch’n’Tangibles) enables tracking of concurrent touch and TUI input on LC-displays and is an enhancement of the MightyTrace technology. It enables the detection of multi-touch on the MightyTrace system, but needs some adoptions of the MightyTrace hardware. The system fulfills all requirements presented in the requirements chapter.

**DIGISKETCH**

Digisketch is a completely different system that bases on a commercially available technology: The Anoto pen tracking. Again LC-display technology is used, but has to be adapted in order to make the Anoto system work on the LC-surface. It also fulfills all requirements in terms of TUI tracking. Additionally, the pens can also be used on normal paper and practically any surface extending the range of application drastically.
5 MIGHTYTRACE PROTOTYPE

5.1 INTRODUCTION

In the following chapter, the basic considerations that lead to the concrete design and electronic layout of the MightyTrace prototype are presented. This includes feasibility tests such as IR-transparency and sensor reception characteristics. The concept and an early version of this prototype have been published in [OPS].

MightyTrace enables the precise tracking of position, orientation and state of multiple devices on LC-displays. The basic concept behind MightyTrace is to take advantage of the facts that the components of LC-displays are transparent to infrared light, specifically the LC-matrix. Using this knowledge, a system can be set up that uses infrared emitting devices which can be tracked with sensors mounted in a discrete sensor array behind the LC-matrix inside the LC-display.

Figure 28: Basic concept of an infrared-based tracking inside an LC-display
In Figure 28, the simplified concept with its different layers inside an LC-display is shown. The core element of the concept is an additional layer of aligned infrared sensors between light guide and reflector. Devices that actively emit light can be detected by these sensors behind the LC-matrix.

Any distinction between devices is done by using a specific timeslot for each device, in which only one device is currently active. Thus, all devices have to be synchronized in order to make sure they will answer within the right timeslot. This principle has been published in a patent [OP9].

### 5.2 IR-TRANSPARENCY OF LC-DISPLAYS

The transparencies of the LC-display's components have to be determined prior to any other element. IR-transparency depends on the IR-absorption rate of the material. In order to measure the absorption in all the components of a regular display, the following tests were performed.

An infrared LED (DN304, 880 nm) and a sensor (SFH235FA) that corresponds in wavelength and sensitivity were aligned in such a way that components of the display could be inserted between the sensor and the emitter (Figure 29). For each layer, its specific absorption rate for a wavelength of 880 nm was determined. Obviously, the specific reflection of each material is implicitly included in this absorption rate, but was not measured.

For the test, two different displays (Table 4) were used to determine the IR-transparency for each layer. The different LC-panels have slightly different pitches. The components were measured while the LC-matrix was not electrically controlled – thus the LC-cells were transparent.
### Table 4: Monitors used in the transparency test

<table>
<thead>
<tr>
<th>Layers</th>
<th>DELL 1800 FP</th>
<th>SAMSUNG 910 TS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel</td>
<td>IPS (In plane switching)</td>
<td>PVA (Phase vertical aligment)</td>
</tr>
<tr>
<td>Pixel Pitch</td>
<td>0.2805 mm</td>
<td>0.294 mm</td>
</tr>
</tbody>
</table>

![Image of monitors](image)

**Figure 30: Individual IR-absorption in components of LC-displays for 880 nm wavelength**

In Figure 30 the absorption rates for different monitor components are shown (measured individually). The main IR-light absorbing structures are the LC-matrix and the diffusion films. Depending on the display manufacturer, these values can be very different such as 97.5% and 78% for the diffusion film of the two monitors. Generally speaking, most of the infrared radiation is absorbed or reflected by the layers.
In a next measurement series, the overall absorption rate of all the layers is determined. In Figure 31, the residual radiation in each layer in percent of the initial radiation is shown. IR-light that passes through all the layers will be absorbed or reflected by 99.912 - 99.981 percent, meaning that only 0.019 – 0.088 % of the initial radiation passes as far as behind the light guide and can be detected by appropriate sensors.

The measurements were performed using very low LED radiation intensities of 6 mW/Sr in order to use the whole sensitive range of the infrared sensor. Higher levels would have driven the sensor into saturation and prevent an accurate measurement.

![Residual radiation after passing the layers](image)

**Figure 31: Residual radiation in layers**

### 5.2.1 COLOR DEPENDENCY

The IR-transparency tests were performed without displaying any images on the LC-matrix. The results might be very different for active LC-matrixes that are displaying images. Thus, measurements were performed, in which the transparency of the LC-matrix was analyzed while different LC-cell states (black and white) were used. Black and white are the two most extreme states of an LC-matrix. In the black state, every sub-pixel is blocking light, whereas in the white mode, all sub-pixels let visible light pass through. In this measurement, the LC-matrix was tested without any other components such as diffusive films.
Table 5: Influence on transparency depending on displayed image on LC-matrix

<table>
<thead>
<tr>
<th>Displayed image</th>
<th>Analog sensor value [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LED off (no radiation)</td>
<td>2.75</td>
</tr>
<tr>
<td>Full screen black</td>
<td>4.22</td>
</tr>
<tr>
<td>Full screen white</td>
<td>4.28</td>
</tr>
<tr>
<td>Maximum range</td>
<td>1.53</td>
</tr>
<tr>
<td>Absolute maximum difference black / white</td>
<td>0.06</td>
</tr>
<tr>
<td>Percent difference between black and white</td>
<td>3.83 %</td>
</tr>
</tbody>
</table>

Since the matrix alone is only one of several parts in the optical path, this 4% have very little influence on the overall absorption rate (around 0.25%).

5.2.2 SUMMARY

It was shown by the above measurements that a small amount of infrared (between 0.02% and 0.09%) passes through all components of an LC-display without being influenced (0.25%) very much by the current image displayed on the LC-matrix.

5.3 TRACKING OF INTERACTION DEVICES

Multiple active interaction devices used on the system have to be fully determined in

- **Location**: The absolute position on the screen (origin is in the lower left corner, OpenGL convention), also incorporating the dragging and tracking state.
- **Identification**: Explicit identification of the device, e.g. its number and/or type.
- **Status**: If the user has altered the device status such as pressing a button on the device.
- **Orientation**: The orientation angle relative to the screen's coordinate system (origin lower left corner).

To achieve this goal, different approaches are possible with their specific advantages and drawbacks.
5.3.1 LOCALIZATION

A discrete two-dimensional sensor grid can be used to track light sources if the light source can trigger at least three sensors at a time. The sensors have to be able to measure the light intensity with a certain resolution in order to determine the source’s position.

![Diagram](diagram.png)

Figure 32: Setup of a location determination by using multiple sensors. The radiation of the LED is triggering four sensors behind the LC-matrix. A more intensive red is indicating detection of more infrared radiation. The circles around each sensor show the distance at which the actual emitter is expected according to the measured radiation. This amount is shown in fractions of the maximum radiation, when the emitter is straight above a sensor.

In Figure 32, the principle of lateration is shown. An IR-LED throws its radiation cone onto a set of sensors. Each sensor receives a different amount of irradiance which can be measured. By knowing the ratio of irradiance level to distance of the LED to a sensor, the exact position can be determined by computing the intersection polygon. In order to determine this ratio, several measurements had to be performed that determine the ratio of distance and irradiance onto a sensor. In chapter 5.8.3: Driver (Page 125) the proceeding and algorithm for position determination is described in detail. A simple analogy to the center of mass computation is used to determine the position.

In Figure 34, a basic sensor reception profile can be seen. The LED emitter was moved in front of the screen while the position of the sensor behind all LC-components was held constant (see Figure 33). The ratio is not linear, showing that a profile determination/calibration is needed.
Figure 33: Measurement setup to determine LED and sensor reception characteristics

Figure 34: A typical sensor reception profile. The sensor SFH 235 FA was placed directly behind the LC-matrix and the light guide, while the IR emitter DN304 was moved in front of the matrix across the sensor.

For a precise tracking, the ratio of position of emitter and sensor voltage has to be known beforehand, since it influences multilateration. The profile can be measured and saved as a lookup table or the curve can numerically be approximated to perform a correct position detection as shown in Figure 35.
5.3.2 LOCATION AND IDENTIFICATION

Location detection is based on sensor data and multilateration for each device. Distinction between different devices can be achieved as described next:

SPACE MULTIPLEXING

By space multiplexing the system, all the devices are always active. Each device only triggers a small subset of sensors of the whole sensor area close to its location. One measurement of all sensors is enough to determine the position of all devices which results in a high system speed. The system has to distinguish between several groups of sensors and map it to a specific device. However, this method has significant drawbacks:

- **Overlap**: When using multiple devices, certain interactions can lead to an approximation or even merging of the light cones of two or more devices, which leads to undistinguishable sensor groups.

- **Identification**: There is no guarantee of identification, since the groups of sensors do not differ. This could be solved by using device specific LED emission cones or by mounting multiple LEDs on one device that produce a device specific pattern. A path analyzing algorithm that tracks device positions over a certain time can provide a certain degree of identification. But as soon as the device is removed from the detection area and placed at a different location, an explicit assignment is no longer possible. Also when devices are moved too close to each other misinterpretations can occur and identifications might be wrong.
Figure 36: Space multiplexed device identification and location determination. The differently sized dots are the current sensor values. The yellow circles indicate the identified groups.

**TIME MULTIPLEXING**

A time multiplexed approach will assign each device to a separate timeslot (frame), in which it is allowed to actively emit light. As soon as all devices were sequentially activated, the system repeats the sequence. This completely prevents misinterpretations. Overlaps do not disturb the system since each device is time separated (see Figure 37).

![Diagram showing device distinction by using a predefined timeslot (frame) per device](image)

Figure 37: Device distinction by using a predefined timeslot (frame) per device

Time separation requires a synchronization of detection of each device’s IR-emission. By using such a suitable synchronization of IR-detection and emission, a device’s identification by the timeslot’s number in the sequence is easily feasible (see Figure 37). By using a synchronized link between the control system and the devices, each device can be addressed individually. In the MightyTrace prototype, this is realized by an additional optical infrared link. Each device is equipped with a sensor that receives infrared synchronization pulses. The pulses for the start frame are longer, while they are shorter for all frames in-between. Each device receives the pulses sent by the tracking system and determines its individual frame by counting the frames.

**DETECTION OF ADDITIONAL MODALITIES**

The time multiplexed approach supports devices to be tracked in position and identified by their slot in the synchronization chain. In order to track additional modalities such as orientation and inherent state change, the above method is extended. In order to take full advantage of the time multiplexed system, additional time slots are inserted for each device and are reserved for the transmission of internal states and for additional LEDs that enable the determination of the orientation of a device. By using a second timeslot for
the second LED only two LEDs are needed to unambiguously detect the device's position, since the LED order is always the same.

### 5.3.3 ORIENTATION DETECTION

In order to detect orientation, a second LED can be mounted on the device. This LED occupies also an individual frame. Every time the device is queried, the LEDs are turned on in their specific frame, which makes them properly distinguishable by the system. By multilaterating each LED’s position, an orientation can be determined by analyzing the vector from the position of LED 1 to LED 2. Since the order of interrogation is strict, the orientation is distinct. As shown in Figure 38, device four incorporates two position frames. In each frame, a separate LED emits IR-light.

![Figure 38: Extending each device's active time by additional frames to enable status and orientation detection](image)

### 5.3.4 INHERENT STATE DETECTION

A second frame for each device is inserted in order to transmit information about internal device states such as buttons. Device button state is detected by letting the device LED blink again in the frame that is reserved for the status signalization. The button may be placed in the tip of a pen input device in order to realize a tracking and dragging state distinction. The system just checks if any sensor is active in the state frame of the actual device and recognizes the current state. More state frames per device slot offer the possibility to transmit extended binary data. By adding three extra frames for status transmission, a total of $2^3 = 8$ states can be transmitted.

<table>
<thead>
<tr>
<th>State Frames</th>
<th>Possible States</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>8</td>
<td>256</td>
</tr>
</tbody>
</table>
In Figure 38, a possible configuration of state frames per device is shown. Device number three has two state frames, which can be used to transmit 4 states, while device number four can transmit 8 states by using its three-state frames. The transmission of a whole byte (8 bits) enables to distinguish between 256 states, which can be used to transmit potentiometer rotations, using 8-bit analog to digital conversion on the device. However, adding frames to a device will extend the time needed to cycle through all frames.

CONCLUSION

The implementation of a time-multiplexed system offers unambiguous position detection and identification by serializing device activity. By adding additional dedicated frames per device, information about status and orientation can be transmitted without any extra system adaption. These facts justify the disadvantage of the need for synchronization hardware. Figure 39 shows a full sequence including position, state and orientation frames.
Figure 39: Visualization of a whole sequence with two devices having a different amount of individual frames. In the position frame the LED of the device is turned on in order detect its position. In the state frame the LED is only turned on when the internal state of the TUI has changed (e.g. the button on the device was pressed). A second position frame is used for the second LED of an orientation sensitive device in order to determine its orientation.
### 5.4 EVALUATION OF OPTICAL COMPONENTS

There is a significant optimization challenge connected with the design of a discrete sensor grid, namely:

- **Finding a trade-off between number of sensors and optimal detection of IR-light.**

On one side, the amount of sensors has to be kept as small as possible in order to reduce complexity and costs. On the other side, reducing the amount of sensors will increase their distance and thus demands a wider emission angle from the light source in order to trigger enough sensors for multilateration.

In addition, widening LED radiation characteristics opens two significant considerations: The field of available LEDs is significantly reduced and power consumption on the device is increased because more radiation over the whole radiation cone is needed in order to achieve the required irradiance. In addition, the irradiance in the LED radiation cone’s hotspot will also increase when radiation is raised. This also increases the probability of driving the sensor into saturation. In Figure 40, two different sensor reception profiles are shown to illustrate this effect.

In summary, an emitter and its underlying sensor grid have to fulfill the following criterions:

- The more sensors the LED illuminates the better the position can be determined because more data for correction is available. Thus the LED has to illuminate surrounding sensors not only at distances \( d_s \) but also at \( D_s \), which is the diagonal of the sensor square (see Figure 40).
- Sensors must not be driven into saturation by any occurring radiation.
- Sensor distances have to be increased as much as possible

![Figure 40: Sensor profile design](image-url)
SENSOR SELECTION

The SFH 235 FA is a low cost sensor with very wide receiving characteristics and short switching times. Several other sensors were also evaluated (see Table 7), which did not perform in such a wide reception angle, but incorporated lower detection thresholds and higher maximum radiation detection. Since switching times are very important for a responsive system, the other sensors could not fulfill this criterion. Also costs were rated highly since a lot of sensors are needed to cover a suitable multi-user interactive area.

**Table 7: Evaluated sensors and their properties.** The best values per parameter are marked. SFH 235 FA was considered most suitable.

<table>
<thead>
<tr>
<th>Sensor name</th>
<th>Angle of half intensity [°]</th>
<th>Angle of detection limit [°]</th>
<th>Lowest detectable radiation [mW/cm²]</th>
<th>Maximum detectable radiation [mW/cm²]</th>
<th>Switching times [ns]</th>
<th>Costs per 1000 [$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>OP508FA</td>
<td>120</td>
<td>180</td>
<td>0.001</td>
<td></td>
<td>11</td>
<td>2000</td>
</tr>
<tr>
<td>OP593</td>
<td>110</td>
<td>200</td>
<td>0.001</td>
<td>33</td>
<td>5000</td>
<td>490</td>
</tr>
<tr>
<td>OP954</td>
<td>130</td>
<td>180</td>
<td>0.04</td>
<td>4</td>
<td>5</td>
<td>720</td>
</tr>
<tr>
<td>PD481PI</td>
<td>120</td>
<td>180</td>
<td>0.02</td>
<td>?</td>
<td>20</td>
<td>460</td>
</tr>
<tr>
<td>SFH235FA</td>
<td>130</td>
<td>220</td>
<td>0.004</td>
<td>1</td>
<td>20</td>
<td>460</td>
</tr>
</tbody>
</table>

EMITTER RADIATION

The datasheet shows that the irradiance level (radiance per unit area) of the SFH 235FA starts at $S_{\text{low}} = 10 \, \mu\text{W/cm}^2$ and ends at $S_{\text{high}} = 1000 \, \mu\text{W/cm}^2$. Above the upper level, the sensor will be saturated and therefore not be able anymore to measure data correctly. In order to make sure that the sensor is sufficiently triggered if the LED is placed directly opposite to the sensor including all LC-components, at least $S_{\text{low}}$ has to be available after the IR-light has passed all layers (matrix, diffusion films, light guide). Since only 0.019 % of the incident irradiance passes all components, the required sensor threshold levels for the irradiance including loss is:

\[
S_{\text{low, loss}} = S_{\text{low}} / 0.00019 = 0.053 \, \text{W/cm}^2 \tag{E1}
\]

\[
S_{\text{high, loss}} = S_{\text{high}} / 0.00019 = 5.263 \, \text{W/cm}^2 \tag{E2}
\]

The IR-LED in the test setup (DN304) has a maximal radiation intensity of $I_c = 30 \, \text{mW/Sr}$ at a current of $C_L = 50 \, \text{mA}$ and is radiating with a LED radiation angle $A_L$ of 35 degrees. Based on this data, a theoretical approach on the feasibility of the tracking system can be made:

Steradian covered by the LED:

\[
S_L = 2\pi (1-\cos(A_L)) = 1.14 \, \text{sr} \tag{E3}
\]
Total radiant flux:

\[ \Phi_L = I_L \cdot S_L = 34.09 \text{ mW} \quad [E4] \]

The LED is placed \( D_L = x \text{ [cm]} \) above the sensor. Thus, at this distance the LED covers an area of:

\[ A_L = S_L \cdot D_L^2 = S_L \cdot x^2 \quad [E5] \]

Finally, the irradiance \( I_s \) at the distance \( x \) is:

\[ I_s(x) = \frac{\Phi_L}{A_L} = \frac{\Phi_L}{S_L \cdot x^2} \quad [E6] \]

For \( D_L = 5 \text{ cm} \) distance \( I_s \) becomes \( 1.2 \text{ W/cm}^2 \) which is well between the two determined thresholds of the sensor.

