Development of Actuated Tangible User Interfaces: New Interaction Concepts and Evaluation Methods

by

Eckard Riedenklau

A dissertation submitted to the Faculty of Technology at the Bielefeld University
in partial fulfillment of the requirements for the degree of

Doktor der Ingenieurwissenschaften

(Dr.-Ing.)

January 2016

Development of Actuated Tangible User Interfaces:
New Interaction Concepts and Evaluation Methods

Eckard Riedenklau
Cognitive Interaction Technology - Center of Excellence (CITEC)
Faculty of Technology
Bielefeld University
P.O. Box 10 01 31
D-33501 Bielefeld
Germany
email: eriedenk@techfak.uni-bielefeld.de

DEAN OF THE FACULTY:
Prof. Dr. Mario Botsch

THESIS REVIEWERS:
Dr. rer. nat. Thomas Hermann
Prof. Dr. rer. nat. Helge Ritter
Prof. Dr.-Ing. Eva Hornecker

THESIS VIVA EXAMINATION COMMITTEE:
Prof. Dr.-Ing. Ulrich Rückert
Dr. rer. nat. Thomas Hermann
Prof. Dr.rer. nat. Helge Ritter
Prof. Dr.-Ing. Eva Hornecker
Dr.-Ing. Frank Hegel

Date of Thesis Submission for Review: 4 June 2013
Date of Thesis Viva Examination: 2 July 2015

The official print version has been printed on age-resistant paper in accordance with DIN-ISO 9706.

Abstract

Making information understandable and literally graspable is the main goal of tangible interaction research. By giving digital data physical representations (Tangible User Interface Objects, or TUIOs), they can be used and manipulated like everyday objects with the users' natural manipulation skills. Such physical interaction is basically of uni-directional kind, directed from the user to the system, limiting the possible interaction patterns. In other words, the system has no means to actively support the physical interaction. Within the frame of tabletop tangible user interfaces, this problem was addressed by the introduction of actuated TUIOs, that are controllable by the system. Within the frame of this thesis, we present the development of our own actuated TUIOs and address multiple interaction concepts we identified as research gaps in literature on actuated Tangible User Interfaces (TUIs).
Gestural interaction is a natural means for humans to non-verbally communicate using their hands. TUIs should be able to support gestural interaction, since our hands are already heavily involved in the interaction. This has rarely been investigated in literature. For a tangible social network client application, we investigate two methods for collecting user-defined gestures that our system should be able to interpret for triggering actions. Versatile systems often understand a wide palette of commands. Another approach for triggering actions is the use of menus. We explore the design space of menu metaphors used in TUIs and present our own actuated dial-based approach. Rich interaction modalities may support the understandability of the represented data and make the interaction with them more appealing, but also mean high demands on real-time precessing. We highlight new research directions for integrated feature rich and multi-modal interaction, such as graphical display, sound output, tactile feedback, our actuated menu and automatically maintained relations between actuated TUIOs within a remote collaboration application. We also tackle the introduction of further sophisticated measures for the evaluation of TUIs to provide further evidence to the theories on tangible interaction. We tested our enhanced measures within a comparative study. Since one of the key factors in effective manual interaction is speed, we benchmarked both the human hand's manipulation speed and compare it with the capabilities of our own implementation of actuated TUIOs and the systems described in literature.
After briefly discussing applications that lie beyond the scope of this thesis, we conclude with a collection of design guidelines gathered in the course of this work and integrate them together with our findings into a larger frame.

Acknowledgments

I am deeply thankful for the help, support and encouragement from all the people who were involved, making this research possible.

Especially, I thank my supervisors Dr. Thomas Hermann and Prof. Dr. Helge Ritter for drawing me into research and allowing me to freely conduct my studies, for providing me with the guidance I needed and for being a source of inspiration, letting me become the researcher, I am now.

I would like to thank my colleagues and friends from the Ambient Intelligence Group and Neuroinformatics Group – namely Till Bovermann, Christof Elbrechter, Andrea Finke, Florian Grond, Ulf Großekathöfer, Tobias Großhauser, Nils Hachmeister, Sebastian Hammerl, Jan Hammerschmidt, Risto Kõiva, Christian Leichsenring, Oliver Lieske, Jonathan Maycock, Alexander Neumann, Christian Peters, Stefan Rüther, Susanne Strunk, René Tünnermann, Sebastian Zehe, and all the others – for the kind atmosphere, the stimulating discussions, the support and the great fun. Beside the members of the groups I am directly affiliated with, I also thank the colleagues and friends from the Central Lab facility, the CoR-Lab and the other groups of CITEC. I would like to thank the administrative staff and personnel of CITEC, namely Anita Adamczyk, Andrea Caio, Claudia Muhl, Dajana Nordsiek, Armin Wenske and all the others. Furthermore, I would like to thank the organization team of the CITEC Summerschool 2010. It was great fun working with them.

Special thanks go the student groups who were involved in the ISy projects I were allowed to supervise. The first group working on the IMS and the TAOgotchi projects, including the active marker tracking was formed by Andreas Kipp, Dimitri Petker (who also helped in implementing the final ESN application), Matthias Schröder and Dominik Weissgerber. The second group working on the AHEAD project was formed by Birte Carlmeyer, Mathias Lindemann, Viktor Richter and Thomas Schöpping. All of you did a great job!

I am grateful for Dr. Dieta Kuchenbrandt's advices on the design of the comparative study's questionnaire and for the introduction to the analysis of psychometric data. She also proofread and commented on the chapter about the comparative study.

I also want to thank all the participants who took part in my studies. Without their participation in the studies, this thesis would not have been possible.

Furthermore, I thank my cousin Carol Nuernberger, who proofread and commented on the core chapters of my thesis.

I am grateful for my friends' patience, understanding and support: Marnie Ann Spiegel and Sascha Griffiths for the countless coffee breaks that cleared my mind, Kristina Bresch always cheering me up when things were difficult and Felix Reinhart, "thank you for the music!"

Finally, I am deeply grateful to my parents Gerd and Wilma, my sister Ute and her husband Carsten and my nieces and nephew Chiara, Mirja and Jannis for supporting me wherever they could, for deeply believing in me and for just being awesome.

This work has been supported by the Cognitive Interaction Technology - Center of Excellence (CITEC), Bielefeld University.

Contents

1 Introduction and Motivation

> The most exciting phrase to hear in science, the one that heralds new discoveries, is not "Eureka!" but "That's funny."
>
> Isaac Asimov, as quoted in [106, p. 236]

Humans have always been using tools and things. From the Stone Age until today, from the biface to the smartphone – we humans turned out to be masters with our hands in handling artifacts. Until the late 20th century, things in culture and technology were graspable, manipulable and shapeable. Then, with the introduction of computers and the Internet, things started to change, slowly. Nowadays, in the information age, we move away from a pure physical everyday life to a world becoming more and more digital, which in turn becomes literally harder to grasp.

The Vision: The Perfect Universal User Interface

Since the very first beginnings of Human Computer Interaction (HCI)[1], its major aim is the development of computational tools and system enabling users to accomplish all kinds of tasks. The perfect user interface understands the users, their needs and their natural interaction styles and supports them to eliminate the bottleneck of current interaction approaches (the bottleneck is the interface [76]). Humans are extremely good at manipulating objects and interacting with their environment and other humans. They are social beings and vastly profit from the collaborative interaction. Consequently, data should be represented and be acting similarly.

In other words, (given the needed technology) the *Holodeck*, described in science fiction, could assemble such a universal user interface. This fictional technology can instantaneously create sophisticated physical objects and materials as holograms. Even avatars that are interactive and creative with extreme knowledge, technical, medical and social skills etc. are possible here. These capabilities assemble the perfect user interface where information can be modeled as objects and material and even persons. Information can be manipulated naturally and changed in all ways when needed. Such an interface would completely emerge information into the natural environment of the users.

Unfortunately, this is fiction is still a distant prospect. The computational power needed for modeling the physical objects and the artificial intelligence are not yet available. Also

[1] Here the term *interaction* refers to interaction between humans and machines and not only to social inter-person interaction, as in sociology.

holographic projection technology is still in its infancy, far away from instantly creating rigid objects from thin air, though there are approaches for creating haptic sensation, such as by Hoshi et al. [78]. Virtual reality technologies, such as the *CAVE* [31], allow to project three-dimensional environments around the user. Unfortunately, there is still the problem of creating persuasive haptic sensations. Otherwise, virtual and augmented reality can include support for three-dimensional gestural interaction, as demonstrated recently in the *SpaceTop* [120].

Not as hard as creating rigid objects from thin air is implementing shape-changing interaction devices. Rasmussen et al. provide an overview of this research direction [165]. A recent example are the *Smart Material Interfaces* by Vyas et al. [205].

We follow another research direction towards user interfaces that enable the users to naturally manipulate data. Tabletop actuated Tangible User Interfaces are one possibility towards developing interfaces that support physical manipulation of information and blend into everyday environments and tasks.

Tangible Interaction

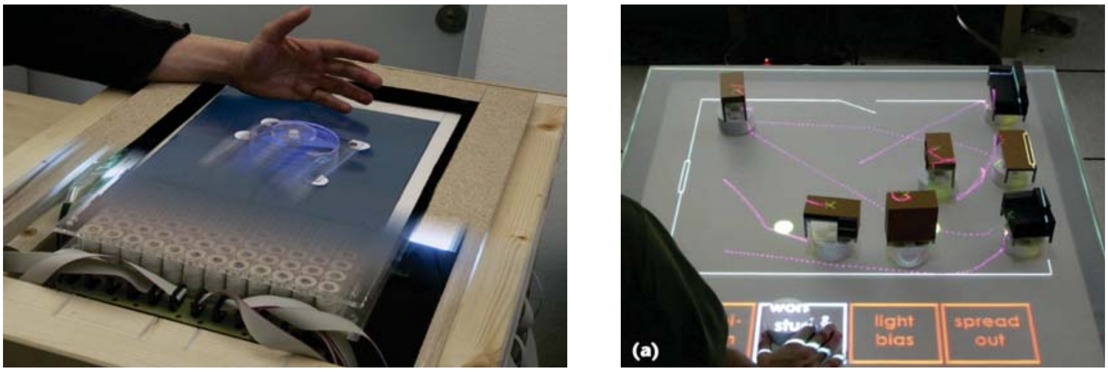
In the research field *Tangible Interaction*, digital information is made available to our dexterity again, by introducing physical objects as representations for data [47, 82]. Objects, such as cubes, similar to building bricks, or things from everyday life, a bunch of keys, a mug or a business card – depending on the applications, can be used as such representations. Tracked by a computer nearly all types of data can be assigned to objects and emerged into the users' environment, enabling new ways of interaction. Data and functionality become graspable again which fosters a deeper understanding.

TUIs and TUIOs

Systems allowing for such interactions are called Tangible User Interfaces (TUIs). We call the objects representing data and functionality Tangible User Interface Objects (TUIOs). The physical properties of these objects determine the ways of usages. Such properties can be the (relative) position, orientation or proximity to other objects etc. and determine the internal state of the underlying computer model of the represented data. For instance music titles in a playlist could be re-sorted by re-stacking a tower of building bricks or a pile of paper. The proximity of the pile to a playback device could represent the volume of the playback (near = loud, further away = quiet). This can be easily understood or learned during interaction by one or more users collaboratively. Such objects may get a new meaning as needed, such as pictures of a slide show. In contrast to touch screens, objects and their handling is not limited to a flat surface and they are really touchable and distinguishable with our tactile sensation. Every human already brings the skills to work with objects by nature which is a large benefit for Tangible Interaction.

Actuation

In the examples above, the TUIOs are passive and only allow a one-directional interaction going from the user to the system. The system itself is not able to manipulate the the TUIOs and represent changes in the data. Unfortunately, information is not necessarily static. Especially in the age of the Internet, information is in constant flux, such as news feeds (in social networks), weather and stock data, sensor readings from distributed devices or even game pieces and avatars in computer games. Thus, there is a need for (active) bi-directional interaction [175]. In order to enable systems to represent dynamic changes of such information, the TUIOs need to be actuated. This allows to autonomously control



(a) Electromagnetic control in the *Madgets* [208].

(b) Small mobile robotic platforms used in the *PMD* [175].

Figure 1.1: Examples of the two major TUIO actuation technologies, currently found in literature.

and reflect these dynamics in the same manner as the users would do. Different actuation approaches enable different actuation qualities and characteristics and have all their very own benefits and disadvantages. Figure 1.1 shows the two major actuation approaches found in literature: *a*) electromagnetic control of magnetic objects and *b*) small-sized mobile robotic platforms.

The TAOs

In an earlier work we created the first basic prototype of the Tangible Active Objects (TAOs) implementing the robotic approach (as discussed in Section 3.3) [167]. In this thesis, we build upon this rather limited prototype of the TAOs and vastly extend it to a full fledged multi-modal actuated TUI. By adding graphical projection and further input and output means, we developed a complex system from several hardware and software components. It allows evaluating existing interaction patterns and exploring completely new interaction approaches. Since the field of actuated TUIs is still in development, it is common in literature to describe technical implementations along with an evaluation of a special-purpose application. The effects on the users and the users' perception of actuated TUIs and the potential for further developments is still not completely explored.

The Gaps and our Approaches for Tabletop Actuated TUIs

As we can imagine, a well designed user interface has to fulfill certain user requirements. In this thesis we focus on concepts and modalities that go beyond and extend those found in literature. We identified multiple concepts and interaction modalities that enrich the feature set of current TUIs. These are non-exclusive and add new interaction possibilities for certain tasks. A good interface addresses multiple interaction modalities of the human. As depicted in Figure 1.2, we explore two different concepts for triggering actions, focus on a highly integrated multi-modal interface for remote collaboration, address evaluation methods for co-located collaboration and benchmark the human hand manipulation speed as a baseline for TUI actuation. These modalities and concepts are presented in the course of this thesis:

Gestural Interaction for Action Triggering A very human interaction modality is *gestural interaction*. Using gestures for non-verbal communication is natural for humans. Though there are already commercial products on the market supporting gestural interaction, this is rarely investigated in the frame of tabletop TUIs. For our TAOs we explore how to gather fitting gestures with them for triggering actions and how to apply them in a communication

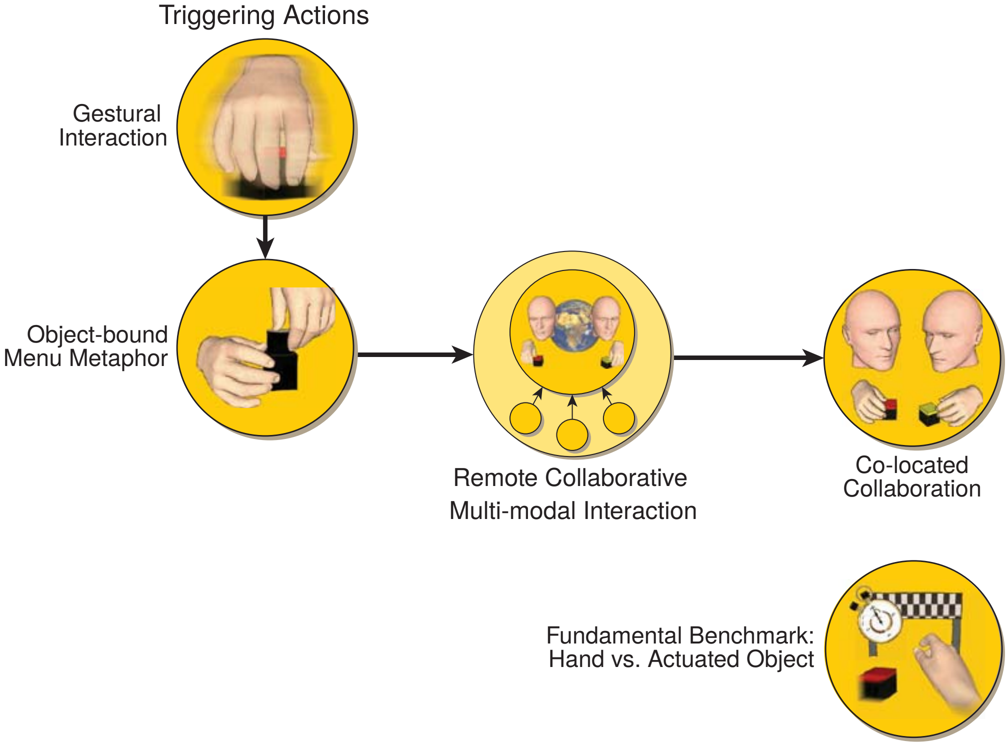


Figure 1.2: Study overview: The main course of this work is composed of five key studies. The first user study investigates gestural interaction and a proof-of-concept study presents an object-bound menu, both of them with action triggering in mind. A feasibility study considers remote collaboration while another user study examines co-located collaboration. The last case study sets a manual interaction speed benchmark for actuated TUIOs.

application for social networking.

Object-bound Menus for Action Triggering Furthermore, we present our concept of parameter selection as a tangible actuated menu metaphor for our TAOs. Along with these interaction modalities and concepts, we include the (audio-)visual domain that is already addressed in literature.

Remote Collaborative Multi-modal Interaction As a stress test for our TAO architecture we created an application for remote collaboration also serving as a concept study for a highly integrated multi-modal interface. Hence, we additionally integrated vibro-tactile feedback and a concept for interdependencies of data represented by the TAOs.

Evaluating Co-located Collaboration To earn additional means for evaluating TUIs, we adapt and discuss interaction measures from experimental psychology that were already applied in neighboring research fields within a comparative evaluation to introduce them to tangible interaction.

Manipulation Speed Benchmark In manual interaction with actuated tabletop TUIs it is important to know the fundamental manipulation speed of the human hand. Vice versa, actuated TUIOs should ideally be able to reproduce this interaction speed to serve as an equal interaction partner in terms of velocity. In literature, this was rarely addressed, so we conducted a pre-study to benchmark both the human hand manipulating a TUIO and our TAOs and compare these findings with interaction data gathered in the other studies conducted during this project.

Finally, we re-integrate our findings and results into tangible interaction research by elaborating design guidelines that help designers of (actuated) tabletop TUIs to develop successful systems.

1.1 Objectives, Contributions and Scope

We address the aforementioned aspects by developing concepts and studies that evaluate the TAOs' general performance and their effects on the users. This challenge demands an interdisciplinary approach which results in different objectives that flow into design guidelines and contributions for future developments:

1. The TAOs serve as a starting base for the work described in this thesis, but for some concepts and studies several *technical* extensions need to be developed.
2. We provide additional *interaction concepts* that extend and enrich the established concepts in TUIs.
3. The results of the *studies and evaluations* of these concepts are given, either qualitative or quantitative.
4. Also *design guidelines* derived from observations during development of applications for our concepts, during the conducted studies and during literature review on actuated and passive TUIs are meant as a major contribution to the research on actuated TUIs.
5. Furthermore, within the studies conducted during this thesis, we transferred and adapted *further measures* for evaluating tabletop TUIs incorporating actuated TUIOs.

Research Questions

Our research is very much driven by exploration. It is broken down to the following general research questions according to the conceptual gaps identified earlier (see Fig. 1.2):

RQ1: Does gestural interaction work with (actuated) TUIOs? How to collect and implement them? (→ Chapter 4)

RQ2: What types of menu metaphors are applicable to actuated TUIs and what is their design space? How can a generic tangible actuated menu metaphor look like? (→ Chapter 5)

RQ3: Can multi-modal feedback and rich interaction capabilities be combined into a sophisticated system for remote collaboration (serving as a stress-test) with TAOs? (→ Chapter 6)

RQ4: How do actuated TUIs compare against a passive TUI, multi-touch interaction and Mouse interaction within the same task? (→ Chapter 7)

RQ5: How can novel interaction measures help to find evidence for theories on tangible interaction? (→ Chapter 7)

RQ6: How quickly does the human hand move manipulating a TUIO? What consequences does this have for actuated TUIs, in terms of actuation velocity, size and structure of the interactive area with regard to social aspects?
(→ Chapters 8 and 7)

Scope

We aim to answer these questions within the scope of tabletop tangible interaction with actuated TUIOs. In particular, we conducted our research with our TAO architecture. On the basis of our TAOs, we elaborate our interaction concepts. Here we focus on the impact of actuated TUIOs on the users and evaluate our approaches. For this, we also transfer and adapt means for evaluation. Beside the conducted studies, we present the concept of our tangible menu metaphor and combine our approach with multi-modal output facilities and advanced features. Beyond the scope of this thesis, we address an application auditory data exploration, one for Ambient Assisted Living (AAL), we touch the field of social robotics and give future directions for hybrid user interfaces. These combine multi-touch interaction, passive TUIOs and the TAOs into one multi-user system.

Structure of this Thesis

We organized this thesis in three parts: The first part is assembled by this general motivation in which we introduce the background of tabletop TUIs and explain the contributions of the field. In the background chapter, we review the theory described in literature. After introducing the state of the art in actuated tabletop TUIs, we introduce the base system of our TAOs, that is used in our studies and applications.

In the second part, every chapter deals with a concept or study, developed or conducted in the course of this research project. With each of these concepts and studies we highlight the different aspects of the topic identified as gaps and view them from various perspectives. Basically, each of these chapters starts with a short introduction to the concept, followed by a brief literature review of the previous work published on the particular topic. After describing additional extensions made to our system, we present a study and / or conceptual interaction design. From the discussion of the results, we derive design guidelines.

The last part of this work discusses our findings within a larger frame. We take some steps back to have a look at the big picture, drawn throughout the thesis. The results from the different studies are brought together and the derived design guidelines are fused and discussed. Furthermore, the final state of the TAO system is presented with all its capabilities. We use this overview to highlight perspectives for future development of actuated TUIs and application possibilities. Finally, we conclude by giving a short summary, pointing out benefits and limitations of the current implementation of our TAOs and giving further general directions for future research and development.

1.2 Remarks

Chronological Course

As this PhD project was mainly driven by exploratory research, we give an overview of the chronological course of developments, as depicted in Figure 1.3. For transparency, this allows to chronologically relate our work with developments in literature, as some foreign papers were published closely to our studies. Furthermore, it gives a more detailed insight into the efforts each work package of this project demanded. This work was supported by a research grant of the DFG with a run-time of 3 1/2 years.

Student projects that dealt with the TAOs are included as well, as they are covered in Chapter 9 and partially contributed to the TAO architecture, too. The topic of these projects were given by the author and were partially co-supervised by colleagues (student projects not dealing with the TAOs are omitted here). Also covered in Chapter 9 is the Interactive Auditory Scatter Plot (IAS). The Embodied Social Networking client (ESN) work package

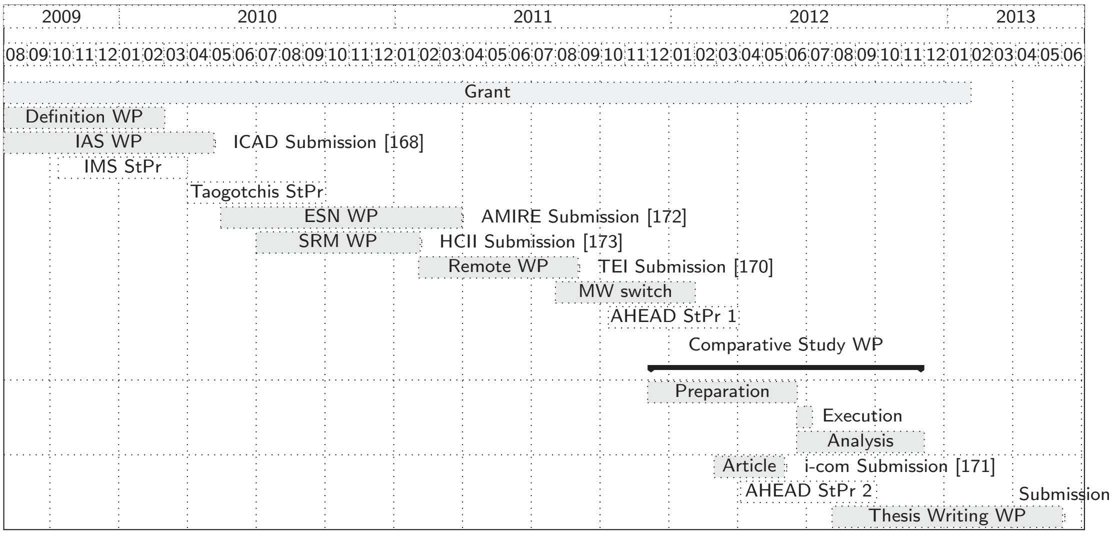


Figure 1.3: Chronological course of the Work Packages. Additionally, the submission dates of publications (camera-ready), the definition phase, the Middleware transition phase (from XCF to RSB) and the Student Projects are included.

resembles the gestural interaction study described in Chapter 4. Chapter 5 describes the saving and restoring mechanisms (SRM) and the development of our tangible actuated dial-based menu. We report on our developments on remote collaboration in Chapter 6. To have a robust and more versatile framework, we switched the middleware including massive testing, before we could start our comparative study for co-located collaboration as covered in Chapter 7.

Resulting Publications

In most instances, our applications, studies and results presented in this thesis have already been published in the following peer-reviewed papers:

[168] Riedenklau, E, Hermann, T., and Ritter, H. “Tangible Active Objects and interactive sonification as a scatter plot alternative for the visually impaired”. In: *Proceedings of the 16th International Conference on Auditory Display*. June 2010. ISBN: 0-9670904-3-1

[173] Riedenklau, E., Hermann, T., Ritter, H., and Jacko, J. “Saving and restoring mechanisms for tangible user interfaces through tangible active objects”. In: *Human-Computer Interaction. Interaction Techniques and Environments*. Ed. by Jacko, J. A. Vol. 6762. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer Berlin Heidelberg, July 2011, pp. 110–118. ISBN: 978-3-642-21604-6. DOI: 10.1007/978-3-642-21605-3

[172] Riedenklau, E., Petker, D., Hermann, T., and Ritter, H. “Embodied Social Networking with Gesture-enabled Tangible Active Objects”. In: *Proceedings of 6th International Symposium on Autonomous Minirobots for Research and Edutainment (AMIRE)*. ed. by Rückert, U., Sitte, J., and Werner, F. May 2011. DOI: 10.1007/978-3-642-27482-4]

[170] Riedenklau, E., Hermann, T., and Ritter, H. “An integrated multi-modal actuated

tangible user interface for distributed collaborative planning". In: *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction - TEI '12*. New York, New York, USA: ACM Press, Feb. 2012, p. 169. ISBN: 9781450311748. DOI: 10.1145/2148131.2148167

[171] Riedenklau, E., Hermann, T., and Ritter, H. "Begreifbare sich bewegende Objekte in Tisch-basierten Interaktionsszenarien Actuated tangible objects in table-top interactions". In: *i-com* (Aug. 2012). Ed. by Hornecker, E., Habakuk Israel, J., Brade, M., and Kammer, D. DOI: 10.1524/icom.2012.0021

Copyright of Figures

The photos, images and illustrations used in this thesis are copyright by Eckard Riedenklau. Exceptions are: Figure 1.1a is reprinted from [208]. Figures 1.1b and 5.1c are reprinted from [175]. Figure 3.4a is reprinted from [89]. Figure 8.1 is reprinted from [24]. Figure 8.2a is a courtesy from my colleague Jonathan Maycock [136]. Figures 5.1b, 5.2c and 5.3 are reprinted from [155]. Figure 5.2a is reprinted from [157]. Figure 5.2b is reprinted from [89].

Supplementary Material

This work is accompanied by demonstration videos. These videos are stored on the Bielefeld University's publication server, accessible via DOI links. Where demonstration videos are available, hyper-referenced QR coded links are given in the caption of respective image stills and storyboards for quick access from both digital and printed copies of this document. All videos are viewable with most common video player applications[2].

Source Code Access and Future Developments

In order to enable other researchers to reproduce our work, we intend to successively publish the source code and schematics of this work after it has been made camera-ready and was enriched with developer documentation and user guides. Furthermore, we would like to report on possible future developments on the TAOs. For these purposes, we created a website that is accessible via `http://www.tangibleactiveobjects.de`.

[2] such as the *VLC media player*: `http://www.videolan.org/vlc/`

2 Background: Non-actuated Tabletop TUIs

For humans, touch can connect you to an object in a very personal way making it seem more real.

From the movie "Star Trek: First Contact", 1996; spoken by the character *Captain Jean-Luc Picard*

In this chapter, we briefly lay out the background and theoretical thoughts that build the foundations for tabletop TUIs. We base this chapter on the substantial and extensive overview of the research on TUIs, provided by Shaer and Hornecker [185]. Since we cannot resemble their complete monograph within the frame of this chapter, we only pick up the most important aspects that apply to our particular research and interweave them with our own subset of background literature. Thus, we highly recommend their monograph for further reference on tangible interaction in its entirety.

From the theory background, there are plenty of publications providing material on the theory behind tangible interaction in general. Some of these review input devices for spatial input [70], introduce situated interaction in combination with activity theory [118], sensing-based interaction [12, 174], tangible interaction especially targeting education [5, 222] and new frameworks for reassessing HCI [85]. We concentrate on background literature that is of particular relevance to tabletop TUIs.

2.1 Characteristics and Terminology of Tabletop TUIs

In the following paragraphs we briefly introduce the common characteristics and terminology for tabletop TUIs in this work. Figure 2.1 gives an overview over these characteristics, whereas details concerning these different aspects are described later in the course of this chapter.

Representation

One of the first important publications directly dealing with aspects of tabletop TUIs is the *Bricks* paper by Fitzmaurice et al. [47]. By introducing physical handles for virtual objects, they described the most important aspect of a tangible interface – the embodiment of data and function. This embodiment is referenced to as the *representation* and can have various forms and characteristics. In advance, TUI representations must have a physical tangible component (e.g. arbitrary objects) and may also have a digital non-tangible component, such as a graphical display [194].

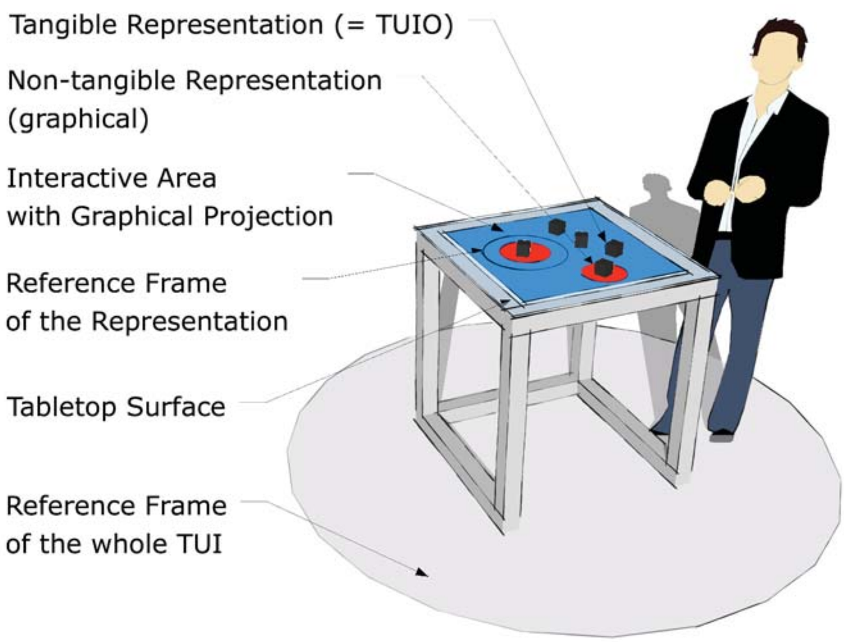


Figure 2.1: Common characteristics of classical tabletop TUIs, including different reference frames for interaction. (Not depicted is the personal interaction space [161].)

TUIO, phicon, pyfo, token, puck...

It is debated in literature what the representations should be called (e.g. *phicon* in [195], *pyfo* in [187], *token* in [73] or *puck* in [155, 156, 157], to name a few alternatives). There are different characteristics of the representations that lead to different nomenclatures, such as the term *phicon* already implies that it has some sort of iconic aspect, which is not the general case. In this thesis, we reference to the physical aspect of the representation, generally the actually graspable object used in a TUI, as the *Tangible User Interface Object (TUIO)*.

Reference frame: The interactive surface

All tabletop TUIs have in common that they all posses a tabletop surface on which the interaction with the system takes place. The *reference frame* of tabletop TUI is the surface where the interaction with the system takes place. In this thesis, we generally refer to this surface as the *interactive surface*. Sometimes the interaction with the system is not limited to the interactive surface. For instance devices installed in the room together with the system, can be controlled with the system. In such cases, the reference frame is extensible. Some tabletop TUIs offer a visual display (e.g. a display is built in into the interactive surface, or the surface is (back-)projected). By this visual display the system often visualizes (parts of) the digital representation. According to Ullmer and Ishii, this visualization is not part of the (physical) TUIO by definition, but it is part of the representation in general (including the digital aspect) [194]. In the same way auditory displays can be part of the digital representation, but not the physical one (although the loudspeakers could be embedded into the TUIO itself).

TUI: The Interface in its Entirety

Basically, these characteristics and the software implementing the interface behavior build the *tabletop Tangible User Interface (TUI)* in general. From now on, we use the term TUI as synonym for tabletop TUI, since we focus on tabletop systems.

2.2 Application Domains

In their survey, Shaer and Hornecker identify several application domains for TUIs. These domains definitely cover most systems, but they are neither meant to be mutually exclusive, nor inevitably complete due to the vast and still growing variety of creative ideas and their implementations. "Dominant application areas for TUIs seem to be learning, support of planning and problem solving, programming and simulation tools, support of information visualization and exploration, entertainment, play, performance and music, and also social communication." [185]

TUIs for Learning Because of the use of embodiment, TUIs are a great means for education and learning. As Shaer and Hornecker point out, "research and theory on learning stresses the role of embodiment, physical movement, and multimodal interaction (cf. [5, 150]). Furthermore, studies on gesture have shown how gesturing supports thinking and learning [56]." [185] From this perspective, learning is an obvious application domain for TUIs.

Problem Solving and Planning Another obvious and well established application domain is problem solving and planning. Tasks, such as urban planning, that benefit from the use of models acting as tangible representations can profit from TUIs in which these models are augmented with a virtual simulation of the particular problem. These tangible representations can be constrained with other physical objects and epistemic actions [103] can be used to structure and better understand the problem.

Information Visualization Plenty of TUIOs provide means for visualization and interactive exploration of information. Here, the tangible representations act as physical handles for the information and are augmented with non-tangible representations (mostly visual). Often, the visualization of the information results in a multi-modal interactive interface. Furthermore, this application domain intersects with other application domains that benefit from multi-modal information representation.

Tangible Programming The application domain of tangible programming often intersects with other domains, too, such as learning and edutainment. According to Shaer and Hornecker, they enable the users to freely play and explore the functions of the system being programmed through interaction.

Entertainment, Play and Edutainment This application domain covers computer-based and electronic games and toys. There is the trend of console gaming incorporating full-body interaction (with special controllers and without), such as the *Nintendo Wii*, the *Microsoft Kinect* or the *Sony PlayStation Move*. Magerkurth et al. provide a good starting point for diving into pervasive games [130]. Often further technologies, such as Augmented Reality are used in this domain in combination with TUIs to enhance tangible playing cards or avatars with non-tangible representations and information. This makes the game experience more interesting and vivid.

Music and Performance A major application domain of TUIs is music creation and live performance. Jordá highlights three important aspects of tabletop TUIs making them a good interface for musical performance: " *a*) Collaboration and control sharing, real-time, multi-dimensional, continuous interaction and interaction bandwidth; and *b*) complex, skilled, expressive and explorative interaction." [88]

Social Communication TUIs also can serve as means for communication between distant users and distributed work groups. Here TUIOs act as representations of users in social networks or messages being transmitted between them. The possibilities range from creating remote awareness to remote intimacy and shared reality, incorporating further remote sensory modalities.

Tangible Reminders and Tags Physical artifacts can serve as representations for information of all kinds. Technologies, such as Radio Frequency Identification (RFID) tagging, make this possible in various applications. Martinussen and Arnall give a good overview of the applications for the use of RFID tags [135]. This application domain greatly intersects with the others, since the idea is a core concept of tangible interaction.

2.3 Frameworks and Toolkits for TUIs

With their approach to map the space of existing frameworks for tangible interaction, Mazalek et al. provided a meta-framework for ordering and relating frameworks [137]. We used this framework and adapted it, resulting in the map depicted in Fig. 2.2. The map is meant as a means for designers of TUIs to broaden the view for design aspects and to navigate the large amount of TUI design considerations found in literature. Each entry in this map represents a publication dealing with major design relevant aspects of TUI development and classification. The entries printed in light blue represent the original map by Mazalek et al. In favor of clarity and relevance we left out publications that are too general. Instead, we extended it with complementing publications (printed in light green). Furthermore, we added publications that provide foundations for actuated tabletop TUIs (light yellow). The map is divided into sections. The horizontal division represents the types of frameworks, ranging from *Abstracting* over *Designing* to *Building*. On these types, Mazalek et al. built the facets the discussed frameworks deal with: *a*) *Technologies*, *b*) *Interactions*, *c*) *Physicality*, *d*) *Domains* and *e*) *Experiences*. We discuss the filled areas of the map in the following paragraphs facet by facet and type by type.