For several values of the LED-sensor distance \( x \), a curve (see Figure 41) can be plotted that shows the distance to the screen being required to generate the corresponding irradiance. The loss of over 99% in the LC-components is already included.

![Figure 41: Theoretical computed irradiance behind LC-components depending on distance to sensor](image)

It is well-known that irradiance levels of the selected LED can trigger the sensor through the whole range of sensitivity, depending on the distance. Even at a distance of \( x = 100 \text{ mm} \), the irradiance level is sufficient. It is also important to note that for short distances it has to be made sure either by irradiance adjustment of the LED or by selecting an appropriate LED that the sensor is not driven into saturation. If the sensor receives irradiance above its saturation level, detection accuracy is reduced since multilateration can no longer be performed precisely.
EMITTER SELECTION

Different LEDs with different emission characteristics and power levels were evaluated together with all display components. The emission characteristic is influenced by the different layers not only in absorbing radiation, but also in changing emission characteristics. It might not be taken for granted that the emission angle data provided by the manufacturer is the same after passing all LC-components, since reflection and absorption in the LC-display’s components influence IR-light paths.

In Figure 43, the measurement results for different LEDs are shown. Each LED was tested with two distances of the sensor to the matrix (to determine the distance influence). The LEDs were always powered in such a way that the targeted sensor would just reach its saturation threshold at the position of maximum intensity (when the LED was positioned right underneath the sensor, see Figure 42). In the measurements, the horizontal positions of the IR-emitter were evaluated, where the sensor could not detect any irradiance - thus determining the maximum emission width including all LC-components.

![Figure 42: Measurement setup for the determination of the emitter emission width for different sensor - matrix distances](image)

It can be seen in the results chart in Figure 43 that the SFH 487 P has the widest IR emission of 59 mm and 42 mm respectively. Half of this value is the maximum distance that sensors are allowed to be apart. In a square alignment of the grid, the diagonal distance must not be larger than 29.5 mm (59/2), which means that the largest grid pitch must be lower than 20.86 mm ($\frac{\sqrt{2}}{2} \cdot 29.5$).
Figure 43: LED evaluation chart: Emission widths of different LEDs with different sensor-matrix distances.

HEIGHT DEPENDENCY

It has to be noted that the distance of emitter to the matrix will increase the emission cone. Thus, theoretically the sensor profile used for multilateration must be changed according to the height the interaction device is hovering above the surface.

5.5 HIGH-SPEED SENSOR DATA ACQUISITION

If a serialization of device interrogation is used (time-multiplexing), it has to be made sure that the query of all frames (one sequence) will be as short as possible. To assure that the required sample rate of at least 10 Hz and a lag of no more than 50 ms are achieved, a high-speed data acquisition circuit was needed. Different concepts were evaluated concerning their feasibility and performance potentials.

Using the evaluated sensor distance of less than 20.86 mm, calculations of the required data acquisition speed can be made. As seen in Figure 44, already at screen diagonals of 24 inches more than 400 sensors are required to cover the whole screen size in a raster of 20 mm.
5.5.1 SENSOR SPEED

For an estimation concerning acquisition timings, the sensor is a good starting point. The Sensor SFH235FA is an infrared-sensitive photo diode. There exist different methods to drive photo diodes:

- **Photovoltaic mode**: The photo diode sources energy, much like a photocell. This mode is normally not used for measurement.

- **Short circuit mode**: The diode sources current, which is linear to the incident light over several magnitudes. This mode requires an additional electrical charge amplifier circuit to detect the very low currents. This mode is also very sensitive to noise.

- **Bias mode**: The diode is connected in the reverse-biasing mode. Current flows in the inverse direction, which is proportional to the incident light - the diode is conducting in reverse direction, but the reaction time is reduced. Linearity can be influenced by dark currents\(^4\).

Only short circuit and bias mode can be used for measurements. Since the short circuit mode requires additional components, it is less suitable in a large sensor grid. A first test with bias mode operated diodes reveals the reduced reaction time. The sensor requires 126 µs to reach saturation (see Figure 45). Compared to 20 ns from the datasheet this is a lot more. But depending on the circuit design, a less complex detection circuit will most likely offer more potential for expansion. Thus for the implementation the reverse-biasing mode is chosen, because it offers low complexity.

\(^4\)Dark current is the relatively small electric current that flows through photosensitive devices such as a photodiode, or charge-coupled device even when no photons are entering the device
5.5.2 SENSOR ACQUISITION CONTROL CONCEPT

In order to be very flexible in respect to the system’s layout and size of the sensor grid, a modular component assembly is envisioned that can be adapted to the current requirements. Many individual slave modules with a defined amount of attached sensors acquire these sensor values and already perform a first filtering. This filtering (threshold check) decides whether a sensor value is usable or whether it is rejected. By using such an approach, the communication between the modules can be reduced, since only relevant data is transmitted. A master module will synchronize parallel sensor acquisition on all modules and will initiate the data transfer afterwards. Parallel read out improves temporal performance significantly. Only the master module controls the synchronization of the whole system and provides the main interface to the personal computer.

![Module Concept](image)

Figure 46: Modular concept. A master module communicates with many slave modules, which read out the sensor arrays.
**DETAILED CONCEPT**

In Figure 47 the concept of one MasterModule and several SlaveModules with their sensor arrays is shown in detail.

Figure 47: Acquisition control concept in detail. The green circles show the temporal activity of the components starting at one.

Synchronization control is performed only by the MasterModule. The synchronization logic (1) is controlling all timings of all components directly or indirectly. At the beginning of each frame a synchronization flash signal is generated (2) and transmitted to the LED emitters (3) mounted on the SlaveModules. This flash is received by receiver demodulators (4) on the devices. The received flash is analyzed and internal device interpretation is determining if the device must reply an IR signal. If so, the internal IR LED (5) is turned on for the time all the sensors need for read out. At the same time a read out of all sensors is induced by the MasterModule with an acquisition synchronization signal. By a first filtering (threshold comparison)(6) the sensor data is buffered (7) until it is queried by the SPI bus controller (8). The data from all SlaveModules is collected on the master and buffered again until all frames have been processed. Only in the last frame the data is sent via a serial to USB convertor chip to the PC.
5.5.3 SYNCHRONIZATION

Synchronization of the MightyTrace system is controlled by the MasterModule. Basically, the synchronization of the whole system can be separated into four different phases, whereas the fourth phase is only entered, when the last frame in a sequence has been processed:

1. **Sync Phase**: Synchronization of all components.
2. **Acquisition Phase**: Analog to digital conversions.
3. **Collection Phase**: Sensor data collection by MasterModule.
4. **Transfer Phase**: Sensor data transmission to PC.

In the following chapter, each phase is described with respect to synchronization issues. For an overview, the processes are visualized in Figure 48.

![Figure 48: Synchronization and timing overview. Timing information for each device and module is shown for one frame in the sequence. Blue arrows show the communication path between modules. The Master generates a modulated IR trigger flash, which each device is receiving. The device that is mapped to the current frame will turn on its LED while all SlaveModules will receive via their sensors. The data on the slaves is pre-filtered and in a last step collected by the master by serially querying each slave for valid data, using the SPI bus.](image)

**SYNC PHASE**

In the Sync Phase, a modulated IR-flash (carrier frequency 455 kHz) is generated depending on the Frame number. The sync flash is modulated to provide stability for the system against unwanted external IR signals from other electronic devices. Although the modulated flash provides more protection against other IR sources the system cannot be used in direct sunlight, because the IR sensors on the SensorBoards are not modulated and will respond to any IR radiation.
In the first frame, a long (length = 94 µs) modulated IR-flash is emitted; otherwise a short (51.5 µs) one is generated (see Figure 49). The IR-flash is modulated in order to achieve a higher stability of the synchronization. Distortions by IR-light from sources other than the IR-emitter are mostly prevented by using this modulation.

The IR-flash is received and counted by all devices. A long IR-flash starts a sequence. If a device is detecting its frame in the sequence, it will be active in the acquisition phase of this particular frame.

After the IR-flash was sent, all the SlaveModules are triggered in order to initiate sensor data acquisition on all SlaveModules.

**ACQUISITION PHASE**

In this phase, all SlaveModules acquire sensor data. Every SlaveModule controls its own analog to digital conversions on all their eight ADC chips. Each analog-to-digital conversion takes a certain amount of time and each ADC has to be addressed sequentially, since the ADC are controlled by a bus from the SlaveModule. During this time, the interaction device that is assigned to the current frame, is active and emits IR-light which passes through the LC-matrix until all sensors are readout.

Every sensor value is only saved to a temporary register, if it is above an adjustable threshold. This method reduces SPI traffic significantly, since only relevant sensor values will be transmitted in the collection phase.
**Figure 50:** Signals that control the ADCs timings on the SlaveModules in the acquisition phase:

- **SLAVE TRIG:** Defines the start of acquisition for all SlaveModules.
- **IR FLASH:** Shows the modulated IR-flash signal generated on the MasterModule.
- **CONVST (conversion start):** Indicates the start of one analog to digital conversion.
- **RD (read):** Is enabled by the slave microcontroller when it reads the ADC data.
- **A0 – A1 (address):** Define the current selected channel on each ADC chip.

**COLLECTION PHASE**

During the collection phase in each frame, the SlaveModules are queried sequentially by the MasterModule via the SPI bus. The SlaveModules answer with the available sensor data ready for delivery. If sensor data is ready, the data is sent directly to the MasterModule. On the MasterModule, the received sensor data per frame is saved to the internal flash memory for intermediate storage until all frames have been processed.

**Figure 51:** SPI data transfer from two SlaveModules to the MasterModule during the collection phase:

- **SLAVE SEL 0:** The line on which the master explicitly selects SlaveModule 0
- **SLAVE SEL 1:** The line on which the master explicitly selects SlaveModule 1
- **SLAVE 0 SPI ACT:** SPI activity monitor line for SlaveModule 0
- **SLAVE 1 SPI ACT:** SPI activity monitor line for SlaveModule 1
- **BUSY, MOSI, MISO, SCK:** SPI communication lines.
TRANSFER PHASE

The transfer phase is entered only after the very last frame of a sequence. If a “request for data”-byte is in the input buffer of the MasterModule, it sends all the collected sensor data to the PC via the USB bus. A serial-to-USB converter cable [W50] with an integrated FTDI chip [W49] is used to generate valid USB data out from native serial data from the MasterModule.

Figure 52: USB data transfer in the last frame of a sequence.
TX: Data traffic from FTDI (PC) to MasterModule
RX: Data traffic from MasterModule to FTDI (PC)

5.5.4 SPI DATA RATE

The SPI interface is the fastest interface available on the Atmel chips and is used for the data transfer from the SlaveModules to the MasterModule. The SPI bus operates with a single MasterModule and one or more SlaveModules. Since the hardware interface of the data pins features tri-state outputs, their signal lines can be switched to high impedance (“disconnected”), which allows the sharing of a single SPI bus among several SlaveModules.

The SPI bus requires four wires for reliable operation, which are:

- **SCK**: Serial Clock. This is the clock line that defines the SPI clock. The signal is generated by the master.
- **MOSI**: Master Out Slave In. In each serial clock cycle, a single bit is transferred to the slave while at the same time a bit is transferred from the slave to the master. The communication is therefore called full duplex.
- **MISO**: Master In Slave Out. Same as MOSI, but vice versa.
- **SS**: Slave Select. The number of SS lines is equal to the number of slaves. Thus, a line for each slave is used to address it directly for communication.

In order to achieve a high SPI data rate, a mode is implemented that combines the advantages of two methods which are burst mode and hand shake:
• **Burst mode:** In the burst mode, one side of the SPI bus is continuously scanning the SPI bus for data arrival, while the other side is sending repeatedly a high amount of data without waiting for input form the other side. This mode is very fast, but has its drawback since the receiver has to continuously scan the input line, which takes a lot of processor resources.

• **Hand shake:** Communication is initialized by an additional control wire which is called BUSY line. The BUSY line makes sure that both sides are set to the correct state before each byte transfer. The transfer becomes more reliable but takes more time.

• **Combined mode:** In MightyTrace, a mode is implemented that combines each of the advantages of both methods. Via the BUSY line, a communication is initiated (hand shake). However, the amount of data is communicated before any data is sent. Then, the data is sent in one stream of bytes without feedback (burst mode). This proceeding makes sure the communication is timed perfectly, but doesn’t need a hand shake for every byte (see Figure 53).

![Figure 53: SPI communication principle](image)

By using this mode, the data rate could be doubled compared to a pure hand shake proceeding. But of course an overhead for communicating the data amount is involved, which reduces the absolute theoretical maximal data rate of 610 kBytes/s down to 250 kBytes/s (59% reduction) for the overall communication. This reduction can be explained by handling communication with multiple slaves and by the need for hand shake and data amount communication.

### 5.5.5 UPDATE RATE

The system’s update rate depends on various factors. In order to determine a theoretical update rate for predictions of update rates for different system sizes, the timings of all processes are analyzed.

Basically, the update rate can be determined by knowing the display size, the aspect ratio and the number of frames used. However, specific update rates can only be determined for a particular condition of input.
activity (how many devices are active). It has to be defined, how many frames are active (receive input) at the moment and how many sensors are triggered in these frames.

**TIMINGS**

Computations can only be made by knowing the exact timings of the involved components. This can be determined experimentally. In Figure 54, definitions of important timings are shown.

![Definitions of important timings](image)

Derivations for the different timings are given here:

**DEVICE ANSWER DELAY (DAD)**

This delay occurs when the system has to wait for the device’s answer. Processing on the device and demodulation of the IR sync flash takes time. This delay is constant and was measured to be:

\[ t_{DAD} = 107 \mu s \]  \[ \text{[E7]} \]

**SENSOR PROFILE DELAY (SPD)**

The sensor needs some time until it reaches its full amplitude. This is also a constant value:

\[ t_{SPD} = 142 \mu s \]  \[ \text{[E8]} \]
ANALOG TO DIGITAL CONVERSION AND FILTER TIME (ADCFT)

ADC will always be performed, but the filtering will depend on the amount of sensors measured above the threshold, which influences the times mentioned in the above. In Figure 55, a measurement of the active sensors’ influence on the ADCFT time is shown. Thus, the ADCFT can be calculated by:

\[
t_{ADCFT} = 0.893 \cdot N_{ActSensPerFr} + 256.17
\]

[Figure 55: Measurement of the ADC and filter time. It scales linearly with amount of sensors]

SPI TRANSFER TIME (SPITT)

Transmitting data to the MasterModule takes a significant amount of time depending on the number of active sensors values. In Figure 56, the measurement shows the correlation. SPITT will be linearized using the following equation. For each SlaveModule that is connected, a SPITT is used. Even without sensors, 10.1\(\mu\)s are used for the querying.

\[
t_{SPITT} = 12.201 \cdot N_{ActSensPerFr} + 10.1 \cdot N_{Boards}
\]

[\(E9\) and \(E10\) are mentioned in the text]
**USB TRANSFER TIME (USBTT)**

Data transfer via USB is relatively slow, but occurs only in the last frame of a sequence. Analyzing USB traffic, it can be linearized for sensor amounts above four. But since the emitter radiance will always trigger more than four sensors, this linearization can be applied.

\[ t_{USBTT\text{OneFrm}} = 59.229 \cdot N_{ActSensPerFr} - 50 \]  \[ \text{[E11]} \]

\[ t_{USBTT} = 59.229 \cdot N_{ActSensPerFr} \cdot N_{ActFr} - 50 \]  \[ \text{[E12]} \]
ESTIMATING UPDATE RATE FOR LARGE SCREEN SIZES

Having evaluated all required data for the individual timings, the update rate can be determined.