Theory, Frameworks and Trend-setting Related Work

Building Technologies

The *building technologies* area of the map contains toolkits and technologies for building TUIs. Since there is a variety of toolkits, we discuss further toolkits for non-actuated approaches in this area later in the toolkits section of this chapter. We discuss the actuated approaches for tabletop TUIs in Section 3.1. In the map we only mention the original toolkits, as proposed by Mazalek et al. (2009). We added the first implementation of the actuated tabletop TUI *PSyBench* by Brave et al. (1998) [21]. Furthermore, we included the papers, originally presenting the **two major actuation approaches** for tabletop TUIs: *electromagnetic* by Pangaro et al. (2002) [152] and *robotic* by Rosenfeld et al. (2004) [175].

Abstracting Interactions

This area deals with interaction related design aspects of TUIs. Koleva et al. (2003) discussed the **linking between physical and digital objects** and their level of coherence [110]. They

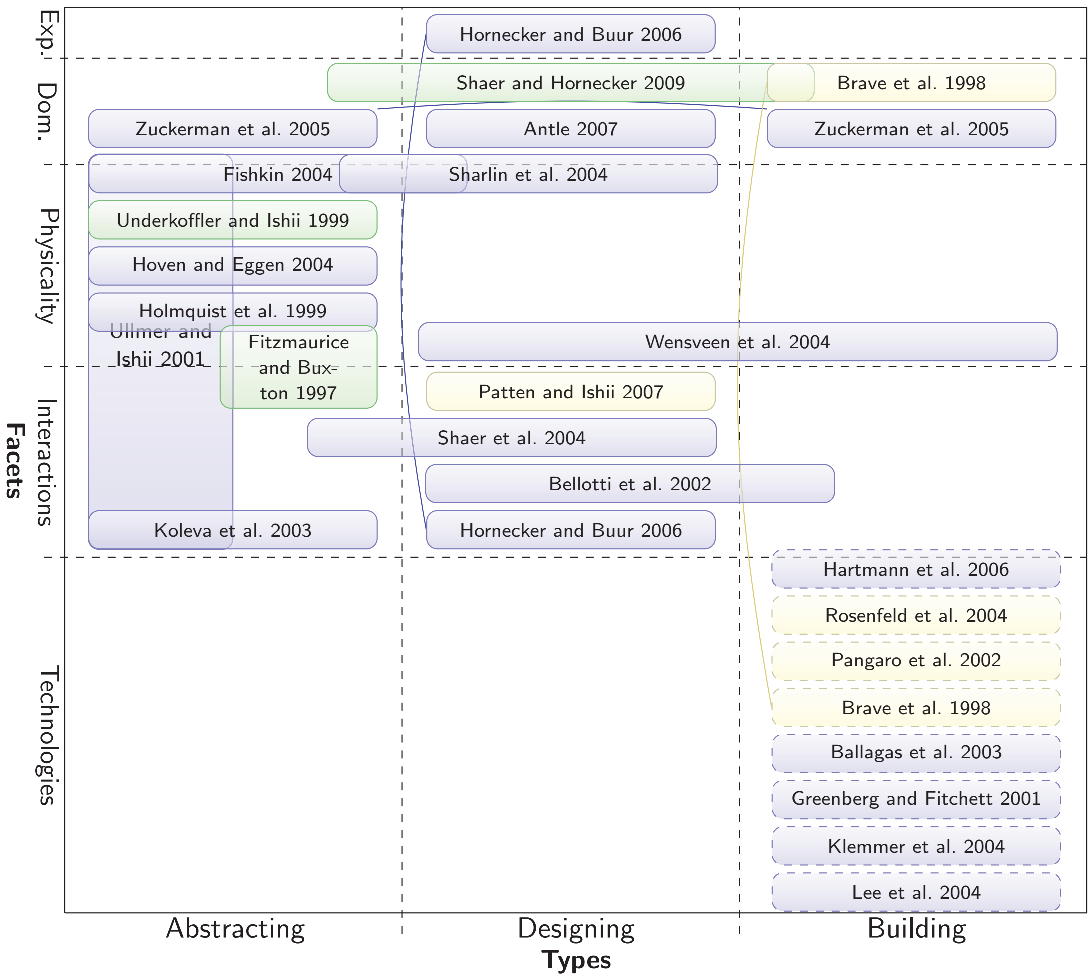


Figure 2.2: The adapted framework map after Mazalek et al. [137]. The frameworks they originally mapped are printed in light blue. We extended it with publications on TUIs that are of particular interest within the frame of this thesis (light green). Furthermore, we added publications providing foundations for actuated tabletop TUIs (printed in yellow).

contemplate this linking from different perspectives, such as the quality of the link (or coupling) or the lifetime. This also interplays with the **container concept** by Holmquist et al. (1999) and Ullmer and Ishii [73, 197] and the **time- vs. space-multiplexing concept** by Fitzmaurice et al. (1995) [47].

Ullmer and Ishii (2001) transfer the *Model View Controller (MVC)* concept known from Graphical User Interfaces (GUIs) to TUIs, here called **Model Controller Representation (physical and digital) (MCRpd)** [194]. The MCRpd gives designers of TUIs means for comparing and addressing important aspects of tangible interaction, mainly both tangible and non-tangible aspects of data representations. Furthermore, they provide a nomenclature for TUI classification.

Designing Interactions

Bellotti et al. (2002) spotlight the interaction with sensing systems by sensitizing designers of such systems from the social point of view. They rise five aspects regarding *a*) addressing the system, *b*) gaining its attention, *c*) interacting an action, *d*) monitoring the response and *e*) recovering from errors [10]. This only applies to reactive systems, while actuated proactive systems are not covered here. Nonetheless, being aware of this point of view already helps keeping this aspect in mind.

Related to Holmquist et al. and Ullmer and Ishii, Shaer et al. (2004) provide a high-level language to identify and describe the relationship between **"pyfos" (physical objects), "tokens", "constraints"** and the represented data. They evaluated their sophisticated paradigm with various examples of TUIs found in literature [187]. Shortly after this, Ullmer et al. came up with a similar approach dealing with "Token+Constraint Systems" [198].

Hornecker and Buur (2006) broaden the view of tangible interaction towards user experience and social aspects. With their framework, they introduced an interdisciplinary research approach that addressed four themes: *a*) Tangible Manipulation, *b*) Spatial Interaction, *c*) Embodied Facilitation and *d*) Expressive Representation [76].

Patten and Ishii (2007) picked up the concept of constrained tangible interaction as described above and extended this idea to **constrained actuated TUIs** [154]. They provide various implementations of constraints and demonstrate them in their Physical Intervention in Computational Optimization (PICO) system, using electromagnetic actuation for the TUIOs.

Building Interactions

Though Hartmann et al. (2006) do not explicitly target tabletop TUIs, their *d.tools* approach for building and evaluating sensor-based interactive devices is of particular interest due to their **evaluation methods**. This method, incorporating alignment of video and sensor recording, partially inspired the design of our comparative study, described in Chap. 7.

Abstracting Physicality

Hoven and Eggen (2004) identified situations in which the nomenclature by Ullmer and Ishii is not successful. They extended the nomenclature to cover **personal objects** as well. Users already have mental models for personal objects, so they can relate better to the represented data [79].

Presenting multiple TUIs, including the often cited *Urp*, *Illuminating Clay* and *Illuminating Light* systems, Underkoffler and Ishii (1999) also proposed a **continuum of object meanings** [199]. This continuum ranges from *pure object* over *object as attribute*, *object as noun* and *object as verb* to *object as reconfigurable tool*.

Fishkin (2004) partly picked up this continuum and interweaved it with Holmquist et al.'s categorization of TUIOs as tool, token and containers. In their resulting taxonomy, **embodiment and metaphor** are the two major axes [43].

Designing and Building Physicality

Wensveen et al. (2004) elaborated on the idea of not just coupling physical objects with data, but also **action and function**. Here, they consider six aspects of natural coupling on action and reaction: *a*) Time, *b*) Location, *c*) Direction, *d*) Dynamics and *e*) Modality [210]. Building upon these characteristics, they provide a practical framework for coupling action and information. By this, the framework covers the *designing physicality* and the *building physicality* area of the map.

Sharlin et al. (2004) approach TUIs from the perspective of **spatiality**. They define the term *spatial TUI* as a subset of interfaces that facilitate the users' spatial skills and discuss three aspects of spatial interaction: *a*) Spatial mapping, *b*) I/O unification and *c*) Support of "trial-and-error" activity [188]. In this frame, they review seven systems known from literature.

Domains

Zuckerman et al. (2005) and Antle (2007) cover this facet by targeting TUIs for children and education. Shaer and Hornecker (2009) give a much broader and quite exhaustive view on the application domains, as we already discussed in Sec. 2.2. They cover the following application domains: *a*) Learning, *b*) problem solving and planning, *c*) information visulization, *d*) programming, *e*) entertainment, play and edutainment, *f*) music and performance, *g*) social communication and *h*) reminders and tags [185].

The user experience facet was initially targeted by Hornecker and Buur (2006). Their interdisciplinary research approach covering *tangible manipulation*, *spatial interaction*, *embodied facilitation* and *expressive representation* started a vivid research line. Experiences

Toolkits and Technologies for Tabletop TUIs

The variety of toolkits for building TUIs is vast. Naturally, there are toolkits for hardware and for software development, some of them address even both sides. In these paragraphs, we concentrate on those that are of interest for tabletop TUIs, particularly for actuated interfaces.

Hardware Toolkits and Implementations

Building Blocks for TUIOs

The *TUImod* by Bovermann et al. acts as general building blocks for TUIOs [20]. Here, a TUIO is assembled from elements divided into three layers: *a*) Computer Interface elements (CI), *b*) Physical Functionality elements (PF) and *c*) User Interface elements (UI). The CI elements have fiducial markers for tracking the TUIOs with computer vision software. Optional PF elements between the CI and UI elements incorporate magnets, saw shaped edges, clip-in mechanisms etc. These optional elements allow to build TUIOs that can be connected and constrained to combined meta-objects. Finally, the UI elements address the user by customizing the TUIOs in color and adding distinguishable shapes on the top of the TUIOs. All elements were produced from acrylonitrile-butadiene-styrene (ABS) material using a rapid-prototype 3D-printer. We used the *TUImod* as basis for creating the TAOs' housings.

RFID and RF-Sensing

RFID is a widely established industry standard for wireless tagging and identification of objects. There are many TUIs, using this technology to electronically identify TUIOs at certain locations. Martinussen and Arnall provide a detailed introduction to the design and implementation of systems making use of the RFID technology. They discuss typical application domains, such as payment, transport, access control and toys, implementation design, the shape of objects incorporating RFID tags etc. [135].

Though the RFID standard is used for identifying objects placed on a special tag reader, a similar technique is used for example in the *Sensetable* [157] and the *Musical Navigatrics and Atmosphere* [153] to not only identify the objects, but also localize them on a tabletop surface or in three-dimensional space.

Capacitive Sensing

Another rather unorthodox way of localizing TUIOs on interactive surfaces is capacitive sensing. This technology is meant to be used for tracking finger touch points on smartphones, tablet PCs and displays. The *TUIC* [218] by Yu et al. use this technology by simulating finger tips to localize TUIOs on such displays. They presented three different tag designs with application examples: *a*) spatial, *b*) frequency-based and *c*) hybrid tags. The first application was a demonstration using the *TUIC* tags for representing famous painters and multi-touch interaction to manipulate the artists' paintings on the interactive surface. The second application was an adaption of the *SLAP Widgets* keyboard [209] by Weiss et al. The *SLAP Widgets* are thin passive widgets made of silicone to be used on multi-touch surfaces using the Frustrated Total Internal Reflection (FTIR) technology for, an optical approach for touch tracking [62]. Yu et al. transferred the *SLAP Widgets* idea to capacitive surfaces using their *TUIC* tags. In the last application example, they proposed their tags as authentication keys for mobile devices. The tags are not easy to copy and replace authentication methods, such as PINs that bystanders could easily spy out [218].

Electronics

There is an increasing tendency to equip TUIOs with electronic devices to augment the interaction with additional input and output channels. Beside completely custom built electronics, multiple toolkits for the rapid-prototyping of electronics find one's way into tangible interaction. The works by O'Sullivan and Igoe [151] and Igoe [81] give a comprehensive introduction into the field of physical computing. The number of available platforms for physical computing is vast. The most popular example is the *Arduino Platform*[1] [8]. Another sophisticated platform with a wide palette of extensions is *Tinkerforge*[2]. For wireless communication with such microcontrollers, standards, such as infrared, Bluetooth, WiFi and *XBee*, etc. are used. Within the TAOs we made use of *Arduino* microcontrollers and *XBee* radio communication.

Sensor-based TUIOs

Related to actuated tabletop TUIOs are sensor-based TUIs using electronics, as described above. TUIs of this kind also incorporate electronics and wireless communication to make use of sensor readings within the interaction between the users and the system. Transferring the concept of widgets from GUIs to TUIs, the *Phidgets* by Greenberg and Fitchett represents a complete architecture of physical widgets, including electronics, software and Application Programming Interface (API) [57]. The *Phidgets* were evaluated with a set of example applications. Further examples for sensor-based interfaces are the *iStuff* framework [7] by Ballagas et al., the *Calder Toolkit* [121] by Lee et al., *CookieFlavors* [99] by Kimura et al. *Atlas* [100] by King et al., *VoodooIO* [203] by Villar and Gellersen.

Software Toolkits

General Middleware

The increasing complexity of TUIs demand certain effort of implementation. Often their components are organized in reusable software modules that require (networked) Inter-Process Communication (IPC). A very popular and established network protocol for tabletop TUIs is the *TUIO Protocol* [91], which is based on *Open Sound Control (OSC)* [217]. Other more sophisticated middleware and network protocol examples are the *XML enabled Communication Framework (XCF)* [51] and its successor *Robotic Service Bus (RSB)* [211], which we used for the TAOs. In literature, we also found systems using the *Extensible Messaging and Presence Protocol (XMPP)* (such as the *RemoteBunnies* [58]), which we in turn used for coupling distant TAO systems. Also *Robot Operating System (ROS)*[3] [163] is a

[1] http://www.arduino.cc/
[2] http://www.tinkerforge.com/
[3] http://www.ros.org/wiki/

promising middleware candidate that provides a variety of additional software components for developing interactive systems.

Computer Vision for Tracking TUIOs

There are multiple approaches for visually tracking TUIOs. The simplest way is tracking on a *plane with two degrees of freedom* using (color) blob tracking. Grain-based systems [16, p. 62], such as *AudioDB* [18] and *Turtledove* [140] use this approach for detecting the positions of small rotation-invariant TUIOs using the *Image Component Library (ICL)*[4]. The *ICL* is a generic computer vision library with a variety of image processing methods. It also implements the *Hungarian Algorithm* [116] for assigning IDs tracking the identified blobs. *OpenCV*[5] is another very popular multi-purpose image processing library. The *Community Core Vision (CCV)*[6] directly addresses development of tabletop interactive systems and supports blob tracking for multi-touch applications, supporting multiple communication protocols, including the *TUIO Protocol*. This makes *CCV* also usable for tracking small rotation-invariant TUIOs.

There are various approaches for tracking TUIOs on a *plane with orientation (three degrees of freedom)*. Here, the *reacTIVision* [90] by Kaltenbrunner and Bencina is one of the most popular approaches. In their paper describing their *reacTIVision* [11] Bencina et al. presented their *Amoeba* markers and their tracking in detail. These topological markers are generated according to graphs defining “Left Heavy Depth Sequences” which make the markers unique and distinguishable. In the first prototypes of the TAOs, we used smaller markers that were trackable with the *libfidtrack* [11] (cf. Chapter 3). Other approaches, such as *TRIPcode* [124] and *TrackMate* [117] use markers with circular patterns.

Approaches for *three-dimensional Tracking of TUIOs with six degrees of freedom* are for instance *ARToolKit* [92], *ARTag* [42], *ARToolKit Plus* [206]. These approaches’ ability of tracking structured visual markers with position and orientation in three-dimensional space makes them widely used in Augmented Reality (AR) systems. Nevertheless, they can basically be used in tabletop TUIs as well.

Another recent approach is *dSensingNI* [108] by Klompmaker et al. It aims to support multi-touch and tangible interactions with arbitrary objects on ordinary surfaces by using only depth information from a *Kinect* sensor.

Integrated Toolkits

Multiple systems described in literature provide integrated hardware and software components for developing TUIs. *Papier-Mâché* [104] by Klemmer et al. integrates multiple computer vision approaches, such as color-based tracking of ordinary objects and barcodes. Furthermore, it integrates support for RFID. Those components are integrated by a higher-level programming API, enabling developers to quickly and easily produce working TUIs. *ToyVision* by Marco et al. is a more recent but similar approach, aiming at development of tabletop tangible games in particular [132].

With their *d.tools* [63], Hartmann et al. presented a sophisticated integrated toolkit for developing sensor-based tangible interfaces. The *d.tools* incorporate a large range of electronics for quick-and-easy building of sensor devices, already pre-programmed with a generic

[4] http://www.iclcv.org/
[5] http://opencv.org/
[6] http://ccv.nuigroup.com/

firmware that transmits the sensor values to the host computer. The sensor readings are gathered by the authoring environment that supports the developer in generating programs for the system. An outstanding feature of the authoring environment is the possibility to align the continuous sensor readings with multiple video recordings for analysis and evaluation of the system's performance for iterative improvement of the system design. A generic approach for creative coding provide the *openFrameworks*[7]. They encapsulate and integrate multiple open source frameworks, including *OpenCV* to provide a simple but versatile development environment for interactive systems, including TUIs.

Up-coming Standards These integrated approaches finally lead to standardization of TUI development. The *Tangible User Interface Modeling Language (TUIML)* by Shaer and Jacob is a description language for specifying and developing TUIs, based on the Extensible Markup Language (XML) and the User Interface Description Language (UIDL). It even allows to describe the behavior of the system using state graphs and petri-nets. With the *Tangible User Interface Management System (TUIMS)* it is possible to semi-automatically translate these TUI specifications into working systems [186].

2.4 Strengths and Limitations of TUIs

When it comes to the design of a TUI one must know what is possible to implement and what not, since a tangible interaction approach may be beneficial for some applications while for other problems other interaction approaches might be more suitable. In their survey, reviewing the existing body of work on TUIs [185], Shaer and Hornecker describe multiple strengths and limitations of TUIs.

Strengths of TUIs

Shaer and Hornecker highlight several beneficial aspects of TUIs, which we briefly describe in the following paragraphs: *a*) Collaboration, *b*) Situatedness, *c*) Tangible Thinking, *d*) Gesture, *e*) Epistemic Actions and Thinking Props, *f*) Tangible Representation, *g*) Space-Multiplexing and Directness of Interaction and *h*) Strong-Specificness Enables Iconicity and Affordance [185].

Collaboration Usually, current desktop computing interfaces (using Mouse, keyboard and display) are quite exclusive and only usable by a single user. In contrast, data represented in TUIs is mutually accessible by multiple users due to the physicality and embeddedness in our realm – in other words, here the data simply shares the same space. Based on this, Klemmer et al. elaborate on the observability of manual interaction with physical objects. This embodiment facilitates group awareness and interaction coordination in collaborative tasks [105].

Situatedness The physicality is a well-discussed aspect of TUIs. As they are part of the real world, the TUIs' situatedness is a great benefit for designing meaningful and understandable interfaces that are embedded into the actual interaction context [33, 40, 76]. Furthermore, the situatedness of TUIs lays the foundation for social interaction between multiple users. It goes hand in

[7] `http://www.openframeworks.cc/`

hand with tangible thinking and gesticulation providing means for deixis [71], as pointed out in our design guidelines in Chapter 10.

Tangible Thinking

Our own embodiment plays a major role in how we interact with and understand our environment and the objects within. Under the theme *thinking through doing* Klemmer et al. highlighted perspectives of tangible interaction for learning, gestural interaction and epistemic actions [105].

Gesture

Gestures are important for producing and understanding speech and for social interaction between multiple users of a system [56]. Physical objects provide anchors for gesticulation and support the kinesthetic memory of the users [183].

Epistemic Actions and Thinking Props

In contrast to pragmatic actions, epistemic actions are not goal-oriented actions, but help the users of a TUI to better understand the problem being worked on and to explore different solutions [103]. TUIOs and other objects introduced by the users serve as thinking props. Slight alterations in position or orientation that have no effect on the result help the users to structure the problem, for instance ordering and sorting the TUIOs or slightly turning them to make them distinguishable more easily from objects that are not of particular interest for the current problem.

Tangible Representation

Zhang indicated the benefit of external representations, of physical objects, supporting the comprehension of a problem [220, 221]. Zhang "found that an increase in the amount of externally represented information yielded improvement in solution times, solution rates, and error rates." [185]

Space-Multiplexing and Directness of Interaction

Being in a world defined by space and time, it is obvious that the use of tools can be tied to a certain position or to a certain point in time. This also applies to technical devices, as well as to TUIs. Fitzmaurice and Buxton [46] found that input devices can be space-multiplexed or time-multiplexed. While a Mouse is a time-multiplexing input device, since it controls different functions such as menus or buttons in the GUI at different points in time, TUIOs are dedicated to a particular function (assuming a static mapping) and can be manipulated simultaneously at different positions on the interactive surface [45, 47].

Strong-Specificness Enables Iconicity and Affordance

Static mappings between function and tangible representation allow the use of specific shapes instead of generic objects. Task-specific objects can foster the users' performance creating affordance by meaningful properties that generic objects barely have. The way how users might handle different object designs may lead to meaningful and understandable TUIO [41, 189]. Nevertheless, there is no complete design space for TUIOs due to the vast number of different possible design properties and combinations.

Limitations of TUIs

Along to the strengths of TUIs, Shaer and Hornecker highlight several limitations: *a*) Scalability and the Risk of Loosing Physical Objects, *b*) Versatility and Malleability and *c*) User Fatigue [185].

Scalability and the Risk of Loosing Physical Objects

Having physical objects that are not firmly attached to the system has some risks and drawbacks. First of all, the number of TUIOs to be used effectively is limited by the task and the size of the tabletop surface, which in turn is limited in size by ergonomic constraints [185, p. 106]. Too many TUIOs resulting in *physical clutter* may cognitively overwhelm the users' comprehension with regard to performance and effectiveness, as described by Fitzmaurice [45, p. 135]. They might lose the particular TUIO they are looking for. Furthermore, such objects may literally get mislaid and lost, destroyed [102] or even stolen, e.g. in public spaces, such as museums or fairs. Another aspect regarding scalability is the *bulkiness* of TUIOs [35]. Normally, TUIOs are rigid objects that cannot be scaled in three dimensions, but this would be required for example if a map with TUIOs representing buildings was scaled [185]. The TUIOs do not scale accordingly, demanding the creation of scaled objects. Multiple TUIOs cannot occupy the same space, causing *physical displacement* [16, p. 54]. This intrinsic benefit of TUIOs can also be a disadvantage when different solutions of a problem need to be compared, since physical *juxtaposability* (overlay of the solutions) of them is not possible [35]. Shaer and Hornecker also rise the problem of *mutability* [185]. Here, an arrangement of **TUIOs cannot be easily shifted** when more space is needed at a certain side. In contrast to GUIs where the content of the screen can be scrolled, the users of a TUI need to be carefully moved one TUIO by another into a particular direction to gain more space to add TUIOs at the opposite side. This also relates to Edge and Blackwell's concept of *premature commitment* [35] and the inability to "adequately support **manipulations of several objects**." [185]

User Fatigue

"TUI tokens are constantly lifted and moved about as their primary modality of interaction." [196, p. 154] Especially long-term use of tabletop TUIs can tire the users, as they need to reach far to manipulate objects and look constantly down to a horizontal surface. From the perspective of ergonomics, this is a major disadvantage [185, p. 106].

Versatility and Malleability

GUIs are extremely versatile and malleable. They serve as general-purpose tools, being used to accomplish a vast bandwidth of tasks due to their flexibility and adaptability. Unfortunately, TUIs are special-purpose tools, each of them designed for a particular task. They are not flexible because of the rigid and special design of the TUIOs.

They are not as adaptable as GUIs, since the system can neither **manipulate the TUIOs' position, orientation**, color, shape nor size. Also, TUIs suffer from the "difficulty of supporting an **automatic undo, a history function, or a replay of actions** (cf. [102])" [185] or even means for **saving and restoring** the state of the current task. Furthermore, the rigid TUIOs are unable to **reflect dynamic scenarios** and **enforce spatial relations** between them, though they support the users' spatial memory, this may lead to inconsistencies in the tangible representation [185].

The latter limitations printed in bold can be addressed by introducing actuated TUIOs. Our TAOs are our implementation of actuated TUIOs, which we will present and discuss in the following chapters according to the gaps identified above in the introduction chapter.

3 Actuated Tabletop TUIs and the Implementation of the TAOs

Motion however will not help unless we have things moving.

Simon Blackburn
Think (1999), Chapter Seven, The World, p. 244

In literature one mostly finds two approaches to actuate table-top TUIs. In the first approach the tabletop surface applies magnetic forces to the objects to move them, while the other generally introduces small-sized mobile platforms with a differential drive to the objects themselves to make them move. For this we distinguish between electromagnetic manipulation and the differentially driven robotic approaches in the following sections.

After discussing the approaches and the respective systems described in literature, we present a comparison of the technologies including a discussion of their advantages and disadvantages. Finally, we present an overview of the TAOs' hardware and software design and the interplay of components within their architecture.

3.1 Actuation Technologies in Related Work

The First Major Approach: Electromagnetic Actuation

This approach can be principally divided into two sub-approaches. One where a single electromagnet is moved inside the interactive surface and one where the whole surface consists of a massive array of electromagnets that move magnetic objects.

PsyBench Because traditional interfaces, such as keyboard and Mouse, limit physical interactions with digital content, Brave et al. introduced the concept of *Synchronized Distributed Physical Objects* for Computer Supported Cooperative Work (CSCW) [21]. The first prototype was built with two synchronized *Excalibur* chessboards, incorporating a two-axis positioning mechanism with an electromagnet for actuation and a grid of 10×8 membrane switches for position sensing. This technology enables the system to sense and move magnetic objects. The discrete sensing with its low resolution and the ability to only move one object at the same time without orientation control are drawbacks of this system. Because of the disadvantage that this sub-approach (moving a single electromagnet within the surface) can only move one object at a time, this approach has been abandoned and replaced by the introduction of an array of electromagnets in later systems.

Actuated Workbench The *Actuated Workbench*, developed by Pangaro et al. [152] ensembles a highly sophisticated system for actuated tangible interaction. Instead of using a single movable electromagnet, the surface consists of tileable arrays of 64 electromagnets (8×8), each. This technology allows to almost silently move multiple objects equipped with a permanent magnet and an infrared LED for visual tracking simultaneously across the surface. An special control approach also allows for interpolation between electromagnets, resulting in smooth motion. Beside the technical details the authors describe a number of possible high-level applications, such as remote collaboration in a planning scenario (extending *Urp* [199]), simulation and entertainment. Still there are drawbacks: The system is quite complex and presumably expensive and the orientation of the objects is not controllable and thereby unusable as an interaction parameter.

PICO Patten and Ishii demonstrated the technology of the *Actuated Workbench* combined with RF tracking of the TUIOs in a compelling application they call *PICO* [154]. Here, they used this approach to simulate and optimize the distribution of radio towers represented by the tangible objects in a projected landscape. To influence this optimization process, the users can utilize arbitrary objects for example to limit the space for the moving objects, to tie them together or make them stationary. The authors proposed rubber bands, ring spacers, an artist's curve (flexible drawing aid) and weights as probable objects for this task. They call these objects mechanical constraints; in parallel they also demonstrated virtual constraints that offer similar dependencies between the tangible objects, but without the need of physical objects (actually the optimization algorithm is such a dynamic high-level constraint). Both types of constraints can again be mixed, which creates a versatile user experience.

Madgets The technology of the *Actuated Workbench* was picked up by Weiss et al., creating their *Madgets* [208] to solve issues and enhance the concept. They built their own surface and modified the hardware to get rid of possible occlusion problems when tracking the objects with a camera from above the surface by adding a dense grid of fiber-optic cables along the electromagnets to track the objects through the array. To overcome problems that occur with projection from above the surface, the authors also integrated a large TFT panel into the surface along with electroluminescent foil and infrared illumination for tracking (also fingertips) and illumination of the TFT panel. To make the orientation of the objects controllable, they combined about four permanent magnets into one object. With these four anchor points, the system is able to control all three degrees of freedom of object movement on a flat surface. The last addition to the system was the introduction of magnetically controllable widgets (this is where the system's name comes from). They added a magnetic dial or a button to their objects, which is also controllable by the magnetic field of the surface. Also a gear, a bell and even an LED (using induction on the magnetic surface) was implemented. The abilities of this system are impressive, but one can imagine, that the complexity of the presented hardware is also extremely high.

Approaches based on magnetic forces have the advantage that even if the user has picked up the tangible object a little from the interactive surface, the system can still influence the objects to a certain amount because the magnetic forces still apply. The movement of the objects using this technology is almost silent, since there are no moving parts (only the

TUIOs themselves). Furthermore, the objects can move in a holonomic way and are relatively cheap. Otherwise, the interactive surfaces explained here are quite expensive and complex.

The Second Major Approach: Differentially Driven Mobile Robots

The systems discussed in the following paragraphs use small-sized robotic mobile platforms in every tangible object to make them move and controllable through the system. For this a differential design is the most simple (due to the size) and easy-to-implement mechanical design. Here two independently driven wheels are assembled on one axle, enabling the robots to move forwards, backwards, on curves and to rotate in-place. Compared to the electromagnetic approach, the technical effort is moved from the interactive surface to the TUIOs. The surface often is assembled of a (back-)projectable glass plate that is much cheaper and less complex to establish than in the electromagnetic approach. Otherwise, the actuated TUIOs are more complex and more expensive.

Planar Manipulator Display Rosenfeld et al. built the *PMD* [175]. To enable their tangible objects to act in a bi-directional manner, the used small mobile platforms with a footprint of 6.8 cm $\times$ 6.3 cm and put miniature models of pieces of furnitures on top. They used these objects in a sophisticated approach for placing pieces of furniture in a projected plan of an apartment. To make use of the actuation of the tangible objects, they added a projected menu at one side of the interactive surface of their table that enables the user to save and restore arrangements of the objects for later use. With their system, Rosenfeld et al. made an important contribution to the field of table-top tangible interaction. In our opinion, such saving and restoring mechanisms are one essential feature towards general-purpose TUIs. Otherwise, the design of this system can still be improved. The menu that controls those saving and restoring mechanisms is fixed at one side of the interactive surface. Thus, in a multi-user scenario with users standing around the table, this menu is not equally accessible by every user standing at the table.

Augmented Coliseum and RATI The *Augmented Coliseum* by Kojima et al. [109] uses small-sized mobile robots to physically represent entities of a virtual game environment in a projected tabletop surface. To track and control the robots, they developed their display-based measurement system. It utilized the projection to control the robots by displaying fiducial markers at the robots' positions. These markers have a particular gradient pattern the robots can sense with light sensors. The robots automatically adjust to match the fiducial markers when the markers are moved or rotated. Richter et al. picked up this approach in their *Remote Active Tangible Interactions (RATI)* system [166], a TUI for distributed planning. Specifically, it is intended to enable distant users to collaboratively place pieces of furniture on a virtual plan of an apartment. The first iteration of the system only used one robotized tangible object, a projected bird-eye view of the plan on the interactive surface and an additional 3D view presenting a perspective front view of the scene. Two of these setups were coupled over a network with a custom XML protocol. Later publications claim extensions of this system with multiple (up to six) redesigned robots, synchronizing the arrangement of pieces of furniture on both sides involved.

Tangible Bots Pedersen and Hornbæk developed the *Tangible Bots* [158]. These actuated tangible objects are based on Pololu's commercially available *3pi mobile robot*[1]. These robots have a diameter of 9.5 cm and are quite sophisticated according to their specifications. The authors conducted two studies, investigating the combination of the *Tangible Bots* with multi-touch input and their usefulness. In a nutshell, it turned out "that *Tangible Bots* are usable for fine-grained manipulation (e.g., rotating tangibles to a particular orientation); for coarse movements, Tangible Bots become useful only when several tangibles are controlled simultaneously. Participants prefer *Tangible Bots* and find them less taxing than passive, non-motorized tangibles. A second study focuses on usefulness by studying how electronic musicians use *Tangible Bots* to create music with a tangible tabletop application." [158]
Pedersen and Hornbæk state that they see their ideas as generalization to the concepts described by Patten and Ishii [154]. But working with motorized TUIOs, Pedersen and Hornbæk ignore the difference between those and electromagnetically actuated TUIOs, which may turn out as drawbacks: Considering attraction and repulsion between TUIOs for interaction guidance and assistance, electromagnetic TUIOs are superior to motorized TUIOs, since magnetic forces even work when a TUIO has been (slightly) lifted off the surface. Motorized TUIOs cannot simulate attraction or repulsion when lifted. Furthermore, electromagnetic TUIOs support holonomic movement, while motorized TUIOs (using a differential drive) may need to rotate in order to move in a particular direction. This might violate user-defined values of representations.

Exotic Approaches: Legged Robots and Ultrasound-based Air Propulsion

Another rather new and exotic approach for TUIOs actuation is the use of legged robots. So far, only one application using a legged robot has been presented, but the idea of graspable robots with legs may find further support in the future. Also, ultrasound-based air propulsion for moving lightweight objects on an interactive surface is a recent exotic approach, which we briefly discuss here.
Spidey The first legged robot in a tabletop tangible environment is *Spidey* [191], introduced by Somanath et al. It is a small six-legged robot, working on a multi-touch enabled tabletop interface. In an interactive reservoir engineering application, it is intended as a so called 'butler', assisting the users of the system.
Kilobots Another related approach that could be also useful for actuating tangible objects is the use vibrating legs. Rubenstein et al. describe this technology as an extremely low-cost technology to actuate their small-sized swarm robots *Kilobot* [176]. From different video demonstrations it is obvious that this technology is relatively slow and imprecise, but for special-purpose applications where speed and precision are of low priority, this could be an interesting alternative to other technologies.
Ultra-Tangibles The *Ultra-Tangibles* [134] by Marshall et al. use focused waves of air controlled by an array of ultrasonic transducers placed around the system's display. The 7-inch display is surrounded by three rows of 144 ultrasonic transducers. The TUIOs are tracked

[1] `http://www.pololu.com/catalog/product/975`

Approach	Advantages	Disadvantages
Electromagnetic Actuation	• The TUIOs are quite simple and inexpensive. • It is possible to apply forces to the TUIOs even when they are lifted off the surface. • The TUIOs can be rather small. • No batteries are needed.	• The surface is not easily scalable. • The surface is rather complex and expensive. • The minimum distance of the TUIOs is limited by the magnetic fields.
Differentially Driven Mobile Robots	• The surface is easily scalable. • The surface is rather simple and inexpensive (depending on the display technology used). • The TUIOs are more easy to equip with further circuitry, such as sensors.	• The TUIOs are more complex and expensive. • When lifted off the surface, the actuation has no effect on the TUIOs. • The TUIOs require a certain minimum size for the internals. • The TUIOs need batteries.

Table 3.1: The benefits and disadvantages of the two major TUIO actuation approaches.

with a camera working at 100 fps using the *CCV* tracking software. This innovative approach allows to move multiple TUIOs simultaneously as presented in a demonstration video. Here, up to two TUIOs are moved at surprising speed, though no hard numbers are given. Unfortunately, this implementation has visible drawbacks: The large number of transducers demand a rather high controlling effort with complex hardware. Furthermore, it requires even more effort to scale the system (more and / or stronger transducers). Also, the frame of transducers around the display may hinder users to effectively manipulate the TUIOs and the lightness of them might be an issue, too.

3.2 Summary: Benefits, Disadvantages and General Comparison

Both major actuation approaches for TUIOs certainly have different benefits and disadvantages. We discuss the differences regarding the interactive surface and the actuated TUIOs, as summarized in Table 3.1.

Interactive Surface

The technical surface design differs significantly between the two actuation approaches. The key factor for the differences in advantages and disadvantages between the two approaches is the location of the mechanism responsible for the TUIOs' actuation. In the electromagnetic approach, the actuation mechanism is located in the interactive surface. First of all, this makes it rather complex and expensive. The array(s) of coils determines the size of the interactive surface and also limits the effort needed to add graphical display and tracking of the TUIOs. The easier possibility is using top-projection and -tracking, as demonstrated in

Table 3.2: Comparison of the actuated TUIOs' properties, as found in literature. We added the numbers of the TAOs for comparability.

System	Actuation Speed [cm/s]	Footprint Size [cm]
Actuated Workbench [152]	$15 - 25$	$\varnothing 2.54$
Madgets [208]	$5 - 8$	$\approx$ palm size
Planar Manipulator Display [175]	$12.7 - 14.3$	6.8×6.3
Tangible Bots [158]	< 24.5	$\varnothing 9.5$
Tangible Active Objects	$5 - 18$	5×5

the *Actuated Workbench* [152]. The problem of the hands of the users disturbing the tracking by occlusion was solved in the *PICO* system by introducing RF tag-based sensing as shown in the *AudioPad* [155]. Weiss et al. demonstrated a far more complex (and presumingly more costly), but completely integrated approach. They incorporated a display and fiber optic cables allowing to integrate visual display and visual tracking of the TUIOs from below (through the interactive surface).