Five parameters can be set freely:

- Display size X and Y: $L_{DispX}, L_{DispY}$
- Number of frames used: $N_{TotFr}$
- Number of active frames in a sequence: $N_{ActFr}$
- Number of active sensors per active frame: $N_{ActSensPerFr}$

In order to determine the total amount of sensors and boards necessary for the current configuration, the required boards for the chosen screen size (rounding up or down) are computed. The following hardware parameters are fixed:

- SensorBoardSizeX: $l_{SensBoX} = 75$ mm
- SensorBoardSizeY: $l_{SensBoY} = 300$ mm
- SensorsPerBoard: $N_{SensPerBo} = 64$

For the amount of Total Boards ($N_{Boards}$) we get by using roundup for fractioned boards:

$$N_{Boards} = \text{ROUNDUP} \left( \frac{L_{DispX}}{l_{SensBoX}} \right) \cdot \text{ROUNDUP} \left( \frac{L_{DispY}}{l_{SensBoY}} \right)$$  \[E13\]

Again, the constant timings are noted:

- $t_{DAD} = 107 \mu s$
- $t_{SPD} = 142 \mu s$

Variable timings are noted:

- $t_{ADCFT} = 0.893 \cdot N_{ActSensPerFr} + 256.17$
- $t_{SPIIT} = 12.201 \cdot N_{ActSensPerFr} + 10.1 \cdot N_{Boards}$
- $t_{USBTT} = 59.229 \cdot N_{ActSensPerFr} \cdot N_{ActFr} - 50$

The Total Frame Time (TFT) without USB transfer will be computed by adding all timings:

$$t_{TFT} = t_{DAD} + t_{SPD} + t_{ADCFT} + t_{SPIIT}$$  \[E14\]

$$t_{TFT} = 505.17 + 13.094 \cdot N_{ActSensPerFr} + 10.1 \cdot N_{Boards}$$  \[E15\]

Including USB, a mean frame time has to be generated including a whole sequence:
And finally for the mean update rate over all frames:

$$f_{\text{mean}} = \frac{10^6}{t_{\text{mean,USB}}} \text{Hz}$$  \[E18\]

**UPDATE RATE EXAMPLES**

To theoretically compare update rates for different screen sizes, it is necessary to setup a scenario. A table with seating places for four users is considered. It provides a pen input device to each user. Additionally, two specialized TUIs are taken into account (see requirements). Further, it is assumed that each device is on the interactive surface, generating sensor data in each of the two frames it occupies, meaning that its state is currently set to drag (in the case of the pen). Finally a device will normally trigger not more than 10 sensors at the same time. Thus the following constants can be defined:

- \(N_{\text{TotFr}} = 6 \cdot 2 = 12\)
- \(N_{\text{ActFr}} = 12\)
- \(N_{\text{ActSensPerFr}} = 10\)

![Figure 58: Mean update rate for a standard scenario for different screen sizes](image)
It can be seen (see Figure 58) that the critical update rate of 20 Hz (requirement) is not reached even for screen sizes of 100” and more. The actual limit for the update rate is for screen diagonals of 146” or more.

For the case that the screen size is constant and the amount of frames is adjusted, the following diagram is shown. Varying the amount of frames shows how the update rate will change for different amounts of TUIs, each typically occupying two frames.

![Diagram showing mean update rate for different number of frames](image)

**Figure 59: Mean update rate for the same screen size and different number of frames**

In Figure 59, the effect of different amount of frames on the update rate can be seen. Here the critical level of 20 Hz is reached at 33 frames (of which all are active). Thus, the system can track 16 devices simultaneously (each being in the dragging state) without failing the requirements. Note that it is very unlikely that each of the devices is used at the same time in the dragging state. Thus, the above assumptions are worst-case considerations.

## 5.6 ELECTRONICS DESIGN

### 5.6.1 OVERVIEW

MightyTrace is modularly designed. The MasterModule synchronizes all SlaveModules by using several communication lines. In Figure 60, all electronic communication paths are shown. The following parts can be identified:

- **SPI Bus**: The SPI (Serial Peripheral Interface) is used to transfer data between MasterModule and SlaveModules. The SPI bus is a full duplex bus that enables a synchronous serial data link between a Master- and a SlaveModule. Physically, the bus consists of at least four control wires.

- **Slave Trigger**: This signal makes sure that all SlaveModules start their sensor value acquisition at exactly the same time.
- **Sync Flash**: In order to synchronize the TUIs on the interaction surface, a flash pulse has to be generated. Every SlaveModule incorporates IR-diodes directly mounted on the PCB that can be switched on or off from the MasterModule in order to emit synchronization pulses.

- **PC Interface**: A simple serial RS232 Interface connects the MasterModule to the PC (via a serial to USB converter). Pre-processed sensor data is sent via this channel.

- **Program Interface**: This port can be used in order to program each module.

- **Slave Program select**: Is used to select the SlaveModule that should be programmed.

*Figure 60: Electronic communication between the MasterModule, SlaveModules, and PC.*
5.6.2 MASTERMODULE

The MasterModule is the core component of the MightyTrace System since it synchronizes all SlaveModules and generates the synchronization pulses. Additionally, it buffers the sensor data and handles transmission of the data to the PC over USB.

The MasterModule consists of a microcontroller, reference voltage generation, indicator LEDs, programming switches, and connection headers.

An ATmega644 microcontroller is selected for this purpose that runs at 20 MHz. The most important technical data of ATmega644 is listed in Table 9.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash</td>
<td>In system programmable 64 kB</td>
</tr>
<tr>
<td>SRAM</td>
<td>4 kB</td>
</tr>
<tr>
<td>EEPROM</td>
<td>2 kB</td>
</tr>
<tr>
<td>Timers</td>
<td>2 x 8 bit timer/counters</td>
</tr>
<tr>
<td></td>
<td>1x 16 bit timer/counter</td>
</tr>
<tr>
<td>PWM</td>
<td>6 channels</td>
</tr>
<tr>
<td>ADC</td>
<td>8 channel, 10 bit</td>
</tr>
<tr>
<td>Interfaces</td>
<td>1x USART</td>
</tr>
<tr>
<td>IO</td>
<td>32 programmable IOs</td>
</tr>
<tr>
<td>Speed</td>
<td>0 – 20 MHz</td>
</tr>
</tbody>
</table>

Table 8: ATmega644 properties

The MasterModule is equipped with an interface to address each connected SlaveModule individually (See Figure 62). The SPI header is used to transfer the sensor data, while the SlaveSelection header is used to individually address the slaves. This header also comprises connections for the individual reprogramming of the SlaveModules. This is necessary because once the whole MightyTrace Board is integrated into the
screen, access to the Slaves is blocked. A 2.5 Volt voltage reference is used to generate the sensor reference for all 168 ADCs on the 21 SlaveModules. The MasterModule can be reprogrammed as well. For that a switch is mounted that can be used to choose between Master or Slave programming. If Slave is selected, additionally one of the Slave select switches has to be enabled to enable one of the 21 SlaveModules for programming. Since data transfer from the Slaves to the Master is realised over the SPI bus the SPI bus is occupied and interference might occur when trying to program the Slaves. Therefore the Master can be decoupled from the SPI bus lines by removing the three programming jumpers. Indication LEDs provide visual feedback of the Status of the whole system. LED1 indicates SPI bus activity. The LED brightness indicates the amount of active sensor data. LED2 indicates USB bus activity and will signal every USB packet transfer by a blink.

![Diagram of MasterModule PCB and its components]

**Figure 62: MasterModule PCB and its components**

### 5.6.3 SLAVEMODULE

One SlaveModule consists of a SlaveBoard and two SensorBoards that can be mounted onto the SlaveBoard. In order to keep implementation complexity low, only 8 bit RISC (Reduced Instruction Set Computer) architecture based microcontrollers are used. Atmel [W41] provides a long list of available devices. For MightyTrace, a microcontroller was selected that supports a high system clock, enough IO Pins, SPI and USART (Universal Synchronous and Asynchronous serial Receiver and Transmitter) interfaces, PWM (Pulse Width Modulation) generation and a package that is still manually solderable. An ATmega644 microcontroller is selected for this purpose that runs at 20 MHz. The most important technical data of ATmega644 is listed in Table 9.
The ATmega644 properties are listed in Table 9:

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash</td>
<td>In system programmable 64 kB</td>
</tr>
<tr>
<td>SRAM</td>
<td>4 kB</td>
</tr>
<tr>
<td>EEPROM</td>
<td>2 kB</td>
</tr>
<tr>
<td>Timers</td>
<td>2 x 8 bit timer/counters</td>
</tr>
<tr>
<td></td>
<td>1x 16 bit timer/counter</td>
</tr>
<tr>
<td>PWM</td>
<td>6 channels</td>
</tr>
<tr>
<td>ADC</td>
<td>8 channel, 10 bit</td>
</tr>
<tr>
<td>Interfaces</td>
<td>1x USART</td>
</tr>
<tr>
<td></td>
<td>1x SPI</td>
</tr>
<tr>
<td></td>
<td>1x TWI</td>
</tr>
<tr>
<td></td>
<td>1x JTAG</td>
</tr>
<tr>
<td>IO</td>
<td>32 programmable IOs</td>
</tr>
<tr>
<td>Speed</td>
<td>0 – 20 MHz</td>
</tr>
</tbody>
</table>

Table 9: ATmega644 properties

Since the internally available Analog-to-Digital Converter (ADC) of the Atmel Device is too slow for a suitable conversion rate and only provides eight channels, several external ADCs are used. Analog Devices [W42] is specialized on such components. The AD7829 was selected in respect to conversion rate, resolution, costs and interface type. Its properties are listed in Table 10.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conversion Time</td>
<td>420 ns (2 MSPS)</td>
</tr>
<tr>
<td>Resolution</td>
<td>8 bit</td>
</tr>
<tr>
<td># channels</td>
<td>8</td>
</tr>
<tr>
<td>Reference</td>
<td>On Chip</td>
</tr>
<tr>
<td>Interface</td>
<td>Parallel</td>
</tr>
</tbody>
</table>

Table 10: AD7829 Analog to Digital Convertor

The microcontroller on the SlaveBoard handles communication from and to the SPI bus. The slave is selected via the slave select lines by the MasterModule. A parallel bus to the ADCs selects the chips and transfers digital sensor data to the ATmega644 (Figure 63). Each ADC acquires analogue voltage values from eight sensors and converts these into eight bit binary data that can be read by the microcontroller over the parallel bus. In total, 64 sensors are read out by the circuit in a very short time.

In order to be able to synchronize all interaction devices, the synchronization flash is mounted directly on the SensorBoard. This will make sure that the user cannot disturb the line of sight required for a reliable synchronization. A switching circuit on each SensorBoard consisting of a HEX inverter and a MOSFET is chosen to avoid switching the current centrally for all SensorBoards. This prevents large currents being switched at high rates centrally, which can lead to unwanted electromagnetic fields. Also switching high currents at high rates is demanding in respect to switching components. Thus, every SensorBoard has its own flash power source and a switching circuit to switch eight IR-flash LEDs.
Figure 63: Simplified schematic of a SlaveModule = 1 SlaveBoard + 2 SensorBoards

The Printed Circuit Board (PCB) of the SlaveBoard (Figure 64) was designed in respect to the following criterions:

- SPI bus connection traverses each board in order to enable inter-board connection
- Bus connection to adjacent boards by using standard pin connectors
- Integration of all ADCs and the microcontroller on the board (apart from sensors)
- Debug pads for functional control
- Side connector for all power supplies:
  - Control supply 5V
  - Sensor supply 2.5 V
  - Sensor middle reference VMID. This line is optional and can be connected in order to equal the different voltages from the ADCs internal middle reference.
  - Infrared flash supply 5V
- ISP (In system programming) interface via SPI bus and local pins
- Through hole connection to sensor board, including power supply pins for sensors and IR flash LEDs
- Fixing holes for PCB mount
- Small dimensions to reduce costs
Figure 64: The SlaveBoard and its main components and connectors

SENSORBOARD SUB MODULE

The SensorBoard (Figure 65 and Figure 66) is a sub-module of the SlaveModule and is mounted onto the SlaveBoard. The SensorBoard is designed according to the maximum sensor distance found in the previous measurements and with respect to the dimension of the LCD support frame of the 40” monitor. The distance between the sensors is set to 18.9 mm, which is slightly smaller than the maximum allowed value. Various holes make sure that a SlaveModule can be mounted on a support frame.

Several connector pads can be used to mount a pinhead connector that can be soldered into the through-holes of the SlaveBoard. The SensorBoard can be mounted on both sides (right or left) of the SlaveBoard due to its redundant connector pads (see Figure 67).

The resistors required for generating the voltage dividers at each sensor are realized by arrays close to the connector pads. Additional resistors for adjusting and protecting the IR-Flash LEDs are soldered onto small heat distributing pads.

Figure 65: A SensorBoard and its components on the bottom side.
SLAVEMODULE ASSEMBLY

One SlaveModule (Figure 67) will cover an area of around 310 x 75 mm. Multiple SlaveModules can be connected via the SPI bus plug to create a larger array of sensors.

Figure 67: The SlaveModule. Two SensorBoards are mounted on a SlaveBoard. Top: View onto the bottom side. Bottom: View from the top.
5.6.4 INTERACTION DEVICES

ELECTRONIC COMPONENTS

The TUI devices are equipped with an own PCB, a battery and peripheral components. In order to reduce weight, Li-Ion batteries were chosen, which require a special protection circuit to prevent overcharging and over discharging. Some batteries come with included protection circuit, which makes it easier for integration. Since single Li-Ion cells only generate 2.7 to 4.1 V output voltages, a step-up converter is used to transform the voltage up to 5 V. This has been done to not destabilize the system at three volt when boosting the connected LEDs (SFH 487P) with maximum currents of 1 A at 3 V. The connected LEDs intensities can be adjusted by individual potentiometers. Thus the device can be optimally adjusted for the tracking system. The device’s PCB also incorporates a place for a switch plug, which makes sure the device is being charged when a plug is inserted and is turned on when it is unplugged. An Atmel ATtiny26 microcontroller is managing synchronization of the device and the tracking system. For that an infrared receiver demodulator (TSOP7000) is mounted on the PCB, which receives sync pulses from the sync flash on the SensorBoards. Additionally, several buttons and switches can be connected to the ATtiny26 microcontroller for user input detection (Figure 68). Every of the three IR-LED can be switched on and off individually and an RGB (Red, Green, Blue) LED can be used for status feedback to the user. A programming port can be used to write code onto the microcontroller.

![Figure 68: Simplified schematic of the TUI electronic components](image)

PCB LAYOUTS

Two different base designs for TUI PCBs were created. One for use in a specific design for integration into a pen with a very small form factor, called the XS-PCB. The other design is used in larger TUIs, which do not need a very small form factor. This is called the S-PCB (see Figure 69).

The S-PCB is designed in such a way that it can be used in different configurations. It consists of two PCB parts (each 15 x 50 mm) that can be connected through solder bridges in one of three ways. This adjustable design makes sure the PCB can be integrated into different intuitive shapes. The smallest possible size is the Box S-PCB, which measures 30 x 50 mm. As described earlier, it is important to give the TUI a characteristic shape for little cognitive load, when being used for interaction. The LED positions were chosen in such a way that their distance and geometrical alignment is unique and not redundant. Although for MightyTrace it is
not necessary to address more than two LEDs to determine the TUI’s position unambiguously, three LEDs were implemented, since the PCBs were also used in setups in which parallel LED and device readout occurred [OP6][OP3].

![LED positions](image)

**Figure 69: Top:** Different bare S-PCB configurations (basing on one base layout) for the creation of individual TUI shapes. **Bottom left:** The XS-PCB specifically designed for use in an interactive pen.

**HOUSING DESIGN**

Housing for the individual TUI designs was accomplished by using rapid prototyping. The following design examples were manufactured using FullCore720 epoxy resin with a layer thickness of 0.016 mm by Inspire IRPD [W48].

The Pen (see Figure 70) can be used as a pointing, selecting, drawing and writing device for a variety of tasks. The ColorPaletteTUI (see Figure 71) is used as a color storing tool in creativity tasks. Colors are accessed by dipping the pen into the compartment with the desired color. The pen will take on that particular color. The metaphor is based on an artist’s palette which is used to place and store colors, which then can be used by dipping brushes into the color spots.

The FrameTUI (see Figure 72) uses the metaphor of framing a particular object of interest. Framing means increasing the importance level of an object thus accessing details or further information of it. By placing the frame around an object of interest, this additional information can be accessed.
Figure 70: The Pen interaction device: Housing is shown transparent for illustration purposes.

Figure 71: ColorPaletteTUI: Housing is shown transparent for illustration purposes.

Figure 72: FrameTUI: Housing is shown transparent for illustration purposes.
5.6.5 BACKLIGHT

Standard LC-display backlighting is realized by using cold cathode fluorescent lamps (CCFL). Up to around 30 inch screen diagonals, the backlight is constructed using an acrylic glass as a light guide. At the edges of this light guide, the CCFL tubes are mounted. They in-couple light into the light guide. A special scratch pattern on the light guide makes sure the light is scattered at optimal locations. The scattered light then passes several diffusion films and brightness enhancement films in order to homogeneously light the matrix from behind. The CCFL tubes in the NEC MultiSync 4020 [W47] that is used for the MightyTrace setup are mounted directly behind the diffusion films and the matrix (see Figure 73).

Unfortunately, the light emitted by the CCFLs is also significantly radiating in the IR range of the MightyTrace sensors. The IR light emitted by the CCFLs is oscillating at around 200 Hz, thus interfering drastically with the systems inherent frame rate of 2 kHz (see Figure 74).

A solution would be to synchronize the two optical systems. But since the CCFL radiation is never exactly zero, interference is always possible. Another solution is to equip the CCFL tubes with an infrared blocking filter. Because such filters are very expensive and would have to be mounted around each tube and even might reduce radiation brightness additionally, a pragmatic solution is chosen:
LED BACKLIGHT

The CCFL lamps are replaced by white LEDs that do not emit radiation in the infrared spectrum. There is little effort involved in exchanging side in-coupling CCFLs, since wide angle LEDs can be used instead of the CCFL tubes and no adjustments have to be made to the light guide. Only the distance between the LEDs has to be optimized to prevent inhomogeneous illumination. This can be difficult if the space for the mounting of the lighting is limited, since the LEDs have to be mounted in a small distance to each other to ensure the light is homogenously distributed in the light guide. In Figure 75 an inhomogeneous light distribution is shown that results from a LED alignment with too much space between the single LEDs.

![Figure 75: Inhomogeneous indirect LED backlight (as a replacement for CCFL illumination) with a light guide](image)

When in-coupling LED backlight from the side, homogeneity is usually easy to achieve along the LEDs radiation direction.

![Figure 76: Different solutions for replacing CCFL lights by LEDs for the two possibilities of backlight design: indirect and direct illumination](image)

In contrast to side in-coupling LED backlight, direct LED backlight requires a more cautious proceeding, since homogeneity is two dimensionally influenced by the LED’s placement. Homogeneity can be adjusted by decreasing LED-LED distance, by increasing the distance LED-matrix, and by adjusting the diffusion film’s properties. Adjusting one of these parameters has also direct influence on the sensors mounted on the same layer. For example increasing the distance from sensor layer to interaction plane will change the emitter’s influence on the MightyTrace sensor array (see Figure 77).
Different tests were performed to find an optimal solution for MightyTrace. The fixed sensor distance determined from the previous chapters required that the LED rows could be placed either in every row or every other row in order to generate a homogeneous illumination (see Figure 78). Parameters that could be optimized were:

- Distance LED strips – diffuser
- Diffuser material
- Additional light guides
- LED costs

A satisfying solution was found with a relatively cheap LED strip. In order to achieve a homogenous illumination, the LED strips were placed in every row. The original display’s CCFL diffuser could be used with LEDs as well. The brightness enhancement films were removed since they did not improve the image quality.
5.7 INTEGRATED DESIGN

The MightyTrace technology was integrated into a table in order to show its suitability for a collaborative environment.

All components (see Figure 79) of the tracking system are integrated into the table. The table can seat 4 users, two on each side, fulfilling all the ergonomic requirements for office tables. In order to provide a fluid manipulation, the interaction devices are stored and charged in a special drawer integrated into the table. Operation aids such as keyboard and mouse are substituted by a very small wireless keyboard with an integrated track pad.

A large hardened glass is covering the surface of the table providing a smooth transition between image and deposition area. The uniform surface provides enough space for artefact placement, and is robust enough even for unintentional drops of keys or the like. Since the glass enlarges the distance between the LC-matrix and the glass surface, it creates an offset between imaging and interaction plane. This offset can be confusing for the user if it is too large as has been found by Douglas et al.[B118]. A tradeoff between offset reduction and glass thickness has been defined by using a thickness of only 4 mm. This does not increase the offset significantly but still provides enough stability.
Figure 80: MightyTrace integrated into an ergonomic table for intuitive group work
Figure 81: Components of the MightyTrace interactive table

Figure 82: Two users interacting at MightyTrace
5.8 SOFTWARE

5.8.1 MASTERBOARD

The software running on the MasterModule synchronizes the whole electronic components of MightyTrace. It initiates all the different phases and makes sure that all SlaveModules and devices run in sync. A central part in the software is data storing. Since the data of all frames of a sequence is latched on the microcontroller’s SRAM, the data has to be stored in a suitable way in order to be transmitted to the PC in the last frame without any extra processing effort.

The data is aligned in a three dimensional matrix. The frame number defines the first dimension while the sensor number defines the second. Thus for each frame a specific amount of sensors can be stored. Each sensor contains three values comprising its position on the screen and its sensor value (see Figure 83).

Of course there exists a limitation of the SRAM size on the ATmega644. The size for SRAM cannot exceed 4kB. A single sensor packet will occupy 3 bytes of SRAM; a byte each for x and y coordinate and the ADC-value. For a screen size of 42”, 1344 sensors are needed to cover the screen with the required grid distance. Hence, one single frame will already occupy $1344 \times 3 = 4032$ kB of SRAM. Thus, theoretically the MasterModule is not even capable of storing one frame. But assuming a standard usage scenario, only a fraction of the sensors reach the filter threshold. A maximum of 60 simultaneous sensors above the filter threshold per frame can be considered as a reasonable choice. This would give a maximum of 21 Frames (for 3800 bytes available program memory: \(mem_{tot}\)).

\[
N_{TotFrm} = \frac{mem_{tot}}{N_{MaxSensPerFrm} \cdot 3} \tag{E19}
\]
In Figure 85, the general synchronization process running on the MasterModule is shown.

When a request from the PC is detected one whole sequence is transmitted using the following protocol:

![Table](image)

The question might arise why a whole sequence of frames is stored until it is transmitted. The reason lies in the limited update capability of the USB scheduler. Because USB is scheduler controlled it is prone to delays. This scheduler puts a request onto the list of tasks for the USB host controller to perform. This will typically take at least 1 millisecond to execute because it will not pick up the new request until the next 'USB Frame' which is controlled by the operating system's kernel (the frame period is at least 1 millisecond). If data were sent in small packets by an application, this would severely limit the overall throughput of the system as a whole.
Synchronization with the PC driver software is realized by a simple polling mechanism. The MightyTrace hardware is continuously acquiring sensor data which is stored in the hardware memory until the next new dataset has been acquired, or until a request from the driver is detected. Then the most current data is sent to the driver software.
5.8.2 INTERACTION DEVICE

The code on the interaction device is optimized for low power consumption. The devices only run at 4 MHz and are interrupt-driven. An internal timer is started as soon as a synchronization pulse is detected. The pulse is compared with two timer values in order to decide if it is a long or a short pulse. A counter is counting the frames and detecting the device’s own frame, in which it is allowed to turn on its LED(s). Additional input on the device is checked and the IR-LED is switched on or off in the second frame correspondingly (see Figure 86 for the flowchart).

![Flowchart](image)

Figure 86: Software running on the device. Basically, it scans for long and short pulses answering with a LED pulse when the right frame is triggered.
5.8.3 DRIVER

The driver software running on the PC is processing the tracking data and delivering data to other applications that can process interaction data. The driver reads in configuration data from an XML file and tracking data from the MightyTrace hardware via USB. The tracking data is processed and delivered to one of three ways. Interaction data can be sent via the user datagram protocol (UDP) using the high level TUIO protocol. TUIO is used in many research projects and has gained a lot of popularity since its introduction in 2007 by Kaltenbrunner et al. [B82].

In Figure 87 the general flow of data through the software components is shown. Tracking data is read in from the MightyTrace Hardware via USB. A specialized FTDI chip equipped cable [W50] is used for this purpose and the provided FTDI library is used for interfacing the chip to the software. While initializing the driver software an XML configuration file is read in. It defines essential adjustments for the whole driver framework such as how many devices are tracked and what functions they have. Also connection properties and target display resolutions are defined here. Tracking data and configuration data are filled into several classes that handle the data by separating it into different devices with their specific frames. Position, state and orientation determination as well as sensor profile adjustment is performed at the frame and device levels. The tracker class provides the processed tracking data. It can be accessed via the Trackers API to feed different outputs. In the current implementation an output via the TUIO library is implemented. Additionally the mouse cursor can be controlled using the windows API overwriting current mouse data. Only devices that are marked for cursor control in the configuration file will do that. Last any C++ application can use the tracker API to use interaction data directly, such as the Demo application.
TUIO

In the TUIO protocol two main classes of messages are defined: SET messages and ALIVE messages.

- **SET** messages are used to transmit information about an object’s current position and orientation.
- **ALIVE** messages indicate the current set of objects present on the surface using a list of unique Session IDs.

There exists no explicit ADD or REMOVE messages in the TUIO protocol. This is the task of the receiver and can be deduced by examining the object lifetimes which is the difference between sequential ALIVE messages.

Additionally another type of messages is used the FSEQ message:

- **FSEQ** messages are used to uniquely tag each update step with a unique frame sequence ID.
- **SOURCE** messages are optional and identify the TUIO source in order to allow source multiplexing on the client side.

The TUIO messages are transmitted using the UDP network protocol, which provides low latency, but can be error prone, therefore redundant information is sent in every message bundle. The UDP packet sizes are efficiently used by optimizing the bundle sizes. Accessing UDP transport layers the Open Sound Control (OSC) [B83] format is used.

The TUIO protocol definition defines four different profiles. Each profile provides a specific set of properties that can be transmitted to the clients. The profiles are: 2D, 2.5D, 3D and Custom. Today many applications exist that use the TUIO protocol. Most of these use the 2D profile that provides data fields for the following properties (Table 11)

<table>
<thead>
<tr>
<th>Data field</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>s</td>
<td>Session ID</td>
</tr>
<tr>
<td>i</td>
<td>Class ID</td>
</tr>
<tr>
<td>x,y</td>
<td>Position</td>
</tr>
<tr>
<td>a</td>
<td>Angle</td>
</tr>
<tr>
<td>X,Y</td>
<td>Velocity vector</td>
</tr>
<tr>
<td>A</td>
<td>Rotation velocity</td>
</tr>
<tr>
<td>m</td>
<td>Motion acceleration</td>
</tr>
<tr>
<td>r</td>
<td>Rotation acceleration</td>
</tr>
</tbody>
</table>

Table 11: TUIO data fields

The 2D profile is composed by adding these fields into a message:

- `/tuio/2Dobj set s i x y a X Y A m r`

One problem to address for MightyTrace is how the state of a TUI is transmitted. Of course a 3D profile could be used to encode the state into the z variable. But since most standard application use the 2D profile...
abuse of the rotation acceleration parameter in the standard 2D profile for state transmission is preferred. Many applications use multi touch interaction anyway, where no rotation detection is wanted. Most applications will not evaluate the rotation acceleration parameter. If state transmission is desired this parameter can be used.

**POSITION DETERMINATION**

Position determination is performed for each frame that requires it. For example a pen with two frames will need a position determination in the first frame only, since the second is used for state detection exclusively.

Position is determined by using the principle of center of mass calculation. Every sensors intensity value represents a weight at a specific location. The center of mass of a system is defined as the average of their positions, weighted by their masses.

The same principle can be used for the TUI position determination: The center position vector $\vec{R}$ can be computed as follows:

$$
\vec{R} = \frac{\sum_{i=1}^{N} V_i \cdot \vec{r}_i}{\sum_{i=1}^{N} V_i}
$$

[Eq. 20]

Where $\vec{r}_i$ is the direction vector of the corresponding sensor value $V_i$.

However a problem is the non-linearity of the sensor value $V_{orig}$ in terms of LED position (see Figure 35, page 81). A correction of the original sensor value $V_{orig}$ has to be performed according to a polynomial trend line of the original measurement data. The regression curve is defined as (see Figure 88 for the plot):

$$
V_{corr} = -2.3564 \cdot 10^{-11} \cdot V_{orig}^6 \\
+ 1.5446 \cdot 10^{-8} \cdot V_{orig}^5 - 3.7527 \cdot 10^{-6} \cdot V_{orig}^4 \\
+ 4.1429 \cdot 10^{-4} \cdot V_{orig}^3 - 1.7359 \cdot 10^{-2} \cdot V_{orig}^2 \\
+ 4.2293 \cdot 10^{-1} \cdot V_{orig}
$$

[Eq. 21]

Basically the original sensor data (black) is linearly mapped onto the original distance from the measurement (grey), to finally map it against the measured sensor curve and get the corrected sensor value. Thus before the actual position is computed the correction is performed for every single original sensor value.
The effect of the correction is that especially values in the midrange (around 125) are corrected downwards, while very high and low values do receive a soft correction (see Figure 89).
In Figure 90a visualization of a position computation is given. The target positions of corrected and original centers are shown. Here only four sensors are taken into account for reasons of readability. In the real setup around 20+ sensor values are considered when computing center of mass for all corrected sensor values.

![Visualization of position computation for corrected and original values](image)

**Figure 90: Visualization of position computation for corrected and original values**

### STATE AND ORIENTATION DETERMINATION

State processing is done by analyzing the corresponding frame of a device. If that frame has more than an adjustable amount of active sensors the state is set otherwise not.

Orientation determination is done by computing a center for the corresponding frame of the second LED of a device. Orientation is then computed by defining a vector relative to the two centers.

### 5.8.4 DEMO APPLICATION

A demo application has been implemented that shows promising possibilities for supporting creative group work at tables. Four pens can be used to draw and sketch on a white surface. Each user can set the personal pen color by dipping his pen into a color compartment of the ColorPaletteTUI. Underneath this TUI its virtual representation is rendered to the screen. Different colors are shown in the compartments. In the center compartment an erase area is implemented. Users can click into that area to erase all strokes on the screen.
Figure 91: Usage of the ColorPaletteTUI: Users can dip their pen into a color compartment to change their pens' color. Drawing can be deleted by pressing the trash bin in the middle.

For demonstration purposes the FrameTUI is used as a magical lens for the MightyTrace technology. When the TUI is moved onto the screen it reveals the sensor boards underneath the matrix by rendering a digital image of the sensor boards within the FrameTUI. By pressing the TUI the whole sensor area under the screen is revealed.

Figure 92: Usage of the FrameTUI: By moving the FrameTUI a virtual sensor layer can be observed like using a magical window. By pressing the TUI the whole surface shows the sensors layer.
Figure 93: Demo application for drawing, selection of colors and magic lens manipulation
5.9 PROTOTYPE PERFORMANCE

5.9.1 LAG DETERMINATION

The lag in the MightyTrace system is the sum of all components processing times - from the start of a user input (tip button click) to the display of the virtual position on the screen. A lot of different stages influence the final overall lag. In the following figure (Figure 94) the single stages of lag on the MightyTrace hardware are shown. But the most lag is generated as soon as the data is on the PC side. The USB scheduler can fall into a special state where it awaits the next full packet until the data is read. This leads to additional lag. Finally the processed data is put into the rendering pipeline where up to 16 ms can be necessary for displaying the content of the graphics buffer. Another 16 ms is needed for the screen to process the new graphics input, since the used screen has such a low response time. Thus theoretically around 60 to 70ms lag are generated from a user input to the reaction of the system.