For robotic TUIOs, the technical design of the interactive surface can be rather simple. Basically, it only requires a transparent tabletop surface, as in the early stages of the TAOs, allowing visual tracking of the TUIOs from below. Adding visual display can also be accomplished by using top- or back-projection or adding a modified LCD monitor to the interactive surface, as demonstrated in the *Tangible Bots* [158].

Actuated TUIOs

The shift of the actuation mechanism from the interactive surface to the TUIOs themselves has different benefits and disadvantages for the TUIOs. In contrast to the electromagnetically actuated TUIOs, the robotic ones are more complex and expensive, as they include electronics and mechanics, but this makes them much more extensible, allowing to incorporate further circuity, such as sensors. The way of actuation has a slight but distinct effect on user experience. Electromagnetic actuation allows to apply force to the TUIOs even when they are slightly lifted from the surface by the users. This is not possible in robotic actuation. Furthermore, the differential drive does not allow to perform holonomic motion, unlike the electromagnetic approach. Otherwise, it easily allows to control the TUIOs orientation, which was only demonstrated in the *Madgets* by adding multiple anchor points to the TUIOs [208]. The electromagnetic approach also requires a certain minimum distance between the TUIOs to prevent the controlling force fields to merge unintentionally. Another major drawback with robotic TUIOs is the dependence to batteries required to power the actuation mechanism. This strongly limits the operation time. Finally, robotic TUIOs integrate all the needed electronics and mechanics which results in a certain minimum size and weight.

Actuation speed and size of the TUIOs found in literature also differs. Table 3.2 gives an overview of the numbers given in the respective publications. We elaborate on the TUIOs' actuation velocity in Chapter 8.

Though its hard to tell from literature whether one actuation approach is superior to the other, this definitely depends on the target application(s) and the will or need to make trade-offs.

In our opinion, the robotic actuation approach has benefits that make it more flexible and extensible from the scientific point of view. Having TUIOs already incorporating electronics and mechanics massively reduces the effort needed to include further circuitry and components, such as sensors and actuators. Though the limited operation time constrained by the batteries definitely has practical drawbacks, this extensibility enabled us to easily explore new interaction approaches which was the key argument to decide for robotic actuation. In the following sections of this chapter, we describe the major design and implementation aspects of the TAOs.

3.3 The TAO system

In this section we briefly describe the TAOs' fundamental hardware and software design. Beginning with a short description of the Tangible Desk (tDesk) that resembles the major reference frame of the TAOs, we continue with the description of the TAOs' hardware and software design.

The TAOs' Stage: The tDesk

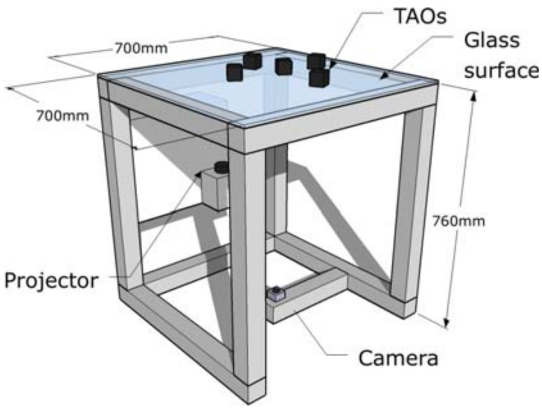
The setting for the TAOs and thereby the first part of the hardware to mention is the Tangible Desk (tDesk). The current implementation of the tDesk is designed as a cubical table with an edge length of 70 cm custom made from aluminum profiles. As depicted in Figure 3.1, it is equipped with an acrylic glass surface with projection foil, a *Hitachi ED-A101* projector mounted for back-projection and a *Point Grey Flea2 FL2G-13S2C-C* camera with an IEEE-1394b interface and an additional infrared notch filter for tracking the TAOs' active infrared markers. The camera runs at a frame rate of 30 fps and has a maximum resolution of 1288×964 pixel. This allows the interactive surface to cover an area of about 56×42 cm. The projector and the camera are connected to the host computer along with an *XBee* transmitter for wireless control of the TAOs.

The TAOs' Hardware Design

The first prototypical hardware and software of the TAOs were initially developed during the author's Master's thesis [167]. Before this, the author already worked with passive table-top TUIs in the course of a student's assistant position. Motivated and inspired by the need of bi-directional interaction (cf. [175]), the TAOs were designed based on the small-sized swarm robots *Jasmin* [111] and later *Wanda* [95]. The *Jasmin* platform was very inspiring, whereas the *PMD* was the first tabletop TUI using a robotic approach for actuating TUIOs. To be open for later extensions, we decided on the differentially driven robotic approach, since it allows to incorporate electronics and mechanics within the housings what makes the design easier to extend, as discussed above.

Because we aimed at making the TAOs usable in multiple applications, we decided in favor of an abstract cubical shape. To reduce the TAOs' abstractness, we made used of graphical,

Figure 3.1: The principal tDesk design. Our tDesk is equipped with a glass surface with projection foil on which the projector mounted behind the table can project from underneath. A Firewire camera underneath the table allows visual tracking of the TAOs.



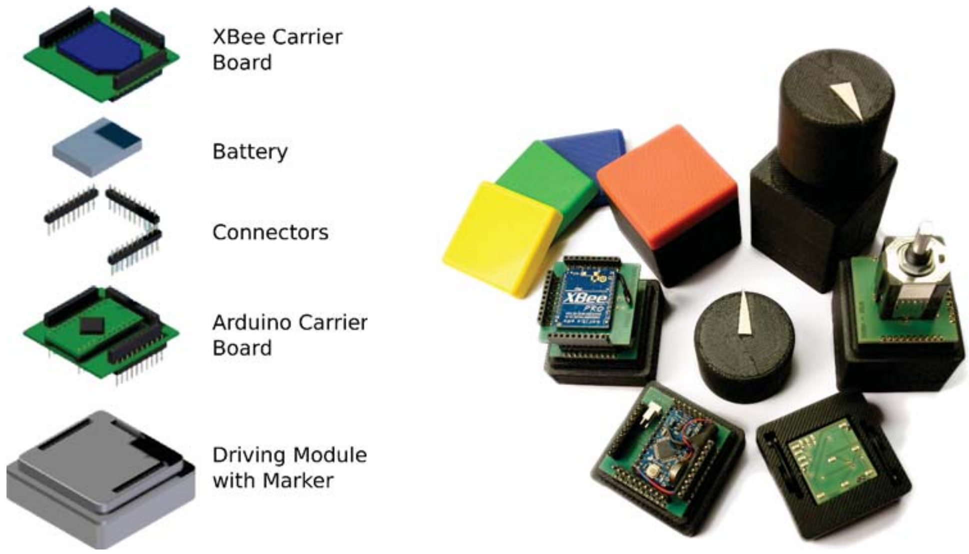
(a) Drawing of the general tDesk setup.

(b) Picture of the tDesk along with some TAOs and the experimenter desk next to it.

auditory and vibro-tactile feedback. The TAOs' housings were designed using SolidEdge[2], a Computer Aided Design (CAD) program. With the construction data a rapid prototyping printer produced the housings and all mechanical parts of the TAOs. The design of the housings was based upon the *TUImod* building blocks for easily reconfigurable TUIOs by Bovermann et al. [20]. As a result, the TAOs are modular cubes with an edge length of 5 cm with rounded edges which makes them easily graspable.

Built within the housings are modular custom designed Printed Circuit Boards (PCBs), horizontally connected via pin headers. Figure 3.3 depicts the most essential assembly parts the were developed for the TAOs. As depicted in Figure 3.3a, the main PCB holds an *Arduino pro mini*[3], an open source microcontroller board using an *ATmega138* for rapid prototyping of electronic devices. Powered by 200*mAh* lithium-polymer batteries, it runs the *SerialControl* firmware[4], specially designed for remote controlling the TAOs. To have wireless communication between the TAOs and the host computer, another PCB holds an *XBee* wireless serial module[5] (see Fig. 3.3c). The *XBee* modules are configured to operate in a star-network between the host computer and the TAOs, in which every TAO has its own ID. The firmware only reacts on commands starting with the TAO's own ID. With the *SerialControl* firmware it is possible to control each interaction relevant component of the TAOs, such as the differential drive, driven by another driver PCB basically carrying an L293D H-Bridge and a 7404N inverter IC. The small DC motors, individually controlled by this board drive two small wheels, arranged on a single axle (see Figures 3.3e and 3.3f). This compact design allows to smoothly switch between driving forward, turning in-place, driving on a curve or driving backwards. For tracking the TAOs, a unique marker was placed

[2] `http://www.plm.automation.siemens.com/en_us/products/velocity/solidedge/index.shtml`
[3] `http://www.arduino.cc/en/Main/ArduinoBoardProMini`
[4] `http://www.arduino.cc/playground/Code/SerialControl`
[5] `http://www.digi.com/products/wireless/point-multipoint/xbee-series1-module.jsp`



(a) Explosion drawing of the basic TAO design.

(b) Different assembly states.

Figure 3.2: Hardware design of the TAOs.

underneath each TAO. At first, these markers were especially designed fiducial markers, that were later replaced by active infrared markers (see Fig. 3.4b, 3.4c and 3.2b on the lower right). The batteries allow these components to operate for about 30 minutes, depending on the amount of movement and wireless communication. This design makes the TAOs easily extensible for further hardware extensions. All mentioned PCBs were designed using the *EagleCAD* circuit design and layout program[6].

Hardware Extensions

For certain applications and studies, the basic design of the TAOs needed to be extended or modified. Some of these extensions were used in more than one application after they were introduced, such as the active marker tracking or the actuated dial. We describe these general modifications in the following paragraphs, along with prototypes of modifications, that were rarely used or never passed the design stage. Other extensions, such as the vibration feedback (see Chapter 6) and touch sensing (see Chapter 7), are described in the respective chapters describing the study or application in which they were used.

From Passive to Active Marker Tracking

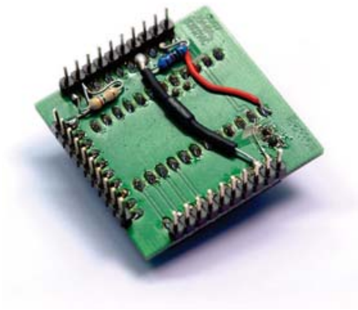
Until the TAO project, blob tracking and the *Amoeba* marker set along with the software library of the *reacTable* [11, 89] was used for tracking non-actuated TUIOs at Bielefeld University. An example of these markers is shown in Figure 3.4a.

Since the usable bottom area of the TAOs was smaller due to the space that is taken by the wheels, we developed a new marker set. The new marker set which we call *Alien Faces*, is much more simple than the *Amoeba* set. Its markers are basically divided into two halves. The upper half is white with black dots (resembling the face's eyes) and the lower half is

[6] http://www.cadsoftusa.com/

Figure 3.3: Essential assembly parts of the TAOs.

(a) Main PCB with the *Arduino*.

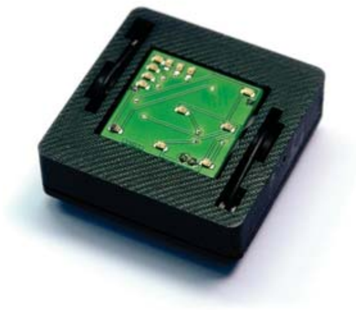


(b) Bottom side of the main PCB.

(c) PCB with the *XBee* module for wireless communication.

(d) The actuated dial PCB for the mTAOs.

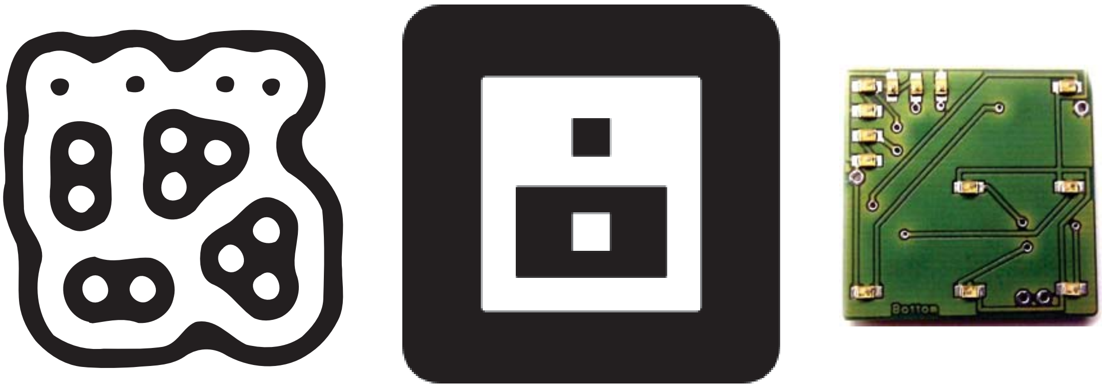
(e) Mechanics and electronics of the differential drive.



(f) Bottom side of the assembled differential drive with the wheels and the active marker.

a black rectangle with white dots (the face's mouth). The different numbers of black and white dots within the halves make the markers unique and distinguishable. The two halves are surrounded by a white rectangle which itself is embedded into the black housing of the TAOs. By this, it is possible to make them smaller to fit between the TAOs' wheels. An example of the set of smaller markers is depicted in Figure 3.4b. The case study for collecting gestures performed with TUIOs for the ESN (see Chapter 4) used this tracking approach. The TAOs were robustly trackable and there was no need for projection on the tabletop surface of the tDesk.

A completely new marker tracking was developed to allow back-projection on the tDesk's surface combined with robust tracking. Because even with improved local thresholding of the input image for the fiducial tracking, this was not robust anymore when combined with projection because the projection massively changed the local illumination of the camera image. So we decided to switch from a passive marker tracking to actively illuminated markers working with infrared Light-emitting Diodes (LEDs) (see Fig. 3.4c). With these LEDs, the visible light of the projector can easily be filtered with an infrared notch filter mounted in front of the camera's lens and a clear image of the LEDs remains in the camera image for tracking.



(a) An example marker of the *Amoeba* set used in the *reacTable* [89].

(b) An *Alien Faces* marker designed for the use with the TAOs. The design uses the *reacTable's* tracking system [167].

(c) One of the TAOs' active LED markers [172].

Figure 3.4: Different marker styles used in TUIs and in the TAOs, in particular.

The markers' LEDs have a special arrangement. Each marker has a corner illuminated by seven LEDs for marker detection and further six LEDs for encoding the marker's ID, as depicted in Figure 3.4c and 3.2b in the lower right. The PCBs' LEDs are controlled by an *NXP PCF8574T/3* 8bit I/O Expander IC that is interfaced with the *Arduino* over an I^2C link. The formerly used *Alien Faces* markers were removed by this marker PCB.

Because we developed these markers from scratch, also the tracking software was redeveloped using the ICL[7] and its implementation of the corner detection algorithm by He et al. [65]. With the corner detection, we track the triangular LED corner of the illuminated PCB. Additionally, the LED lying opposite of the corner was used to stabilize the position and orientation of each marker. The remaining five LEDs are used to encode 32 individual IDs for the TAOs which can be changed instantly in the running system.

Both the development of the PCB and the tracking software was accomplished by a group of students under the author's supervision according to his requirements.

The Tangible Actuated Dial Extension

For two applications, one for saving and restoring mechanisms for TUIs (see Chapter 5), the other one for remote collaborative placing of furniture (see Chapter 6), we needed a tangible actuated menu metaphor. We did not want it to be complex like the menu structures of the *AudioPad* [155] and we also did not want it to be tied to one side at the table-top surface like in the *PMD* [175]. So we decided to create a new type of TAO with an actuated menu dial, the mTAO. These new mTAOs were an enhancement of the basic TAO design as described before, including the active marker tracking. To this design we added a new PCB which we put on top of the basic design. This PCB holds an *ALPS RK25T11M* motorized potentiometer that can be used to sense the orientation of its dial, but can also be actively controlled by the system. By this, the dial acts as input and output modality at the same time so that it can indicate internal states of the system and it enables the users to change the states instantly. The saving and restoring application heavily utilized these

[7] http://www.iclcv.org

capabilities, accompanied by a projected circular menu and speech output for selecting menu items without the need to look at the mTAO. The latter property was useful in the furniture placing application where a second display was used to render a three-dimensional view of the scene, so that the user can inspect this view while changing the state of the mTAO.

Vibro-tactile Feedback and Touch Sensing

For our remote collaborative furniture placing application, we added vibro-tactile feedback to our TAOs. This was achieved by simply incorporating a coin-sized pager motor, driven by a transistor which is controlled by a single pin of the *Arduino*. It is possible to drive the pager motor at different speeds which results in the TAOs to vibrate in varying intensities. In the furniture placing application (see Chapter 6) we used the vibro-tactile feedback to inform the users of inconsistent states in the simulated model.

Touch sensing was used in the comparative study, described in Chapter 7. By adding a high-value resistor and an antenna, we were able to implement basic capacitive touch sensing. We used it to detect whenever TAOs are touched by a user and used this information to create and alter constraints between multiple touched TAOs. When only one TAO was touched, existing constraints were maintained between the TAOs by moving them autonomously according to the TAO moved by the user.

Battery Monitoring and Charging

Depending on the use of the TAOs' motion and communication, the batteries last for about half an hour. Within an experiment, it can be a big problem if a TAO suddenly stops moving or is not responding to requests for sensor values, not knowing if there occured an error or if the batteries ran out of power. For this convenience, we added simple circuitry to the main PCB and some additional lines of code for the firmware to enable monitoring of the TAOs' batteries and to replace them before the TAOs stop working. As a proof-of-concept, we also added a tiny PCB for charging and prevention of deep discharge of the battery. Due to the very limited space inside the TAO, it was not possible to charge it while it's running without a complete redesign of the main PCB. So we did not extend the other TAOs with these features.

The System's Software Architecture

The control of the TAOs' actuation along with synchronized graphical display, sound output, additional sensors and actuators etc. is a complex task. Thus, we decided to use a distributed approach for the software design even in the earliest stage of the development. This also allowed us to encapsulate the different control and interaction aspects in generic stand-alone software components that can be easily extended and re-combined. To enable communication between the components we utilized *XCF*[8] [51], an XML-based middleware, developed at Bielefeld University. Later, we switched to the *RSB*[9] [211], the successor of *XCF*, which is more lightweight but still flexible and versatile. Both middlewares feature the Publisher-Subscriber paradigm which allowed us to loosely connect the software components by transmitting all relevant data over the network and registering on the different data streams relevant to the particular components. Adding further components to the system

[8] `https://code.ai.techfak.uni-bielefeld.de/trac/xcf`

[9] `https://code.cor-lab.de/projects/rsb`

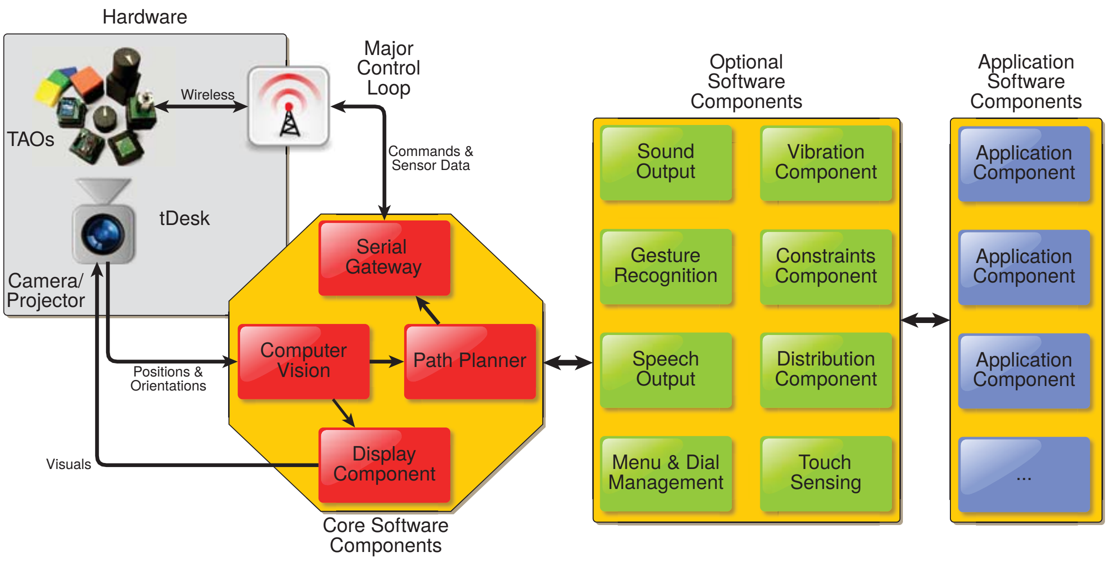


Figure 3.5: The software components of the TAO system architecture and its main control loop. The essential components are printed in red, optional generic components are printed in green. Special-purpose components, such as the sonification, the three-dimensional view or the remote synchronization are not included here, but are covered in the respective sections.

is simple with this architecture. Each new component can simply pick up the needed data streams that are relevant to the component without interfering others and provide its own information to the middleware from where other components can use them.

Through the course of this project many different software components were developed. There are some essential components almost every application or study design needed to run properly, such as the tracking component and the path-planning component, while others are optional. We briefly describe one iteration of the control loop, the involved fundamental components and their interplay in the following paragraphs; Figure 3.5 gives a graphical overview of this control loop along with an overview of further available components.

The Basic Control Loop

The iterative control loop starts with the TAOs standing on the tabletop surface of the tDesk. In each iteration of the loop, the camera underneath the surface takes an image of the TAOs' markers and the tracking component extracts their position, orientation and ID. These information are distributed to each component listening to this data stream via the middleware.

Path-Planning and the Serial Gateway

The path-planning component listens for the position and orientation information from the tracking component. Its plugin-based design implements different replaceable path-planning approaches, including a potential field plugin, implemented after Latombe [119] and a physics-based planning approach using the *Box2D* physics engine[10] offers its path-planning capabilities with obstacle avoidance to the system. A third very simple planning plugin implements a rather naive approach for applications where obstacle avoidance is not explicitly needed. By requesting a TAO to be navigated to a new target position and orientation, this component plans a trajectory according to the current planning approach and

[10] `http://box2d.org/`

calculates control commands that are again spread over the middleware to the serial gateway. This gateway component transmits the motor commands over the serial port of the host computer to the *XBee* module which provides wireless communication with the TAOs.

Closing the Loop and Adding Further Components

These motor commands make the TAOs move, which results in a slightly changed camera image and the basic loop for controlling the TAOs' movement is closed. Further components hook into this loop to control additional aspects of the TAOs. They provide interfaces to the visual display and optional interaction aspects of the TAOs, such as the gesture recognition, the actuated dial, vibro-tactile feedback or touch sensing.

Visual Display

The visual display component is another essential component. In its basic configuration, it just visualizes the position of each TAO, but it offers further custom visual augmentations on request. It provides additional TAO visualizations, such as menus and drawing capabilities ranging from basic geometrical shapes, such as rectangles, ellipses, lines, text, to drawing images, additional labels and a full featured web view which is able to show Flash videos.

Additional Interaction Aspects

There are optional software components for controlling further interaction aspects of the TAOs. Each of these components encapsulates the respective feature's capabilities and properties at different levels. For instance, the menu and dial control component simply allows to automatically rotate a TAO's dial to a certain position. As higher-level functionality, it is able to receive a complete menu structure over the middleware and to manage the users' interaction with the dial accordingly, emitting events when a menu item has been selected or should be selected by the system. The software components interfacing with the vibro-tactile feedback, the touch sensing or the speech output work similarly. An additional software component provides scripting possibilities for rapid prototyping of basic applications using the *Python* programming language.

Also, abstract interaction control mechanisms can be easily incorporated. When started, the constraints component enables the users to define spatial relations between TAOs by simply touching them simultaneously. When only one TAO is moved by the user, the other constrained TAOs move along autonomously. This interaction behavior of the system can be easily added or removed by starting or stopping this software component.

LibTAOs: A closer Look

This software architecture provides sophisticated means for designing rich interactions for the TAOs. To conveniently encapsulate the communication between the components and to enable application developers to easily create integrated applications for the TAO architecture, a programming library was written along to the software components. This object-oriented programming library was implemented in *C++* and the *Qt*[11] toolkit and provides convenience classes for interfacing with the architecture's components.

These classes provided by LibTAOs through the factory method pattern mainly deal with communication between the different software components by wrapping the middleware to Qt's signal/slot mechanism and vice versa. For each software component there are two classes, a master singleton class used in the component itself and a slave class which can

[11] http://qt-project.org/

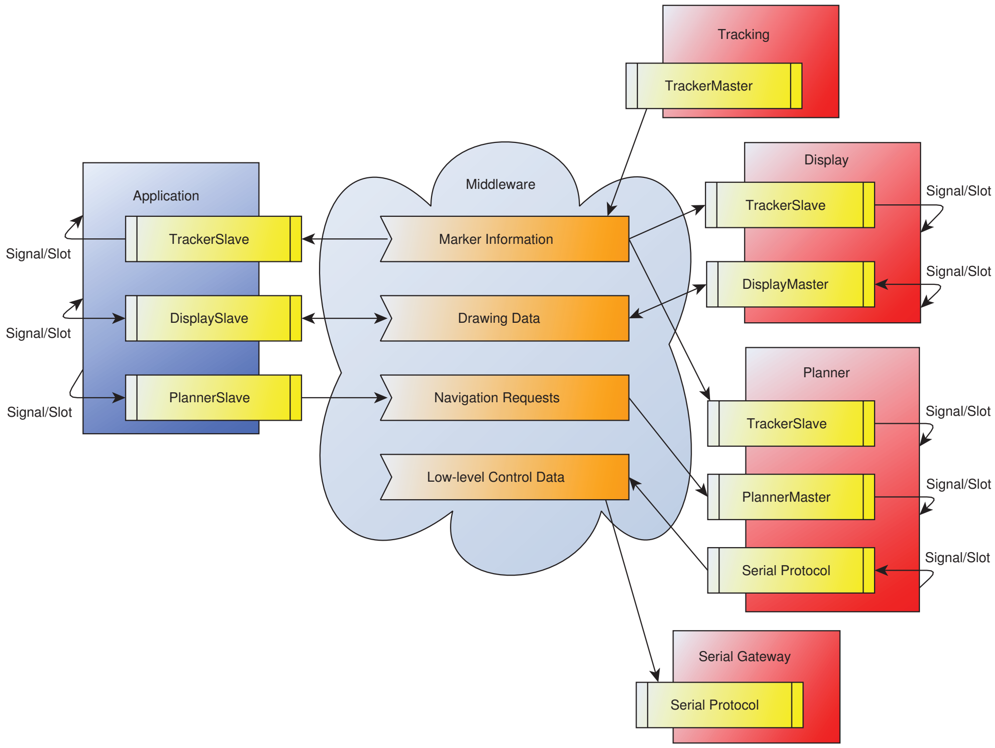


Figure 3.6: A typical simplified case of application development with the four core components using the LibTAOs. The core components are printed in red. The application (printed in blue) accesses the core functionalities through the slave classes provided by LibTAOs (all printed in yellow). Please note that for each component there is only one master class instance, while the slave classes can have multiple instances across the software architecture.

have multiple instances in other components. The master class is used in the software components providing certain features, serializing the components' data stream through slots and publish these data on the middleware. On the other side the slave classes receives these data streams, parses the data and emits signals that can be processed on the application side conveniently. This mechanism makes the middleware transparent from the application developer's perspective and provides versatile and convenient management of data streams within the TAOs' software architecture making them easily accessible across components. Figure 3.6 depicts a typical case of application development with the four core components and explains how LibTAOs' communication classes work together providing the 'glue' between the software components and the application.

4 Triggering Actions: Gestural Interaction with the TAOs

When we speak, in gestures or signs, we fashion a real object in the world; the gesture is seen, the words and the song are heard.

Émile Chartier
The Gods (1934), Introduction

One important step towards versatile TUIs is the ability of the user to trigger different commands and to react interactively on certain events represented by the systems TUIOs. Though often used in multi-touch applications to manipulate the data being displayed (zoom, rotate etc.), gestural interaction is rarely used in tabletop TUIs, as already indicated in the research gaps (see Chapter 1).

In this chapter we investigate if and how users would accept performing gestures with our TAOs to trigger actions and describe the process of collecting fitting gestures for and example application. Though this approach does not explicitly add to actuated TUIs in particular, it contributes to the field of Tangible Interaction in general. Without the need to build actuated TUIOs, system designers can make use of gestural interaction to provide a means to select from a larger range of actions. We also describe our Embodied Social Networking client (ESN) [172] as an example application. It provides a TUI for accessing a social network and features 11 base functions for this interaction style. From the process of building this system, we also derive first design guidelines for gestural interaction with the TAOs.

4.1 Related Work

Gesture-based interaction is a well established technique for enabling the users to trigger commands, either through Mouse, multi-touch or whole body interaction, using a depth camera such as the *Kinect* sensor. Gesture control can be found in consumer products, such as smartphones and tablet-PCs, web browsers and even television sets. Using gestures is a much more natural way of interaction compared to using Mouse and keyboard, but at the same time much more complex in terms of computational perception and processing on the computer side. Nonetheless, there is a large community working on gestural interaction paradigms. These paradigms include whole-body gestures, gestures with objects (such as dolls [87, 202] or a baton [133]) or surface-based (multi-) touch gestures. There are systems combining surface-based touch gestures with a table-top TUI. But until the conduction of this study, there was no publication investigating gestural interaction with TUIOs on a table-top TUI.

Surface-based Gestural Interaction

Buxton gave an overview of existing devices supporting multi-touch interaction (until 2008) and elaborates characteristics of multi-touch interaction [25]. Due to the problem's complexity, the community offers a vast variety of different gesture recognition approaches with different qualities and application fields. Examples for these approaches are: [1, 4, 113, 114, 122, 125, 214].

The collection of a suitable set of gestures for a particular application is not trivial, as Wobbrock et al. described [216]. They also introduced a taxonomy for surface gestures, involving aspects such as *a*) *form* dealing with hand pose and path, *b*) *nature* which could be symbolic, physical, metaphoric or abstract, *c*) *binding* referring to object or world relations, comparable to our definition of the interaction frame (see Sec. 2.1) and *d*) *flow* meaning whether the system's response occurs during (continuous) or after (discrete) the users' act. Using this taxonomy, they collected and classified a set of user-defined gestures. Comparing this user-defined set with a set defined by researchers, Morris et al. [144] made the interesting observation, that users prefer the user-defined set over the researcher-authored set. Another problem with such gestures is their guessability – no one wants to browse a handbook for finding the right gesture currently needed. As a consequence, Wobbrock et al. described a method for maximizing the guessability of symbolic input [215]. *Gesture Works* is working on a standardized set of gesture definitions which is collected in the *Open Source Gesture Library*[1]. It is based on *GestureML*, a markup language for gestures. Another domain-specific language for defining gestures is the *Gesture Definition Language (GDL)*, introduced by Khandkar and Maurer [96] which is now part of the *GestureToolkit*[2].

Table-top TUIs and Gestural Interaction

As one of the first TUI, *RoboTable* by Krzywinski et al. [115] combined the use of surface-based touch gestures with a TUI. Within a mixed-reality game scenario, it enabled the users to remotely control mobile robots with passive TUIOs. Unfortunately the authors did not clearly explain if and how gestural input is actually used in their approach.

Another approach combining multi-touch interactions with actuated TUIOs was the *Tangible Bots* system [158]. Here Pedersen and Hornbæk elaborately described their ideas of combining actuated TUIOs and multi-touch interactions: In the first combined approach they proposed indirect interaction commands. By drawing a path with a finger on the surface, the users could command the TUIOs to move along this path. As another possibility, users could tap near a TUIO to command it to rotate into this particular direction. To apply interactions to a group of TUIOs, Pedersen and Hornbæk implemented three ways for grouping TUIOs according to recommendations by Micire et al. *a*) "A user can group two tangibles by placing a finger below one tangible and double tap below another", *b*) "users can group multiple tangibles by lassoing them with a finger or" *c*) "by forming a bounding box around the tangibles with two fingers." [141]

[1] `http://gestureworks.com/features/open-source-gestures/`
[2] `http://gesturetoolkit.codeplex.com/`

4.2 Motivation

Striving to extend TUIs with means for triggering a wider variety of actions making them feature rich, we considered gestural interaction for the TAOs. For a first application, this already wide-spread interaction style required no hardware modifications to the TAOs. This allowed us to use components already at hand that only needed few additions to the software to work for our purposes. Central piece of software here is the *LibStroke*[3], a rather simple gesture recognition library for the *X11-Desktop* system.

Gesture Definition

In the literature mentioned above, the term *gesture* refers to (multi-)touch or finger gestures, performed on a planar surface incorporating a graphical display. Within the frame of the following study, we refer to motions which participants perform with one single pointing device / item (Mouse, digital pen, finger, or other object) in order to trigger certain commands. For instance, when using a web browser, such a gesture might be like drawing a straight line from the right to the left in order to go one page back in the browsing history.

Now, the aim of this study is not to collect a generally applicable task independent set of gestures as described in literature. On the contrary, we wanted to investigate which different qualities user-defined gestures can have and how they differ. To study the use of gestures with TUIOs, we chose simple communication within a social network as a straightforward toy setting. We developed our ESN with a manageable number of 11 commands of varying complexity, some of them with different meaning, some semantically related, according to the participatory design study approach proposed by Wobbrock et al. [216]. Such similar commands are *accept contact request* and *remove contact*. Of course, there could be more commands to be used within the interaction with a social network, such as *share*, but we chose not to add more commands to not overwhelm the participants. Table 4.1 explains the commands used in these studies.

In our study described in this chapter, we ask participants to elicit gestures or choose gestures from a given set which they find fits best to given commands. The more often a combination of gesture and command is given as an answer, we can suppose that this combination is easy to guess and remember for potential users of our system.

4.3 Collecting User-defined Gestures with the TAOs

Technical Extensions

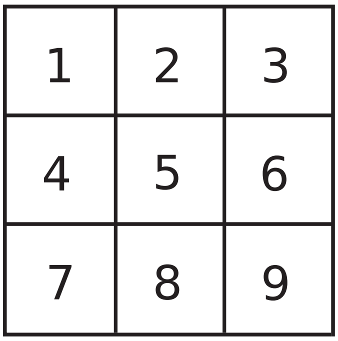
Gesture Recognition

For gesture recognition we modified the already mentioned *LibStroke* to be able to process trajectories the users performed with the TAOs and wrapped it into a software component for the TAO system. Applications and programs supporting *LibStroke* allow to define number sequences representing gestures according to Figure 4.1 that trigger commands after performing such gestures with a Mouse. The gesture recognition component feeds recorded trajectories performed with the TAOs into the library and retrieves the resulting sequence of

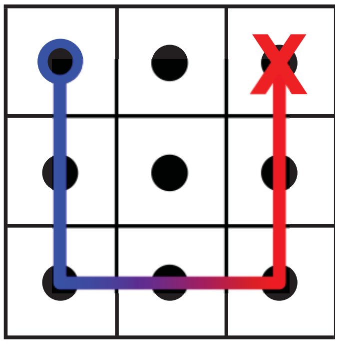
[3] `http://etla.net/libstroke/`

Table 4.1: Overview of the commands used in the gesture experiments.

#	Command	Description
1	read sender	Triggering the *read sender* command lets the system display the sender of a particular message beside the message's TAO and lets it read the name of the sender out using a TTS engine.
2	read message	The *read message* reacts similarly to the *read sender* command, but displays and reads out the message instead of the sender's name.
3	open link	If there is a link included in the message assigned with the current TAO, this command opens the link and displays the website on the interactive surface.
4	close link	If a user opened a link included in a message, it can be closed again by triggering the *close link* command.
5	compose answer	In order to get a graphical input widget for composing a textual answer with the keyboard, the user has to trigger the *compose answer* command.
6	add contact	The *add contact* command allows the user for entering a contact's name to be added to the contact list.
7	remove contact	Removing a contact from the contact list can be achieved by triggering the *remove contact* command.
8	accept contact request	The user can accept received contact requests by performing the gesture assigned to the *accept contact* command.
9	decline contact request	Likewise, the user can decline a request with the *decline contact request* command.
10	search	To get an input widget for entering a specific topic to search the social network for, the user can trigger the *search* command.
11	compose new message	To give the users the possibility to not only react to events on the social network, they can also compose new messages by triggering this command.



(a) Grid numbering used by *LibStroke* to generate numbering sequences for gesture trajectories.



(b) Example gesture trajectory starting at the blue dot and ending at the red x.

Figure 4.1: Specification of gesture trajectory sequences in *LibStroke*; the example trajectory results in the sequence "1478963" [172].

numbers which can be easily processed using string comparison. Gesture recognition can be turned on and off individually for single TAOs or all at once.

Gesture Management using Finite State Machines

In the final application, we used a finite state machine approach to manage the different gestures and actions to be triggered. The Qt framework offers a convenient way to define such state machines. In applications signals can be automatically triggered on certain events, such as the occurrence of different gesture trajectory sequences. This allows for flexible definition of gesture action connections and even multiple gestures per action.

Experimentation Software

We used state machines in the automated experiment procedure as well, to developed a control component which eases the execution of the processes and also helps to detect and prevent errors. For this, we implemented a state machine in our study control software that randomizes the sequence of commands, organizes the trials, triggers speech playback, records the performed gestures, transmits navigation requests to the TAOs' path-planning and starts and stops the audio recording during the whole experiment.