Figure 94: Different stages of lag generation through the whole data acquisition process. An interaction in the worst moment can cause a lag delay of $14\,\text{ms} + 13\,\text{ms} = 27\,\text{ms}$ (Base: 12 frames, 9 sensors active in each frame)

The determination of all the single lags in the system is very difficult and only feasibly with extensive effort. Here only the overall lag is measured and of interest.

Lag on the system can have significant influence on the performance. There exist several papers that describe methods for measuring lags on tracking systems. The most commonly reported in use (e.g.[B120],[B119] and a motorized version of it by [B123]) is Mine’s method[B121] which uses an oscilloscope to measure the time between the firing of two photo-diodes, one on a pendulum which passes a small light, and another that registers the flash of a pixel on a screen. Another method that is technically not as demanding as the last is the video based determination of lag. He et al. [B122] propose to record a video stream of both a physical controller and the corresponding virtual cursor at the same time. By analyzing the video frame by frame the latency can be deducted.
Here a similar method to that of He et al. [B122] is used. In order to measure the time difference between physical input and virtual screen output the physical input is moved on the screen at a fixed linear motion. This was realized by using a motorized car that moves the pointer across the whole screen at a constant speed. The car was filmed by a camera mounted above the screen. The speed of the car was determined by analyzing the position of the car at two specific times in the video stream (The position can be observed in the video stream: see Figure 96). The offset between real and virtual cursor is a distance. At the current speed of the car this distance represents the lag of the system and can be computed in a time unit.

$$t_{lag} = \frac{s_{offset}}{v_{car}}$$  \[E22\]

Several measurements were performed and revealed lags around 85 ms.

<table>
<thead>
<tr>
<th>$v_{car}$ [mm/ms]</th>
<th>$s_{offset}$ [mm]</th>
<th>$t_{lag}$ [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>0.3</td>
<td>25</td>
<td>83.3</td>
</tr>
<tr>
<td>0.215</td>
<td>20</td>
<td>93</td>
</tr>
<tr>
<td>Mean Lag</td>
<td></td>
<td>85.4</td>
</tr>
</tbody>
</table>

Figure 95: Results of the lag measurement

Figure 96: Screenshot of the video stream: Measuring the lag of the system. A car is moved at constant speed across the interactive screen. The offset between virtual and real cursor characterizes the system lag.
5.9.2 TRACKING ACCURACY

To reveal the tracking accuracy a simple method was chosen that makes sure the TUI position moves on a known path. A ruler was mounted on the screen and served as guidance for the pen in this case. The pen was moved at a constant speed along the ruler. Since the rulers position was known the pens path was defined. By comparing the known path against the tracked path, the tracking accuracy could be determined. The distance of the known straight line to the tracked center was computed and evaluated for every tracked center (see Figure 97).

![Figure 97: Tracking error at different positions of the pen at the ruler](image)

It can be seen in Figure 97 that a jitter with amplitude of around 1 mm is present during all of the measurement data. This jitter is generated by the Analog to Digital convertors internal LSB (Least Significant Bit) jitter. The uncertainty of one bit leads to tracking uncertainties of around 1 mm. Mean values of the position uncertainty Jitter lie between ±1.5 mm. When looking at the low resolution of the screen with a pixel pitch of 0.65 mm this is a good value. Methods to increase system accuracy are described in Chapter 8.2: Outlook (Page 172).

5.10 CONCLUSION

A prototype was developed that complies with all requirements for a TUI tracking system. MightyTrace can track up to 16 fully equipped (allowing dragging and tracking state) TUIs maintaining an update rate of more than 20 Hz. Orientation, identity and if desired inherent input detection of all TUIs can be determined. For the current prototype, three different interaction devices were designed in order to illustrate possible applications. The pens are used for sketching, selecting and writing, while the ColorPaletteTUI can be used...
to assign colors to a pen by dipping it into a compartment of the ColorPaletteTUI. The FrameTUI is used as selection and menu tool. All tools can be used concurrently without any interference. Also additional objects on the surface will not influence the tracking system or its characteristics. The table holds the interactive surface with the underlying tracking technology and the interaction devices.

The system’s lag of 85 ms lies within the requirements of 100 ms. But a lower value would be preferable, since user performance is affected significantly. And according to MacKenzie et al. [B59] a good value is 25ms. The value of MightyTrace can be improved by using other interface technologies than USB. Since USB is scheduler and packet based, it is prone to delays. Interfaces such as RS485 or RS422 like they are used in high speed optical motion tracking systems could be an alternative to USB, but require special reception boards on the PC side. Other possibilities to reduce system lag and increase update rates are discussed in Chapter 8.2: Outlook (Page 172).

MightyTrace was designed in a modular way as to provide the possibility to scale it to larger or smaller table sizes. The display diagonal can be scaled up to 146” without reaching the lower limit of a 20 Hz update rate for the tracking of 16 devices in parallel.
6  TNT: TOUCH ‘N’ TANGIBLES ON LC-DISPLAYS

6.1  INTRO

The MightyTrace system was presented in the previous chapter. It is able to track many different interaction devices, the so-called TUIs, on the surface with high spatial and temporal resolution. But the challenge of multi-touch detection on MightyTrace is not mastered yet. In this chapter, the development of a multi-touch implementation for the MightyTrace hardware system is described in order to fulfill the requirements for multi-touch and direct finger interaction.

First, the FTIR (Frustrated Total Internal Reflection)-based concept of the touch overlay is presented. In a next step, feasibility measurements are performed in order to optimize the technology for the MightyTrace system. In the next chapter the combination of two systems is presented. The MightyTrace systems will be extended by a multi-touch overlay. Separation of the two inputs is realized by time multiplexing.

6.2  FRUSTRATED TOTAL INTERNAL REFLECTION

The FTIR (Frustrated total internal reflection) phenomenon is well-known and has been used in the biometrics community to image fingerprint ridges since at least the 1960s [B107][B108]. Jeff Han [B86] has rediscovered this principle in 2005 for application in multi-touch input detection in direct manipulation devices. The setup uses the effect of total internal reflection (TIR). TIR describes a condition that is present in certain materials: When light enters one material from another material with a higher refractive index at an angle of incidence greater than a specific critical angle, no light can pass through and all of the light is reflected. The angle at which this occurs can be calculated mathematically using Snell’s Law. By coupling light into a thin acrylic glass plate from the side, most of the rays are totally internally reflected at the top and bottom media interface and do not exit the plate (see Figure 98).
By touching the surface of the acrylic plate, a change in the ratio of the refractive indexes is created since parts of the skin that are covered with water particles will couple to the acrylic instead of air. Light rays that hit the water-covered area are no longer totally reflected and refraction will occur instead. The light leaves the acrylic until it hits upon the skin where it will be scattered. The scattered rays enter the acrylic again in order to pass through it towards the opposite surface and indicate the location of the touch (see Figure 99). By using infrared light, the scattered light is not visible to the user but can be detected by infrared sensitive cameras behind the acrylic as realized in the setup presented by Han. A diffusive layer underneath the acrylic provides an image plane for back projections, which allows direct interaction on the setup.

This method of touch detection allows an easy realization of multi-touch detection on large surfaces with high spatial and temporal resolution only depending on the update rate and resolution of the used IR camera. Many multi touch projects have been started basing on this easy to implement technology.

**TIR IN DETAIL**

The TIR touch principle works because air and water have a different refractive index. Snell’s law defines ray propagation from one medium to another:
Snell’s Law

\[ \frac{\sin \theta_1}{\sin \theta_2} = \frac{n_2}{n_1} \tag{E23} \]

\( n_1 \) and \( n_2 \) are the refractive indexes of the medium. And \( \theta_{\text{crit}} \) is the critical angle at which total reflection occurs:

\[ \theta_{\text{crit}} = \arcsin \frac{n_2}{n_1} \tag{E24} \]

With refractive indexes of the media \((n_{\text{air}} = 1.00, n_{\text{water}} = 1.33, n_{\text{acrylic}} = 1.58)\), three different critical angles can be determined.

<table>
<thead>
<tr>
<th>Interface 1</th>
<th>Interface 2</th>
<th>Critical Angle for total reflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylic</td>
<td>Air</td>
<td>( \theta_{\text{acrylic-air}} = 39.2^\circ )</td>
</tr>
<tr>
<td>Acrylic</td>
<td>Water</td>
<td>( \theta_{\text{acrylic-water}} = 57.3^\circ )</td>
</tr>
<tr>
<td>Air</td>
<td>Water</td>
<td>( \theta_{\text{air-water}} = 48.8^\circ )</td>
</tr>
</tbody>
</table>

By touching the surface, only light rays within angles of 39.2° to 57.3° are decoupled. Thus the maximum touch window equals

\[ \theta_{\text{touch}} = \theta_{\text{acrylic-water}} - \theta_{\text{acrylic-air}} = 18.1^\circ \tag{E25} \]

Only rays that totally reflect within this touch window will lead to a decoupling into the water (see Figure 101). Rays that travel at angles below 39.2° will exit into the air at the very first reflection and are thus not contributing to the TIR effect. Rays that lie above this threshold will be totally reflected inside the acrylic and those which do not exceed the upper touch window at 59.2° will be decoupled by water particles on the surface.

In order to achieve the best decoupling, the rays will be chosen to travel at angles as close at the critical angle as possible.
FTIR IN NANO SCALE: EVANESCENT WAVE PHENOMENON

Within every TIR, a quantum mechanical effect is present: the evanescent field. At the boundary surface of a total internal reflection of an incident wave an evanescent wave will be generated behind the surface, which is a standing wave that disperses exponentially into the optical thinner medium. The penetration depth of this evanescent wave into the second medium only measures a few wavelengths of the incident light. However, if a third medium with a higher refractive index than the second medium is placed within less than several wavelengths distance from the interface between the first medium and the second medium, the evanescent wave will be frustrated and it will enable the incident beam to tunnel across the second into the third medium. In the case of a touch, rays will tunnel through air or water into the finger where they illuminate the skin by scattering effects.

An interesting side effect is that the whole phenomenon is also accompanied by a slight shift between the incident wave and the reflected wave at the boundary surface and is called after their explorers: Goos-Hänchen shift [B110].

6.2.1 USING FTIR ON MIGHTYTRACE

The core idea behind TNT is to combine the described FTIR principle with the MightyTrace tracking system. By overlaying an FTIR layer in front of the LC-matrix, light can be decoupled from the acrylic by touching the surface (see Figure 102). If the scattered light is strong enough, the underlying sensors can be triggered and the location can be determined by interpolating between the sensor intensity values.
Figure 102: The principle of how to use an FTIR acrylic on the MightyTrace tracking system

Like in the MightyTrace system, also the FTIR emitter radiation needs to meet the following requirements (see Figure 40):

- **Intensity**: The radiation passing through all LC-display components has to be high enough to trigger the sensors. On the other side it must not be too high to drive the sensors into saturation.
- **Width**: The scattering cone has to be sufficiently wide in order to cover enough sensors and enable a reliable tracking.

In contrast to the widely used camera-based FTIR systems, MightyTrace does not use CCD (charge coupled device) chips to detect light. CCDs are capable of integrating radiation over a certain amount of time in order to be read out by a special circuit. This makes them far more sensitive than the sensor circuit used in the MightyTrace system. Here the sensors do not integrate but will be deflected to a certain extent, indicating an amount of radiation, which is virtually not time dependent. Additionally, the integration times of a CCD chip lie around 20 ms whereas in MightyTrace sensors will have a saturation time of 0.12 ms and then be read out in around 0.002 ms, increasing read out times by a factor of 164.

### 6.3 PARAMETER ANALYSIS

To understand and optimize the FTIR overlay, influencing parameters concerning light scattering and collection have to be analyzed first. Two groups of influencing parameters were identified (see Figure 103):

- **In-coupling**: The whole process of introducing and collecting light from a specific emitter into the acrylic is called the in-coupling process.
- **De-coupling**: The process of scattering the trapped light out from the acrylic is called de-coupling
6.3.1 MEASUREMENT SETUP 1

The basic setup for the determination of the effect of different in- and de-coupling can be investigated by using a sensor underneath the FTIR plate. The sensor is moved in discrete steps in y direction from one side of a touch to the other (see Figure 103). In order to exclude variations in touch pressure and accuracy, the sensor is moved instead of the finger.

![Figure 103: De-coupling and In-coupling and how the effects can be measured by using a sensor.](image)

A setup (see Figure 104) was constructed that uses two independent axes. Arbitrary positions on both axes can be targeted between -50 and 50 mm. A controller and a motor driver basing on an Atmel Atmega644 are controlling the sensor’s position. Positioning accuracies on both axes lie around 0.1 mm. The sensor is positioned 1 mm underneath the acrylic and reads out with the same electronics as used in the MightyTrace system, thus ensuring the same receptions characteristics. Sensor voltage values are acquired every 0.5 mm and can have digital values between 0 and 255, which equals 0 to 2.5 Volts.

![Figure 104: The constructed cross table for the measurement task and the implemented GUI for its control.](image)
6.3.2 IN-COUPLING

Several parameters were identified for the in-coupling group. Two main physical explanations can be used for categorizing the parameters. Three module groups are defined, which comprised the elements of the respective mechanical construction. Within Table 12, all parameters are listed together with their influence on the sensor reception curve and the physical explanation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Module</th>
<th>Effect on intensity curve</th>
<th>Physical explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase of IR-LED intensity</td>
<td>Emitter array</td>
<td>++</td>
<td>Photon energy increase</td>
</tr>
<tr>
<td>Increase of number of IR-LEDs</td>
<td>Emitter array</td>
<td>++</td>
<td></td>
</tr>
<tr>
<td>Decrease of distance between LEDs</td>
<td>Acrylic</td>
<td>++</td>
<td>More total internal reflection points</td>
</tr>
<tr>
<td>Increase of LED emission angle</td>
<td>Acrylic</td>
<td>++</td>
<td></td>
</tr>
<tr>
<td>Decrease of acrylic thickness</td>
<td>Interface acrylic – emitter</td>
<td>+ if optimal angle - otherwise</td>
<td>0</td>
</tr>
<tr>
<td>Increase of inclination of LEDs</td>
<td>Interface acrylic – emitter</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Acrylic edge taper</td>
<td>Interface acrylic – emitter</td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>

Table 12: In-coupling parameters and their effect on the sensor profile with physical explanation

In a next step, each module is presented with a detailed description of the involved parameters. Three modules will be discussed:

- Emitter array
- Acrylic
- Interface acrylic – emitter

**EMITTER ARRAY**

Basically, every emitter that radiates in the range of the sensors reception wavelength (peak around 880 nm) is suitable. An emitter is used that provides a wide emission characteristic and is small enough to be mounted in a high-density array of discrete emitters. Widening the emitter radiation angle will potentially increase TIR, since the rays travel less until they hit an acrylic surface. On the other side, rays that exit the LED at very wide angles will not enter the acrylic, or be decoupled right at the first surface contact, because their reflection angle lies below the critical angle of TIR (see Figure 105).
Figure 105: Increasing the emitter emission angle will increase the amount of TIRs. Rays above a critical emission angle of $\theta_{\text{crit\_emission}} = 50.8^\circ$ are not totally internal reflected, but exit the acrylic right at the very first medium interface contact.

Therefore, wide emission emitters were chosen. OPTEK OP250 [W46] are used for this application, since their angle of half intensity is at 45 degrees, maintaining almost constant radiation up to an angle of 30 degrees. Additionally, their SMD (surface mount device) form factor has the potential for creating a dense emitter array. In order to maximize the amount of in-coupled rays, the emitters are mounted at a very small distance to each other of 7 mm (see Figure 106).

Figure 106: Radiant intensity of the OP250 IR-LED and the mounted IR LED array with discrete distances of 7 mm

By using the above emitter configuration the amplitude could be increased to a high level. As well as the width of the curve could be extended. In Figure 107, the effects of different power levels at the IR LEDs and different array configurations can be seen. Obviously, dense and high-powered arrays perform best.
By decreasing the acrylic thickness, the number of TIRs can be increased, since the distance between reflection at the top and the bottom is reduced.