Speech output was used to supported the requirement to have consistent instructions for the participants without the risk of unintentional priming. This speech output component was also used for the implementation of the actual system when it came to reading messages to the user.

Experimental Design and Procedure

Setting

For our study we used the tDesk and the TAOs as described in Section 3.3. We were not able to use the active marker tracking and back-projection during the study, because they were still in development at this time. On first sight this could be a disadvantage, however, there was less risk of distracting or somehow priming the participants with eventually misleading graphics. This allowed us to develop the active marker tracking while conducting the study so it would be ready when implementing the actual system with a projected graphical interface. Furthermore, having a clear glass surface allows to perform gestures where the TAO was lifted during gesture performance. Also depending on the outcome of the study, a suitable design can be implemented. Consequently, each participant of the case study was asked to stand at the tDesk with its clear glass surface under which the camera was mounted to track the TAOs. We marked the border of the interactive surface with tape.

Procedure

Each single participant was sequentially faced with the eleven commands from Table 4.1 in random order. Each command was presented using computer generated speech output. At the same time an audio recording was started. For every command, the participant had to elicit a gesture which he or she thought it would fit, thinking aloud. When a fitting gesture was found, the participant was asked to perform it three times with the TAO standing in the middle of the interaction area of the tDesk. During gesture performance, the performed trajectory was recorded in a log file. Additionally, every trial's sequence of TAO coordinates was fed into the gesture recognition module utilizing the *LibStroke*. After every gesture performance, the TAO automatically moved back to the middle of the interactive area to have the same initial situation for every trial.

Questionnaire

After performing the just elicited gestures three times for each of the eleven commands, the participants were asked to complete a digital questionnaire. Here we asked for demographic information, such as age, sex, handedness etc. Like in the paper questionnaire, we also wanted to know whether the participants were familiar with gestural interaction and social networks and if they use them. Additionally, we asked if the participant could imagine to use a system with TAOs supporting gestures and if they would prefer a pre-defined set of gestures or if they would like to be able to alter the gestures supported by the system. Appendix A.1 gives a detailed overview of the questions asked.

Participants

For our case study we randomly recruited $N = 15$ colleagues and students from the institute's area. As illustrated in Figure 4.2, all of them were right-handed and were on average 32.33 years old from which 20% are female. About 60% knew about technical systems supporting gestural interaction, including multi-touch interfaces such as smartphones and tablet-PCs, but only 20% of these participants knowingly used gestural interaction. In contrast, the participants were quite familiar with social networks (about 87%) and eleven participants (73%) actually used one or more social networks.

Quantitative and Qualitative Study Results

Transcribing the Gestures

To avoid the influence of eventual bad recognition results of the *LibStroke*, we coded and transcribed the collected data based on the recorded trajectories, audio recordings and gesture recognition. Figure 4.3 depicts the results for the transcribed gestures the same way as for the paper questionnaire. Here we can observe a relative ambivalent situation, due to two classes of performed gestures in terms of their recognizability with *LibStroke*.

Two Classes of Gestures

The first class is the group of rather simple which are easily recognizable by the *LibStroke*, as intended. According to taxonomy defined by Wobbrock et al., the gestures can be characterized by the following attributes: They are mostly performed with a *static pose and path* (*Form*) and originate from a *symbolic Fature*. As the gestures have to be performed with a TAO in hand, they have an *object-centric binding*. By design, the *flow* is *discrete*, as the

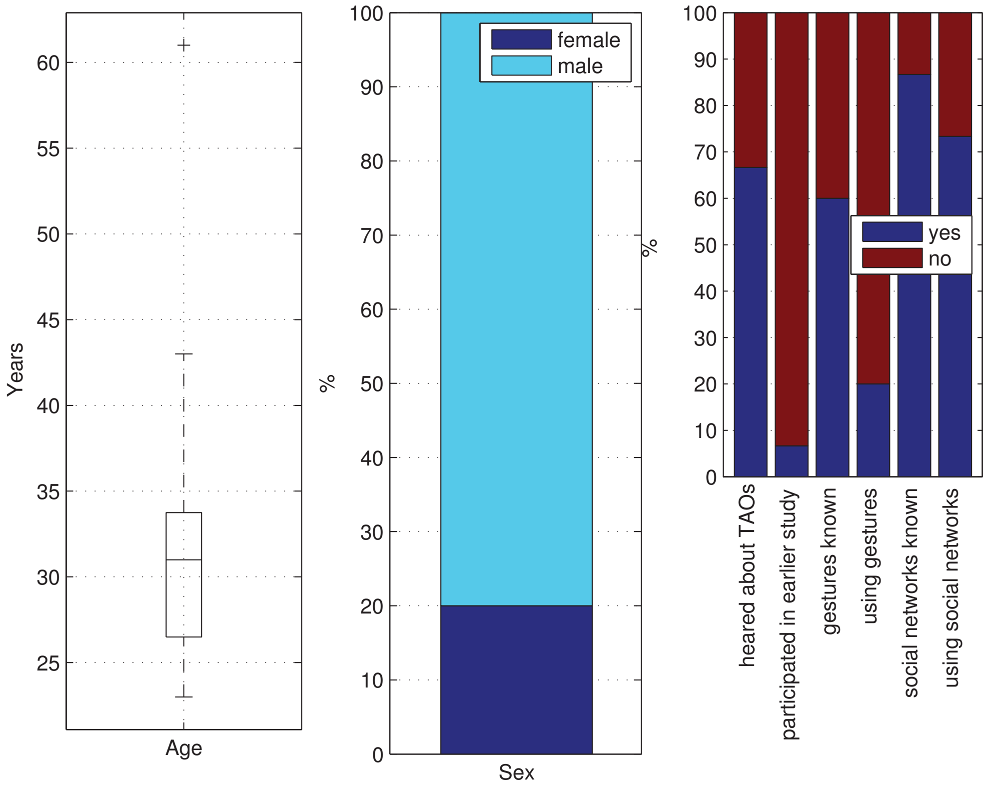


Figure 4.2: Overview of the demographic information and answers given in the digital questionnaire the participants filled out at the end of the experiments.

action is triggered after the gesture is successfully recognized [216]. The gestures include single-stroke trajectories, such as "down" (258), "left" (456), "right" (654), "up" (852) "up left" (951) and "up right" (753). Also gestures with shifts in drawing direction can be observed, such as "down, right" (14789), "left, right" (45654) and "left, up" (98741). We were surprised to find a second class during the conduction of the study, which we unluckily expected *LibStroke* to be unable to recognize robustly. This class includes more complex gestures, such as "check", "circle clockwise" and "X". Though the "check" gesture is basically recognizable by *LibStroke*, its recognized number sequence may vary due to slightly different ways to perform this gesture. For the other gestures of the second class this applies even more. Figure 4.5 depicts recorded trajectories of transcribed gestures, gathered during the experiments.

Recognized Gestures

Having a look at the gestures recognized by *LibStroke*, we can easily find most of the gestures of the first class, as described above in Figure 4.6. Here we find comparable frequency distributions for the gestures for the first class. Unfortunately, we can also observe a rather large number of low frequencies spread over the diagram. These are artifacts of false recognitions for the gestures of the second class. For instance the recognized sequence 47863 is an artifact that very likely refers to the "check" gesture, while most other recognized sequences cannot be referenced at all. Otherwise, we observed complex gestures that were recognized as rather simple gesture sequences. For instance, the very rare "wave" gesture depicted in Figure 4.7f was mapped to the 456 gesture. So far we can say that at least for

Figure 4.4: Compact overview of the high frequency gesture-command combinations observed in the case study after coding and transcribing the collected data.

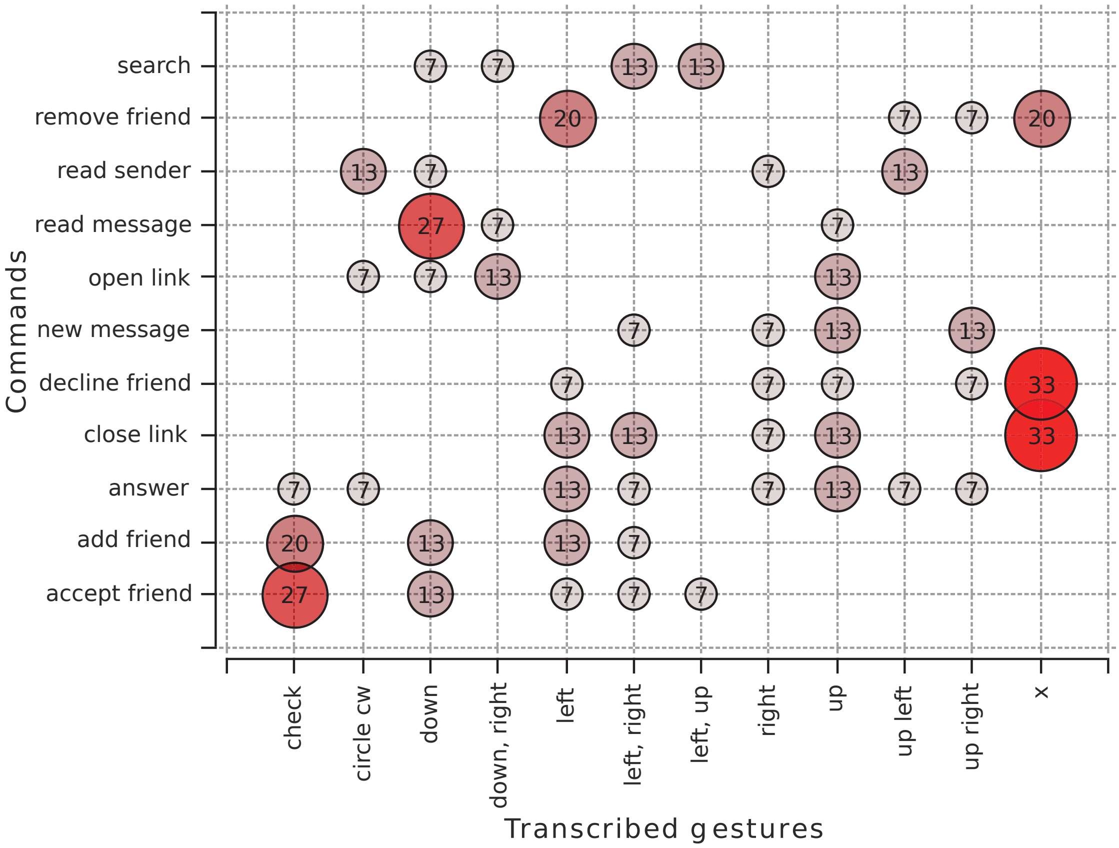
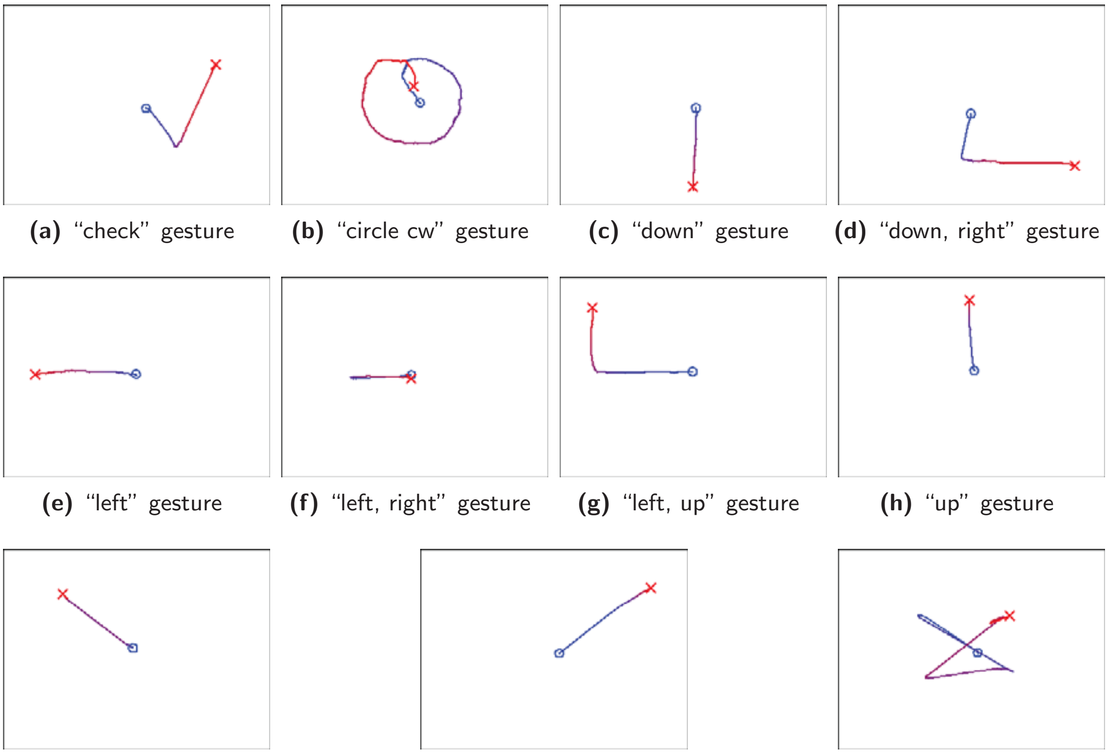


Figure 4.3: Compact overview of the high frequency gesture-command combinations observed in the case study after coding and transcribing the collected data.

Differences between Recognized and Transcribed Gestures

the second class of gestures, our recognition approach using *LibStroke* is mostly unsuitable. The overview given by Table 4.2 helps us understanding the situation. Remarkable is the relatively high number of used recognized gestures. This applies for each command, the mean (28.7) and the general number of gestures (189). In contrast, the number of transcribed gestures is surprisingly low. Altogether, the participants only performed 59 gestures and on average only 14 different gestures per command. This also reflects the average frequency of the performed gestures (3rd major column of the table). With respect to the high number of different recognized gestures, the relatively high average here indicates a broad distribution of frequencies, which is supported by the ranked bar plots in the appendix (see Sec. A.1). Otherwise, with the low numbers of transcribed gestures in mind, the surprisingly high average frequencies here point to well-fitting gesture-command combinations. Also interesting is the second major column of the table with the maximum frequencies. Here we can easily distinguish between the two gesture classes we identified earlier. Those commands with similar maximum frequencies indicate gestures of the first class, while commands with rather different maximal frequencies (lower for the recognized gestures) denote candidates of the second class of gestures. We can easily see that the gestures *accept contact request*, *add contact*, *close link* and *decline friend request* definitely belong to the second class of gestures. There



(a) "check" gesture (b) "circle cw" gesture (c) "down" gesture (d) "down, right" gesture

(e) "left" gesture (f) "left, right" gesture (g) "left, up" gesture (h) "up" gesture

(i) "up left" gesture (j) "up right" gesture (k) "X" gesture

Figure 4.5: Visualizations of the final gestures used in our implementation of the ESN. An X symbol marks the start of the gesture movement, a circle symbol marks the end. The transition from start to end is represented by a color gradient from blue to red [172].

is only one exception: The *remove contact* command has two corresponding gestures with 20 % each. Gesture "left" (654) belongs to the first class and gesture "X" belongs to the second. As a consequence, we unfortunately have to admit that our approach using the *LibStroke* is not applicable for gestures of the second class of gestures. We can observe, that both a high maximum frequency and a high average frequency for the transcribed gestures at the same time already hint to very good fitting gesture-command combinations.

User Reactions

At the end of each experiment we asked the participants to fill out a digital questionnaire. Beside the general demographic data we already described earlier, we also asked if the participants could imagine to use an actual system with the TAOs supporting gestural interaction and if they would prefer a pre-defined set of gestures or if they would like to define their own set of gestures. The results from these two questions support the other results from the questionnaire and the study. While about 26% of the $N = 15$ participants can imagine using a system with TAOs supporting gestural interaction and 20% cannot, and over 50% are unsure. On the contrary, we can observe a trend regarding the wish for user-defined gestures. Nine of the $N = 15$ participants (60%) would prefer user-defined gestures. Only 12% were unsure, while 23% would accept a pre-defined or standardized set of gestures.

Further Observations

During the experiments and the evaluation of the audio recordings, we made further observations. We asked the participants to think aloud during the experiment and we asked for explanations of their decisions. From these qualitative evaluations we observed that some of our participants tried to perform gestures which we had not expected. Because we only

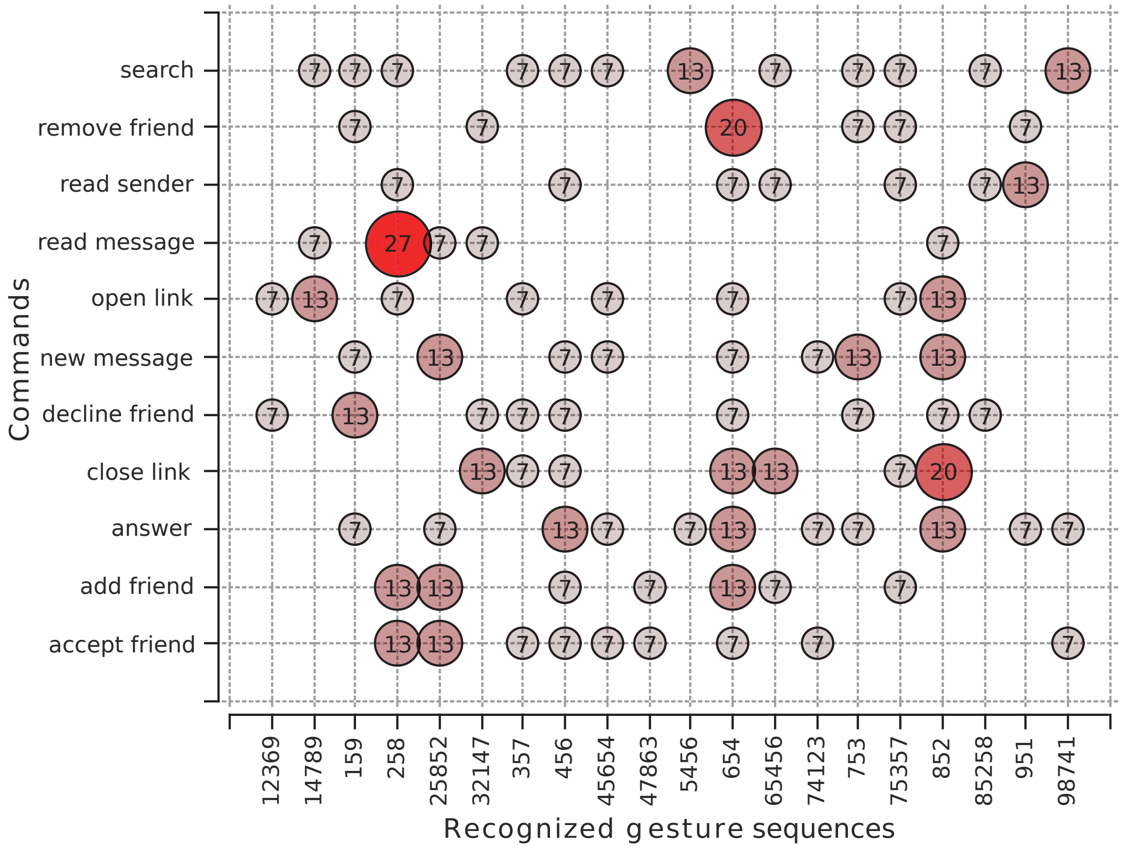


Figure 4.6: Compact overview of the most frequent recognized gesture-command combinations observed in the case study.

focused on trajectories of translational 2D positions, our gesture recognition was not able to cope with intended rotation (in-place rotation, to be specific). Furthermore, some participants tried to shake or lift the TAO as part of their gesture performance. Due to the technical limitation of 2D tracking of the TAOs, this is currently not possible. As a consequence, for TAOs supporting gestural interaction, full 6 degree-of-freedom interaction is desirable in future implementations.

Applying the surface gesture definition by Wobbrock et al. [216] to our case study, we can observe that the hand pose is rather static while the hand moves during gesture performance with the TAOs, very much like in Chapter 8. Furthermore, the observed nature of the gestures is mainly abstract and symbolic. Many participants argued for moving the TAO in a particular direction to reflect abstract actions, such as "down" for reading a text or "up" for pushing something away. In the case study we also observed a number of participants, arguing for the interactive surface as reference frame for gesture performance, such as corners or sides of the area which was rather surprising to us. Due to the command-like characteristic of our approach, all gestures show a discrete action flow. Some participants also oriented their performance on trajectories shaping one or two letters, such as "L" for *open link*, "X" for *remove contact*, "OK" or an "arrow" gesture for *accept contact request* or "?" for *search*. While the first two gestures were already presented in Figure 4.5, the latter three trajectories are printed in Figures 4.7a and 4.7b. On rare occasions, participants also elicited gestures

Command	# of used Gestures rec.	# of used Gestures trans.	Maximal Frequency % rec.	Maximal Frequency % trans.	Average Frequency % rec.	Average Frequency % trans.
read sender	30	14	13	13	6.23	7.50
read message	26	13	26	27	6.77	7.54
open link	24	14	13	13	6.58	7.00
close link	21	9	20	33	7.67	12.11
compose answer	26	15	13	13	6.81	6.93
add contact	24	11	13	20	6.88	9.81
remove contact	30	12	20	20	6.47	8.33
accept contact request	31	14	13	27	6.45	9.93
decline contact request	27	11	13	33	6.52	9.09
search	28	14	13	13	6.52	8.00
compose new message	20	13	13	13	7.05	8.15
mean	28.7	14	17	22.5	7.10	10.53
over all commands	189	59	24	33	0.94	1.82

Table 4.2: Basic parameters of the collected study data.

that are rather complex and metaphoric. Figure 4.7 depicts some examples. One participant worked with a lassoing metaphor which resulted in complex gestures incorporating a circle which got checked or crossed out, as depicted in the Figures 4.7d and 4.7e. Also another participant came up with a “wave” gesture representing sound waves and a “mouth” for the “read message” command. These rare but diverse gesture occurrences reflect the complexity of the experiment task.

4.4 Implementation of the Embodied Social Networking Client

Hardware Extensions

To generally allow to implement the ESN client, we extended the tDesk to be back-projected, as described in Section 3.3. For this we applied semi-translucent foil that allows projection with a wide-range projector from underneath the tabletop surface without occlusions by the users' hands. Since the projector works only with visible light, we equipped the TAOs with special markers using infrared LEDs. By applying an infrared notch filter to the Firewire camera that captures the images for tracking the TAOs we get a clean image of the markers without any interferences by the projection. A specially developed tracking software tracked the new markers while offering the same interfaces as the formerly used tracking component.

Graphical Display

Figure 4.8a gives an overview of the software component collaboration of the final ESN implementation. We added a software component for creating the visual display that is projected at the interactive surface of the tDesk. This component provides drawing and interactive management of graphical primitives widget support covering labels, text entry and web content rendering, which even includes full-screen flash videos. While the name of the sender and the actual message is read out by the speech synthesis component, label support was also needed. The text entry widget enables the user to compose answers and new messages. The web content view allows to display web pages, even including embedded videos.

Twitter Gateway

We chose *Twitter* as a social network to interface with, due to its openness and the relatively simple API. For interfacing with the social network we made use of our *Python* scripting module of the TAO system and wrapped the *Tweepy* for our purposes and made the relevant action call accessible to our TAO system. This enabled the system to receive messages and posts, search the timeline and manage contact requests.

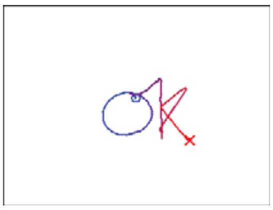
Gesture Recognition

To stick with the gesture recognition component we already developed, we also decided to only use first class gestures for our first proof-of-concept. As the tangible metaphor, the TAOs should represent messages in the social network and events, such as contact requests. Based on the results of the recognized gestures (see Fig. 4.6), we chose the gestures-command mapping listed in Table 4.3.

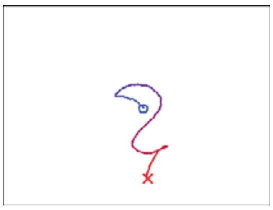
Main Component Design

Because of the string comparison-based approach, we used a state machine implementation for the application component to model the interaction with the system. Fortunately, *Qt* already offers a versatile state machine API which we could not just incorporate in the study, but also in our application implementation. This implementation also allows context-sensitive gesture-command assignment, which was helpful as gesture 258 is ambiguous for the commands *read message* and *accept contact request*. If the TAO currently used by the user is a message, the state machine assigns gesture 258 with the *read message* command and with *accept contact request* if the used TAO is a contact request. Figure 4.8b depicts

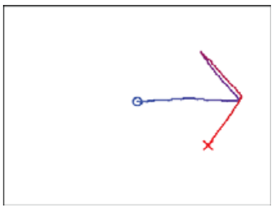
Figure 4.7: Visualizations of rare but all the more interesting gestures that participants performed during the study.



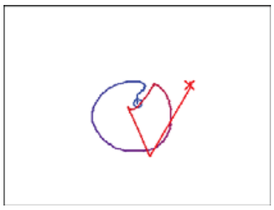
(a) "OK" gesture



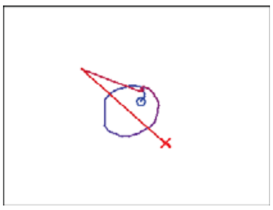
(b) "questionmark" gesture



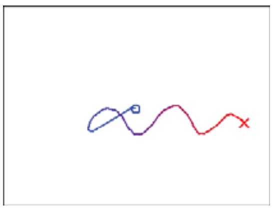
(c) "arrow" gesture



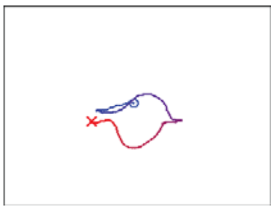
(d) "checked circle" gesture



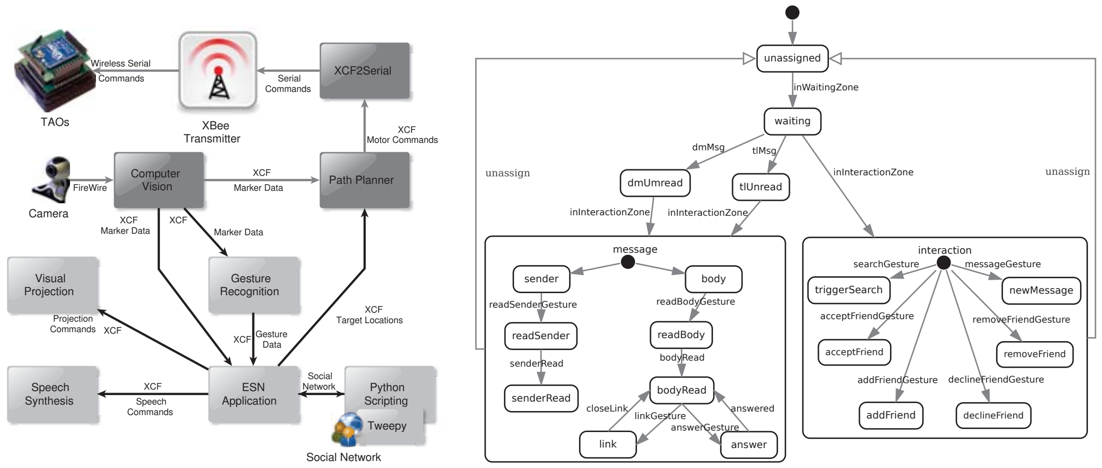
(e) "striked out circle" gesture



(f) "wave" gesture



(g) "mouth" gesture



(a) Collaboration diagram of the software modules including data flow.

(b) State diagram: Transition conditions emit message based events (such as *tlMsg*, indicating that a timeline message was assigned) and location based events (such as *inWaitingArea*, indicating that a TAO is in the waiting area).

Figure 4.8: General software component overview and state machine design of our ESN implementation [172].

the behavior of the TAOs. For each TAO there is an instance of this state machine. As the interface is meant to provide access to one Twitter account at a time, we decided on a single-user interface design. That allowed the design of the graphical interface to be oriented to one side of the tDesk. Having the TAOs waiting at the furthest border of the interactive area of the tDesk and message queues at the sides, left enough space for gestural interaction with the TAOs.

4.5 Interaction Design

Our interaction design approach allows for versatile interaction possibilities. The storyboard depicted in Figure 4.9 and the demonstration video give an insight into the interaction possibilities that covers three examples (*read sender*, *read message* and *answer*) of the implemented 11 actions and how they can fit into the general work-flow. This work-flow follows the same interaction scheme for all commands. In the following, we describe the scheme for the reactive commands:

- On startup all available TAOs are in the *unassigned* state. They automatically switch over

read sender		951	compose message		753
read message		258	add contact		25852
compose answer		456	remove contact		654
open link		14789	accept contact request		258
close link		32147	decline contract request		85258
search		98741			

Table 4.3: Promising candidates for well-fitting command-gesture combinations based on the recognition results of the case study.

to the *waiting* state when placed in the waiting area (see Fig. 4.9a).

- Whenever a message is received from the *Twitter* interfacing component (see Fig. 4.9b), it emits *dmMsg* or *tlMsg* events, which trigger an unassigned TAO to autonomously enqueue into the "direct message" or "timeline message" queue and switch into that particular *unread* state (Fig. 4.9c).
  This behavior inherently reflects the temporal order of the messages within the two queues.
- When the users takes an enqueued TAO to the interaction area, the gesture recognition for this particular TAO is automatically activated and transmits every recognized gesture to the application component. Here the gestures make the state machine switch to the corresponding states which triggers the respective actions (see Figures 4.9d, 4.9f and 4.9h).
- When the TAO's state machine reaches the end transitions *close link* or *answer* from the *message* branch or the end transitions of the *interaction* branch, a timer for an interaction timeout is activated. After that timeout, the TAO's state machine switches to the *unassigned* state which deactivates the TAO's gesture recognition and lets it move back to the waiting area again (Figure 4.9j).
  If messages arrive when all available TAOs are in queues, the messages are stored.
- When a TAO becomes unassigned again and has returned to the waiting area, it directly gets assigned to the next stored message until all stored messages are processed.

Likewise, the interaction works for the action initiating commands when an unassigned TAO is taken from the waiting area to the interaction area: The TAO's state machine activates the gesture recognition, but reacts to other gesture sequences and triggers their corresponding actions.

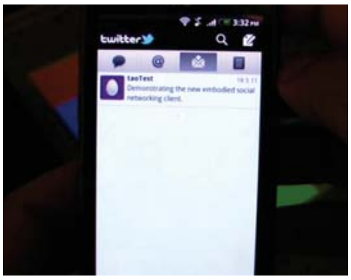
4.6 Discussion

With this study, we only searched for gestures that are applicable in a single-user and task-specific application. In other words, we cannot directly transfer the findings to other applications. This especially applies to multi-user scenarios when the users stand around the tDesk. The system has to respect the users' directions towards the table to correctly rotate the gesture trajectories for recognition, since most of the observed gestures are rotation dependent. Additionally, users wish to be able to alter the gestures as long as there are no standardized gestures. This supports the findings of Wobbrock et al. [216]. Users should also get assistance by the system on what gestures are available, when needed. Finally, one has to keep in mind that conflicts between commands may occur when the same gesture is a well-fitting candidate for different commands.

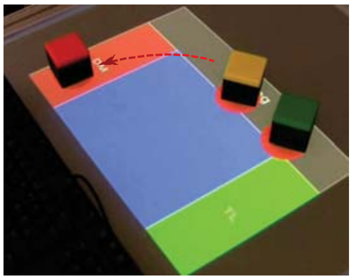
Implementation Critiques

The described implementation is meant solely as a proof-of-concept and to demonstrate the basic ideas. An optimal implementation should feature a larger interaction area embedded into the everyday life environment of potential users. To enable the development of meaningful applicability beyond concept demonstration, the system should also be equipped with more TAOs. Obviously, the gesture recognition has to be replaced in favor of a more versatile and robust recognition approach. To support the recognition component, it is worthwhile to review the necessary commands, since some could be unified and assigned to the same

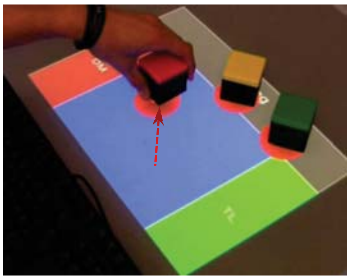
(a) In the initial state of the system, the TAOs stand in the waiting area until new messages are received.



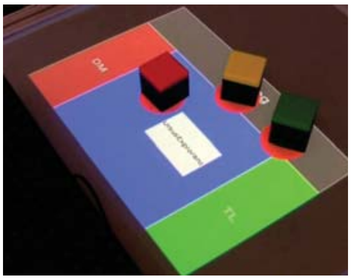
(b) A message has been sent to the social network from a mobile device.



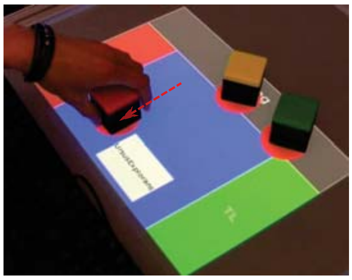
(c) Received by the system, the message gets represented by a TAO which automatically moves to the direct message (DM) queue.



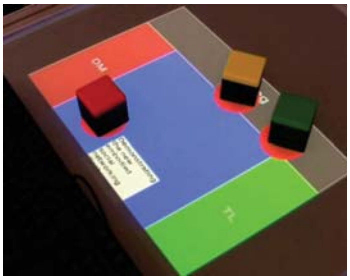
(d) The user takes the TAO from the message queue and performs the *read sender* gesture with it in the interaction area.



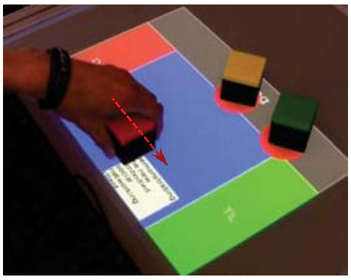
(e) The sender is displayed next to the TAO and read out loud by the system.



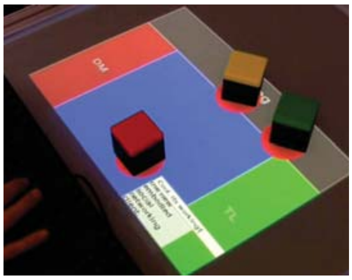
(f) The user performs the *read message* gesture with the TAO.



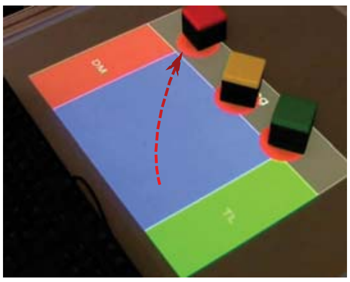
(g) The message content is displayed next to the TAO and read out loud.



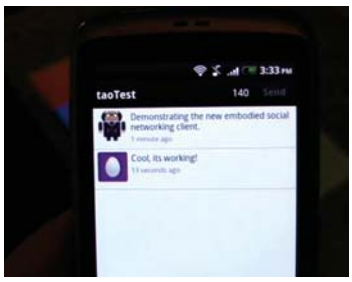
(h) The user performs the *answer* gesture with the TAO.



(i) A text entry widget is displayed next to the TAO and the user enters the answer via keyboard.



(j) After transmitting the answer, the TAO automatically moves back to the waiting area.



(k) The transmitted answer is instantly received on the mobile device.

Figure 4.9: Storyboard of an interaction including triggering of three different actions and performing the associated gestures with a TAO representing a message (stills from the demonstration video).

gestures. An unobtrusive and more appealing graphical design that supports the embeddedness into the working environment of potential users is desirable, as well. Furthermore, the addition of more graphical information without gestural interaction, such as sender, date and time, can ease the workflow with the system. All these proposed improvements can enable long-term studies for investigating the suitability of the system in the user's normal environment.

Younger Related Work

In related publications that appeared after our study was conducted, we found further interesting approaches that definitely show that gestural interaction for (active) TUIs is a promising trend in the field. Just after we finished our work on the ESN, Milosevic et al. published their work on sophisticated smart devices using Inertial Measurement Units (IMUs) and Hidden Markov Models (HMMs) for gesture recognition [142]. Though HMMs require off-line training, we see this approach as a good example for technical improvements. Hoven and Mazalek published a comprehensive survey on gestural interaction including implications for TUIs [80] shortly after our study. Mazalek et al. "considered conceptual, cognitive, and technical dimensions for gestural interaction with tangible active tokens" [138], such as the *Sifteo cubes* [139]. Valdes et al. conducted a study using these active tokens in a participatory design study [201] and elaborated on design space implications. Recently, Angelini et al. even presented a comprehensive "Framework for Tangible Gesture Interactive Systems" [2].

Derived Design Implications

In this section we described how to cope with these issues and what designers of tabletop interfaces with TUIOs supporting gestural interaction should keep in mind.

Multi-user Support

To support multi-user gestural interactions with TUIOs, we basically see two possible solutions. The first and most desirable solution is to technically enable the system to detect which user performed a certain gesture and their orientation to the tabletop surface and then feed it correctly rotated into the gesture recognition. An orientation sensitive gesture recognizer approach was presented by Li [122]. The second approach only supports rotation invariant gestures which look the same regardless of the direction of the performing user towards the tabletop surface. This greatly restricts the number of gestures and does not leave many simple symbols and mnemonics users can easily remember.

Multi-gesture Support

Another helpful aspect is a clever interaction design which may allow for using multiple gestures for one command. Users then would have a variety of gestures from which they can decide which gesture they personally prefer without disturbing other users. Furthermore, we observed different uni-stroke permutations of the "X" gesture (cf. Fig. 4.10), that also supports the findings by Anthony and Wobbrock [4]. We can easily see that execution of gestures based on more complex symbols or metaphors can vary enormously – not only in the number of geometrically possible permutations, but also in terms of number of shifts in direction, area used for performance, accuracy etc.

Learning Gestures

This leads to the next problem of gestural interaction: How do users know which gestures are available and what effect they have? For the case of deployment of the ESN, we propose context sensitive projection of the available commands and their corresponding gestures

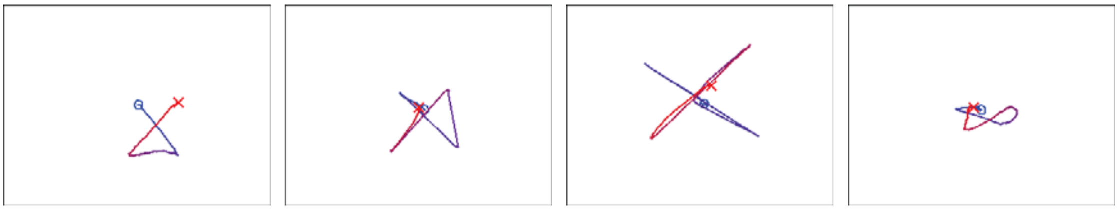


Figure 4.10: Visualizations of examples of “X” gestures that different participants performed during the case study.

behind the interactive area of the tDesk. This would be possible because the area covered by the projector is larger than the interactive area covered by the tDesk's Firewire camera. For systems where the whole tabletop area is interactive, such as the *Samsung SUR40* device, or in multi-user scenarios, one does not want to waste a certain amount of the interactive area just for permanently displaying available commands and their gestures. In this case some kind of tool-tip could be displayed, as they are known from GUIs when hovering the Mouse pointer over a widget which makes the tool-tip pop up with information about the widget. Freeman and Benko [50] presented a similar approach for multi-touch gestural interaction. Such a tool-tip can be displayed on the interactive surface near by a TUIO when it has been touched for a few seconds without further interaction (as a kind of *help* or *explain gestures* gesture). When there is no touch sensing, tool-tips can be displayed for the TUIOs when there is no interaction for a certain amount of time (maybe for all TUIOs at once or sequentially for a few seconds) depending on the application. Also speech output can be utilized as an alternative to visual tool-tips.

Interaction Modeling

Especially for gestural interaction the state machine approach has proven to be very versatile and useful. It allows easy interaction modeling and adaption. Depending on the interaction design, it may even enable the use of the same gesture for different commands and multiple gestures for one command. Our gesture recognition approach utilizing the *LibStroke* is very simple, but obviously not powerful enough to cover all gestures that users perform. Another more versatile recognition approach should be incorporated, supporting full 6 degrees-of-freedom trajectories. This might need further extensions to the TAOs and the system, incorporating a new gesture recognition approach, such as *Protractor3D* by Kratz and Rohs [114].

4.7 Summary and Conclusion

In this chapter we presented a study for collected user-defined gestures for our ESN client with the TAOs by adapting the approach by Wobbrock et al. [216]. Here, we identified candidates for fitting gesture-command combinations after coding and transcribing the collected data and got valuable feedback from the participants that helped us to develop first design guidelines. These were already applied in the first prototype of the ESN client with which we successfully demonstrated the concept of gestural interaction with TAOs. Finally, we could show that the use of gestural interaction with the TAOs is possible and that a reasonable fitting set of gestures was found during the two studies for interaction with a social network. Based on the current results it is hard to say whether users could adapt to such a system embedded into their working environment. Only a long-term study can help to find an exhaustive answer.

5 The Menu Metaphor: An Inner Degree of Freedom for the TAOs

The difficulty in life is the choice.

George Moore, Bending of the Bough, Act IV.

In the last chapter we focused on gestures for triggering actions. The introducing of gestural interaction to TUIs added a valuable interaction mean to the field of Tangible Interaction, in general. But with our findings and design implications of the last chapter in mind, we wanted to strive for a different interaction mean that does not require the user to learn special gestures and also adds value to actuated TUIs. We consider menus in this chapter as an alternative interaction mean for triggering actions.

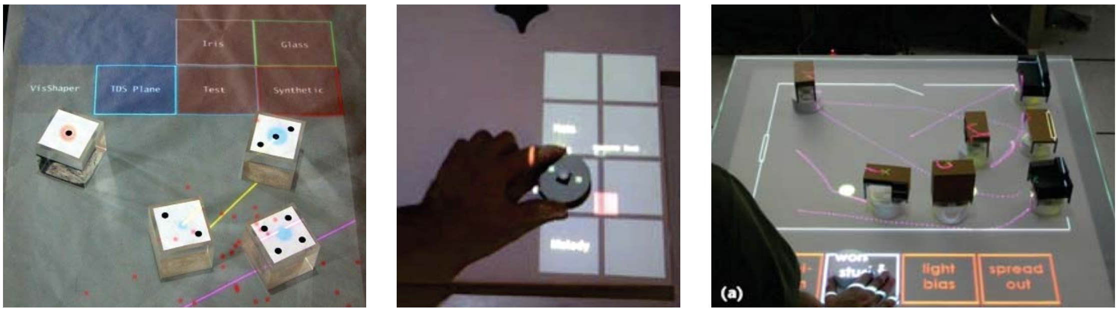
Menus are a widespread interaction pattern; they are well-known by the users and offer rich interaction possibilities for altering values and internal states of digital information. They allow to organize a large number of items that can be used for triggering actions, making systems feature rich. In this chapter we examine different implementations of menu styles, already implemented in table-top TUIs. We identify problems and derive requirements to motivate the development of our own tangible actuated menu metaphor as another possibility for the user to trigger actions. We wanted our approach to be easily understandable and able to represent changing internal states of TUIOs at its best. For this, it has to be actuated and should be incorporated into the TAOs to be embedded into the object of interaction.

As a demonstrator for our approach, we developed saving and restoring mechanisms as a generic extension to existing TUIs, since many TUIs lack the possibility to save the interaction result so that it can be restored later. Through actuated TUIOs these concepts become transferable to TUIs. With another application for furniture placing, we describe further improvements of our implementation. We investigate a menu metaphor for a hybrid application supporting tangible and multi-touch interactions in the frame of a third application for interfacing home entertainment devices. Finally, we address design guidelines with regard to menu design for TUIs.

5.1 Menu Related Interaction Styles in Table-top TUIs

In this section, we review menu related interaction techniques for table-top TUIs, found in literature. By menu related, we mean interaction techniques that are applicable as a menu metaphor, even though that may not always have been the developer's original intention.

Figure 5.1: Examples for space-multiplexed menus in TUIs.



(a) Tool and dataset selection menus behind the interaction surface of the TRecS TUI [32].

(b) Track assignment in the AudioPad system [155].

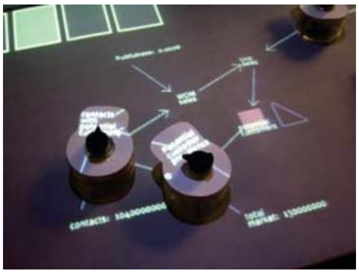
(c) Arrangement selection infront of the actuated TUIOs of the PMD [175].

Space-multiplexed Menus

The first implementations of menus for table-top TUIs were developed in conjunction with the container concept [197], as described in Section 2.3. With the container concept, information and media can be dynamically assigned and unassigned to physical objects. Often, this concept is applied by using space-multiplexed menus, as described by Fitzmaurice et al. [47].
The *TRecS* TUI [32] is an example application which allows to dynamically assign datasets and tools to TUIOs for exploring the datasets, as shown in Figure 5.1a. In this example the users can assign different datasets to particular tangible objects by placing objects in the datasets assignment areas (red) on right, behind the interaction area. In the same way the users can assign data exploration tools to TUIOs. This enables the users to freely decide which of the datasets to explore with which tools (and combinations of tools and datasets at the same time). *AudioPad* by Patten et al. [155] works in the same way. Here different audio tracks can be assigned to TUIOs, as shown in Figure 5.1b.
Dealing with saving and restoring mechanisms as well, the *PMD* by Rosenfeld et al. [175] allows saving object arrangements in space-multiplexed saving slots from which the arrangements can be restored (see Fig. 5.1c).
Though space-multiplexed menus are used by quite a number of systems, they also have some drawbacks. Space-multiplexed menus always require a certain part of the interactive surface to be available for menu item display. Since the menu area is always spatially limited, the number of selectable menu items is limited, too. Often space-multiplexed menus are located at one side of the interactive surface which is not equally reachable by all attendant users in multi-user scenarios.

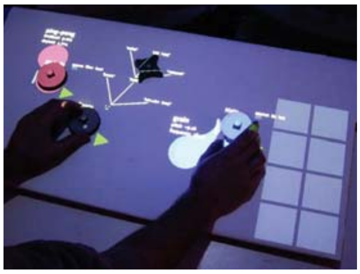
Dial-based Menus

Expanding the definition of menus to the possibility to choose an item or value from a (continuous) list of possible items, the *Sensetable* by Patten et al. [157] is one of the first table-top TUIs that incorporated physical (non-actuated) dials and modifiers. With these dials the users are able to tangibly alter the state or value of the digital information being



(a) *Sensetable* incorporates pucks with physical dials to enable the users to physically change the values of the underlying simulation [157].

(b) Parameter assignment with rotation and finger touch interactions [89].



(c) The *AudioPad* being used [155].

Figure 5.2: Examples for dial-based menus in TUIs.

worked with. The *Sensetable* and its described applications ("Chemistry" and "System Dynamics Simulation") lets users assign TUIOs with a physical dial to properties of the underlying simulation, such as atoms, molecules or populations of predators and prey, as shown in Figure 5.2a. Another example for non-actuated dial-based device which can be used as TUIOs was presented by Bianchi et al. [13].

Though Patten et al. are not really using the dials as a menu, they describe important findings which are helpful for designing tangible menus [157]: Though "users liked the idea of being able to physically manipulate simulation parameters in this manner, they wanted the information about the changes caused by manipulating the dials to be displayed on the sensing surface in addition to being displayed on a screen behind the surface." Since this critique is applicable to TUIs equipped with one or more additional vertical rear displays behind the interactive surface, the second finding is even more important, as it also addresses systems without such additional displays: "Users want graphical feedback near the dials themselves to provide a better sense of what the dial setting was at a particular point in time." Both findings were user criticisms and emphasize the importance of the users' need to get direct feedback upon their actions. After integrating these findings, the users could completely concentrate on interacting with the TUIOs, since the whole interaction frame (input and output) is combined and localized at the TUIO being interacted with. Based on the *Sensetable's* technology, Patten et al. developed the *AudioPad* [155] to explore tangible interaction techniques (see Fig. 5.2c). Further improvements are described in their follow-up publication *Interaction Techniques for Musical Performance* [156]. Though *AudioPad* addresses music performance, the explored interaction techniques are applicable in other contexts, as well. In the first iteration of *AudioPad*, the volume level for each track was controllable by rotating the track's TUIO, just like a dial.

Nulling Problem

Evaluating this approach, Patten et al. observed an effect, Buxton describes as the "nulling problem" [27]. Here, the interface designer has to balance between speed of adjustment and precision (cf. Fitts' Law, Sec. 8.1). In other words, to allow for very precise adjustments of e.g. volume, several revolutions of the TUIO are needed, which is time consuming. Allowing for quicker adjustment by using one revolution for the whole parameter continuum, however,

Figure 5.3: One of *AudioPad's* floating menus [155].

results in less precision.

The *reacTable* by Jordà et al. also supports a dial-based parameter control using touch interaction. "All *reacTable* objects can always be spun, which allows controlling one of their internal parameters; a second parameter is controlled by dragging the finger around the objects' perimeter [..]. Although the exact effect varies from one type of object to the other, rotation tends to be related with frequency or speed and finger dragging with amplitude." [89]

Hierarchical Item Browsing and Selection

As already mentioned, *AudioPad* [155] uses space-multiplexed menus to assign audio tracks with TUIOs, as described above. Beyond this, users can control parameters of the assigned track in different ways.

"Once a track has been associated with a puck, the performer can select from a tree of samples using the [additional] selector puck". The users "can then browse the tree by moving one or both of the pucks". Patten et al. emphasize this effect by arguing with the *Kinematic Chain Model*, described by Guiard [59]. In such "asymmetric two-handed tasks, one's dominant hand acts in the frame of reference provided by the non-dominant hand. For example, when writing with a pen on a piece of paper, right-handed people often orient the paper with their left hand, and this improves their performance in the writing task." [155]

Floating Menus

As a more convenient addition to the space-multiplexed menus described above, Patten et al. introduce the floating menus [156] that enable the users to directly select items related to the current interaction context. This allows for quicker item selection instead of tediously navigating through the available items.

Floating means that the menu moves along with its TUIO. "The important design issue in this interaction is when the menu should move, and when it should be stationary" for selecting an item with the TUIO, as shown in Figure 5.3. "To determine when the menu should move and when it should be still, we define an area surrounding the icons called the selection area[..]. When the puck is inside of this area, the menu stays still to make selection easier. If the puck moves outside of this area for more than 3 seconds, the menu recenters around the puck, such that the currently selected choice from the menu is underneath the puck." [156, Sec. 5.2]

Changing Continuous Parameters

The next two interaction technologies for parameter adjustments are not directly connected to menus, since they are intended for continuous parameter control. Nonetheless, they are partly transferable when the parameter space is quantized (like a volume slider using steps of ten units for increasing or decreasing the volume).
As already described above, the first iteration of *AudioPad* included dial-like volume control by rotating the TUIOs, which turned out to be problematic. In the second iteration [156], a new so-called microphone TUIO was introduced. Now the distance between each track TUIO and the microphone TUIO is mapped to the tracks' volume, much like in *AmbiD* [17] or *TI-Son* [66]. With carefully chosen parameters for the mapping function, this approach turned out to be very fitting and natural for continuous volume control.

Setting Two-dimensional Parameters

Patten et al. experimented with absolute and relative displacement mapping for altering item settings within the *AudioPad* system and realized that the latter is much more natural than absolute mapping. Users naturally verbalize adjustments in relative terms, which the system should support [156]. Furthermore, absolute mapping would interfere with the kinematic chain model and the two-handed tree navigation for sample selection, because only the selection TUIO, not the track's TUIO may be moved when altering a sample without accidentally changing effect settings. As a third effect they also observed that "the effect and volume settings of a track are two conceptually different types of parameters. [But] if absolute puck positioning were used to control effect settings, users might inadvertantly change effect settings while changing volume", which "would suggest a causal link between volume and effects where there is none" intended [155, p. 4]. According to this aspect, Patten et al. argue for the approach by Jacob and Sibert of modeling multidimensional physical interaction related to the perceived structure of the manipulated parameters [83]. Additionally, we identified another benefit of relative mapping: It allows spatial organization and grouping of TUIOs by user given criteria. This supports the users' spatial memory for organizing the interface according to their needs.

5.2 Evaluation of Benefits and Disadvantages of Current Menu Metaphors in TUIs

Viewed from different perspectives all these discussed menu approaches for table-top TUIs showed benefits and disadvantages, as summarized in Table 5.1.
From our point of view, in the discussed TUIs *Space-Multiplexed and Floating Menus* are the simplest approach to implement menus for TUIs. They are relatively easy to implement

Space-Multiplexed and Floating Menus

due to their low complexity and by this they are also quite easy to understand by the users. Unfortunately, space-multiplexed menus are fixed in one particular area of the interactive surface, except for the Floating Menus. Being fixed has four drawbacks: (1) they are space consuming even when not needed, (2) they are spatially limited in the number of items, (3) they are aligned in one direction, e.g. text may be aligned vertically or upside down for some users in multi-user scenarios and (4) they are not equally accessible by all attendant users standing around the table-top TUI.

Dial-based Menus

Like space-multiplexed menus, *Dial-based Menus* are not complex and easy to implement. In comparison, a tangible dial has the advantage of a persistent physical representation, which is widespread and easy to understand. As a drawback, representing a continuous range of values or a big number of menu items, dial-based menus may become imprecise and hard to handle. One solution may be the use of multiple revolutions to widen the dial's range, which in consequence leads to a slower interaction. As long as the number of items is manageable the nulling problem, as discussed above, is not an issue.

Hierarchical Menus

Hierarchical Menus allow very complex menu structures while the needed interaction time increases with the menu's complexity. As a result repeated browsing of the menu gets tedious for the users, especially when time matters. Furthermore, due to the hierarchical item management, the implementation of such menus is more complex than the implementations of the menu metaphors described above.

General Problems

Generally, we observe that the physical dial-based menu metaphor stands out for its persistent tangible representation compared to the other menu styles. Of course, the interaction artifacts are graspable, but the selected menu item or state is not physically represented and recognizable without looking at the visual representation. In other words, using the menu metaphors that require visual monitoring block the visual sense, while the dial's state can be completely estimated with the tactile senses.

Furthermore, it is obvious that the discussed menu metaphors are not actuated in terms of a moving physical object. A system induced selection adaption cannot not be represented and may lead to inconsistency of the physical representations.

5.3 Reference Frames of Menus in TUIs

Interaction Reference Frame

The activity of choosing an item from a menu is an abstract process. As we have seen, this process can be implemented in various ways with different characteristics. One important aspect to identify in terms of tangible interaction is the menu specific *Interaction Reference Frame*, as defined in Section 2.1. This frame denotes the area or place of the reference frame in which the menu interaction takes place. For each menu metaphor we can identify three different interaction frames:

Fixed Reference Frame The interaction frame of space-multiplexed menus often requires a certain amount of space, is locally fixed in position to the interactive surface and relies on a graphical representation.

Graphical TUIO-bound Reference Frame The floating menus and the hierarchical menus offer a still pure graphical, but TUIO-bound interaction frame. This type of interaction

Metaphor	Advantages	Disadvantages
Space-multiplexed (and Floating) Menus	• quick and easy to use • relatively simple implementation	• space consuming • number of items is limited by space • aligned in one direction • interaction frame is locally bound and not equally reachable in multi-user scenario (unless the menu items are arranged in a circle in the center) • necessity of visual monitoring while interacting
Dial-based Menus	• quick and easy to use • persistent physical representation • interaction frame is bound to object	• nulling problem [27] • trade off between speed and accuracy
Hierarchical Item Browsing and Selection	• allows for complex menu structures • interaction activated and relocatable	• requires longer interaction time which is tedious

Table 5.1: An overview of the benefits and disadvantages of the discussed menu metaphors.

frame is more dynamic since it is relocatable with its TUIO, but still completely part of the interaction surface because of the graphical representation.

Physical TUIO-bound Reference Frame Physical dial-based menus are always localized at the TUIO and through its tangible physicality it is not necessarily dependent from a graphical representation.

These observed forms of reference frames (and their benefits and disadvantages, as discussed below) are worth to be kept in mind when designing menu metaphors.

5.4 Design and Implementation of our Tangible Actuated Menu Metaphor

Based on the discussed criteria, problems and observations, we can define the desirable characteristics of a menu metaphor that is generically suitable for most TUI use-cases.

First of all, such a menu metaphor should not be bound to a particular area on the interaction surface to make it relocatable and accessible to all attendant users. With potential multi-user scenarios in mind, the menu metaphor should be rotation invariant. This implies abandoning text items which is not always possible. In these cases, the text's rotation must

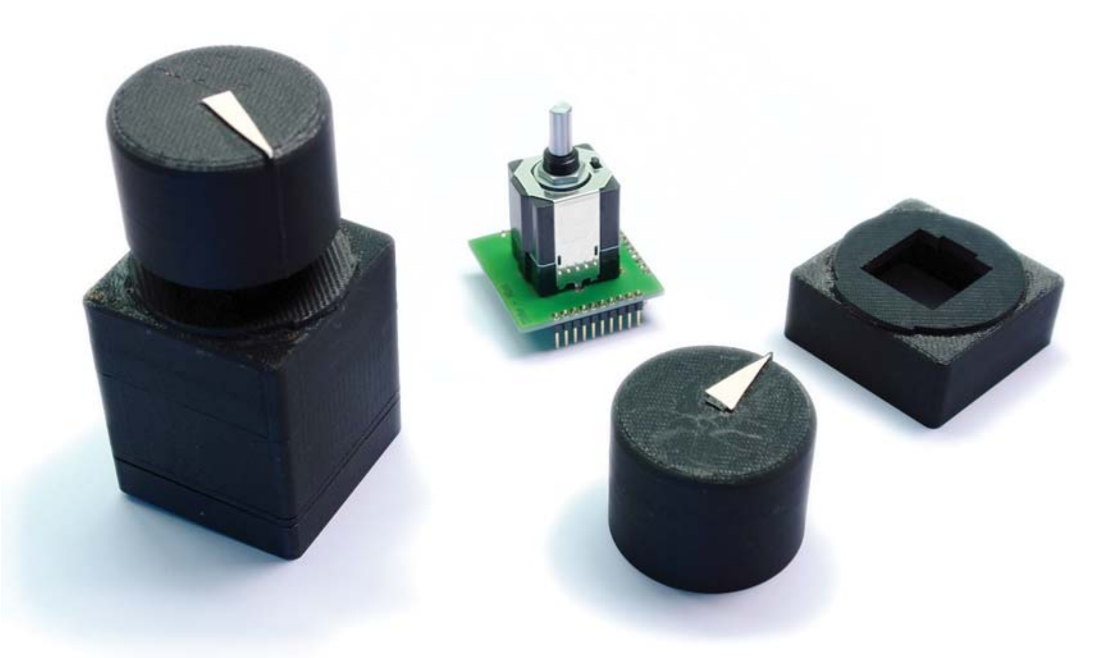


Figure 5.4: Am assembled mTAO and the assembly parts of the actuated tangible dial.

be interactively adjustable to make it easily readable for all users. Preferably, it should not consume too much space when the menu is not used in order to leave sufficient space for other interactions. A persistent physical representation which is stable over time during interaction is preferable to obtain correctness of the data representation. Obviously, the physical interaction reference frame is most desirable for tangible menu metaphors. It follows the basic tenor of tangible interaction and allows pure tactile interaction while looking at other aspects of the system or naturally speaking to another user with eye contact. We call our implementation Menu TAO (mTAO).

Hardware Extension and Implementation

In order to meet as many of the above stated requirements as possible, we decided on a dial-based approach. A motor-potentiometer can be used to implement an actuated and tangible menu metaphor with a physical TUIO-bound reference frame for the menu interaction.

We decided on an *ALPS RK25T11M*, a linear high-speed motor potentiometer with a resistance of $10k\Omega$ and $300°/s$ maximal rotational speed. Furthermore, this potentiometer features touch sensing, which we disregarded at this stage. Beside the PCB with the motorized potentiometer, we also designed an additional housing part and a dial knob with a tactile pointer, that was manufactured with a rapid-prototyping printer.

The firmware was extended to transmit angle changes of the dial after a given threshold has been exceeded. This limits communication between host computer and the mTAOs to a minimum. The motor of the potentiometer is controlled by a Proportional–Integral–Derivative (PID) controller, solely implemented on the *Arduino*. Again, this approach significantly reduces the traffic between host computer and mTAO.

Since the motorized potentiometer has given limits for the possible angle and is not completely revolvable, there is no need to avoid the nulling problem. As a drawback, these revolution limits also limit the number of easily and precisely selectable menu items (estimated to 10 to 15 items). To allow more items than possible with one revolution, a hierarchical approach can be incorporated to solve this problem with the actuated dial.

Software Extensions for Menu Control

To manage and control the menu functions and to provide the other software components of the TAO architecture with high-level control, a special component for menu control has been developed. The component encapsulates all low-level control, such as item selection management, hardware control and monitoring (including touch) and optional speech output as an additional interaction modality. The high-level menu control provides interfaces for *a*) reading pre-configured menu files in XML format and *b*) setting a particular menu item. It emits events to the middleware when *a*) a menu item has been selected, or *b*) a TAO's dial has been touched.

According to the basic design of the display component of the TAO architecture, an mTAO's non-tangible representation can easily be extended with visual feedback for the dial. We derived a new base class from the basic TAO visualization, that already comes with all attributes and methods to visualize menus. This visualization class provides proper display of the menu items (text or image), a visual extension of the dial's pointer as an additional anchor between physical and visual representation and highlights selected menu items – all correctly positioned and oriented at the mTAOs' positions.

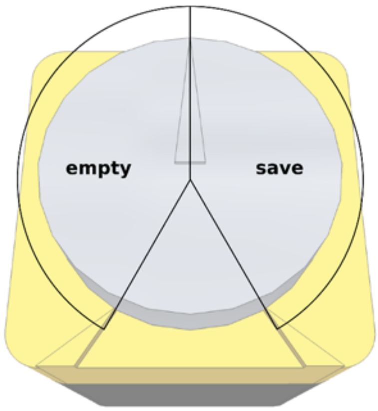
5.5 Applications and their Interaction Designs

As a proof-of-concept, we tested the dial in two applications, one generic for extending existing TUIs with saving and restoring mechanisms and a second one for collaborative remote interior design. In a third application acting as a hybrid interface combining passive TUIOs with TAOs on a multi-touch table, we reviewed a touch-based dial menu.

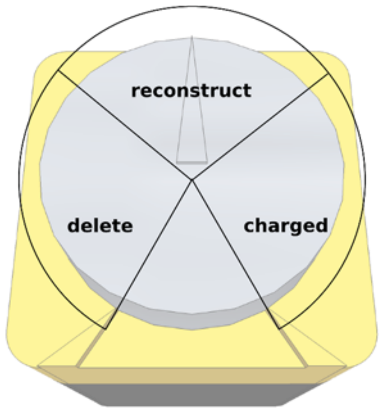
Saving and Restoring TAO Arrangements

We already pointed out in Section 2.4 that many TUIs lack saving and restoring mechanisms to preserve the current state of work for later continuation – or more precisely: the arrangements of TUIOs on the tabletop surface. Only the *PMD* by Rosenfeld et al. [175] implements a solution for this problem, whereas systems implementing actuated TUIs as described in Section 3.1 at least offer the necessary technology for a solution. In our solution, we utilized our tangible and actuated dial-based menu metaphor to extend existing TUIs supporting the *TUIO Protocol* with such mechanisms, as touched earlier [173]. Here, we used the actuated dial as a fully integrated tangible menu metaphor that does not depend on an additional graphical user interface and thereby is included in the tangible interaction. Figure 5.5 shows

Figure 5.5: Menu layouts for the *empty* and the *charged* states [173].



(a) The mTAOs's menu in the *empty* state have two menu items: *empty* and *save*.



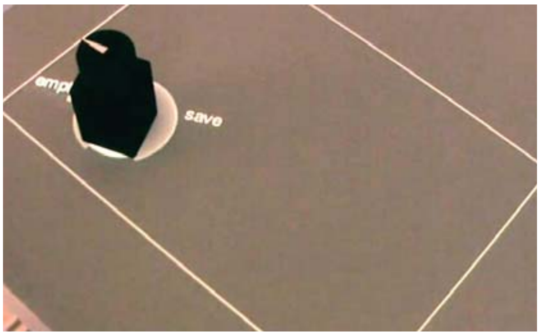
(b) The mTAOs's menu in the *charged* state have three menu items: *delete*, *reconstruct* and *charged*.

the menu item distribution for the two states, we introduced for the dial TAOs according to the container-concept by Ullmer and Ishii [197].

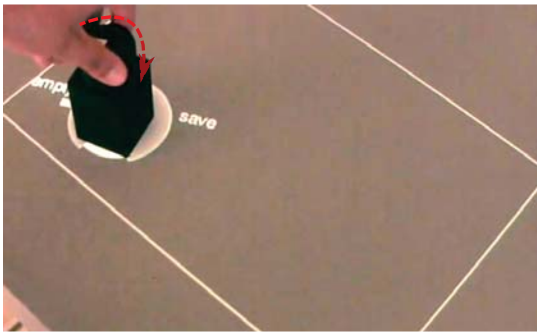
Interaction Sketch

In Figure 5.6 we depict the typical interaction with the saving and restoring mechanism using a single mTAO. After initial start-up, the mTAOs are in the *empty* state. It indicates that there is no TAO arrangement assigned to the mTAOs, as depicted in Figure 5.6a. The dial represents this state by turning its pointer to the *empty* state on the left half. To save the current TAO arrangement, the user has to turn the mTAO's dial to the *save* menu item on the right (see Fig. 5.6b). The arrangement is stored in a file with the mTAO's internal system ID as the file name for persistence. Beside visual feedback, speech output also reflects this aurally as an additional feedback modality, since there might be other applications, where there is the need for monitoring other things or processes visually. When an arrangement of TAOs is assigned (saved) to an mTAO, its context sensitive menu changes according to this new state, as shown in Figure 5.6c): Starting on the most right menu item and going counterclockwise, there is the *charged* item as the first item, where the *save* menu item was before (see Fig. 5.6d). The next menu item is the *reconstruct* item. Choosing this item starts the reconstruction of the TAO arrangement, saved earlier and triggers the TAOs to automatically move back to their saved positions. After choosing the *reconstruct* item, the dial automatically turns back to the *charged* item to represent the mTAO's state, as depicted in the Figures 5.6d to 5.6f. The third and most left item in the menu of the *charged* state is the *delete* item. Rotating the dial to select this item deletes the associated arrangement and the menu layout changes back to the *empty* menu. As a result, the dial has not to be automatically re-adjusted by the system, since it now points to the *empty* menu item, as shown in the Figures 5.6g and 5.6h. When a user deletes a stored arrangement, the dial is moved to the most left position. By this, the dial is already released at the menu item reflecting the *empty* state in the menu layout of an unassigned mTAO.

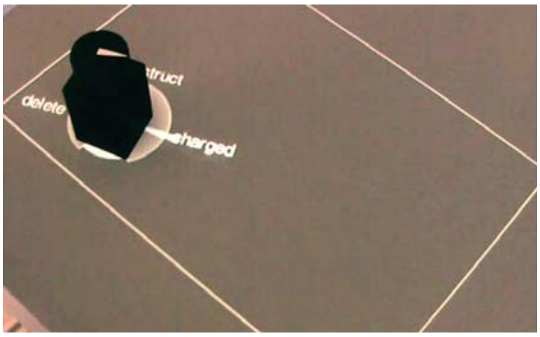
In this generic approach, the positions and orientation of all TAOs (including the mTAO) is saved and associated with the mTAOs. To save multiple arrangements, multiple mTAOs must be used, since one mTAO saves a single arrangement. As a result, each mTAO serves



(a) An empty mTAO on the interactive surface.

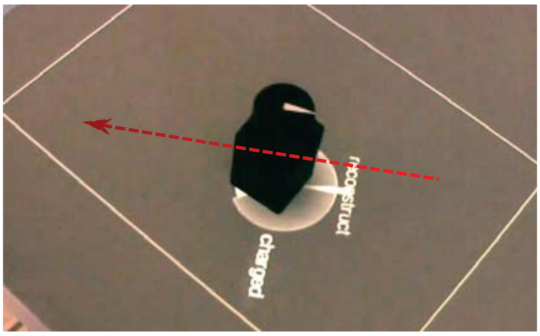


(b) The user saves the arrangement by selecting the mTAO's *save* item.

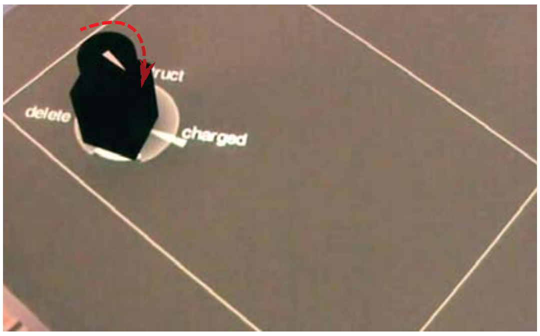


(c) The mTAO's menu has changed to reflect the new *charged* state.

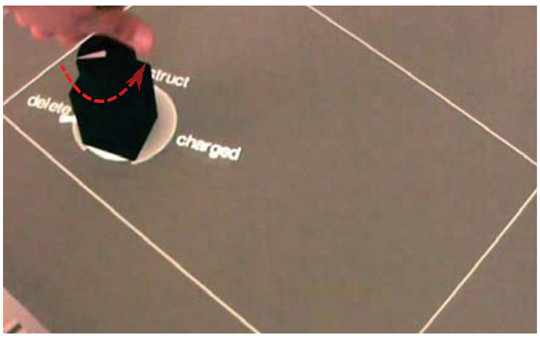
(d) The user has altered the arrangement and orders the mTAO to load the old one.



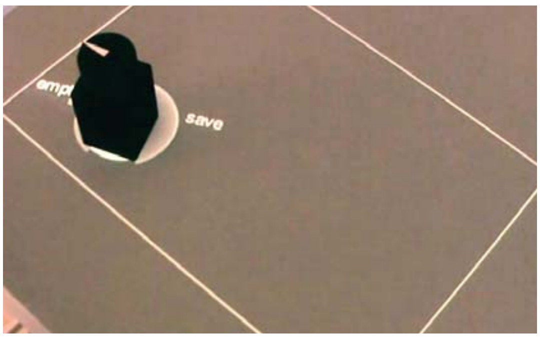
(e) The TAO automatically moves back to its stored position and orientation.



(f) It has reached the stored state. Furthermore, the dial automatically turns back to the *charged* menu item.



(g) The user deletes the stored arrangement.



(h) The mTAO's menu changes back to the *empty* state.

Figure 5.6: A demonstration sequence of the basic interaction pattern of the save and restore mechanism. For better understandability, only one mTAO is shown. The interaction also works with multiple TAOs (stills from the demonstration video).

as a graspable representation for one particular arrangement. A sequence of pictures demonstrating this interaction pattern is given in Figure 5.6. With this rather simple interaction design we were able to demonstrate a generic working prototype with which we could easily extend existing TUIs with saving and restoring mechanisms. As long as the whole interaction state of the TUI is represented solely by the TAOs' arrangement and the represented data is statically bound to the TAOs without using the container concept (cf. Sec. 2.3), the state is directly savable to mTAOs. Otherwise, when the TAOs' digital representations can be altered by the users, the system's internal state changes. As a consequence these alterations need to be recorded and replayed, as well, or otherwise taken care of when it comes to saving and restoring such dynamic system states.

Figure 5.7 shows another storyboard with an actual demonstrator application where an existign (passive) TUI, the *AudioDome Soundblox* engine [19] was extended with our generic save and restore approach using the mTAOs. The storyboard shows how our interaction pattern works for multiple TAOs simultaneously.

Using the mTAO for Altering the State of Non-tangible Representations

In a furniture placing application in a remote collaborative scenario (described in Chapter 6) we use the menu to alter the TAOs' represented information. The interaction surface shows a plan of an apartment (or rooms of such) and each mTAO equipped with a dial represents a piece of furniture. The system features a special function TAO without a dial that acts as an 'avatar' representation of the user and thereby allows to virtually walk through the apartment and changing the perspective of an additional rendering of a three-dimensional scene on a vertical display behind the interaction surface. Virtual models of pieces of furniture represented by the mTAOs can be changed by selecting a new model from the mTAO's dial menu. The menu approach described in the previous section has some minor drawbacks, which we want to address within the frame of this application.

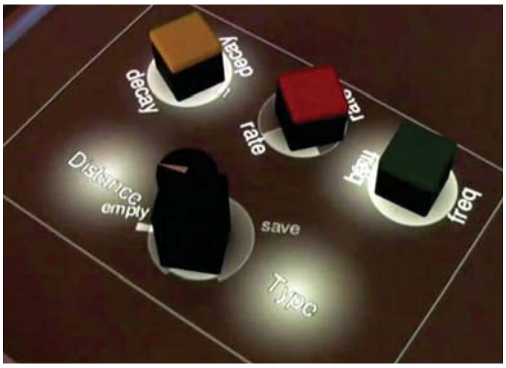
Temporal Availability

Since this application features a rich graphic display, as depicted in Figure 5.8, the menu would unnecessarily hide parts of the rendered graphics in the proximity of the mTAOs and thereby important information including parts of the apartment's plan and the renderings of the mTAOs pieces of furniture. To overcome this issue, we made the rendering of the mTAOs' menu disappear after a few seconds of disuse and reappear after the dial has been turned for a certain amount (so the menu does not appear by slight accidental rotation during placing the mTAOs).