The experiment (using the presented test setup: 6.3.1 Measurement setup 1, page 141) shows that the increase of TIR by decreasing the acrylic thickness will enlarge the width of the radiation cone. Also the maximum of the IR radiation straight above the sensor is increased driving the sensor even into saturation (see Figure 109). An interesting effect can be observed when looking at the curve for the 2 mm acrylic. Since mounting the tiny SMD LEDs is very demanding, a fraction of their radiation is not fully in-coupled but travels above the surface of the acrylic, where it is scattered at finger surfaces which do not contribute to the FTIR effect. The 2 mm curve does not decrease down to zero but will converge to a small level.
Two different parameters can be analyzed. According to the simulation provided by Jason Modisette [W45], TIR will change when adjusting LED angle or acrylic edge taper. The simulation computes the evanescent field strength depending on different emitter-acrylic configurations. The evanescent field strength defines how far the evanescent waves travel from the first into the second medium, decreasing exponentially with the distance to the surface thus indicating how much energy is redirected by the reflection. Maximizing this energy will result in easier decoupling.

In order to determine an optimal adjustment of both parameters, edge taper and LED angle, different values were adjusted in the simulation. The best results were found by choosing TIR angles that are close to the critical angle, which could be achieved by using a very narrow LED beam of 10° and a 45° taper (see Figure 110). The found best case contrasts to the OPTEK 250 LED being used in the array and having a very wide emission angle. Values for the chosen OPTEK 250 LED were simulated too and the results showed that the array had to be tilted by 10° in combination with an edge taper of around 33° to increase evanescent field strength (see Figure 111). Tapering and polishing the acrylic in the way as required was not achieved, thus the theoretical values could not be verified.
Figure 110: Strong evanescent field generated by a very narrow beam and 45 degree edge taper. Simulation provided by Jason Modisette [W45].

Figure 111: Simulation of the OP250 LED emission angle and corresponding edge (32°) and LED angles (-5°) and their influence on the evanescent field strength.
6.3.3 DE-COUPLING

In this chapter, de-coupling is analyzed. De-coupling occurs at the location of a finger touch and includes all the effects connected with rays leaving the acrylic because of being frustrated at the acrylic surface. Five parameters were identified in the de-coupling domain.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Module</th>
<th>Effect on intensity curve</th>
<th>Physical explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additional material</td>
<td>Overlay</td>
<td>++</td>
<td>More total internal reflection points (increase of touch area)</td>
</tr>
<tr>
<td>Decrease of touch inclination angles</td>
<td>Touch</td>
<td>++</td>
<td>Enhancement of touch coupling</td>
</tr>
<tr>
<td>Higher touch pressure</td>
<td></td>
<td>--</td>
<td>Increase of radiation area (up to a certain distance, this depends on used LEDs)</td>
</tr>
<tr>
<td>Wet or dirty fingers</td>
<td>Sensor layer</td>
<td>++</td>
<td></td>
</tr>
<tr>
<td>Increase of distance sensor-acrylic</td>
<td></td>
<td>--</td>
<td></td>
</tr>
</tbody>
</table>

Table 13: De-coupling parameters and their effect on the sensor profile with physical explanation

OVERLAY

Smith et al. [B111] found that silicone rubber on top of a FTIR system can increase performance in respect to decoupling rays by light touches. They presented two systems; one with an overlay of 10 mm using front projection, and one with 1 mm using back projection. Both systems were capable of detecting blobs from very light touches with near zero force. The thick overlay was even capable of detecting brushes moved on the surface, but caused the contour of the contact to become fuzzy.

Such an overlay was also tested on the MightyTrace sensor array using the setup shown in chapter 6.3.1 Measurement setup 1 (page 141).
In contrast to Smith et al., a significant hysteresis effect was found, which still affected the sensors’ reception after several seconds. This can be explained by the fact that the used silicone was not in contact with the acrylic during curing. Thus the overlay did not glue to the surface. Beside this negative effect, it could be shown that the silicone overlay improves overall performance of the system by widening the reception curve and increasing decoupled ray intensity.

![Figure 113: Silicone overlay improves the width and height of the sensor reception curve but also incorporates hysteresis effects](image)

Another significant drawback of the overlay solution is its sensitivity to detect foreign objects. Object that did not decouple rays from the acrylic such as books or laptops now are able to do so. This effect is not wanted according to the requirements. Additionally, image quality is reduced by the overlay depending on the transparency of the used silicone rubber material.

Although the overlay improves decoupling performance, it will not be used on MightyTrace because of its tendency for hysteresis, its sensitivity to foreign object irritation, and its influence on image quality.

**TOUCH**

The effect of touch on the FTIR acrylic depends on various factors such as touch angle, pressure and humidity of the skin. These factors are analyzed in this chapter. Again, the same measurement setup as described in chapter 6.3.1 is used.

**FINGER INCLINATION**

Finger inclination has a considerable influence on the reception profile of the sensor. Different inclinations mean that the touch area changes. The width of the curve is influenced linearly by finger inclination (see Figure 114).
Figure 114: Top: Finger inclination and the resulting reception curve. Bottom left: Finger areas, generated by inclined index fingers on blue tack. Bottom right: Inclination angles and the resulting area / curve width / curve height in % of the maximum. Width defines the distance where the sensor receives IR radiation. It is measured in mm. Height is the maximum value of the IR radiation in volts. Area is measured in pixels.

MEASUREMENT SETUP 2

The measurements concerning the following parameters were evaluated on a different measurement setup:

- Influence of finger pressure
- Influence of finger humidity
- Influence of sensor distance

The setup used for these cases already included the matrix. Since the above influences are above the sensors upper reception threshold the matrix was included in the tests as well. Otherwise the sensor would be operated above the saturation level not enabling a reliable measurement. Also the FTIR unit was now tested with the complete MightyTrace setup incorporating all layers. In order to incorporate the FTIR technology into MightyTrace, the matrix and the light guide were added to the test setup (see Figure 115). The distance of the IR-sensor to the FTIR acrylic increased from formerly 1 to new 11 mm because of the new layers.
FINGER PRESSURE

Also the finger pressure has significant influence on the sensor reception curve. Much like inclining the finger, also increasing touch pressure increases the area of contact on the surface.

Figure 116: Finger pressure and the resulting reception curve. Bottom left: Finger areas, generated by different pressures of index finger on blue tack. Bottom right: Finger pressures and the resulting area / curve width / curve height in %. Width defines the distance where the sensor receives IR radiation. It is measured in mm. Height is the maximum value of the IR radiation in volts. Area is measured in pixels.
FINGER HUMIDITY

Finger humidity improves the FTIR effect significantly. People with slightly sweaty fingers will have the system react to their fingers with much less pressure or inclination. No measurements were made concerning this parameter, since measurement of finger humidity is very difficult and subject to fast changes.

6.3.4 OTHER INFLUENCES

ACRYLIC LENGTH

In terms of the scalability of the FTIR systems for larger screens, it is fundamental to see if and how larger acrylics influence ray propagation and de-coupling. In the following section, measurements with a short (42 cm = 21” diagonal of MightyTrace) and a long acrylic of 1430 mm length are performed, simulating a screen diagonal of 65” (1650 mm). The measurements are taken in the middle of the acrylics.

![Graph](image)

Figure 117: Influence of acrylic size on sensor reception

It can be seen in Figure 117 that large screen diagonals will decrease the ability to trigger the sensor. An explanation can be that the rays trapped in the acrylic loose energy every time a total reflection occurs and the longer they travel in the medium. In the middle of a long acrylic, only a fraction of the energy of the original radiation is available, since the acrylic is not 100% transparent and is considered as an optical resistance to the rays. By looking at the sensor reception profile of the different acrylics (Figure 117) the following conclusion can be made: The width of the curve for long acrylics is 30 mm while it is 15 for short acrylics. By linear interpolation it can be found that at widths of 20 mm screen diagonals of 50” (1270 mm) or smaller will trigger the sensors at a sensor distance of 10 mm. 10 mm means that the current sensor distance of the MightyTrace system is halved. This increases the amount of sensors by a factor of 4.
6.3.5 OCCLUSION

In traditional FTIR setups, in which webcams are used to track the de-coupled light, occlusion is hardly noticed. However, in TNT this issue can become of concern if a lot of touches influence each other. Here, this influence will be shown by some illustrative examples. In Figure 118 the effect of touch influence is observed. A wet paper is used to decouple light on a large area (simulating a large touch). It’s clearly visible that the central part of the wet paper is not decoupling any light and that the edges of the paper do decouple light up to a certain border thickness. The reason that the central part of the paper is not decoupling light lies in the fact, that not enough light is available anymore to be decoupled. The light is already completely decoupled in the “border area”. Additionally it is visible that a finger touch is influencing the decoupling behavior in the border area. Occlusion effects are clearly visible.

Figure 118: Occlusive effect of multiple touches.

Thus for TNT it can become critical at some very specific interactive moves. A very rare but possible configuration is shown in Figure 119.

Figure 119: Critical touch configuration, where too much occlusion might occur.
6.3.6 CONCLUSION

The analysis of the influencing parameters shows that many different parameters are relevant for the design of an FTIR overlay for MightyTrace. Specifically for MightyTrace, the following parameters should be used:

Emitter array:
- OPTEK 250 SMD LED array with wide emission angle
- 7 mm array distance
- High power driving

Acrylic:
- 3 mm acrylic thickness
- Maximum 1110 mm length (mm screen diagonal)

Sensor layer:
- Maximum 10 mm sensor distance

Usability recommendations:
- Do not use with completely dry fingers
- Apply more than 20 N pressure
- Use with low finger inclination (in respect to surface)

6.4 TOUCH AND TUI DETECTION

The FTIR overlay will generate touch data and can also be synchronized with the MightyTace detection of the TUIs. For doing so, an additional touch frame is inserted into the synchronization process. Only in this particular frame the touch overlay will be activated. This proceeding makes sure that a proper distinction between touch and TUI input can be made. Thus, a touch input can never disturb the tracking of a TUI.

![Figure 120: Insertion of an additional dedicated touch frame](image-url)
6.5 IMPLEMENTATION

Basically, the MightyTrace electronic components were reused. Just the SensorBoard had to be adjusted in order to fulfill the requirements of 10 mm sensor distance (see Figure 121). Now, two SlaveModules share one SensorBoard (see Figure 122).

Figure 121: The TNT SensorBoard with half the sensor distance compared to MightyTrace

A small MOSFET transistor circuit was added on the MasterModule to drive and synchronize the FTIR LEDs.

Figure 122: Left: The FTIR LEDs mounted at the acrylic side. Right: Two SlaveBoards sharing one SensorBoard.
6.6 SOFTWARE

The software for the TNT prototype is basically the same as for the MightyTrace, because both use the same hardware. Just one difference exists: TNT provides an additional frame with sensor data from touch detection. This specific frame has to be analyzed in the software for multiple touch points.

6.6.1 MULTI TOUCH DETECTION

The raw sensor data in a touch frame does not distinguish between different fingers. The software first has to separate the sensor values into different finger groups (blobs) in order to then compute the corresponding center for every finger.

Blob detection is implemented using an algorithm that moves along the sensor value rows and in a second step along the sensor value columns. For each movement direction each sensor is marked either as a peak, a rising, a falling or a valley type. If a sensor has been marked as a peak in the column and row scanning procedure it is marked as a blob. For the computation of the touch center as described in chapter “Position determination” on page 127 the surrounding sensors in an adjustable radius are used.

In the current version no identification of the different fingers is implemented. This would require that each blob is being tracked over the whole lifetime in order to evaluate its distance and position in relation to other blobs to determine its possibility for a certain finger.

6.7 PROTOTYPE PERFORMANCE

A summary of the technical properties is listed in

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Update rate</td>
<td>80 Hz</td>
</tr>
<tr>
<td>Lag</td>
<td>70 ms</td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.5 mm</td>
</tr>
</tbody>
</table>

Table 14: Technical properties of the TNT prototype
6.8 CONCLUSION

TNT extends the capability of the MightyTrace technology by adding touch detection. To achieve this, an overlay is mounted in front of the LC-matrix. The overlay uses the effect of frustrated total internal reflection to de-couple light. This light hits the MightyTrace sensor array and a touch location can be computed. In order to separate touch and TUI detection, a time multiplexing method is used, which enables touch and TUI detection at different timeslots in the MightyTrace sequence.

TNT achieves update rates at around 80Hz, but only covers an area of 160 x 160 mm by using four SlaveModules with reduced sensor distances of 10 mm. The tracking area can be increased by adding more modules and is limited by a display diagonal of 50" since then the lost of light intensity at every total internal reflections is too high.

6.8.1 THE NEXT STAGE

To overcome this limitation in size and flexibility another technology is analyzed in the following chapter.

Since group work to a large extend bases on the use of pen and paper it is obvious to try to combine this analogue way of working with the potential of digital data access and manipulation. To achieve this and to be independent of size and surface limitations a tracking technology basing on a pattern detection algorithm is analyzed for its usability in tabletop surface environments. It uses a pattern that can be applied to paper in any size and a pen that can track its position on that pattern.
7 DIGISKETCH: PAPER CODE BASED TRACKING TECHNOLOGY

7.1 INTRO

In the next chapter a completely different technology is analyzed for its potential to be used in horizontal table top interactive systems. It bases on a commercially available pen that can track its position on a sheet of paper. The technology was adapted to be also usable on LC-displays in order to support multiuser input tracking on a digital surface. Special films had to be found that could be applied onto the LC-screen to enable a proper tracking of the pen. An optimization of the film had to be made to find a solution that enable a good tracking but also maintained a reasonable picture quality. The final prototype was realized on a 15 inch monitor and is called Digisketch.

7.2 THE ANOTO TECHNOLOGY

7.2.1 BASIC PRINCIPLE

Technologies such as the Anoto paper code tracking technology [W43] base on a pattern that is printed on ordinary paper. A pen with an integrated camera detects this pattern that is unambiguously trackable (see Figure 124). Such a setup enables users to use coded paper instead of normal paper. All notes and sketches are saved to the pens internal memory and are available as digital versions when the pen is put back into its cradle for synchronization. A standard printer is used to print the pattern. Special software can even print pattern enabled forms that allow easy in-field data acquisition.
In Figure 125, the principle of optical pattern detection is shown. Infrared light is used to illuminate the area of interest; while the ink is absorbing IR-light and the white paper is reflecting it.

7.2.2 PATENT HISTORY

The principle of using an optically detectable code on a medium such as paper, and a device reading that code in order to position itself was patented by several inventors in different forms. Burns et al. used grey scale coded cells printed on paper to absolutely locate a pen [B98]. Oral F. Sekendur proposed other types of codes and a reading device to locate a pen hovering or writing above the printed pattern code [B99]. Ericson et al. got the first patent for Anoto for a pattern based tracking method issued in May 2003. He proposed a pen that incorporates a camera that recognizes tiny differently sized dots printed on paper. The pen determines the absolute position on the paper by illuminating the area in front of the camera, and it recognizes the dots and the depicted code generated by the different circle sizes. In December 2003, the current pattern used in today’s products was patented also by Ericson [B101].
7.2.3 ANOTO LICENSING MODEL

Anoto divides the whole area of the pattern in many different pages, which are then merged into groups and shelves. On this layer of definition, Anoto sells licenses for printing and using the pattern. Every sold pattern space is unique – meaning that Anoto will not sell it to other customers. In order to efficiently use the bought pattern, software is also offered. The Forms Design Kit (FDK) provides means to design customer specific forms that can be used together with an Anoto enabled pen. Whereas the Paper SDK Kit will help developers to access pattern generation and design Anoto enabled applications based on forms and documents.

7.2.4 THE ANOTO PATTERN IN DETAIL

The Anoto licensed pattern consists of equally sized dots aligned on a 0.3 mm grid. Each dot has a slight offset in one of the four principal directions to the grid’s nodes (see Figure 126). For the eye, this pattern is experienced as a soft grey color since the tiny dots only reach diameters of 30 – 50µm. For allowing the pen to detect the pattern reliably, at least 600dpi resolution prints have to be used. The ink has to contain enough carbon particles in order to absorb the infrared illumination. If wax prints are used, the pattern is not trackable. By using the patented specialized algorithm, only a very small part of the pattern (6 x 6 dots or 1.8 x 1.8 mm) has to be analyzed to unequivocally define the absolute pen position on the full pattern, which encompasses an area exceeding 4.6 million km². X and Y coordinate matrices are encoded into the pattern by using circular number sequences. At every node, the state of the combination of the two matrices is characterized by one of four offsets to the grid node: up, down, left, right. Specific adoptions to a base algorithm even make it possible to detect the pattern when seen from arbitrary angles.