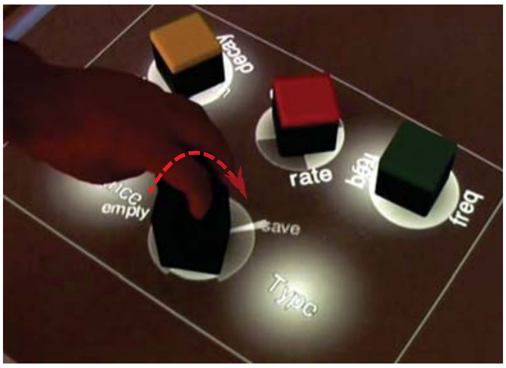
Rotation Invariant Rendering of Menu Items

Obviously, the textual renderings of the menu items in the saving and restoring application are sometimes hard to read, because for some users the text may be rendered upside down. Of course, the particular mTAO can easily be turned to have better readability of the menu items, but then other users again might have problems reading them. Furthermore, the orientation of the mTAOs is important for the represented data in this application, such as having a chair unintentionally facing a wall instead of a table. Here is a need for a different solution. As a consequence, it is desirable to use a rendering for the menu items that is understandable from all viewing angles wherever this is possible. A first approach can be

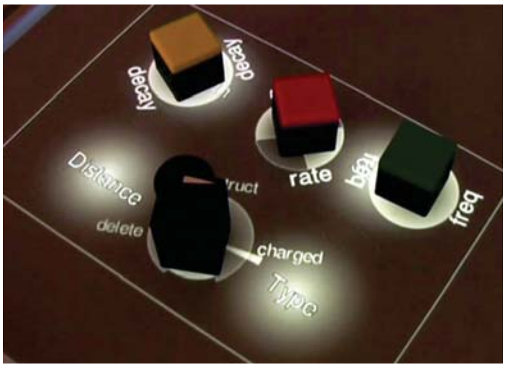
Figure 5.7: A second demonstration sequence of the basic interaction pattern of the save and restore mechanism with an actual application. Now three normal TAOs and one mTAO are involved (stills from the demonstration video).



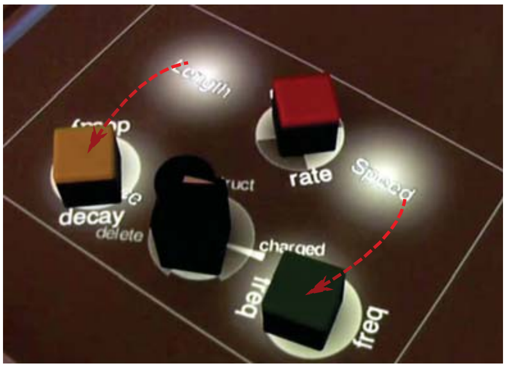
(a) Running system with four TAOs (one mTAO).



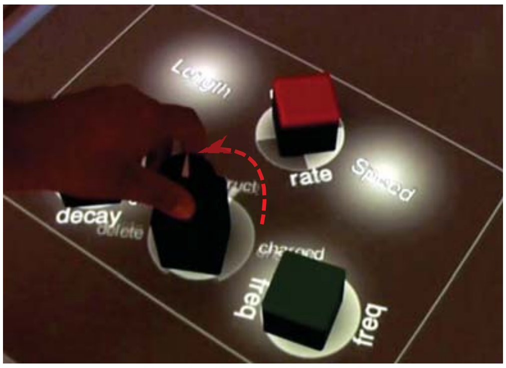
(b) The user saves the current state for later usage.



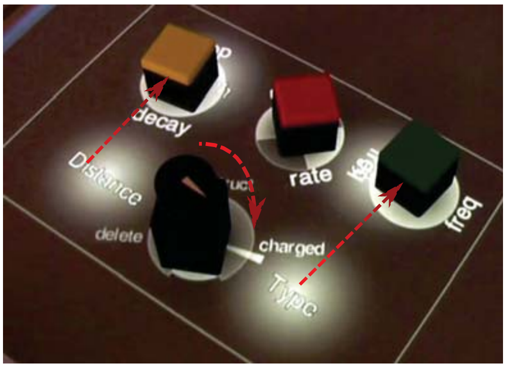
(c) The mTAO's menu reflects the saved state with a changed menu.



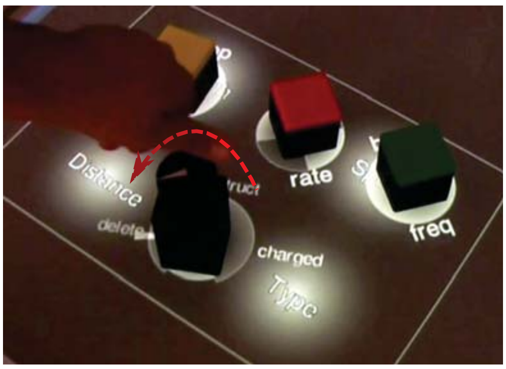
(d) The user has changed the arrangement.



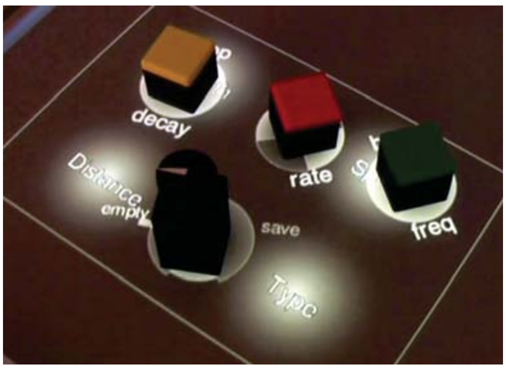
(e) The user choses the *reconstruct* menu item.



(f) The two displaced TAOs move back to their saved positions.



(g) The user deletes the formerly saved state.



(h) The mTAO has deleted saved state.

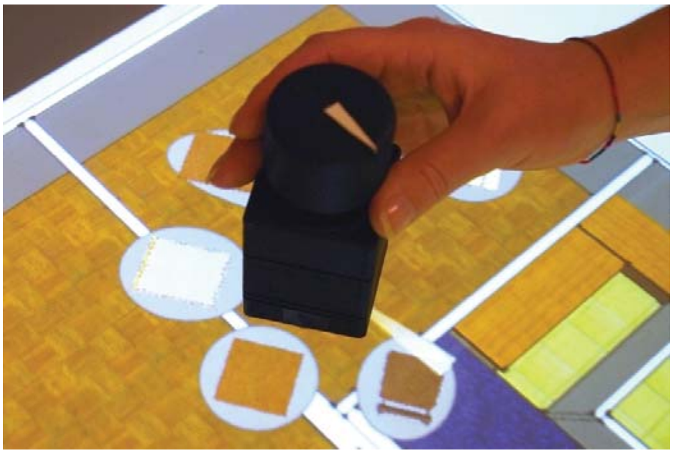


Figure 5.8: Menu with pictures as menu items in the remote collaborative furniture placing application.

the use of icons as they are used in conventional GUI applications. Icons may be easier to recognize as text, even if they are rendered upside down, but it is worthwhile to find an even better graphical representation for the menu items which is recognizable independently of its orientation. For the interior design application this was quite easy (see Fig. 5.8). Since the plan of the apartment is rendered as a top view, it is natural to render the menu items' models of the pieces of furniture from a bird's eye view. Because it is natural to rotate a piece of furniture when rearranging it in the map, the rendered menu items remain recognizable, much like a map that remains readable even if it is held upside down.

Actuated Space-multiplexed Menus for TUIs

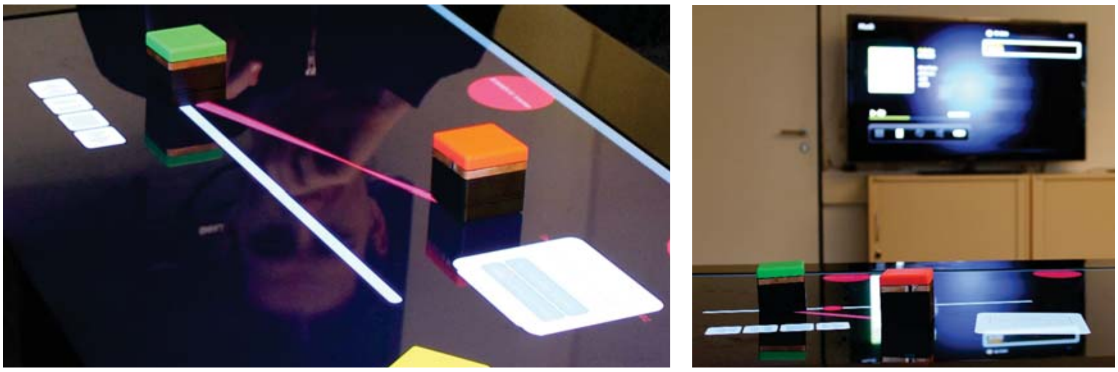
Beside our actuated dial-based approach for tangible menus, actuation can also be used in conventional space-multiplexed menus like those described in Section 5.1. Within the Active Home EntertAinment Desk (AHEAD), as described in Section 9.4, we implemented an interaction pattern that utilizes the TAOs's actuation to reflect the progress of a media file played back by the system (see Fig. 5.9a). By re-placing the playback TAO on its progress bar, the users can change the playback position or even jump to chapter marks (if available) of a movie being played back by the system. Like for space-multiplexed or floating menus, this menu interaction pattern can have different reference frames. This can be fixed to the interactive surface and aligned to one of the two main axes or, in case of our AHEAD system, it can be fixed to the respective TUIO and can be moved with it.

Beyond Actuation: Menu Metaphors for Hybrid User Interfaces

With the AHEAD, we adapted three further menu-like interaction patterns with hybrid user interaction in mind, combining multi-touch with passive TUIOs and our active TAOs. In the recent development iteration of AHEAD we used a full featured multi-touch table, which features visually tracking of fingertips, whole hands and objects at the same time.

Touch-based Dial Menus

We decided to use the TAOs in their standard configuration without the actuated dial and implemented the dial approach using touch, very much like the *reacTable* [89]. We im-



(a) Detail view of the actuated space-multiplexed menu. The green playback TAO moves along the light blue diagonal bar to reflect the playback position of the currently played media file represented by the red TAO.

(b) The AHEAD system connected to a smart TV.

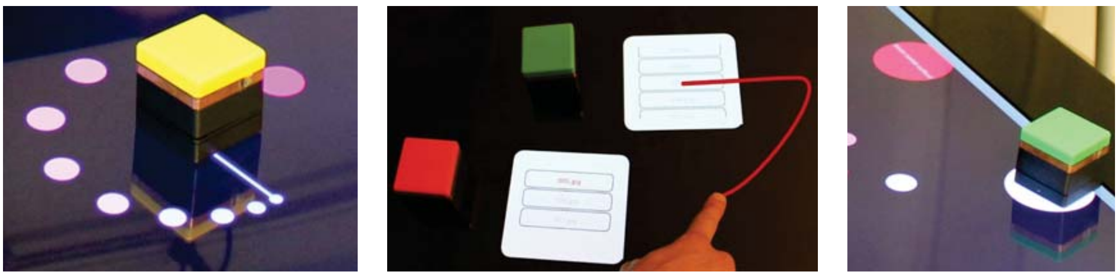
Figure 5.9: Pictures of the actuated space-multiplexed menu implemented in the AHEAD system.

plemented it as an interactive rendering on the interaction surface for volume control, as depicted in Figure 5.10a. The volume control menu is based on the well-known dial approach, where the volume control dial is turned clockwise to increase the volume and vice versa. Its menu items' graphical design supports this metaphor by rendering circles fading from blue to red with slightly increasing diameter; the higher the volume, the bigger the menu item's circle. In this way, the user who wants to change the volume can grab the volume control TUIO, orient it appropriately to his or her needs and easily adjusts the volume by touching the particular menu item.

In the middle of the second part of the AHEAD project, Catalá et al. published a very similar, though not actuated, approach implementing a touch-based dial menu [29].

Personal Menus and Personal Interaction Space

AHEAD enables the users to create and manage playlists associated with TUIOs. The system is designed to provide each user with one or more playlists and their representing TUIO. A playlist is rendered on the right of a TUIO and lists the contained titles. With simple touch-based swipe gestures, items can be browsed, transferred between playlist TUIOs, or deleted, as shown in Figure 5.10b. Since the rendered list menu addresses a single user at the



(a) The multi-touch implementation of the volume control menu.

(b) Two playlist TAOs with their touch-enabled list menus.

(c) The dynamic space-multiplexed menu for assigning devices.

Figure 5.10: The three adapted menu stiles in the AHEAD system.

same time and the interaction with the menu itself takes place solely in the user's personal interaction space (cf. Sections 2.1 and 7.4), there is no need for rotation invariant display. This allows the use of text for the menu items.

Dynamic Space-multiplexed Menus

As we have already seen, space-multiplexed menus are an easy-to-use menu metaphor for dynamically assigning information to TUIOs according to the container concept [194]. Since one of the biggest observed drawbacks is the space consumption, we explored an extension to this kind of menu to save as much space as possible. In AHEAD, we use this menu metaphor to assign representations for media sources, but the number of menu items automatically adapts to the number of available unassigned media sources.

So far, the three presented adaptations of menu metaphors for hybrid user interfaces serve as a working proof-of-concept starting point for future research directions.

5.6 Design Guidelines

Drawbacks

Interaction designers have to decide on the menu style according to the application or task and the number of menu items to represent. Our actuated dial-based menu metaphor, we described in this chapter, is an appropriate solution for menus with up to approximately ten menu items. For a larger number of items, it gets harder for the users (and the actuation feature of the dial) to quickly and correctly select the desired menu item. Here, other approaches, such as a dial that allows for multiple revolutions may help. But also this approach has its drawbacks: the nulling-problem. If the technical (design) frame allows for this different approach, a scrollable list might be helpful. A definite generic solution still needs to be found and investigated.

Nulling

When it comes to multiple revolutions, because of too many menu items, dial-based menus suffer from the nulling problem [27]. To be able to precisely select the desired menu item, the users have to revolve the dial multiple times in the worst case. This is time-consuming and tedious and often disliked by users. Furthermore, a dial allowing multiple revolutions has no natural start and stop marker. Consequently, the users may get lost in the multitude of menu items. Often, such as for volume, the data represented by the dial is not a (mathematical) ring. This may cause huge jumps in the manipulated parameter when the end is reached and continued at the start of the continuous parameter interval. If the menu does not allow for such jumps, this may cause confusion when the system stops to respond to the manipulation when a border of the interval is met without providing a tactile start or stop position.

Display and Perception of the Menu

We have seen that the representation of a menu is important for the users. For the graphical representation text should be avoided in multi-user scenarios or when the orientation of the mTAO is important for the task. In such cases pictures instead of text ease the reading of the menu items even if they are displayed upside-down. According to the observed interaction frame, all menu-relevant information should be displayed at the menu itself to allow the users to concentrate on their interaction with the menu. If there is a need for eyes-free manipulation, the tactile representation also plays a huge role when the menu has a physical representation. Orientation markers at the dial and start and stop markers at the housing help the users to precisely manipulate the menu – even without the need to visually monitor their interaction. Speech feedback also supports the users in eyes-free interaction. It makes menu items with pictures easier to understand when they are not self-explanatory. In other words, speech output can serve as textual representation without the need to read text that may be displayed upside-down.

Multi-user Design

Depending on the task and user scenario, the designer may consider the use of personal menus in the users' personal interaction space. An interaction reference frame that only affects the direct vicinity of the menu (without dependence on other views or other users), allows the users to pay attention to the menu manipulation without any restrictions. Furthermore, when multiple users are involved in the interaction with a menu, such a design enables the users to focus on the menu and their conversation without any distraction. We discuss this shared personal interaction space concept in detail in Chapter 7.

Context Sensitivity and Availability

When the interaction with the menu is not the core aspect of the general task of the application, it should behave as conservatively, as possible. For instance, by displaying the available menu items, only when a user interacts with the menu leaves more space for displaying task-relevant information. Furthermore, dynamic and context sensitive adaption of the menu regardless of its style, is desirable. In the generic application for saving and restoring arrangements with the actuated dial-based menu and in the AHEAD application using space-multiplexed menus, this adaptability reduced the number of needed menu items and saved interaction space. The floating menus of the *Sensetable* has similar features. Consequently, this may enable the users to quickly grasp the relevant information, to easily make decisions.

5.7 Conclusion

In this chapter we considered the concept of menus for use with the TAOs and passive TUIOs, as well. We reviewed the menu interaction styles and metaphors for TUIs found in literature and qualitatively evaluated them. Beside identifying benefits and disadvantages of the different approaches, we found several reference frames for the different implementations of menu interactions. Based on these findings, we described our approach for a dial-based object-bound actuated menu metaphor that was implementation with the mTAOs. Within two different applications (the save and restore mechanism and the interior design application), we successfully tested our implementation and qualitatively observed first indications of our implications. For our media control application we also implemented an actuated space-multiplexed menu interaction pattern. As the latter AHEAD system is a hybrid system also incorporating multi-touch interaction, we transferred our menu approaches to touch-based interaction and observed potential opportunities for menu design and dynamic space-multiplexed menus.

The decision for a particular menu interaction style and for the combinations of possible ways of implementations strongly depends on the number of users (single-user or multi-user oriented menu interactions) and the need for collaboration support, the application and of course the available technologies. Here, actuated tangible menu interaction patterns offer great opportunities for remote collaboration which is covered in the following chapter. The highlighted benefits and disadvantages of the reviewed menu metaphors and the derived design implications are meant to sensitize the interface designers to consider the criteria of the various interaction styles.

Possible adaption and recombination of the discussed interaction styles makes our actuated dial-based menu metaphor even applicable beyond the use of menus. For instance, it can be used within an implementation of the family system test (FAST) after Gehring and Wyler [53], where each mTAO could represent a member of a family. With its inner degree of freedom offered by the dial, mTAOs offer the possibility to represent spatial relations, such as distance, orientation, view, between persons, by characterizing them with their head orientation. With this metaphor, each member of the family can easily describe his or her view of the relationships within the family, as sketched in an earlier publication [173].

Furthermore, the possibility for hybrid systems demands systematic evaluation of the recently described new implementations of the different menu metaphors against established techniques within a comparative study similar to our study described in Chapter 7. As a new research direction, the AHEAD system is suitable both for trial-based studies, as well as for long-term investigations. However, our actuated menu interaction patterns greatly contribute to the field of actuated TUIs.

6 Remote Collaboration and Multi-modal Interaction

Making interaction rich and interesting to the user is one major aim for table-top TUIs. An important milestone towards general-purpose TUIs is a variety of interaction modalities that allow the presentation of information that is both easy to understand and appealing. Within this chapter we describe the development of a sophisticated mixture of multi-modal feedback, such as visual, auditory and tactile feedback. Furthermore, we add advanced features to our TAO architecture, as described earlier [170]. As an example application for demonstrating and discussing these extensions, we chose a furniture placing task. In this approach we combine into one system ideas from related works together with additional features. We strongly believe that a rich set of modalities and features widens the applicability of tangible interaction. We believe that sophisticated and integrated combinations of multiple approaches and interaction possibilities actuated TUIs can to pull TUIs out of the niche of special-purpose applications. Thus this application serves as a feasibility study for reasonable possibilities of integrating different modalities into one system. Additionally, this proof-of-concept implementation serves as a stress test for our TAO architecture, as it means high demand for the communication structure between the involved software components.

6.1 Related Work

Distributed Collaboration with TUIs

One of the first actuated TUIs described in literature that deals with distributed collaboration is the *PSyBench* by Brave et al. [21] (see Sec. 3.1). Two electronic chessboards extended with sensing technology allow the synchronization of positions of magnetic TUIOs over distance. Brave et al. built the *PSyBench* as a "generic shared physical workspace across distance" for "Tangible Interface applications, such as *Illuminating Light*." [21] In their paper discussing the *actuated workbench* [152], a system using magnetic forces to actuate tangible objects, Pangaro et al. state that their system could be used in remote collaboration tasks. Mostly dealing with technical details about the system, they only briefly argue for "synchronizing multiple physically separated workbench stations." [152] Later in 2007, Richter et al. presented the *RATI* [166]. Also dealing with a furniture placement task, they describe the *RATI* as an enhancement of the *Augmented Coliseum* by Kojima et al. [109] (see Sec. 3.1). By adding a custom XML messaging protocol they were able "to allow multiple instances of the application to communicate with each other over a network." [166] The development of the *RATI* described by Richter et al. only incorporated two sides (tables) with one robot, each. A new version of *RATI* by Furuhira et al. [52] allows interaction between three tables with six robots, each [145, 160]. They also describe enhancements made to the robots, such as using Bluetooth instead of WiFi communication and DC motors instead of stepper motors. This allowed them to reduce the robots' size and change to a cylindrical shape which makes them easy to grasp and manipulate.

Interiour Design

Rosenfeld et al. also deal with furniture placement in their *PMD* which is able to save and restore different furniture arrangements [175]. It projects a minimalistic map of an apartment on the system's interactive surface and has physical models of furniture assembled on top of their robots. This setup serves as a proof-of-concept application for interior design with an actuated tabletop TUI. The first actuated and networked TUI dealing with furniture placement featuring an additional 3D view of the manipulated scene is the already mentioned *RATI* by Richter et al. [166]. Later Furuhira et al. extended the system in the frame of a game application. The system's 3D view "provided users with a simple front-on perspective of the room." Furthermore, the authors describe the *costume* concept which is comparable to the container concept by Ullmer and Ishii [197] (see Sec. 2.3). The *costume* concept allows the system's robot to be switched between the pieces of furniture by simply putting it on the particular graphical representation. An association between the robot and the graphical representation is then established which allows physical interaction with the virtual model. We refer to this concept as *soft coupling*. This interaction is synchronized to the other networked TUI via a custom XML network protocol. The *KOMME®Z* project used both the *Mixed-Reality Interface (MRI)* and the *tangible workbench*, an extended version of the *MRI* with changeable markers [97, 200]. Both systems are tabletop TUIs with passive TUIOs. They feature a sophisticated perspective view which can be adjusted through the addition of a user-controlled camera TUIO. Uray et al. and Kienzl et al. name architectural visualization as one application for the *MRI* and the *tangible workbench*.

Constraints and Relations between TUIOs

Physical constraints in TUIs in general have been framed in a paradigm almost simultaneously by Shaer et al. [187] and Ullmer et al. [198] (cf. Sec. 2.3). Here the term is used to describe physical constraints that limit the interaction space of TUIOs. The same idea has been picked up in the frame of actuated TUIs by Patten and Ishii in their PICO system [154]. Mechanical constraints limit the interaction space of the actuated TUIOs that represent entities in a computational optimization process. The users can interactively influence and control this process by manipulating and constraining the TUIOs. The definition of virtual constraints of relations between TUIOs has been described by Pedersen and Hornbæk in their *Tangible Bots* project [158]. Here the users can interactively define groups of actuated TUIOs through multi-touch interaction and manipulate them simultaneously by interacting with a single member of the group.

Vibro-tactile Feedback

Vibro-tactile feedback in active interaction device was already presented [13], though they did not present any elaborate TUIs application.

6.2 Extensions

To create a sophisticated system that integrates multiple interaction modalities and features from approaches found in literature, the TAOs' architecture was massively enhanced. The

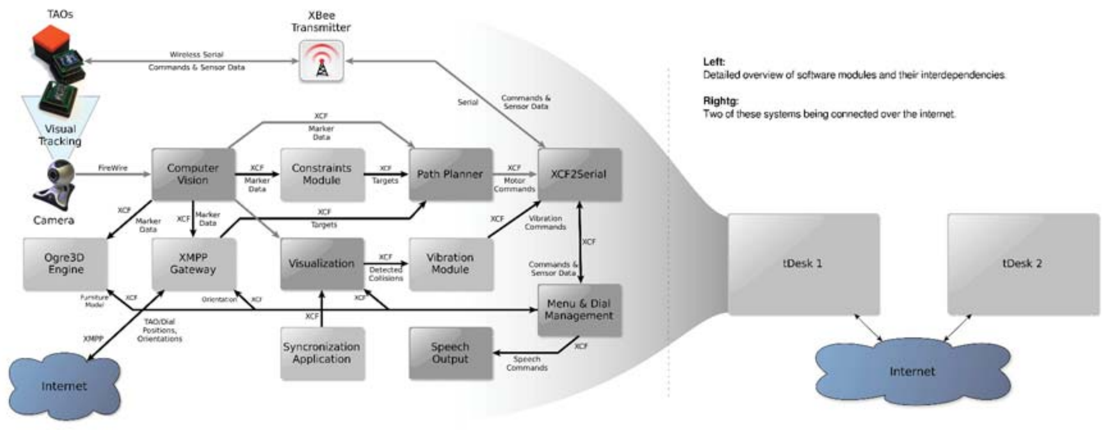


Figure 6.1: Software collaboration diagram. The core modules are printed in dark gray, the additional modules are printed in light gray [170].

most important enhancements are described in this section. Figure 6.1 gives an overview of the interaction between the involved components. We included an additional 3D view of the two-dimensional view projected on the tDesk's interactive surface, that is adjustable through a camera TAO. The distributed collaboration component synchronizes two tDesks over the Internet. We also incorporated relations between furniture models as virtual constraints. To contribute to the ideas already introduced in prior works, we add vibro-tactile feedback which conveys eyes-free feedback to the users.

Additional 3D View

The first component needed to keep pace with other state-of-the-art systems is the additional perspective display of the simulated scene across the interactive surface of the tDesk (see Fig. 6.1). We utilized *Ogre3D*[1], a versatile open source 3D engine, often used in computer games. In our component we add the models of the apartment and the pieces of furniture to be used in the furniture placing task. Furthermore, we added facilities to synchronize the perspective view according to the setting on the interactive surface in real-time. This includes all furniture instances, their position and orientation in the map and the camera TAO's position and orientation.

Distributed Collaboration

We implemented the distributed collaboration component as a generic interface between two tDesks, synchronizing the interaction using the XMPP protocol for instant messaging. Our XMPP gateway monitors the physical state of the TAOs including their dial's orientation and whenever they change and transmits this information to the other tDesk and vice versa. By this, both tDesks are only coupled using the XMPP protocol which allows simple and easy point-to-point communication. No other information or other communication channels are needed to successfully synchronize physical interaction between the tDesks which makes this approach generic and easily transferable to other systems. Our current implementation only allow to connect two tDesks, but this can be easily extended by incorporating the multi-user chat extension of the XMPP protocol.

Relations and Constraints between TAOs

Our constraints component manages the relationship between pieces of furniture represented by mTAOs. It is possible to maintain constraints between them in terms of relative distance and/or orientation. Figure 6.2 shows how a triangular formation of three TAOs adjusts according to user interaction. The automatic

[1] `http://www.ogre3d.org/`

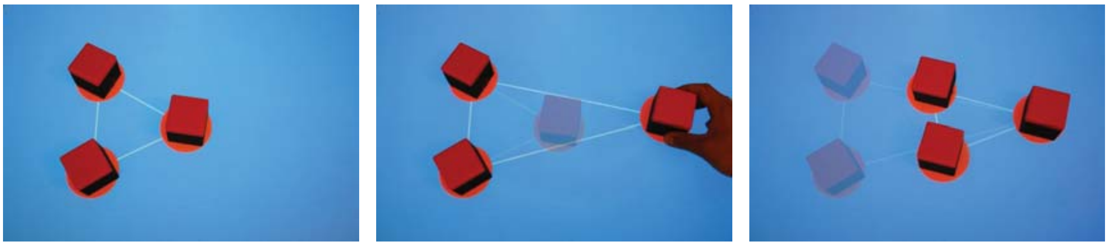


Figure 6.2: Sequence of pictures showing the constraints component at work with three TAOs in a predefined triangle formation [170].

(a) Three TAOs aligned in a triangle formation.
(b) One TAO gets pulled out of the formation by the user.
(c) The other two TAOs automatically realign to re-match the triangle formation.

realignment process is triggered whenever the user changes the orientation or position of a TAO. The reference point for this process is always the last TAO moved by the user. In our furniture placing application the constraints component automatically re-aligns the sofa and television set to face each other across the coffee table, as depicted in Figure 6.4c. In this application these constraints are hard-coded into the system as a proof-of-concept. Later in the comparative study (see Chapter 7), we allow the users to interactively create and alter such constraints. We also projected a "red glare" around autonomously moving TAOs to visually inform the users about the movement state. The implementation of the constraint component used a graph-based approach and supported three different types of constraints: " *a*) The system can maintain distances and orientation of TAOs as graph-leaves relative to another TAO (root of the graph), *b*) it can keep certain distances between TAOs without respect to direction or orientation and *c*) relative relations, such as to keep TAOs 'left of' another one disregarding the distance." [170]

Vibro-tactile Feedback and Virtual Collision Detection

As another sophisticated feature, we incorporated vibro-tactile feedback into the TAOs. This allowed users to have eyes-free feedback when focusing the perspective view. This kind of feedback is often used to gain user attention (e.g. a ringing mobile phone when in quiet mode). We decided to use this feedback when the users might accidentally move models of furnitures into walls or each other. This is possible, because the mTAOs are often smaller than the display of the virtual models. To inform the user about this situation, the mTAOs involved will vibrate until the issue is fixed. Figure 6.4 depicts such a situation with a collision between a bed, a sofa and a wall. To implement this feature, we included small pager motors into the TAOs and added a software component that controls these motors on the request of other components. In our case we extended the display component with collision detection for the graphical representations coupled to the TAOs which controls the respective pager motors on collision with walls or other models of pieces of furniture. Due to the alarming characteristic of the vibro-tactile feedback, the users' attention can be easily directed to the interactive surface.

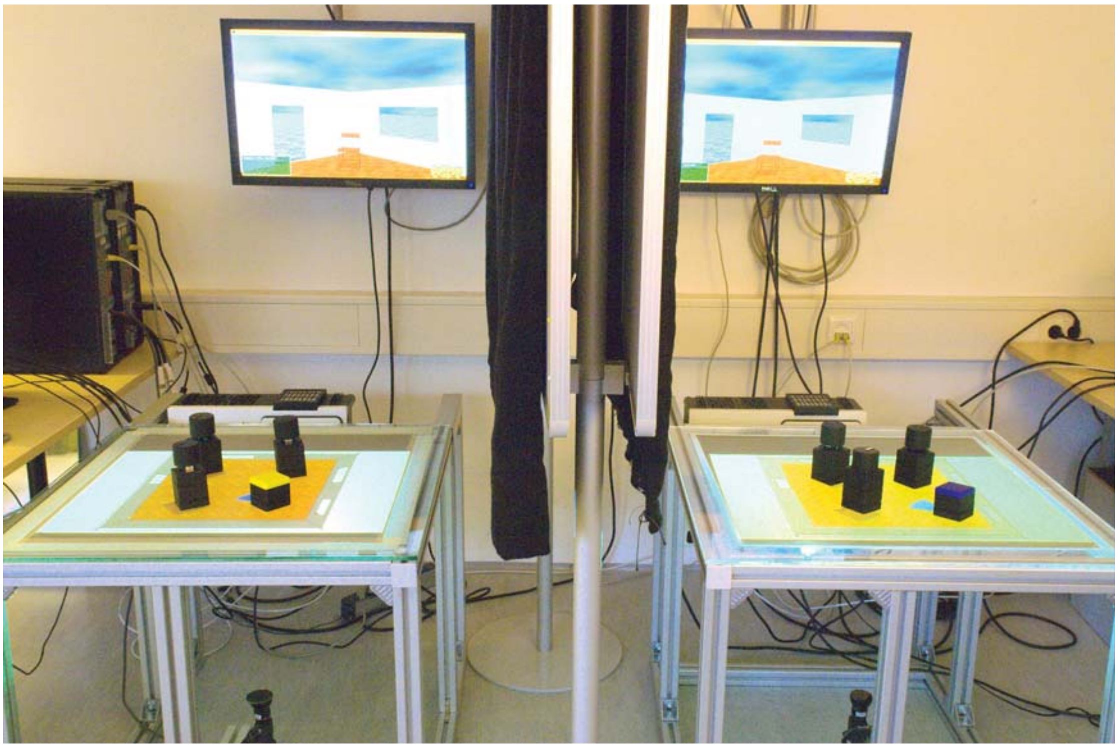


Figure 6.3: This photo shows the complete running system in our laboratory, including two back-projected tDesks with four TAOs each and the two HUDs in the back. Both tables are synchronized only via an XMPP connection [170].

6.3 Basic Interaction Design

Single-side Interaction

As shown in Figure 6.3 and demonstrated in the video, on startup the system shows a bird's eye view of the empty room or apartment on the interactive surface. The camera TAO uses a directional marker to visualize its viewing direction. This allows a user to virtually walk through the room and inspect it from all perspectives – even from the outside through doors and windows. The camera TAO's real-time view across the tDesk's interactive surface presents a perspective view of the scene. By adding mTAOs, it is possible to add pieces of furniture. Each added mTAO is initialized as a chair. Rotating the mTAO's dial makes the rotary menu to appear which allows the user to change the piece of furniture represented by the mTAO (see Fig. 6.4a). In this application, the menu offers a choice of six different models of furniture: *a*) chair, *b*) table, *c*) bed, *d*) book shelf, *e*) sofa and *f*) arm chair. In contrast to the rotary menus used for demonstrating the saving and restoring mechanisms described in Chapter 5, we used pictures for the menu items instead of text. This is necessary, because the orientation of the mTAOs and the pieces of furniture they represent are important in the furniture placing scenario. It can easily happen that the menu is upside-down from the user's perspective which makes text harder to read than to interpret images. These images of the furniture are shown from the bird's eye view, just like they are shown in the apartment's map. Like in the saving and restoring application, the menu items are also read out to the user by the speech-synthesis component as auditory feedback. Turning the dial to the desired menu item makes the represented model switch to the new model which is updated both in the projected map and in the perspective view. After selecting a model, the menu disappears

(a) Detail picture of menu presented around the dial.

(b) Colliding pieces of furniture which triggers the vibro-tactile feedback for each involved TAO.

(c) Detail picture of our virtual constraints.

Figure 6.4: Photos showing different details of the system [170].

to leave more space for the visualization of the map and the pieces of furniture, until it is activated again by using the dial. With these tools at hand, users can easily equip the map with pieces of furniture as long as there are enough mTAOs available. The users can freely decide which pieces of furniture they want to use and how many instances of each model should be placed. It can happen that a piece of furniture is accidentally moved into a wall or another model, because the graphical representations have a larger footprint than the TAOs (see Fig. 6.4b). Since such situations are not possible in the real world, the user needs to be informed that there is a problem with the arrangement of the items. Whenever such an incident happens, the mTAOs representing the models that collide start to vibrate using the vibro-tactile feedback enhancement. The display component rendering the apartment's map supports basic collision detection and requests the software component controlling the TAOs pager motors to vibrate until the problem is fixed. To support the user in the furniture placing task the constraints component helps by re-arranging mTAOs that are assigned to pieces of furniture that depend on each other. We implemented constraints between the sofa, coffee table and television set, as shown in Figure 6.4c. They automatically re-arrange each other to make the sofa and the television set face each other across the coffee table. Whenever one of these three models' mTAO is moved by the user, the other two rearrange accordingly.

Distributed Collaboration

All these interactions with the TAOs on the interactive surface are automatically synchronized between the two tDesks using the XMPP gateway. This is done by simply transmitting changed positions and orientations of TAOs and changed dial orientations to the other tDesk. The complete state of the system can be determined by the TAO's positions, orientations and dial orientations. There is no need to transmit additional higher-level information. When the users of the other tDesk move a TAO during the synchronization process, the automatic movement process is terminated. The new position of the other tDesk's TAO is the new common ground for the synchronization. In other words, the TAO moved last a user determines the position and orientation of the synchronized TAO. To visualize the synchronization process, TAOs being moved by the system have a red glare around their footprint until the have reached their new target position. As the information transmitted via the XMPP gateway uses a low band-width, it is possible to have an audio or even video conferencing link running simultaneously. These could also be integrated into the XMPP connection by using the protocol's *Jingle* extension in future iterations of the system.

6.4 Discussion

With this application scenario we demonstrated a sophisticated TUI offering a rich set of interaction modalities and features. The modalities cover three different cues. There is the visual cue, including the projected map of the apartment and the interactive perspective view of the scene. The auditory cue (speech output) allows eyes-free menu navigation and monitoring the result in the perspective view. The vibro-tactile feedback supports reporting physically impossible situations, also enabling eyes-free manipulation of the pieces of furniture while the users focus the perspective view of the scene. Furthermore, the possibility of having automatic constraints between the pieces of furniture also supports the users in the placing task. The distributed collaboration approach allows long-distance physical interaction between two users or groups of users.

Though not tested in a formal user study, colleagues who were informally confronted with the system had the opportunity to try it and found the interaction design reasonable. They even proposed further possibilities for improvement and extensions (see Outlook Section blow). Also the system performance was rated acceptable, though in the design process we realized potential for performance improvements. Here the used middleware *XCF* [51] turned out as a bottleneck. Hence we opted for its successor *RSB* [211] and re-wrote large amounts of the TAOs' core architecture and library.

Limitations

The hard coupling between the mTAOs and their represented pieces of furniture limits their number to the number of available TAOs. Using soft coupling between the models and the mTAOs would allow a theoretically unlimited number of pieces of furniture (only limited by the size of the interactive surface). With a soft coupling approach it would be possible to lift and uncouple an mTAO from its represented model to create a new model or to manipulate other models. To regain physical access to an uncoupled model, the user just puts an mTAO back on its non-tangible representation. We decided against this soft coupling approach in the first stage because it weakens the benefit of the vibro-tactile feedback. When there is no mTAO coupled to a model, the system cannot provide the users with eyes-free vibro-tactile feedback on this model anymore. Though this feedback is only needed and perceived when a mTAO is actively manipulated, other visual cues might serve as a sufficient workaround. Hence we consider our interaction design to be more concise with hard coupling in the frame of this particular application.

Another limiting aspect of the system is the limited size of the interaction area on the tDesk. Testing the system revealed that an apartment can only be dealt with room by room. In a map of a complete apartment with three or four rooms, there is not enough space left to effectively work with the mTAOs. Furthermore, dealing with only one room at a time is absolutely natural at least in a single-user scenario. This leaves more TAOs for interaction within a single room because of the hard coupling with the pieces of furniture.

Outlook

Beyond the stress test for the TAO architecture, this application also serves as a proof-of-concept for a multi-modal system and there is even more potential for more sophisticated features and extensions which came up when informally presenting the system to colleagues. The first extension proposed is a personal camera view for each of the connected tDesks. In other words, the camera TAOs are not synchronized across the tDesks. Only when one user wants to present a particular perspective of the scene or to give a guided walk-through to the distant users, the camera TAOs can be synchronized temporarily. The switching between *synchronized* and *not synchronized* mode could be implemented using mTAOs instead of the standard TAOs for the camera TAOs or via soft coupling.
Another interesting extension prospect is a room switching feature. Two possible ways of implementation have been discussed. The first incorporates an additional mTAO that allows room selection through its menu. Another more natural interaction possibility would be using the camera TAO that basically represents the user. By moving it through a door or up or down stairs the room is switched, just like one would do moving from one room to another. This does not demand any additional TAO or hardware extension and perfectly fits into the interaction design of the system. Such an interaction pattern was already demonstrated with the *MRI* by Uray et al. [200].

Design Guidelines

Additional Views

As stated by Patten et al. the use of additional views has to be considered carefully [157]. In their *Sensetable*, they offered an additional view displaying the values of the dials on their TUIOs on the interactive surface. The users of their system reported that they would prefer the values to be displayed directly at the dials so that they do not have to share attention between the projected surface and the additional view. The implementation of this feature made the additional view unnecessary. In other words, additional views should only be introduced if the data displayed cannot be added to the display of the interactive surface. Only if the view provides other qualities that are worth sharing attention with justifies the introduction of an additional view. In our opinion both are applicable in our furniture placing application. The perspective view of our additional perspective view cannot be applied to the interactive surface due to its bird's eye view. But it warrants a more natural view of the scene being manipulated.

Sharing and Guiding Attention with Multi-modal Feedback

Vibro-tactile and auditory feedback enable the users to manipulate the TAOs. The users can monitor the changes on the perspective view while switching the TAOs' models supported by the auditory feedback. Vibro-tactile feedback alarms the users if they accidentally push pieces of furniture into a wall or other models. Then they have to direct their attention to the interactive surface to solve the problem. This allows the users to share attention between the tDesk's interactive surface and the additional perspective view. Furthermore, the feedback helps to guide the users' attention when needed.

Distributed Collaboration

The distributed collaboration component described in this chapter is a working proof-of-concept. Due to its generic nature it can be easily transferred to other applications using hard coupling. It only uses the TAOs' positions and orientation and their dials' orientation for synchronization. For applications using soft coupling, the binding information between non-tangible representations and the TAOs needs to be added to the data stream synchronizing the tDesks. The XMPP protocol used for synchronization can also be used to synchronize more than two tDesks by introducing the multi-user chat extension. Furthermore, the *Jingle* extension can add audio and video conferencing while using the TAOs in future iterations of the system.

6.5 Conclusion

The integrated system we presented in this chapter serves as a proof-of-concept for feature rich multi-modal tangible interaction and seems desirable. More recently, Erp et al. presented their *Sensators*. These are active TUIOs providing multi-modal interaction channels, including vibro-tactile feedback, colored light (RGB LED), audio playback and touch input [36, 37, 38].

By combining multiple state-of-the-art approaches from prior works and adding further feedback, we created a sophisticated system using the example application of placing pieces of furniture. The multi-modality enriches the interaction and may encourage, support and guide users in their interaction with the system. Beside the applicability of multi-modality, we also examined the use of automatically obtained relationships and constraints between TAOs and included distributed collaboration abilities. Furthermore, we discussed the multi-modal aspects and their interaction with each other, with the constraints and distributed collaboration features. Additionally, we highlighted the possible use of soft coupling between the TAOs and their non-tangible representations and discussed its impact on the interaction design. We pointed out limitations and potential for improvements of the current implementation and derived certain design guidelines that assist interaction designers to reproduce and recombine such aspects effectively.

7 Co-located Collaboration: Comparative Interaction Measures

The nice thing about teamwork is that you always have others on your side.

Margaret Carty

The development of most actuated TUIs is still driven by applications. This is because the possibilities of actuated TUIs still need to be explored as this field of research is still in the state of basic research. Nonetheless, there are concept driven approaches, such as the *PICO* system [154] and those by Ishii and Ullmer [82, 194]. They proposed fundamental concepts for (actuated) TUIs. However, in general-purpose or everyday life applications there is currently no clear evidence that tabletop TUIs are equal or even superior to GUI-based systems. The community builds most of their research upon theories (see Sec. 2.3) and can show this mostly in user studies dealing with special-purpose applications.
The scope of evaluations of TUIs is quite diverse. Ranging from very small system specific case studies to empirical evaluations, the contributions to the research field differ considerably. Even though, small or non-experimental studies with a within-subjects design are important and may reveal major insights. In this chapter we describe and adapt evaluation measures from neighboring fields that were not yet used for (actuated) TUIs. As these measures are additionally intended to evaluate collaboration, we conducted an exploratory user study comparing four different interface types.

7.1 Related Work on Comparative Studies and Collaborative Interaction

In this section we briefly describe important studies dealing with the comparison of table-top TUIs with mainly Mouse or multi-touch interaction. As most of them deal with single-user scenarios, we also highlight studies investigating collaborative scenarios. For a better overview, both kinds of studies are summarized in Table 7.1.

Comparative Studies on different Interface Styles

One of the first comparative evaluations on TUIs was conducted by Fitzmaurice and Buxton [46]. Focusing on time- vs. space-multiplexed interface designs, they compared three conditions with the same task in a within-participants experimental design. The participants were asked to align graphical representations of objects (stretchable square, ruler, brick and rotor) into target positions determined by the system using the respective condition's devices. Those conditions are: "*a*) space-multiplex with 4 specialized devices using 4 tablets *(SpaceS)*, *b*) space-multiplex with 4 puck and brick pairs of generic devices using 4 tablets *(SpaceG)* and *c*) time-multiplex with one puck and brick device operating on a large tablet *(Time)*." [46] In a nutshell, the results collected with $N = 12$ participants, revealed a superiority of the first over the second over the third condition *(SpaceS > SpaceG > Time)*. This finding is based on the conditions' Root Mean Square (RMS) error of the displacement of target and actual position of the graphical representation and the active usage time of the devices.

In another study Jacob et al. [84] evaluated different interface designs of a system for organizing information within a grid. The interface consists of a whiteboard sensitive to objects equipped with RFID tags *(Senseboard)* and a projector. Within four conditions, the participants' task was to create a work schedule according to given resources and constraints. The conditions covered *a*) Paper (no system support), *b*) Reduced-Senseboard, *c*) Pen-based projected GUI and *d*) full Senseboard support [84]. In this study $N = 13$ participants took part. Evaluating the participants' performance (time to task completion) did not reveal any significant difference between the conditions. But the results from the questionnaire showed a significant effect. Here the *Senseboard* condition was preferred over each of the other conditions, while the paper condition was disliked by the participants.

The *RATI* system by Richter et al. [166] is a networked actuated TUI, featuring two instances that are coupled over a network for remote collaboration. In a furniture placing task, they evaluated their system according to two measures for social presence (*Semantic Differential* [64] and *Networked Minds* [14]). The system was evaluated in a study and was compared to a GUI implementation of the task. The participants remotely collaborated in pairs using the distant systems. In the evaluation of their approach, the *Semantic Differential* measure did not yield any significant interaction. But the *Networked Minds* measure's analysis revealed a higher level of social presence for the *RATI* compared to the GUI implementation.

The *PICO* system was also evaluated within a comparative study. Patten and Ishii compared actuated with non-actuated *PICO* TUIOs and with a screen-and-mouse condition. The task was a radio tower placing task, partially supported by the system's actuation feature. The results indicate a superiority of the actuated *PICO* TUIOs over the other conditions within this special task [154].

Couture et al. built the *GeoTUI* system to compare the GUI and a TUI design for the *Jerry On tHe Net (JOHN)* system, a geographical data analysis tool for the manipulation of the three-dimensional volumetric geographical subsoil models [30]. In the comparative experiment, the task was to create a cutting line through the model by specifying two points to get a cutting plane. Twelve experts participated in this study and evaluated four different conditions: *a*) Mouse (M), *b*) one-puck prop (1P), *c*) two-puck prop (2P) and *d*) ruler prop (R). Arguing with Fitzmaurice et al. [47], Couture et al. found support for the superiority of the specialized space-multiplexed conditions over the generic space-multiplexed conditions.

Pedersen and Hornbæk evaluated the audience's perception of a live performance of electronic music. They compared the performance with a traditional setup for electronic music performance (laptop with music software) and their own *mixiTUI* system [159]. Though they have carefully designed the *mixiTUI* in collaboration with electronic musicians, Pedersen and Hornbæk focus on the perception of the audience ($N = 117$) and conducted a questionnaire study after a concert given with both interface types. As expected, the audience found the use of *mixiTUI* much more observable, understandable and more visually appealing compared to the traditional performance setup.

In a comparative study involving planning tasks, Lucchi et al. demonstrated superiority of their TUI approach over a multi-touch interface [126]. With $N = 40$ participants, they were able to show that the TUI allowed for faster manipulation and that its persistence and haptic feedback is beneficial for fulfilling the planning tasks. To provide similar manipulation possibilities, the multi-touch interface incorporated gestures, such as lassoing multiple items for parallel manipulation, which the participants disliked.

Comparing multi-touch, tangible and Mouse with puck manipulations in the style of [46], Tuddenham et al. were able to prove significantly short manipulation times for $N = 12$ participants in an artificial placing task. Furthermore, the participants reported to prefer the tangible interface followed by the multi-touch interface in therms of ease of use. Also accuracy in a second tracking task was measures best for the tangible interface using a root-mean-square (RMS) measure [193].

In 2011 Pedersen and Hornbæk conducted another comparative study with their actuated TUIOs *Tangible Bots*. They compared them to non-actuated TUIOs within an artificial task where the TUIOs had to be aligned to particular target positions and orientations. The actuation feature of the *Tangible Bots* was used to synchronize multiple TUIOs so that only one had to be manipulated, affecting the other TUIOs, as well. With $N = 16$ participants, they found "that *Tangible Bots* are usable for fine-grained manipulation (e.g. rotating tangibles to a particular orientation); for coarse movements, Tangible Bots become useful only when several tangibles are controlled simultaneously. Participants prefer Tangible Bots and find them less taxing than passive, non-motorized" TUIOs [158].

Co-located Collaboration Studies

A very comprehensive overview on comparative studies investigating co-located collaboration with GUIs and TUIs was given by Kim and Maher. In an experiment incorporating a planning task comparing a TUI and a GUI, they deeply analyzed the interaction with three pairs of participants from an linguistic point of view. They indicated superiority of the TUI according to *action-*, *perceptual-*, *process-* and *collaboration levels* [98].

Though not directly addressing tangible interaction, Hornecker et al. contributed to the neighboring field of CSCW by comparing interaction with *single mouse*, *multiple mice*, *signle touch* and *multi-touch* in a co-located collaborative study setting. In their study investigating a planning task, they focused on higher-level awareness indicators and found benefits for touch interaction [77].

Another comparative study dealing with graphical and tangible programming languages in an educational context, is the *Robot Park* exhibit by Horn et al. [75]. They created a simple graphical and tangible programming language offering features like the *Logo* programming language for programming a mobile robot. The participants could create programs with a graphical or a tangible interface, both using the jigsaw puzzle metaphor for the instruction blocks. Connecting the instruction blocks to sequences results in a program a robot could execute. The results of the evaluation with a large number of participants ($N = 260$) showed "that the tangible interface was more *inviting*, more supportive of *active collaboration*, and more *child-focused* than the Mouse-based interface." Furthermore, "the tangible and graphical interfaces were equivalently *apprehendable* and *engaging*, and the resulting visitor *programs* were not significantly different." [75]

A similar comparative study with children programming robot was described recently by Sapounidis and Demetriadis. They compared the tangible *T_ProRob* cubes with their graphical *V_ProRob* interface (parts of the *PROTEAS* kit) for programming a *Lego NXT* robot. The results indicated that younger children, especially girls, liked the tangible interface more than the graphical implementation. On the contrary, older children preferred the graphical interface. Sapounidis and Demetriadis explain this effect with the older children's familiarity with computers [178].

Limitations of the Previous Work

As we can easily see from Table 7.1, none of the studies found in literature deals with all four major interface styles at once. Most of them compare Mouse-based interaction against one other interface while only Tuddenham et al. compare Mouse (and puck) with touch interaction and (passive) TUIOs.

Some studies (e.g. [30, 159, 166]) show slight problems in procedure and design, as their within-subjects design was not counterbalanced [9, pp. 165] at all. Such as in the study by Richter et al., all subjects started with the Mouse-based condition which may likely lead to biased results. Hence, practicing in the first condition may result in better user performance in the second condition. Further carryover or novelty effects might influence the results of unbalanced studies with a within-subjects design, as well. New things are often more interesting than familiar ones. The curiosity for the new technology may generally bias the participants to give more positive responses when completing questionnaires after an experiment, especially when comparing to familiar conditions. The evaluated systems are mostly special-purpose applications, it is likely that a specially designed interface may outperform a general-purpose interface (like the ordinary, but well-known desktop computer).

Furthermore, long-term effects, such as learning and adaption may not be observable to their full extend in trial studies, as Shaer and Hornecker point out [185, p. 95]. Such issues can be overcome by conducting long-term studies outside of the laboratory in the everyday environment of the participants. There are first long-term evaluations, such as those by Edge and Blackwell [34], but full comparative field studies with a larger number of participants have not yet been carried out.

While some of the discussed studies had a quite large number of participants, some had only few ($N < 15$). When dealing with special-purpose tasks carried out by experts, it is rather hard to find a large number of participants. But such results may only provide limited support for the respective research hypotheses.

Study	Conditions	Supported Conditions: Mouse	Touch	passive TUIOs	active TUIOs	*Other*	N	Crit. F	Task	Used Measures
[46]	3	Single, Multi		X			36 (12)	3.03	artificial	Accuracy and manipulation time
[84]	4	Pen-GUI		Red., X		Paper	52 (13)	2.64	organization	Time
[154]	3	Single		X	X		45 (15)	3.03	planning	TUIO switching, questionnaire
[30]	4	Single		1 Puck, 2 Pucks		Button Box	48 (12)	2.64	exploration	Questionnaire
[159]	2	Single		X			117 (117)	3.89	observation	Questionnaire
[126]	2		Multi	X			80 (40)	3.89	planning	Time and accuracy
[193]	3	Single + Puck	Multi	X			36 (12)	3.03	artificial	Time and accuracy
[158]	2			X	X		32 (16)	3.89	artificial	Time, error rate and questionnaire
Collaborative Studies:										
[166]	2	Single			X		40 (20)	3.89	remote planning	Semantic Differential and Networked Minds
[98]	2	Single		X			14 (7)	3.89	planning	Protocol analysis
[77]	4	Single, Multi	Single, Multi				52 (13×3)	2.64	planning	Coded awareness indicators
[178]	2	Single		X			62 (61 in dyads+1)	2.64	programming	Questionnaire, interview and observations

Table 7.1: Overview of the comparative and collaborative studies in literature. The first column holds the sources for each study. The next six columns summarize the supported conditions. The 8th column gives the number of participants (as for all studies use a within-subjects design the actual number of individual participants is given in brackets) followed by the corresponding critical F (estimated using *G*Power* [39]), the basic task and the significant measures.

7.2 Motivation and Design Ideas

In the course of this project, we realized that there is an increasing need for empirical studies that allow us to transfer and find support the community's theories to actuated TUIs. To follow on from the empirical studies found in literature, we propose a comparative experimental design that adapt psychological and social measures from neighboring research fields or introduce new measures for analyzing co-located collaboration.

Though we strongly believed in the benefits of tangible interaction, we were also a little skeptical. This is why we came up with the idea to design a comparative study with all four major interaction styles at once. Because we had no practical experience in designing and running comparative or collaborative studies of such dimensions, we consulted colleagues from psychology and asked for hints and advice. This resulted in the following study design.

Single-blind between-subjects design

For this study, we concentrate on the quality of interaction between pairs of participants in a co-located collaborative task. To investigate interaction quality of each single interface style, we decided on a single-blind study design that explicitly lets the participants uncertain if they are rating the interface devices. This inherently leads to a between-subjects design. Although this has certain disadvantages (a within-subjects design requires less participants[1] and allows for "greater control over participant differences and thus greater ability to detect an effect of the independent variable" [9] when counterbalanced), we wanted to put focus on the task while the interface type only plays a subordinate role (from the participants' point of view). Though the interface type is inherently part of the task, the participants are told that focus is explicitly put on the intellectual and collaborative challenge throughout the whole study.

Furthermore, we knew from our own experience, that sitting in front of a back-projected table-top surface for a longer time can be very tiering and may even cause headache. For reconsidering a within-subjects design, we roughly estimated the time for one trial with all four conditions. Each condition was estimated with half an hour which would result in over two hours per trial (including modification and preparation for each condition). Thus, we did not expect our participants to bear staring on a projected surface with only glass and a sheet of projection foil between their eyes and the projector's lens for over two hours at a stretch. This is another argument against a within-subjects design while dealing with this aspect by spreading the four condition trials for each dyad over several days would have required a tremendous overhead of additional organizational work.

The Task

To put the intellectual and collaborative challenge of the task upfront for our participants, we defined requirements, the task had to meet:

- be applicable in all four conditions and still comparable across the conditions,

[1] However, a complete set of all correctly counterbalanced condition orders would result in $4! = 24$ dyads (48 individual participants) producing $4 \cdot 24 = 96$ trials. The amount of time for experimentation, post-processing and analysis would have exceeded our resources. Thus we stick to our exploratory study design dealing with all four major interface types at once which only allows for detecting large effects.

- offer a possibility to make use of the actuation feature of the TAOs,
- allow a feature similar to the TAOs' actuation for the other conditions,
- be performable collaboratively (by two participants, working together),
- demand or even support interaction between the two participants,
- be with modest difficulty,
- "only" demand basic education (or creativity) and
- it should be from office live, such as meetings, etc.

A task that fits these requirements is *mind-mapping*. Mind-mapping is a creativity technique where groups or single persons visualize different aspects of a certain topic with their associations. In our case, the topic was intrinsically given by seven predefined mind-map items ("Stars," "Earth," "Sun," "Galaxy," "Space travel," "Asteroids" and "Moon," as depicted in Fig. 7.1). These terms from the general topic of *astronomy* should be commonly known to the public so that the participants are able to draw somehow meaningful associations. These items are generally known and even if their scientifically correct definition may be unknown, most people have at least a vague idea of their concepts. We expected most participants to have a rather good concept of items, such as Earth, Sun and Moon. Other items, such as Asteroids or Galaxy are conceptually not so well-known. This was intended to provoke discussion between the participants and ideally invoked basic teaching and learning processes.

Mind-mapping

General Study Design

We propose an exploratory user study comparing interaction with Mouse, multi-touch, passive TUIOs and our TAOs. All conditions should be as similar as possible, except for the actual interface. This affects the setup including the hardware and software design, the experimental procedure and the task. Both, the hardware and the software should provide the same basic features and only change when the interaction style of the particular interface demands adaption.

Beyond using questionnaires, we considered audio and video recording the trials and collecting and analyzing detailed system logs containing as much relevant interaction information as possible. These are used for (semi-)automatic annotation and analysis to adapt additional measures for (actuated) tangible interaction. To be able to investigate co-located collaboration, we invited participants pair-wise. Given restricted resources, we decided on at least ten trials each which resulted in ($N = 80$) participants which is just acceptable for an exploratory user study compared to the studies mentioned above.[2]

Interaction Possibilities

In each condition, associations can be drawn between mind-map items by moving them item into each other (they have to overlap) and moving them apart, again; a line is drawn between the items to visualize the association. An existing association can be erased by

Associations

[2] with respect to our between-subjects design and the number of conditions.

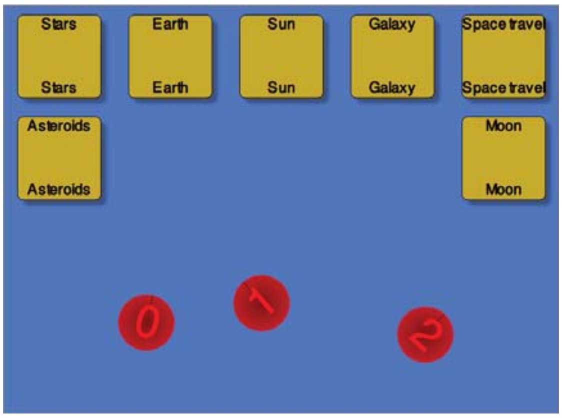


Figure 7.1: Initial task situation (screen shot) in the TAOs condition.

moving associated items far apart from each other. This was possible to implement for all four conditions and metaphorically can be explained as tearing apart some kind of rubber band connecting the items, as depicted in Figure 7.2.

Simultaneous Item Manipulation

To investigate if and how participants might use the actuation features of the TAOs , we extended our constraint concept described in [170] and recapitulated in Chapter 6. For this we enabled the participants to interactively define constraints between TAOs. Such constrained TAOs move along each other automatically when one of them is moved by a participant. We implemented *simultaneous* movement possibilities for mind-map items for all four conditions. This means that it is possible to select mind-map items, such as a branch or a group of items, belonging to a subtopic. The selected items then move along with another item being moved by the users and maintain their relative position to the item being moved. Even though the situation could be found in every condition, this feature was implemented slightly different for each condition due to technical differences.

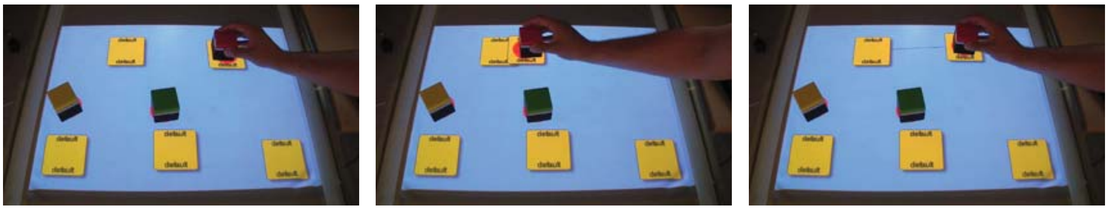
Goal

Given a system with these features, the participants were instructed to create a mind-map from the given items within five minutes of using the system. Both participants of the dyad should agree on the solution and should be as equally happy with the resulting mind-map as possible. To achieve this goal, they had to talk to each other and argue which items should be connected in which way. There was no intended standard solution for the task.

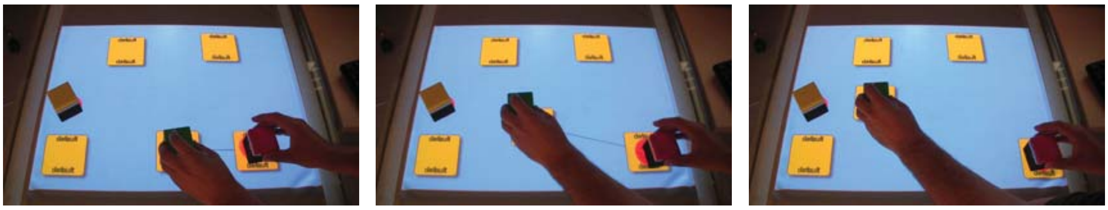
Design and Implementation of the four Conditions

The four conditions we address in this study, range from the most common interface device, the Mouse, over multi-touch interaction to passive TUIOs and TAOs. All these conditions were based on the same hardware design around the tDesk (as already described in Chapter 3.3) and technically only differ in few details. This was necessary to quickly adjust for the condition that was randomly chosen directly before each trial and to keep the conditions as comparable as possible. The whole setup and the differences between the conditions are depicted in Figure 7.3 and described in the following paragraphs:

Condition 1: Mouse In the first condition, the two participants of a dyad working together had to negotiate who uses the Mouse and if the other participant takes over the Mouse. The Mouse rests on an additional small table placed in front of the tDesk, as depicted in



(a) Creating an association. **(b)** A mind-map item is moved into another one. **(c)** A line visualizes the created association.



(d) Removing an association. **(e)** Two associated mind-map items apart are pulled apart. **(f)** The association is deleted.

Figure 7.2: Creating and removing associations between mind-map items (stills from the introductory video for the TAOs condition).

Fig. 7.3a. Though it is technically possible to have multiple Mice, the common way is to use one Mouse and one Mouse pointer per display. In real live, multiple users face the same problem when they want to use a computer collaboratively. Another conceptually similar condition would have been pen-based interaction, as found in literature [84]. But due to the sparse spread of graphic tables in ordinary offices, we decided not to test this special condition. Moving mind-map items is done via Drag&Drop, while selections to move them simultaneously is possible by just clicking the desired items one after another. They light up to visually represent their selection state. Selected items can be deselected by simply clicking them again.

Condition 2: Multi-touch Because of the technical constraint of not having a touch sensitive back-projectable interaction surface, touch sensing was implemented using a *Kinect* depth camera and the *dSensingNI* software presented by Klompmaker et al. [108]. We used this software to analyze the depth information from the *Kinect* sensor and to track the finger touch points in the interactive surface. Furthermore, this software features distance-to-surface measuring, which allows tracking of objects not touching the surface, such as hands, fingers and even stacked objects and touch points on them. Compared to capacitive touch sensing methods, this solution has drawbacks, such as (self-)occlusions of the users' hands and fingers. But regarding implementation effort and expense, this solution worked sufficiently. To minimize the possibility of occlusions, we placed the *Kinect* sensor across the interactive surface pointing directly at the surface's center, as shown in Fig. 7.3b. Direct simultaneous movement of multiple mind-map items is possible in this condition, but the selection possibilities as implemented in the Mouse condition are still usable and introduced to the participants.

Condition 3: Passive TUIOs For the participants this condition conceptually is similar to the multi-touch condition, except that one object grasped with the whole hand serves as

(a) Setup of the Mouse condition. (b) Setup of the multi-touch condition. For finger tracking we used the *Kinect* sensor behind the tDesk. (c) Setup of the passive TUIOs and TAOs condition.

Figure 7.3: The setup designs for the four different conditions. Though the *Kinect* sensor is visible in all three pictures it was only used in the multi-touch condition. The camera for video recording the trials was placed slightly below the *Kinect* sensor.

handle a for the mind-map items instead of the participants' fingertips. For maximum comparability in this condition, the TAOs already serve as the TUIOs even though they do not move (see Fig. 7.3c). Using the TAOs in this condition also enables having a robust object tracking together with back-projection. In this condition, the participants have three TUIOs available to accomplish the task – one for each participant and one additional spare TUIO. Again, selecting items for simultaneous movement works similar to the first two conditions. By touching an item with a TUIO the item is selected. Tapping the TUIO on a selected item again deselects it.

Condition 4: TAOs This condition is exactly the same as in condition 3, except for the fact that the participants can make use of the TAOs' actuation feature, which can be used to move multiple mind-map items simultaneously by only manipulating one TAOs. It is no longer necessary (but still possible) to select mind-map items. The participants can put TAOs on all the mind-map items that should move simultaneously. The selection-by-touching feature is still available as a fall back when the participants want to move more than three mind-map items simultaneously with the TAOs at hand. Both methods are explained in the introduction video. Additionally, we added visual feedback to the display to inform the users about the autonomous movement of the TAOs. This was accomplished by simply drawing a line from each moving TAO to its target position.

Expectations and Planned Difficulties

Based on results of prior studies found in literature, we believed in the superiority of the two tangible conditions, we expected rather large effects which also influenced our study design. The Mouse as in our setup is a single-user interface. Thus, we can expect this condition to be obviously least effective, e.g. only one participant makes use of the device for the whole trial which results in low or even none shared interaction space between the dyads' participants. In common tabletop multi-touch applications and demonstrations it is possible to rotate and scale items. Such features do not help in this particular task and thus were not implemented.

Figure 7.4: The touch sensing enabled TAO. A band of copper was wrapped around the upper part of the TAOs' housings, acting as the antenna.

However, the lack of these interaction patterns might confuse the participants.
As a planned difficulty, it is also not possible to pick items up and release them somewhere else. Thus, the users have to plan ahead if they want to move items across the interactive surface with other items blocking the path. To successfully execute such a movement, the items blocking the way have to be moved aside beforehand. By this, we hoped to stimulate the interaction between the participants and induce collaborative use of the system. Also the size of the mind-map items demands such practices. They have a quadratic shape with an edge length of 8.4 cm. The interactive surface on the tDesk measures 56 $\times$ 42 cm.

7.3 Extensions: Touch Sensing and Dynamic Constraints

In the fourth condition, the TAOs are able to move along another TAO being moved by a user. For this ability, the system maintains constraints that define if and how TAOs move along. Whenever a TAO is assigned to a mind-map item, the system automatically creates a constraint model between this TAO and all other TAOs standing on top of mind-map items. At the moment of assignment, the constraint is initialized with the current relation (relative position) between the TAOs. The relation between the TAOs can be adjusted by touching TAOs while repositioning them. Whenever a single TAO is touched and moved by a participant, all other TAOs that are constrained to this TAO (all TAOs assigned to a mind-map item) move along autonomously. To detect whether a single TAO or multiple TAOs are touched, we added simple touch sensing to the TAOs. When a single TAO is moved by a user, the constraints software component continuously updates the target positions of the other assigned TAOs in the path planning module. This module navigates the TAOs to the new positions relatively to the TAO being moved.
To properly manage constraints, the system needs to be able to sense if and how many TAOs are touched. For this, a very simple capacitive touch sensor was added to the TAOs, as depicted in Fig. 7.4. To keep the amount of necessary hardware modification as low as possible, fast Pulse Width Modulation (PWM) of the *Arduino* was used instead of an additional touch sensing Integrated Circuit (IC). This solution is not as sensitive and reliable as special-purpose ICs, but it was very low cost and simple to build. Due to the low sensitivity,

the antenna was placed outside of the TAOs, because the participants had to directly touch the TAOs to reliably sense touch. Our touch sensing implementation is similar to the approach of the more recently presented *Smart Tangibles* by Gelineck et al. [54], introducing touch sensing for passive TUIOs using Grove I^2C touch sensors.

7.4 Data Collection and Dependent Measures

In our study we collected a data corpus with a time length of over 3 hours trials (plus learning phases) including the detailed interaction data logs produced by the system. The collected raw data, their post-processing and the derived measures are described in the following sections.

Raw Data

We audio and video recorded every trial with a video camera positioned behind the interactive surface (below the Kinect sensor; cf. Fig. 7.3). In the video data we hoped to observe two-handed interaction, as described by Buxton and Myers [26]. When observing two-handed input, we hoped it supported the kinematic chain model for (asymmetric) division of labor, as described by Guiard [59]. We also annotated the audio and video data as described in the post-processing subsection below for later analysis. Furthermore, we recorded system logs for condition specific interaction data:
Mouse: Pointer coordinates, Mouse button press and release events and items being dragged.
Multi-touch: Touch point coordinates.
Passive TUIOs: The TUIOs' positions and orientation, touch and release events – all with the TUIOs' IDs.
Active TAOs: The TAOs' positions and orientation, touch and release events and navigation events – all with the TAOs' IDs.
For all conditions, we additionally recorded the mind-map items' positions, their selection states and events of connection creation and deletion. All recorded information were equipped with time-stamps in milliseconds. The coordinates are relative to the interaction area and unified to the range $[0,1] = \{x, y \in \mathbb{R} \mid 0 \leq x, y \leq 1\}$. The collected system logs are extensive enough to render detailed interaction videos.
The recording of the raw data is managed and synchronized by our study control software. At the end of each trial we automatically took a screen shot of the final state of the mind-map.

Subjective Ratings

Along with the raw interaction data, we also asked our participants to complete a digital questionnaire after attending the trial. All gathered information were treated in an anonymized way. The first questions items regard general aspects, such as age, sex, handedness, occupation, education and if the two participants of the dyad knew each other before the experiment.

Own Questions

The questionnaire's items are listed in Appendix A.2, including which item was recoded for analysis. The participants rated these items on a 7-point Likert scale without the possibility for marking a "does not apply" field. We used the items to form indexes of the following dependent dimensions: *a*) system usability, *b*) collaboration, *c*) task, *d*) user type, *e*) design and *f*) task. Using Cronbach's α to evaluate the indexes' reliability, we had to break some scales apart because of too low α-value. The following indexes remained for the later analysis:

System usability This index covers aspects, such as if the participants had fun working with the system, if they liked to use the system for a longer period or more frequently and if it was motivating, interesting and inspiring.
(7 items: 1, 2, 4, 5, 6, 11 and 12; $\alpha = 0.90$).

Collaboration The items that build this index deal with the interaction between the trial partners. Here they rated the productivity, communication, if the system facilitates collaboration or if the system hindered the trial partners from effective collaboration.
(5 items: 3, 17, 19, 20 and 21; $\alpha = 0.80$).

Task The task index is build from items relating to the task complexity. Furthermore, the participants rated if the system was suitable for the task or distracting.
(4 items: 7, 8, 9 and 10; $\alpha = 0.68$).

User type The items about the user type were asked to allow the participants to self-asses their computer skills and how they use computers.
(4 items: 23, 24, 25 and 26; $\alpha = 0.70$).

The following dimensions were assessed with only a single item, because their indexes' α was too low ($\alpha < 0.70$ is already questionable):

Other tasks In this item the participant is asked to rate if he or she found the system transferable to other tasks (item 13).

System design This item asked if the system design was appealing (item 14).

Expected system behavior Here the participant was rated whether the system worked as expected (item 15).

Redesign The redesign item asked whether the participant would like to change the system's design if he or she could (item 16).

Task familiarity This item asked if the participant dealt with a similar task before (item 18).

Result Here, the participants were asked to rate whether they were satisfied with their result or not (item 22).

System Usability Scale

Along with our own items, we added the items from the *System Usability Scale (SUS)* questionnaire by Brooke, a widely used method for determining usability of a system. The *SUS* items scored by the participants with a 5-point Likert scale were automatically computed [23]. We included the *SUS* questionnaire for curiosity, because it provides a single value score and to have a fall-back measure in case our own questionnaire items would fail. The *SUS* result lies in the interval $[0, 100]$; 0 for worst 100 for the best result. For the *SUS* there is no reliability check intended.

These indexes are the measures we used for scoring the conditions along with the measures, we gathered from the post-processing of the interaction data, as described in the following paragraphs.

Post-processing of Interaction Data and their Measures

Of course we did not want to solely rely on measures gathered from questionnaires, we also processed the interaction data for later analysis. Figure 7.5 gives an overview of the whole post-processing procedure. After the raw data acquisition (step *a*), the first step towards measuring the interaction data demanded semi-automatic annotation of the audio and video data.

Utterances

We automatically detected the participants' utterances. For this we used the *Audacity* program[3] on the videos' audio streams. After removing noise from the recording, we applied the *Sound Finder* analysis tool for automatic detection of utterances. Beside the standard parameters default values, we used the following two parameters with slight adjustments according to the participants' voice: *a*) silence level threshold: 15 [-dB] and *b*) minimum duration of silence between sounds: 0.5 [s]. This results in labeled continuous sentences, single words and utterances. We exported the time-stamps and durations to files which we could use along with the video data in the annotation software *ELAN*[4].

Utterance Classification

In the second stage (step *b*), we used *ELAN* to assign the utterance labels to the two participants for each trial. We classify them according to whether it is produced by the left or the right participant (in the video) and if it relates to the task or the system (e.g. in case of a problem). This results in three tiers for each participant: *a*) all utterances, *b*) utterances regarding the task and *c*) utterances regarding problems with the system. The summed utterance duration of these tiers serve as measures we can directly use for analysis. Of course, these annotation labels (*participant left or right* and *task or system*) are relatively vague as they only cover the time duration the participants talked to each other. They do not include information about the spoken words or any further context. Linguistic methods, such as Protocol Analysis (cf. [98]) can help increasing the value of the recorded audio data with a much higher annotation effort.

Interaction Classification

From the system logs we collected during the trials we also extracted the time stamps of all mind-map item interactions. This is comparable to the interaction time approach by Fitzmaurice and Buxton [46], but only respects interaction with mind-map items instead of interaction with the actual interface device. This information, visible from the video, was imported to *ELAN* as tiers, which we assigned to the participants' interaction. Again, we directly used the summed interaction length as a measure for evaluation. Furthermore, we considered the average interaction length as a valuable measure.

Time-overlap

ELAN allowed to calculate the time overlap between tiers. We used this as additional measures for the calculation of the overlap between the utterance and interaction tiers for each participant. Furthermore, we calculate the overlap between the participants' interaction tiers as a measure for parallel interaction with the system. All interaction measures in the time-domain are measured in seconds [*s*].