![Figure 126: The Anoto pattern as used in today’s products. The dots are placed with a slight offset to the grid nodes.](image)

7.2.5 THE ANOTO PEN

The Anoto enabled pen consists of several electronic and optoelectronic parts. To detect its position, the tracking area is lit by an integrated infrared flash (880 nm) for a short time (155 µs), in which a customized digital CMOS image sensor acquires an image (see Table 15). The camera tracks the pattern very fast with
sampling rates of around 75 Hz. An advanced image-processing unit converts the image into coordinates. And finally, a Bluetooth radio transceiver transmits the coordinates to a PC for further usage.

Looking at the update rate of nearly 76 Hz, it is interesting to analyze if this is enough for fast writing. Of course, concurrency of physical movement and tracked motion will depend on the letter size and speed of writing. According to Groffmann et al. [B104], fast handwriting speeds can be as fast as 30 mm/s at standard letter sizes of around 7 mm. This results in key points every 0.4 mm, which can be considered to be accurate enough.

![Image](image1.png)

Every 13.3 ms (75.8 Hz) an infrared pulse is generated. The infrared pulse has a length of 155 μs.

**Table 15: Measurement of the Anoto pen’s infrared flash**

A special streaming mode exists for the Bluetooth versions of the Anoto enabled pens: The whole Anoto pattern space incorporates special streaming enabled areas. These can be used to acquire live tracking data since the pen constantly send tracking information to the PC. Beside plain coordinates according to Peter Kauranen [B103], the pen also sends information about:

- Current pressure on the tip from the built-in pressure sensor
- Pen identification
- Inclination angle (computed by pattern analysis)
- Rotation of the pen relative to the pattern orientation
- Current accurate time-stamp
THE MAGICOMM G 303 PEN

The G303 Pen from Magicomm [W44] is used for further tests and analysis. Properties of the pen are listed in Table 16. The inside of such a pen incorporates the components depicted in Figure 127.

<table>
<thead>
<tr>
<th>Model</th>
<th>G303 (Bluetooth® + USB Model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>30 g</td>
</tr>
<tr>
<td>Dimensions</td>
<td>153 x 19 x 17 mm</td>
</tr>
<tr>
<td></td>
<td>157 x 21 x 18 mm (with the cap)</td>
</tr>
<tr>
<td>Communication</td>
<td>USB 1.1 Standard (USB 2.0 Standard)</td>
</tr>
<tr>
<td></td>
<td>Bluetooth® 1.2 Standard</td>
</tr>
<tr>
<td>Battery</td>
<td>Lithium-Ion rechargeable</td>
</tr>
<tr>
<td>Operating time</td>
<td>2 h (Standby: 10 h)</td>
</tr>
<tr>
<td>Charge time</td>
<td>2.5 h (Charging via Cradle / USB)</td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.1 mm</td>
</tr>
</tbody>
</table>

Table 16: Properties of the G303 Anoto enabled pen

Figure 127: The Magicomm G303 and its components

7.3 ANOTO ON LC-DISPLAYS

In contrast to an application on paper, the usage of the pattern on LC-displays is not trivial. The pattern can be printed on transparent films and mounted in front of the LC-display. As a result, the pen is not recognizing its position. The reason for this is that the LC-matrix absorbs a high amount of infrared light. Only a small amount is reflected, which apparently is not enough to provide a clear pattern detection for the CCD chip. Investigations on the reflective properties of the LC-matrix showed that only around 4% of the radiation is reflected from the matrix (see Figure 128). Around 10 to 22 percent traverses the LC-matrix according to measurements in Figure 31 and Figure 128.
In order to enable a reliable tracking on the printed Anoto pattern on LC-displays, a possibility has to be found that increases the amount of reflected light (see Figure 129).

Preliminary experiments with additional IR-LEDs mounted on the pen itself did not show any suitable results. Neither adding additional IR light behind the LC-matrix nor in front of it lead to any success (see Figure 130).
7.3.1 ADDITIONAL FILMS

Instead of using additional lighting, special films can be used to improve the IR-reflection on the screen. The films are mounted between the LC-matrix and the Anoto pattern, which is printed on a transparent film (see Figure 131).

![Figure 131: Additional films mounted between the pattern layer and the LC-matrix](image)

7.3.2 PROBLEM DESCRIPTION

The task of providing a detectable pattern on the LC-display for the pen is not an easy one. On one side, it has to be made sure that at least 6 x 6 dots can be detected by the pen, which requires a widely illuminated area on the surface (diffusive surface). So called hot spots which are generated by specular reflection on very reflective materials only illuminate a very small area on the surface. In the most cases this area is not large enough as to illuminate the required 6x6 dots evenly.

On the other side, the illuminated area has to reflect radiation of certain intensity. If the radiation is too low, the contrast between absorbed and reflected light is too low for the pen to detect. If the radiation is too high, the brightness will make it impossible for the pen to detect the single dots (see Figure 132). The threshold, at which the pattern is recognized and at which not can only be found by experiments.
The integrated IR-LED in the pen illuminates the pattern printed on a surface. The black dots absorb the IR-light, while the white areas of the pattern have to reflect the IR-radiation. When using transparent films, it is necessary to provide a diffusive reflection in order to widen the area of reflection (and prevent hot spots). A simple IR-reflective film such as CPF AGHT [W51] does not provide enough diffusion and only generates a small hotspot, which is not wide enough as to illuminate 6 x 6 pixels. Thus the problem space can be visualized by the following illumination design space:

Figure 133: Illumination design space: The reflected radiation intensity has to lie in a defined area (green) in order to not produce a low contrast or an over illumination

By using diffusive films, this problem can be solved, but another is appearing:

Diffusive films will influence display quality significantly, since they will not only diffuse the reflected light but also transmitted light from the display, thus decreasing the screen’s contrast. In order to find a trade-off between screen contrast and tracking quality, these two parameters were analyzed.
### 7.3.3 PARAMETER EVALUATION

Two parameters are analyzed:

- **Tracking quality**: how well the pen is being tracked on the surface or how well the pattern is being detected by the pen.

- **Screen contrast**: How well the screen is still producing a reasonable image for the user.

---

**TRACKING QUALITY:**

Since there is no access to the pens internally processed camera images, the rating must be performed by taking indirect effects into account. These are the status LED, the update rate, and the vibration motor. As soon as the pen is not detecting the pattern properly, it turns on its vibration motor. If the pattern is not detected at all, the motor is shut off and a LED is turned on.

The measurements showed that detection quality depends also on the angle between pen and surface. In order to divide the tracking quality not only in two groups of “working” and “not working”, an additional grading was chosen. This grading can be separated into four qualities, while “0” does not allow any tracking at all (Table 17):

<table>
<thead>
<tr>
<th>Tracking Quality</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Property</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Description</strong></td>
<td>No tracking possible</td>
<td>The pen will only reliably track its position when held between 80 and 90 degrees against the surface</td>
<td>The pen will also detect its position, when being held under an angle of more than 50 degrees, but with a reduced update rate.</td>
<td>The pen will be tracked over a wide range of inclinations down to 40 degrees.</td>
</tr>
</tbody>
</table>

It shall be noted that the pen’s internal IR-pass filter was removed for the measurements since this improved the tracking quality significantly in cases. In Figure 134 a plot shows how many films for each tracking quality were found. It’s very satisfying that as much as 49 films were found that enabled a good tracking with the grading 3.
SCREEN CONTRAST

In order to reduce and optimize the found 49 films down to the best ones the second parameter is analyzed here: screen contrast. Besides the tracking, it is of most importance that the user will not recognize a difference between a Digisketch enabled monitor and a standard monitor in the optimal case. Contrast levels are envisioned to be at the same level. Parameters for image quality are color representation and screen contrast. The ratio of the brightness of the whitest white and darkest black is analyzed in order to determine the screen contrast, while color was considered to be of minor importance, and thus was not analyzed. In contrast to the DIN NORM 9241-302 [B24], not the light density contrast (measured in cd/m²) is used to compute the contrast, but the mean brightness levels of 50 pixels for complete black and white areas in a digital camera image.

To achieve a homogenously lit and wide illuminated area, the 49 different films, which were rated with a high tracking quality of three, were analyzed.

In Figure 135, the results for screen contrasts for the best tracking film solutions are shown. In Figure 136, three films from Kimoto (including the two best) [W57] are shown. A significant difference between a condition, under which environmental lights are turned on and a condition under which they are turned off, can be observed. The diffusive behavior of the films is much more visible if additional environmental light is reflected. It can also be seen that the contrast of a screen with an overlay is significantly reduced compared
to a normal monitor. The contrast ratio is reduced to only 54% of an unmodified monitor (69% for environmental light case).

<table>
<thead>
<tr>
<th>Name</th>
<th>None</th>
<th>100 S</th>
<th>100 MXE</th>
<th>100 SXE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contrast</td>
<td>2.9</td>
<td>1.52</td>
<td>1.49</td>
<td>1.32</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>None</th>
<th>100 S</th>
<th>100 MXE</th>
<th>100 SXE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contrast</td>
<td>1.69</td>
<td>1.16</td>
<td>1.15</td>
<td>1.11</td>
</tr>
</tbody>
</table>

Figure 136: Visual impact on the screen contrast (not brightness) for different Kimoto films (without Anoto pattern applied)

7.3.4 MONITOR MOUNTING

Once a suitable film is chosen, the question arises how to mount it onto large flat surfaces without influencing display quality. Different methods were tested, such as gluing and stretching the film slightly. Since minimal offsets between diffusive layer and LC-matrix will influence display contrast significantly, none of the above methods could be chosen. One promising way of attaching the film to the matrix is to apply a vacuum between film and matrix, thus generating a pressure gradient. This difference in pressure presses the film onto the matrix generating a tight contact without any influence on picture quality. The challenge with this solution is the need for a perfect seal and a good vacuum. In order to achieve a good seal, the glass of the matrix has to provide enough space at the edges as to place a seal tape or other sealing material.

The Digisketch prototype was realized on a 15 inch monitor.
7.4 SOFTWARE

To process the pen’s input via Bluetooth transmission, a Bluetooth dongle and the iTable framework that was originally developed for tabletops solutions, were used. iTable was realized as an application of the more general iPaper platform [B112] for interactive paper solutions, which was developed by the GlobIS (Global information system) research group [W52] at ETH Zurich. The application analyzes the Bluetooth traffic of multiple Magiccomm G303 pens and generates either mouse commands or sends interaction data using the TUIO protocol [B82].

7.5 PROTOTYPE PERFORMANCE

7.5.1 TECHNICAL PERFORMANCE

Technical properties are listed in Table 19. The update rate was measured by detection of the sequential IR-flash from the integrated diode (see Table 15). Accuracy is taken from the manufacturer’s data sheet. Lag was determined by using the same proceeding as presented with the MightyTrace prototype.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Update rate</td>
<td>76 Hz</td>
</tr>
<tr>
<td>Lag</td>
<td>90 ms</td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.1 mm</td>
</tr>
</tbody>
</table>

Table 19: Technical properties of the Digisketch prototype

7.5.2 PRELIMINARY TESTS

In order to evaluate the suitability of the adapted Anoto technology, a preliminary user study was performed. Digisketch was compared to a state-of-the-art interactive system, the Wacom [W15] inductive
pen tracking technology. It features accuracies of up to 0.5 mm, 130 Hz sample rate, and hovering of up to 10 mm above the screen.

The International Organization for Standardization defined the ISO 9241-9:2000 [B23] standard. It defines measuring the input performance based on Fitts' Law [B117]. A draft version of the ISO standard was assessed by Douglas et al. [B116]. Their examination found the standard to be sound.

The test setup consisted of two 15” LC-displays - a Wacom Cintiq15X and the modified Digisketch enabled prototype. The test consisted of a simple point and click task according to Fitts’ Law. The two parameters D and W (see Figure 138) were used to determine the index of difficulty (in bits), from medium to high – 5.5, 6 and 6.5.

Three basic parameters were analyzed to compare the two different technologies:

- **Completion time**: Required time for completing the task.
- **Error rate**: Error rate is the percentage of targets selected when the pointer is outside the target.
- **Throughput (TP)**: The throughput in bits/s where

\[
TP = \frac{i_{\text{effective index of difficulty}}}{t_{\text{mean movement}}} \quad \text{[E26]}
\]

### 7.5.3 PRELIMINARY STUDY RESULTS

The two parameters were assessed using 10 subjects, who completed all three tests on each of the two setups. Table 20 shows the mean values and standard deviations of the throughputs measured in the tests, and results from an analysis of variances (ANOVA) at the significance level of \( \alpha = 0.01 \). In Table 21, the same is shown for the time the participants needed to complete the task. The statistical analysis showed that the differences between the two systems is not statistically significant (\( p>0.01 \)) in the throughput domain, but is (\( p<0.01 \)) statistically significant for the completion time. Thus, concerning the parameter throughput, the Null hypothesis (the two systems perform equally well) cannot be rejected and the two systems seem to perform equally well in a statistical sense. However, for the completion time a significant difference can be observed. The Digisketch system performs worse than the Wacom. This fact can be explained by the fact that users frequently complained about the Digisketch’s low reactivity compared to the Wacom pen. The Anoto pen will sample several acquisitions before sending the data via Bluetooth to the driver application. This results in a larger lag, which influences fast pointing accuracy and enlarges the time the user needs to move and click a target. Another issue is the mentioned inclination dependency, which significantly
influences the error rate at high levels of difficulty. A click combined with missing tracking information will lead to an error. This is particularly possible if the pen is placed at an inappropriate angle below 40 degrees and between 80 and 70 degrees.

<table>
<thead>
<tr>
<th></th>
<th>Digisketch</th>
<th>Wacom</th>
<th>ANOVA (k=2, n=10, α=0.1, F_krit=3.007)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID 5.5</td>
<td>4.375</td>
<td>1.790</td>
<td>5.933</td>
</tr>
<tr>
<td>ID 6.0</td>
<td>5.161</td>
<td>1.703</td>
<td>5.926</td>
</tr>
<tr>
<td>ID 6.5</td>
<td>4.633</td>
<td>1.544</td>
<td>6.081</td>
</tr>
</tbody>
</table>

Table 20: Throughput in Bits/s for different levels of difficulty for the two test setups Digisketch and Wacom.

<table>
<thead>
<tr>
<th></th>
<th>Digisketch</th>
<th>Wacom</th>
<th>ANOVA (k=2, n=10, α=0.1, F_krit=3.007)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean [ms]</td>
<td>SD [ms]</td>
<td>Mean [ms]</td>
</tr>
<tr>
<td>ID 5.5</td>
<td>29218</td>
<td>6529</td>
<td>22465</td>
</tr>
<tr>
<td>ID 6.0</td>
<td>30394</td>
<td>5003</td>
<td>24607</td>
</tr>
<tr>
<td>ID 6.5</td>
<td>34358</td>
<td>6529</td>
<td>25998</td>
</tr>
</tbody>
</table>

Table 21: Completion time in ms for different levels of difficulty for the two test setups Digisketch and Wacom.

7.6 SUMMARY

The Digisketch technology provides an easy to implement technology for large sized interactive screens. More precisely: By applying the pattern to a surface it can be made interactive. The pattern enables direct manipulation of digital content on LC-displays of any size. Although the performance of the Anoto pen on LC-displays cannot beat a state of the art Wacom digital tablet it is far more universal applicable, since the Wacom technology can only be used on screens below 21". Additionally Digisketch can easily be extended by additional pens thus supporting multiuser interaction. Since every pen incorporates its own tracking electronics there is no interference possible. The total number of usable pens is 7 up to now, which is being restricted by the used Bluetooth stack. Display quality is still subject to improvements, since contrast ratios are still below normal screen ratios. Considering the main application case of creative group work, most of the time only few drawing colors are needed while writing or sketching and font sizes or written text is larger than usual.
8 SUMMARY & OUTLOOK

8.1 COMPARISON OF ALL SYSTEMS

In Table 22 the properties of all developed systems are shown using the presented classification systems. It can be seen that all systems fulfill the entire detection modality requirements. All the systems will scale to sizes beyond 40 inch and the tracking technology is integrated into the display (thin construction). This makes sure the systems can be used in an ergonomic position and users can comfortably sit at a table to interact with the system. Another important result is that each prototype provides sampling rates that are well above the required 20 Hz. On the other side only TNT is capable of detecting touch and TUI input concurrently.

<table>
<thead>
<tr>
<th>Category</th>
<th>Sub category</th>
<th>Example product</th>
<th>Remarks</th>
<th>Year</th>
<th>Performance</th>
<th>Size</th>
<th>Detection Modality</th>
<th>Detection Activation</th>
<th>Component Mount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical</td>
<td>discrete sensor</td>
<td>MightyTrace</td>
<td></td>
<td>2008</td>
<td>50</td>
<td>&gt; 20 (100)</td>
<td>146</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>Pattern tracking</td>
<td>TNT</td>
<td></td>
<td>2009</td>
<td>50</td>
<td>&gt; 20 (100)</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>discrete LED</td>
<td>Digisketch</td>
<td></td>
<td>2010</td>
<td>254</td>
<td>76</td>
<td></td>
<td></td>
<td>DT</td>
</tr>
</tbody>
</table>

Table 22: Summary of the properties of the three developed systems

Since lag is not part of the classification system it is discussed here. The following lags were measured for the systems:

<table>
<thead>
<tr>
<th>System</th>
<th>Lag [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MightyTrace</td>
<td>85 ms</td>
</tr>
<tr>
<td>TNT</td>
<td>70 ms</td>
</tr>
<tr>
<td>Digisketch</td>
<td>90 ms</td>
</tr>
</tbody>
</table>

Table 23: The different lags for the developed systems

It can be seen, that none of the system does reach the optimal lag of 25 ms. But this was not required. A value below 100 ms is achieved by all systems. MightyTrace and TNT were built with primer focus on fast
sensor data acquisition. Update rate was very important to achieve a smooth tracking of a lot of different devices serially - unperceivable for the users. Lag on the other side could be improved by several means. Ideas exist to lower the current lag and are discussed in the outlook chapter.

Concerning Digisketch the lag is system inherent. To a large part, influence on the lag was not possible, since the pens internal processing produced the lag to the largest part.

8.2 OUTLOOK

HCI has become an important research field. Especially after the first FTIR enabled multi-touch interaction was shown, numberless imitations and incremental improvements of the original design by Han made it to blogs and have even formed new communities like the NUI group [W56]. This community now even promotes a community book and a framework that enables multi-touch detection. Also some demo applications exist, whereas most of these do not go beyond scaling and sharing photos on a large screen. This leads straight to the central question for the future. Now, much hardware exists for detecting almost every movement on a surface, but still intelligent applications are rare. Hence future research will have to focus on specific applications that take advantage of the strong concepts of touch and TUI and will show how to integrate these findings into industry. Some of the research results will hopefully make it all the way from lab prototypes to industrial products. Under good circumstances, industry will risk putting time and money into promising interaction designs to foster desirable interactive solutions for computer users.

8.2.1 MIGHTYTRACE AND TNT

From a tracking technology point of view the current MightyTrace and TNT system could still be improved in many aspects. Here only a short list of possible technical improvements shall be given, in order to clarify the work packages for future works.

MightyTrace and TNT hardware improvements:

REDUCTION OF SYSTEM LAG / INCREASE OF UPDATE RATE:

This issue could be achieved by using faster electronic components and optimized software, whereas with the later the effect is rather insignificant. The whole data chain from the analog IR sensor to the processing and displaying of the interaction data on the screen several improvements can be thought of:

1. **Sensor speed**: In the current version reverse biased sensor connection is realized. By using a short circuit mode the reaction time can be reduced by the factor 6300 (!) from 126 µs to 20 ns. This results in a speed gain per frame of ~21%. The current connection has been chosen to reduce circuit complexity. To achieve near full sensor speed additional electronic components like charge amplifiers are needed for every sensor. Or a complex network of analog multiplexers that can switch lines from multiple sensors onto one amplifier.
2. **Analog to digital converter speed**: Analog to digital conversion could be increased by using higher sampling rates above 2 MSPS (Mega samples per second). This would decrease the time needed for the conversions. This can provide a speed gain per frame of around ~96% (in case of a 50 MSPS ADC) provided that this high speed of the ADC can also be handled on the MCU side.

3. **SPI Transfer Time**: By using a higher frequency with different MCUs the SPI bus frequency could be increased. This would also require proper noise cancelling and bus termination considerations in order to handle signal noise. But speed increase would be in the order of 50%.

4. **Hardware Interface**: Probably the most effect of overall performance will have the usage of a different transmission from the MightyTrace hardware to the PC. The current implementation transmits data with only 1 Mbit/s (USB 1.1). Specialized hardware can drive up to 480 Mbit/s (USB 2.0 “High speed”). This would improve the data transmission time, but the USB scheduler based communication would remain the same, which means that only once every millisecond a packet can be sent. But looking at the 12/9 Scenario this could improve the 6 ms needed for the data transmission down to only 12 µs (provided the data fits into one USB frame packet).

5. **FPGA/ARM/DSP**: It may be necessary to use very fast hardware for USB 2.0 High speed transfer. Also if ADCs with a very high sample rate are used the interface to the processing unit has to be read out with very high frequencies. The usage of an FPGA, high speed ARM or specialized DSP unit has to be considered.

6. **Faster display response time**: A display with a very low response time in the range of 2 ms like it is common today would reduce the current lag significantly.

In the following table the proposals has been analyzed for their total impact on the system.

<table>
<thead>
<tr>
<th>Time</th>
<th>Old time [µs]</th>
<th>New time [µs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device answering delay</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>Sensor profile delay</td>
<td>126</td>
<td>0.02</td>
</tr>
<tr>
<td>Analog digital conversion time</td>
<td>200</td>
<td>8</td>
</tr>
<tr>
<td>SPI transfer time</td>
<td>150</td>
<td>75</td>
</tr>
<tr>
<td>USB transfer</td>
<td>6000</td>
<td>12</td>
</tr>
<tr>
<td>Display response time</td>
<td>16000</td>
<td>2000</td>
</tr>
<tr>
<td>Total acquisition time for 12 frames (min. lag)</td>
<td>28336</td>
<td>3475</td>
</tr>
</tbody>
</table>

**Table 24: Improvements for different timings with better technology and their final influence on the lag / update rate**

Taking all actions above into account and provided that no other significant lags occur, a reduction of the lag down to around 3.5 ms could be achieved. This would also result in a very high update rate of around 285 Hz!

Of course the above actions will also increase the system costs. The current system was designed to give the required performance at a low price. Still the overall hardware system costs lie at around 10 000 CHF. This includes no manual work or development time.

### OTHER IMPROVEMENTS

- **Increase of accuracy** by decreasing sensor distance or by using ADCs with higher resolution and less noise. This implies that the overall system speed must be increased to achieve similar results as the current prototype.
- **Immunity to interference from sunlight.** This could be achieved by modulation of the device signals and by demodulation of the sensor signals. This procedure requires an increased system speed and results in a complex hardware setup.
- **Increase of screen resolution** to full HD.
- **For TNT: Increase of sensor sensitivity or high power IR light in coupling.** This increases the current limit of 50” diagonals to probably around 100”.
- **For TNT: Find compliant material** that decouples better but is not prone to hysteresis.
- **Development of TUI and touch enabled applications.** The current MightyTrace prototype provides a base for virtually any kind of tangible interaction since interaction devices can be arbitrary shaped and equipped with additional input sensors such as buttons or distance sensors or potentiometers.

### 8.2.2 FUTURE OF TRACKING TECHNOLOGIES

Another possibility for TUI and touch tracking on thin displays was recently shown by Hodges et al. [B92], who use IR sensors behind the LC-matrix (see 8.3.1 ThinSight - 2007). At the same time, researchers have presented related solutions taking advantage of the LC-matrix’s IR-transparency by either use LEDs behind the screen as emission and sensing elements (see 8.3.2 LED-Based multi touch sensor - 2010). Another FTIR-based tracking technology was recently presented (see 8.3.3 Scanning FTIR - 2010). But none of the above mentioned solutions equipped a screen larger than 19”. In this sense MightyTrace still presents state-of-the-art technology.

At the time of writing, new emerging technologies such as integrated sensor pixels inside the LC-matrix are becoming research prototypes [B125] and were recently patented by companies such as Apple [B124]. Integrated pixel sensors are sensitive to light and can be used to track fingers or other objects on the surface. This possibility eases the development of technologies like MightyTrace, since no further integrated components for the tracking are required. However, the amount of infrared from back illumination still has to be reduced by exchanging CCFL tubes. Even tracking of three-dimensional objects in front of LC-displays can become reality by using a special technique known from photography presented in the BiDi-screen paper [B126].

Concluding it can be said that technologies will emerge that have the potential to replace the MightyTrace technology and enable a less complex TUI detection. But to this date there exists no prototypes.

### 8.2.3 DIGISKETCH

Till date no published prototype can offer better image quality for the tracking of an Anoto enabled pen on LC-displays than Digisketch. Anoto itself did not merchandise a product that enables Anoto usage on LC-displays, although recently their webpage claims that this was possible.

A challenge with the Digisketch technology will be to enhance image quality further while maintaining tracking quality at the same level. To solve this problem, it is necessary to get access to the electronics source code to adjust camera parameters accordingly. Inverting the dot pattern would enable a tracking of
reflective dots while the matrix could be left as is to fully absorb the black part of the pattern. IR-reflective ink, that is hardly visible exists and is used in product coding ink processes. Another issue with the Anoto technology is its need to analyze a couple of frames until the position data is sent, which results in a lag. This problem could be fixed by altering the processing in the firmware of the pen.

Another interesting - yet not realized – idea is the seamless usage of the pen on LCDs and paper. On paper, the pen’s tip is needed in order to write and an ink tip is used. For interacting on the LC-display, this tip has to be exchanged by a plastic tip in order to not permanently write or damage the screen. Solutions to this problem could be switchable mechanics that work similar to the current multicolor roller pens. Applying a special anti-graffiti film onto the screen may also be a solution.

8.3 RECENT ADVANCES IN RESEARCH

During the period this work was carried out, other publications in the domain were presented to the community. Some of those publications have presented similar results than the work presented here. For the sake of completeness, research work that falls in the same category will be presented in the following chapter.

8.3.1 THINSIGHT - 2007

Thinsight [B92] by Hodges et al. uses the fact that the matrix of an LC-display is partially transparent to infrared light. Thinsight uses infrared emitters behind the LC-matrix to emit light. The infrared light passes through the LC-matrix and is reflected by objects in front of the display. This reflection again passes through the matrix and triggers sensors, which are also mounted on the PCB behind the matrix. Three modules, covering a small area of the 150 x 70 mm behind the matrix and in front of the display’s reflector film will detect multiple touches. The modules were integrated into a laptop and provided detection of touch. Hovering was said to be possible up to 1mm above the screen, but was not implemented in the prototype software. Finger pressure was also detectable by analyzing the size of the blob a finger creates. Each module is equipped with 35 sensor-emitter pairs in a distance of 10 mm to each other.

The system samples data with 8-10 frames per second, which is very low in respect to speed requirements for natural interaction. Preliminary tests with TUIs incorporating an IR-reflective code were performed and showed promising results.

Thinsight was developed further and a second prototype was introduced in 2008 [B93]. A 21” monitor was completely equipped with sensors behind the matrix. In total, 30 modules were integrated into the screen. Additional components, such as synchronization FPGA hardware, controlling data flow from the modules, were added. In order to enhance image quality, brightness enhancement and diffuser films were removed and replaced by a radiant light film (3M™, CM500) in front of the sensors, combined with a neutral density filter. The new prototype now incorporated the mentioned TUI tracking. Objects with attached fiducials markers or just by shape detection could be tracked in identity, position and orientation. Tracking and communication with active objects was also implemented in this prototype. Mobile phones could be tracked...
and even data transfer from the mobile phones to Thinsight and vice versa was possible by using the phone’s built-in camera and a Bluetooth connection. If more than one Bluetooth device is in range, a distinction between them is needed. Hence, a specific color is displayed on the TFT underneath the mobile phone. The built-in camera is acquiring this color-code and sends a histogram of the color distribution over Bluetooth that can be used to match the displayed position to the device on the screen.

### 8.3.2 LED-BASED MULTI TOUCH SENSOR - 2010

In 2010, Echtler et al. built a multi-touch screen based on standard LEDs [B94]. Already back in 2005, Han patented a method using LEDs jointly as a displaying and multi-touch sensing device [B95], but the idea was not pursued. The principle used in both projects is the same. A LED can basically be used in two ways: as an input or as an output device. In 2003, Dietz et al. showed electronic devices that could communicate bidirectionally using only one LED on each device [B96]. In the output mode, the diode is forward-biased (switched on), electrons are able to recombine with holes within the device, releasing energy in the form of photons in a specific wavelength. In the input mode, the diode is reverse-biased and incident light will induce a photocurrent into the diode. The system uses 6 modules covered with LEDs in a distance of 3 mm, resulting in 256 LEDs per so-called SlaveModule. The modules are connected to a so-called MasterModule over a bus, covering an area almost as large as that of a 17” screen. The overall update rate is around 10 Hz for 6 Modules. The current hardware supports extensions for up to 25 Modules using an FPGA on the Master and an ARM 7 Board for communication with the PC. TUIs cannot be detected at this stage of development and hovering is not supported.

During one measurement cycle, a single LED is switched on while the photocurrent is simultaneously measured by an adjacent LED. Object such as fingers in close proximity to the screen will reflect some of the emitted light back to the receiving LED. A modulation of the LED driving signal is used to prevent ambient light from disturbing the system. In a next step during the measurement the adjacent LED row is turned on and the reflection is measured with the other LEDs. This is done for each LED row correspondingly until all LEDs have been turned on.

The overall update rate is around 10 Hz for 6 Modules. The current hardware supports extensions for up to 25 Modules using an FPGA on the master and an ARM 7 Board for communication with the PC. TUIs cannot be detected at this stage of development and hovering is not supported.

### 8.3.3 SCANNING FTIR - 2010

In 2010, Moeller and Kerne presented Scanning FTIR [B97], which again bases on the FTIR principle to detect multiple touch points on a surface. In their approach, they resign IR-cameras for the detection of decoupled IR-light. An array of IR-light emitting diodes is attached to two edges of an acrylic, whereas IR-sensors are mounted on the other two edges. In-coupled light will totally reflect internally, until it hits upon a sensor on the other side of the acrylic. If a finger is placed on the surface, it will decouple light and scatter parts of the rays towards the back of the acrylic. Thus, the corresponding sensor on the opposite side will detect less radiation. By time multiplexing all emitter-sensor pairs, a map of the touch points can be created. The
advantage of this system is its transparency, although the authors did not implement a screen yet. Also update rates are limited to around 1 Hz in the current prototype due to unspecialized hardware.

Their design showed an interesting effect: the shadowing effect in FTIR systems, which has been presented here in 6.3.5 Occlusion on page 152. A lot of systems use FTIR technology, but neglect the effects generated by occlusion. Touches on the surface can influence each other. Decoupled light energy will not be available for touches that are located behind the decoupling touch point in respect of the light source.

### 8.4 PUBLICATION OVERVIEW

During this PhD thesis, several papers were published. For understanding the temporal relation to other international research work, Table 25 is shown.
VI. APPENDIX: ELECTRONIC SCHEMAS
8.5 SLAVE BOARD

8.5.1 BOARD
8.5.2 SCHEMATIC
8.6 SENSOR BOARD

8.6.1 BOARD
8.6.2 SCHEMATIC

[Diagram of a complex circuit diagram, showing various electronic components and connections.]
8.7 SENSOR BOARD TOUCH

8.7.1 BOARD
8.7.2 SCHEMATICS
9 BIBLIOGRAPHY

9.1 OWN PUBLICATIONS


9.2 OTHER RESEARCH


[B22] DIN EN ISO 9241-11: Ergonomic requirements for office work with visual display terminals (VDTs) - Part 11: Guidance on usability

[B23] DIN EN ISO 9241-9: Ergonomic requirements for office work with visual display terminals (VDTs) - Part 9: Requirements for non-keyboard input devices

[B24] DIN EN ISO 9241-16: Ergonomic requirements for office work with visual display terminals (VDTs) - Part 16: Direct manipulation dialogues


[B105] DIN 4549 Büromöbel, Schreibtische, Büromaschinentische und Bildschirmarbeitsstische, Maße

[B106] DIN 4543: Büroarbeitsplätze; Flächen für die Aufstellung und die Benutzung von Büromöbeln; Teil 1Sicherheitstechnische Anforderungen, Prüfung


10 WEBLINKS

11 FIGURE REFERENCES

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