Participants' Interaction Area

We did not only cover temporal measures, but also investigate the spatial interaction aspects between the collaborating participants. For this, the interaction classification enabled the

[3] `http://audacity.sourceforge.net/`

[4] `http://tla.mpi.nl/tools/tla-tools/elan/`

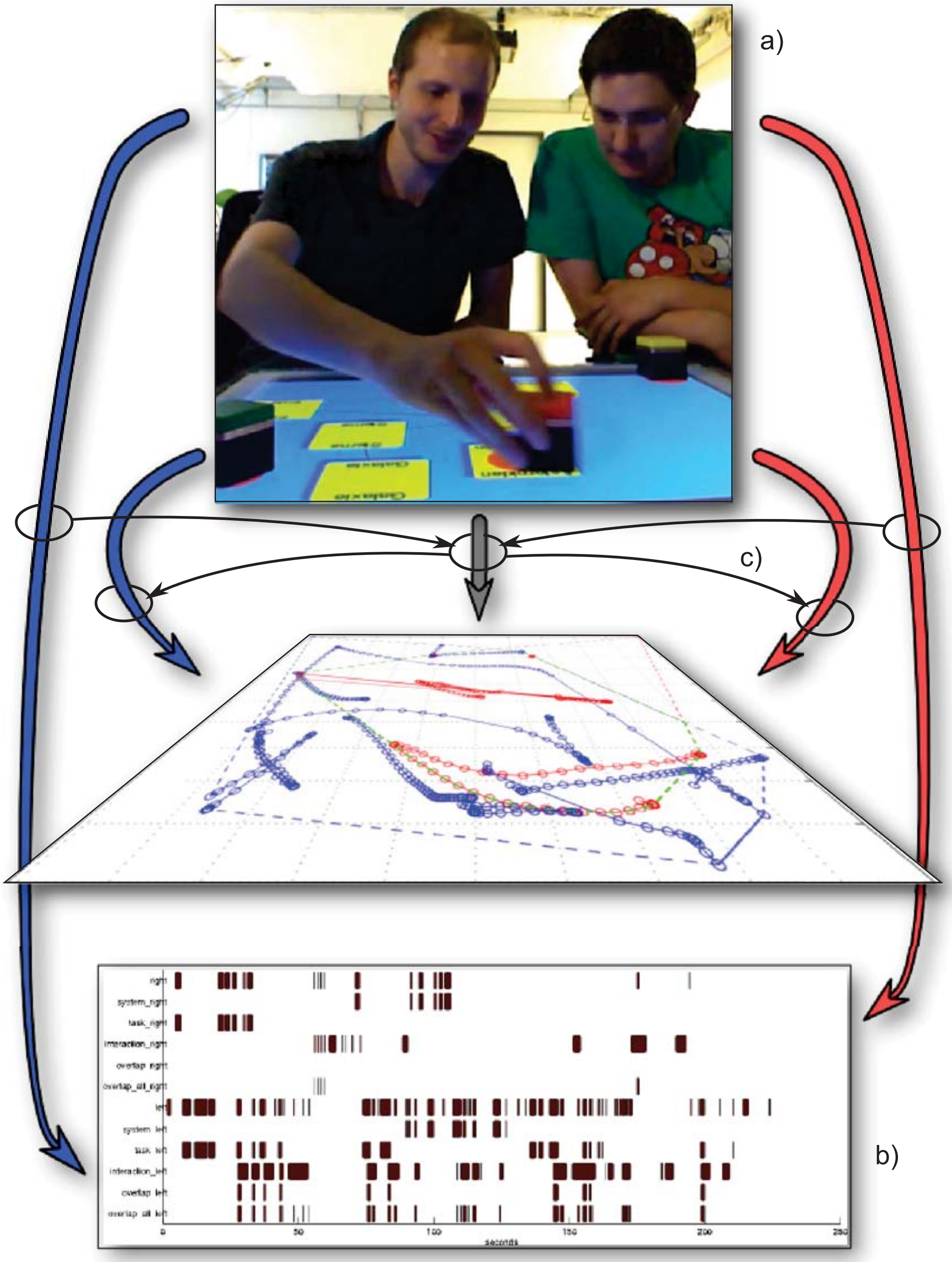


Figure 7.5: Diagram of the data processing pipeline: a) Acquisition: Collection of raw data, including audio, video and system log. b) Annotation: Here the raw data is semi-automatically segmented and assigned to the two participants (left is blue, right is red). This results in tiers containing time information about the utterances regarding the task and the system and interaction with the mind-map items by participant. c) Assignment: The classification of the utterances and item interaction allows for assigning collected trajectories to the participants and the calculation of the used interaction areas and their overlap.

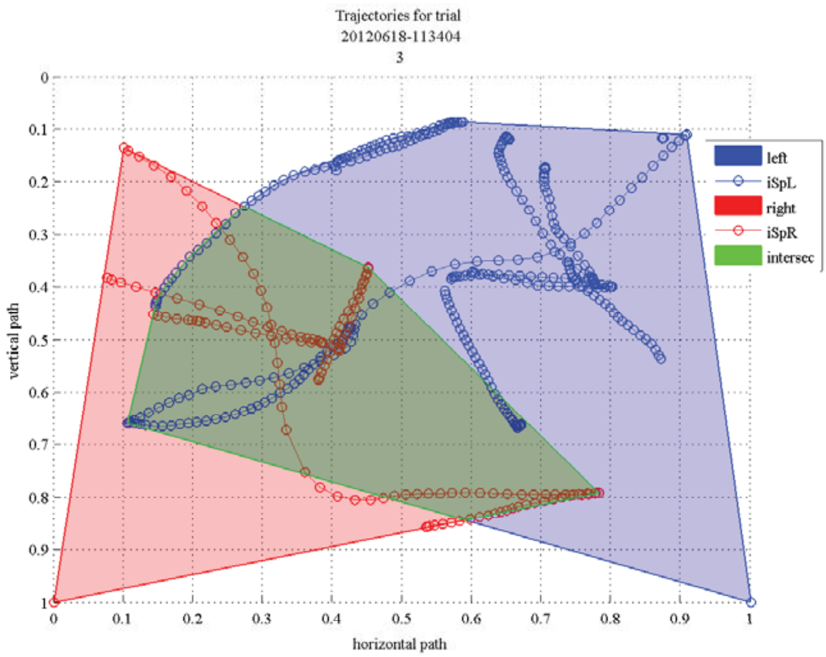


Figure 7.6: Example visualization of one trial's trajectories, interaction spaces and their intersection.

automatic assigning of the participants' trajectories recorded in the log files. By this, we are able to identify which trajectory was performed by whom (step c). To measure the area of the interactive surface the participants actually use for interaction, we calculated the convex hull of the participants' trajectories. The convex hull is calculated from the participants' trajectories and the corner of the interaction surface at which the respective participant sits during the trial. The area of the convex hull is defined by the points that lie on the outer border of the trajectory points, (as defined in Equation 7.1):

$$\left\{ \sum_{i=1}^{|S|} \alpha_i x_i \;\middle|\; (\forall i : \alpha_i \geq 0) \wedge \sum_{i=1}^{|S|} \alpha_i = 1 \right\} \tag{7.1}$$

Here, S is the set of trajectory points and x_i determines the point i. For all points, a coefficient α_i is calculated, that are all positive and sum up to 1. Algorithms, such as the *Gift wrapping* or *Jarvis march* algorithm [86], can be used to easily compute the convex hull of a finite set of points.

The area span by the points defining the convex hull is directly used as a measure for the later analysis. Furthermore, we calculated the intersection between the interaction areas to determine whether the interface has an influence on how far the participants spatially share more or less space for interaction. Figure 7.6 depicts an example visualization of the trajectories performed in one trial, the participants' used interaction space and the intersection. Especially in the Mouse condition we expect a certain difference, because of its exclusive character. It does not support parallel access of the participants which can cause one participant to use the interface alone during the whole trial.

After post-processing and annotation, the *ELAN* tiers were video recorded with a screen capturing program. This allowed us to merge the recorded videos of the participants, the rendered interaction videos of the interactive surface and the annotations into one video for each trial for later detailed analysis.

Motivation Background for new Measures

Of course, these measures are not completely new and may even be successfully used in other research fields, such as CSCW that even shares some overlap with tangible interaction research. But the described measures were not yet used in a study on (actuated) TUIs in comparison with other established interaction paradigms. As inspiration for our studies, the following concepts played a major role:

Peripersonal Space

The idea for measuring the participants' interaction area for later analysis was inspired by the work by Nguyen and Wachsmuth [147]. They present the concepts *peripersonal space* and *interpersonal space* for the virtual agent Max. From the neuro-physiological view, the motivation for this argument is the work by Holmes and Spence [72], Previc [162] and others. The peripersonal space is an egocentric three-dimensional space model defined by the reach of the human hands for direct visual grasping and manipulation [162].

Interpersonal Space

Nguyen and Wachsmuth also integrate the social view and its neural mechanisms by reviewing the work by Hall [60], Lloyd [123], Kendon [93] and others. Especially Kendon [93, p. 209] introduces the *formations* patterns for spatial orientation and grouping of humans in space. For our study the side-by-side arrangement is of particular interest, because the participants sit side-by-side at the tDesk to accomplish the task. Each participant has an "activity space" which Kendon calls *transitional segment*. Kendon calls the intersection of transitional segments *o-space*. We do not stick to Kendon's nomenclature, because our definition of the participants' interaction area is calculated from our collected data. Our interaction area definition is a sub-space located in the space defined by Kendon.

Turn Taking

Additionally, we analyzed the annotated speech and interaction tiers with regard to turn taking, as described by Sacks et al. [177]. This is a conversation analysis approach for modeling and describing the process of turn taking in conversations. In this study we measure the number of turns that occurred between the participants during the trials. We not only focus on speech, but also on the interaction with the mind-map items. Except for the Mouse condition, all interfaces evaluated allowed parallel use of the system. Nevertheless, the turn taking model still works for interaction and we hoped to find interesting effects within this measure between the conditions.

7.5 Experimental Procedure

Introductory Video

The dyads of participants were randomly allocated to one of the four conditions. At first, the participants were introduced to the experiment procedure, starting with an introductory video for the particular condition presenting the features of the system. The basic sequence of the videos and their explanation are the same for all conditions and were only adapted where it was demanded by the condition's interface. Stills of the introductory video for the TAOs condition can be found in Figure 7.2.

Learning and Exploration Phase

After this, a learning phase follows, where the participants were allowed to play with the system to get used to the interface and its features. At this stage there are five mind-map items without any meaning. The participants could try the system in the learning phase as long as they liked and decided by themselves if they are ready for the actual task. This is assured by a little test task where they had to align the items in a circle. Furthermore, this phase hopefully helps to reduce the novelty effect.

Trial Phase

Following the learning and exploration phase, is the trial phase with the actual task. Here the participants get seven mind-map items from the field of astronomy and five minutes to accomplish the task. Both during the learning phase and the actual task, the participants' interaction with the system was audio and video recorded and system logs were collected, as well.

Questionnaire

Finally after the actual task, the participants were asked to complete the digital questionnaire. The whole experiment could be conduced in German or English.

7.6 Participants

We drew our participants from the students and administrative staff of the Bielefeld University using a printed call for participants in the university's cafeteria and the staff mailing list. As we designed our study as a single-blind study, the call explicitly did not mention the fact that we intend to compare different user interfaces. All participants had no detailed prior knowledge of the TAOs and were instructed that we are interested in how they collaborate in creating a mind-map with our "interactive table". So the participants did not know that we are actually interested in how they interact with the system. or how they interact with each other using the system.

For this exploratory study, we were able to recruit 80 participants that made up $N = 40$ dyads which results in 10 dyads per condition. There were 40% female ($N = 32$) and 60% male ($N = 48$). 90% of the participants were right-handed ($N = 72$), 8.75% were left-handed ($N = 7$) and 1.25% ($N = 1$) was ambidextrous. The mean age of the participants was 32.21 years, ranging from 11 years to 70 years ($SD = 11.21$). Within the dyads, 57.5% ($N = 46$) of the participants stated knowing the other trial partner, 17.5% ($N = 14$) stated knowing the other one only a little, while 25% ($N = 20$) did not know the other partner at all. Figure 7.7 graphically summarizes these numbers.

7.7 Results

We conducted one-factorial Analysis of variances (ANOVAs) to analyze the effects of our experimental manipulations and for the post-hoc analysis we used multiple comparison tests with Tukey's Honestly Significant Difference (HSD) criterion (an alternative to the Bonferroni method) from *Matlab's Statistics and Machine Learning Toolbox* that already deal with alpha-inflation compensation. The first dependent dimensions are the *subjective ratings of the participants* on *a*) system usability, *b*) collaboration, *c*) task, *d*) user type, *e*) other tasks, *f*) system design, *g*) expected system behavior, *h*) redesign, *i*) task familiarity, *j*) result and

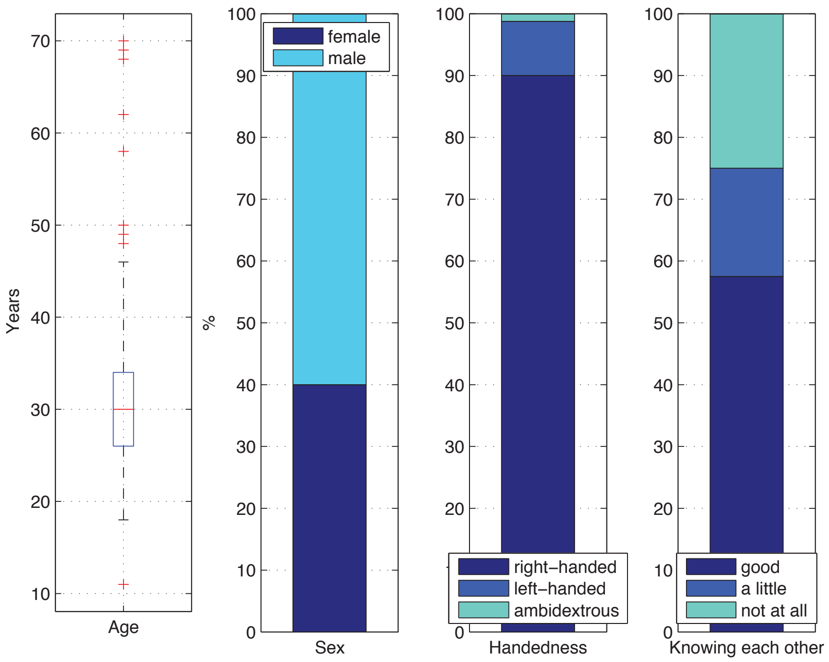


Figure 7.7: The descriptive statistics of the participants.

the *k*) *SUS* according to Brooke [23]. After this, we present the results of the ANOVAs conducted on the *interaction measures* *a*) utterances, *b*) interaction, *c*) time-overlap between utterances and interaction, *d*) time-overlap between the participant's interaction, *e*) interaction space, *f*) interaction space interaction, *g*) turn taking in speech and *h*) turn taking in interaction. The ANOVA results are printed in Table 7.2.

Subjective Ratings

In the following paragraphs we elaborate on the significant results as summarized in Table 7.2 and present the post-hoc test results.

System Usability

The ANOVA showed a significant effect for our *system usability* scale. The post-hoc analysis indicates a significant difference between the multi-touch ($M = 4.69$, $SD = 1.23$) and the TAOs condition ($M = 5.74$, $SD = 0.89$). The TAOs condition was rated best, while the multi-touch condition was rated worst ($p = 0.002$). The other two conditions showed no significant difference compared to the others.

Task

The ANOVA yields a main effect of experimental condition on the *task* index.The post-hoc tests revealed a significant difference ($p = 0.005$) between the Mouse ($M = 6.12, SD = 0.78$) and the passive TUIOs condition ($M = 5.25, SD = 1.39$). The passive TUIOs condition was rated less suitable for the task, while the Mouse condition was rated best.

Task Familiarity

In the *task familiarity* index the results yield significant differences between the multi-touch condition ($M = 2.00, SD = 1.52$) and all other conditions ($M \geq 3.60, SD \approx 2,27$). Our data do not provide any clue for this effect as the participants were randomly assigned to the conditions. This could have happened by chance or there could have been some participants that misunderstood the question.

Table 7.2: Overview of the ANOVA results. Printed bold are results that met the critical $F \geq 2.64$ and yield significant effects ($p \leq 0.05$). Though the ANOVA yielded significant effects in the interaction space intersection, the post-hoc tests did not.

Index / Measure	F-value	p-value	η_p^2-value
Questionnaire Results			
System usability	3.07	0.03	0.06
Collaboration	1.74	0.17	0.03
Task	2.97	0.04	0.06
User type	1.62	0.19	0.03
Other tasks	0.11	0.95	< 0.01
System design	1.45	0.23	0.03
Expected system behavior	1.74	0.17	0.03
Redesign	2.07	0.11	0.04
Task familiarity	3.00	0.04	0.06
Result	0.62	0.60	0.01
SUS	0.66	0.58	0.01
Interaction Measures			
Utterances sum	1.78	0.16	0.04
Interaction mean	10.23	< 0.01	0.17
Interaction sum	1.99	0.12	0.04
Overlap mean (task+interaction)	6.79	< 0.01	0.12
Overlap sum (task+interaction)	1.68	0.18	0.03
Overlap mean (interaction+interaction)	2.30	0.10	0.15
Interaction space	5.51	< 0.01	0.05
Interaction space Intersection	2.97	0.05	0.01
Turn taking (speech)	1.13	0.35	0.03
Turn taking (interaction)	8.30	< 0.01	0.03

Insignificant Results

All other results from our own questions (Collaboration, User type, Other tasks, System design, Expected system behavior, Redesign and Result) did not show any significance. These insignificant results can be found in Section A.2 in the appendix.

Interaction Measures

The interaction measures are mainly based on the annotated video recordings.[5] Figure 7.8 gives an overview of three trials (Mouse, multi-touch and TAOs[6]) to make the results gathered from the interaction measures more graspable. In the stills, we can observe the two participants' in each trial interaction spaces and the overlap between utterance and interaction tiers.

Interaction

We can observe significant effects analyzing the average interaction duration: Post-hoc tests revealed that the average interaction duration in the Mouse condition ($M_1 = 0.80$,

[5] Unfortunately, one video of the Mouse condition was not completely recorded and therefor not usable for analysis. We left it out and continued our analysis on the remaining 39 videos.

[6] As there was no difference between the TUIOs and the TAOs condition in any way, we omit giving examples for the TUIOs condition at this point.

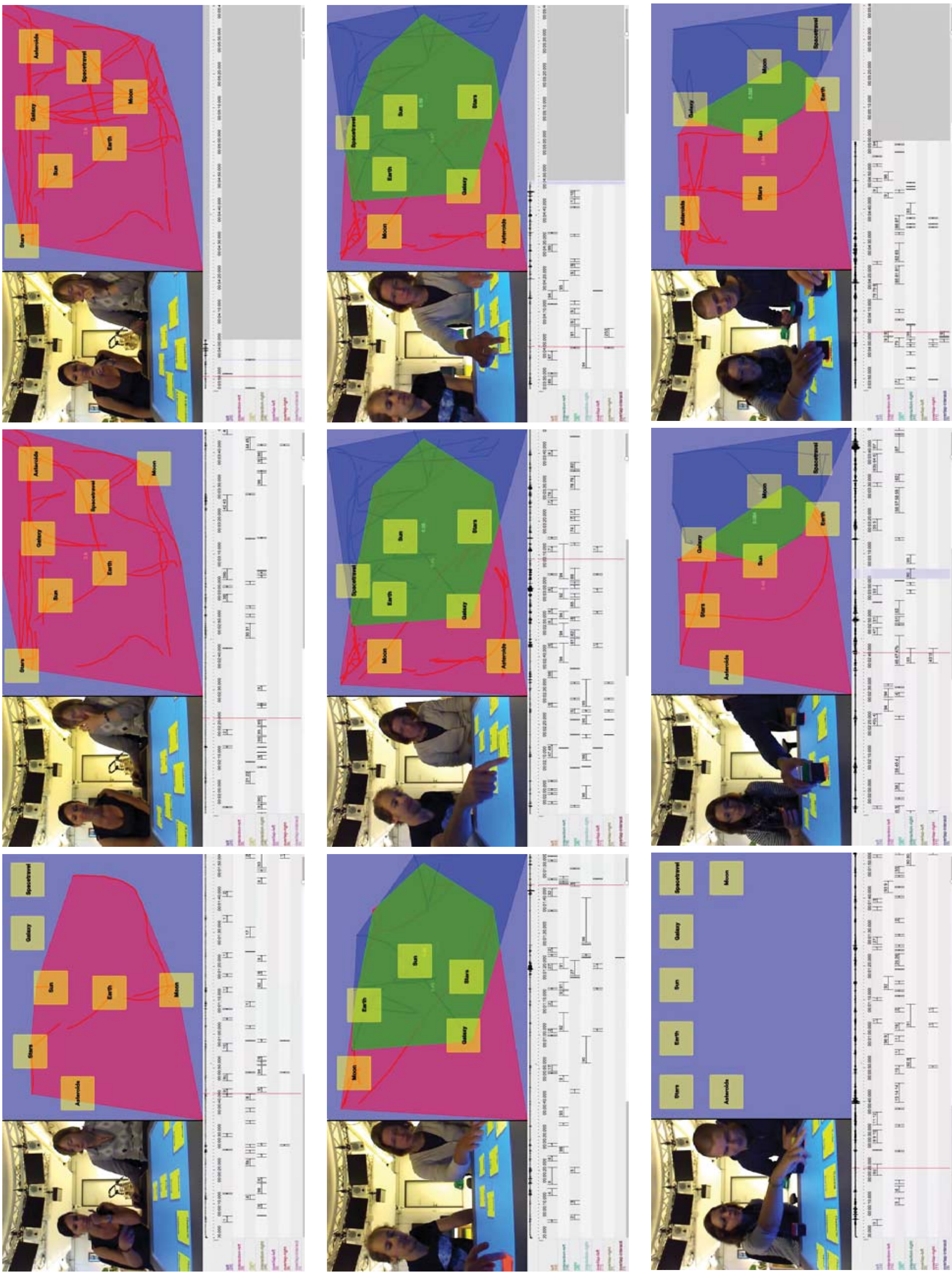


Figure 7.8: Stills from three merged trial videos at three different time indexes (1st row: Mouse; 2nd row: Multi-touch; 3rd row: TAOs). We can observe the participant using the Mouse to take control rather quickly. In the multi-touch and TAOs trials, there is an agreement phase. There is active collaboration in the latter two trials. The shared interaction space in the multi-touch trial is larger than in the TAOs trial.

$SD_1 = 0.49$) is significantly shorter ($p_{1,2} < 0.01$, $p_{1,3} < 0.01$ and $p_{1,4} < 0.01$) than in all other conditions ($M_2 = 2.17$, $SD_2 = 1.16$; $M_3 = 2.05$, $SD_3 = 0.83$; $M_4 = 1.78$, $SD_4 = 0.71$).

Average Time-overlap between Taks discussion and Interaction

The average time-overlap between utterances regarding the task and mind-map item interactions drops significantly in the Mouse condition ($M_1 = 0.35, SD_1 = 0.26$) in comparison with the other conditions ($M_2 = 0.69, SD_2 = 0.38$; $M_3 = 0.83, SD_3 = 0.46$; $M_4 = 0.78, SD_4 = 0.35$). This was expected as the Mouse is a single-user interface. Often the participant not interacting with the Mouse successively told the other participant what to do.

Interaction Space

As described above, we calculated the interaction space of the dyad's participants of each trial. The measure used in this evaluation is the average of these two values for each trial. The post-hoc tests revealed a significant difference ($p_{1,2} = 0.003$) between the Mouse ($M_1 = 0.33$, $SD_1 = 0.13$) and the multi-touch condition ($M_2 = 0.50$, $SD_2 = 0.10$). Furthermore, there was a significant effect ($p_{1,3} = 0.048$) between the Mouse and the passive TUIOs condition ($M_3 = 0.45$, $SD_3 = 0.07$). In other words, the interaction space used by the participants in the Mouse condition is significantly smaller than in the multi-touch and the passive TUIOs condition. This effect was expectable and can be explained with the exclusiveness (single-user implementation) of the Mouse.

Turn Taking in Interaction

The last measure we analyzed in this study is the turn taking in interaction with mind-map items. The test for homogeneity of variance was significant for this dimension ($p = 0.045$). Thus, the Games-Howell post-hoc tests revealed a significant difference ($p_{1,2} = 0.005$, $p_{1,3} < 0.001$, $p_{1,4} = 0.004$) between the Mouse condition ($M_1 = 1.78$, $SD_1 = 0.83$) and all three other conditions ($M_2 = 7.9$, $SD_2 = 4.15$; $M_3 = 6.40$, $SD_3 = 2.07$; $M_4 = 6.10$, $SD_4 = 2.85$). Obviously, the Mouse condition has significantly less turns which again can be explained with the exclusive character of the single-user device. Between the other conditions there is no significant interaction.

Appendix A.2 contains all results calculated in the ANOVAs and post-hoc test, including all non-significant values and provides graphical overview figures of the discussed dependent variables.

Further Observations

When screening the audio and video material we gathered throughout the trials, we made further interesting observations.

Successful Trials

First of all, we counted the successful trials. In result, 82.05% of all 40 trials were successful. In the Mouse condition 88.89% ($N = 8$) of the trials were successfully accomplished by the participants. 70% ($N = 7$) of the participants in both the multi-touch and passive TUIOs condition successfully finished the trials and 30% ($N = 3$) did not. In the TAOs condition, the participants were successful in 90% ($N = 9$) of the trials and did not succeed in 10% ($N = 1$).

Use of Simultaneous Movement Feature

The selection-feature for moving multiple items simultaneously was used seldomly; on average in 17.95% ($N = 7$) of all trials. In the Mouse condition, this feature was used only in one trial (11.11%). The participants in the multi-touch condition made use of the feature in 20% ($N = 2$) of the trials. The simultaneous movement feature was used in 10%

($N = 1$) of the trials in the passive TUIOs condition. In the TAOs condition, the feature was used at most (30%, $N = 3$), but without using the TAOs actuation feature.

Two-handed Input and Kinematic Chaining

Though supported by all conditions, except the Mouse condition, we did not observe two-handed input [26] and kinematic chaining [59]. Both would have been possible to perform by using both hands in the multi-touch condition or by using two TUIOs or TAOs in the respective conditions. Instead, we were occasionally asked by the participants why there are three TUIOs or TAOs for only two users. Intentionally there was one for each user and we hoped, the third would be used for two-handed input.

Unexpected Problems

The size of the interactive surface was problematic in two different ways, as participants reported. First of all, the surface was too small to support collaborative work between two users. Participants reported that they did not want to disturb their trial partner due to the lack of space, especially in the conditions with TUIOs. On the other hand the TUIOs or their non-tangible representation may be too big in relation to the interactive surface. But since the size of the TUIOs is good in terms of graspability, it is more likely that the interactive surface is too small.

7.8 Discussion and Interpretation

We were surprised to find no larger effects between the multi-touch and tangible conditions on the adapted interaction measures. At least with our sample of participants we were not able to find evidence for larger effects. However, we found significant effects in the questionnaire and expectable results for the Mouse condition.

System Usability

With an average rating of $M = 5.74$ and a $SD = 0.89$, the numbers say it clearly: The participants of our study rated the TAOs as best interface according to its usability. The next best condition was the passive TUIOs, followed by the Mouse condition. That the multi-touch condition was rated the worst may be connected with technical problems. The sensing approach which takes advantage of a *Kinect* sensor for tracking fingers touching the interactive surface performed not as well as expected. It suffered from fingers or hands occluding the finger touching the projected mind-map item which disturbs the interaction. Capacitive or optical sensing from below the surface might have yielded better results for the multi-touch condition.

Task

The task index's results are surprising. The index was basically intended to reflect the system's suitability for the mind-mapping task. Here, the participants rated the Mouse condition best, followed by the multi-touch and the TAOs condition, while the passive TUIOs condition was rated worst. A significant effect was only observed between the Mouse and the multi-touch condition. Furthermore, the questionnaire items regarding the task are more abstract and not that easy to answer (all of them were recoded). So one might regard the effect in the task index with suspicion.

Interaction

The multi-touch condition had the longest durations. Furthermore, the significant effect between the Mouse condition and all other conditions regarding the average interaction duration is obvious. Since the interaction with the Mouse happens in a much smaller physical space, the participants are able to interact with the mind-map items much quicker. Interaction with the Mouse is quicker because of the shorter distances that are needed to move the Mouse. This slight drop of interaction duration in the passive TUIOs and TAOs conditions was not significant. Furthermore, the longer interaction durations in the multi-touch condition may also be related with the mentioned technical problems.

Time-overlap between Utterances and Interaction

Considering the findings regarding the utterance and interaction duration, it is not surprising that the overlap between these two measures yield significant effects. The utterances and the interaction in the Mouse condition are both shorter than in the other conditions. The overlap between both measures turns out to be significantly shorter compared to the overlap duration in the other conditions. The longer overlap durations for the passive TUIOs and the TAOs condition may indicate a better balanced cognitive load in these conditions. Nonetheless, this hypothesis definitely needs more investigation from the psychological point of view.

Interaction Space

The results of the analysis of the used interaction space are not surprising. The used interaction space in the Mouse condition is significantly smaller than in the multi-touch and passive TUIOs. Also the used interaction space in the TAOs condition tended to be larger than in the Mouse condition. This can be explained with the exclusiveness of the Mouse interface and the fact that in four trials only one participant interacted with the Mouse (this also happened once in the multi-touch condition). On average, this reduced the used interaction space of the two participants.

Turn Taking in Interaction

The turn taking in interaction is another measure for parallel interaction. The highly significant effect in the Mouse condition can be explained with the interface's exclusiveness, because turn taking in the Mouse condition means a switch between the users. Furthermore, there is a significant effect that multi-touch may facilitate parallel interaction between the participants, other than in the passive TUIOs and TAOs conditions.

Use of Simultaneous Movement Feature

It is interesting that in the TAOs condition the simultaneous movement feature for the mind-map items was used most often, though the TAOs' actuation was not used in favor of the alternative implementation (by selecting and de-selecting the items to be moved simultaneously). This can be explained with the participants' familiarity with the GUIs paradigm. Asking the participants after the trial, they stated that they did not consider using the TAOs' actuation due to the availability of the alternative implementation they are more used to. We think the rather short introduction to the system including the learning phase was not enough to make the participants aware of the additional actuation feature. In a long-term study this effect might change.

Duration of Learning Phase

The videos of the learning phase were no central aspect in this analysis. The learning phases in the Mouse condition were the shortest. This can be explained with the participants' familiarity with the computer Mouse and its usage. We were surprised to find the learning phases in the multi-touch condition about twice as long as in the Mouse condition. Though the participants may be familiar with touch interaction from smartphones or tablet PCs, we suspect they never used a large touch interface like the tDesk before. Furthermore, this effect can be explained with the technical problems, mentioned earlier.

Two-handed Input and Kinematic Chaining

Because the participants always used only one finger or TUIO or TAO, we were disappointed not to observe two-handed input and kinematic chaining. This might be connected with the task; it does not require such interaction patterns. Sometimes when one participant had problems breaking a connection between two mind-map items, we observe the other participant helping out. Here the other participant moved the other mind-map item further away to help to break the connection, collaboratively.

7.9 Conclusion

Our study showed that users seem to be well trained in using the Mouse as the results of the mean interaction duration revealed. The average item manipulation duration with the Mouse took only half of the time as in all other conditions. The other significant findings are mostly related to the fact that the Mouse was used as a single-user device in this study. However, these results fit into major findings reported in literature comparing Mouse interaction with one or two other interaction styles.

Differences between the other multi-user interface conditions seem to be smaller than we expected. So far, we can emphasize the conclusion stated by Fitzmaurice and Buxton: "The Mouse is a general all-purpose weak device; it can be used for many diverse tasks but may not do any one fairly well. In contrast, strong specific devices can be used which perform a task very well but are only suited for a limited task domain. The ultimate benefit may be to have a collection of strong specific devices creating a strong general system." [46] Nonetheless, the desire for comparative studies in the fashion of our own seems to be reasonable and needed, as recently published studies show [28, 37].

Limitations of this Study

Our study was pure exploratory and far from complete. We were able to cover effects with a statistical effect size of $f = 0.69$ ($N = 40$; 10 dyads per condition) which is a very large effect size. To significantly discover large effects ($f = 0.40$) we would have needed $N = 112$ dyads; a medium effect size of $f = 0.25$ would have required $N = 280$ dyads, a small effect size of $f = 0.10$ would have required $N = 1724$ dyads.[7] Changing the between-subjects to a within-subjects design would have required only $N = 24$ dyads for a complete set of counterbalanced trials, but would have resulted in a corpus over twice as large as our current corpus size covering effect sizes of $f = 0.43$. The next larger complete set of counterbalanced trials would have required $N = 48$ dyads with a corpus size of 192 trials covering an effect size of $f = 0.30$. With such an increased number of trials also comes an increased effort for post-processing and analysis. We can easily see that a comprehensive comparative study with four conditions quickly goes beyond the scope of a subproject like ours and would demand a PhD project of its own.

Adapted Measures for Tangible Interaction

However, we adapted and introduced generic measures from other research fields to evaluation of (actuated) TUIs that were derived from (semi-)automatically collected and annotated interaction data. These measures can be transferred to other tasks and study designs and may help to find further evidence for the theories of the research community regarding the benefits of tangible interaction.

[7] Estimated using *G*Power* [39]

Touch Support for TUIOs and Study Control

Beside the study results, we also contributed technical improvements to the TAO by implementing hardware and software extensions supporting touch interaction with the TAOs, comparable to the more recent approach by Gelineck et al. [54].

Our extensions for study execution and (semi-)automatic annotation and post-processing of collected interaction data decreased the amount of necessary analysis effort. After hand-assigning annotations to the participants' tiers, it highly reduces efforts for data fusion, allowing for deriving information for the adapted measures.

Future Work

The corpus we gathered during our study offers the option for extensive linguistic analysis which would have gone far beyond the scope of this thesis. New hypotheses can be investigated, such as if the different interface configurations foster teaching and learning differently. Such high-level measures can be determined by counting the occurrences of one participant explaining one or more of the mind-map items to the other participant. Furthermore, the presented hypotheses can be evaluated in field- and long-term studies to investigate learning effects in general, like presented by Kirk et al. [101] and Wigdor et al. [212]. Aspects like co-orientation [94] are also a promising cross-modal interaction measure that could be analyzed through deeper annotation work. In future studies this could be supported by integrating eye-tracking methods and (marker-based computer vision supported) (semi-) automatic annotation.

Multi-user Interaction

Of particular interest within the frame of this chapter are systems that address multiple users with regard to personal interaction spaces or territories [181]. To even more improve the automatic annotation and data fusion capabilities of our system, identification and tracking of multiple users is needed. One of the first approaches to detect users around a tabletop multi-touch display was presented by Walther-Franks et al. They presented a self-contained integrated approach that used arrays of proximity sensors placed around the frame of the multi-touch table. With the sensor readings, they propose several application ideas that benefit from user detection at the table, user-orientated display and user-assigned touch events [207].

Klinkhammer et al. picked up this approach to implement their museum information multi-touch table. The system addresses multiple users and demonstrates "territories" for the users. On the one hand, these clearly separate the users' working areas, on the other hand, these areas support collaboration and information charing between users [107].

With their *Medusa* system, Annett and Grossman extended the idea of using proximity sensors by adding two further rings of sensors pointing upwards around the interactive surface. This allowed them to more robustly assign touch events to users and even to detect the users' arms without touching the surface [3].

8 The Human Hand's Manipulation Speed: Implications for Actuated TUIOs

> Man is the most intelligent of animals
> because he has hands.
>
> Anaxagoras, overdelivery by Aristotle,
> De partibus animalium, IV, 10; 687 a 7

Our hands are the critical part of our bodies when it comes to manipulation of physical objects. The exploration and investigation of the human hand's properties and skills is an interdisciplinary field of research. To define the boundary conditions and requirements for manual interaction of TUIOs, we briefly touch on this topic within this chapter. One basic but fundamental property of manual interaction is the hand's speed in manipulating an object. In this chapter we review speed specifications of other actuated TUIOs found in literature and compare them to findings from a small pre-study investigating the human hand's manipulation speed as an upper bound for the TAOs' actuation speed. Furthermore, we relate these findings with the TAOs' velocity and review the interaction data gathered throughout this thesis.

8.1 Related Work

Grasps and Grasp Classification

The skills of the human hand and its universal applicability in object manipulation and grasping has always inspired researchers. One key feature for manual interaction is grasping. Taylor and Schwarz give a detailed overview of the anatomy of the human hand and describe various hand movements, including grasps [192]. One of the first classification of different grasp types has been proposed earlier by Schlesinger [180]. Mainly dealing with prosthetics and artificial limbs, this approach is driven by grasping different object shapes, resulting in six prehension types: *a*) cylindrical, *b*) tip, *c*) hook or snap, *d*) palmar, *e*) spherical and *f*) lateral grasp. Napier criticizes this shape-driven classification and introduces his first task-oriented approach which categorizes grasps into two classes: *a*) power grasp and *b*) precision grasp [146]. Though this approach is widely accepted in literature, it is still debated. Multiple different taxonomies were developed with different purposes in mind, such as for robotic grasping [179]. Bullock and Dollar proposed another hierarchical taxonomy with regard to aspects such as contact, motion, whether a grasp is prehensile or if it is within the hand [24] (see Fig. 8.1).

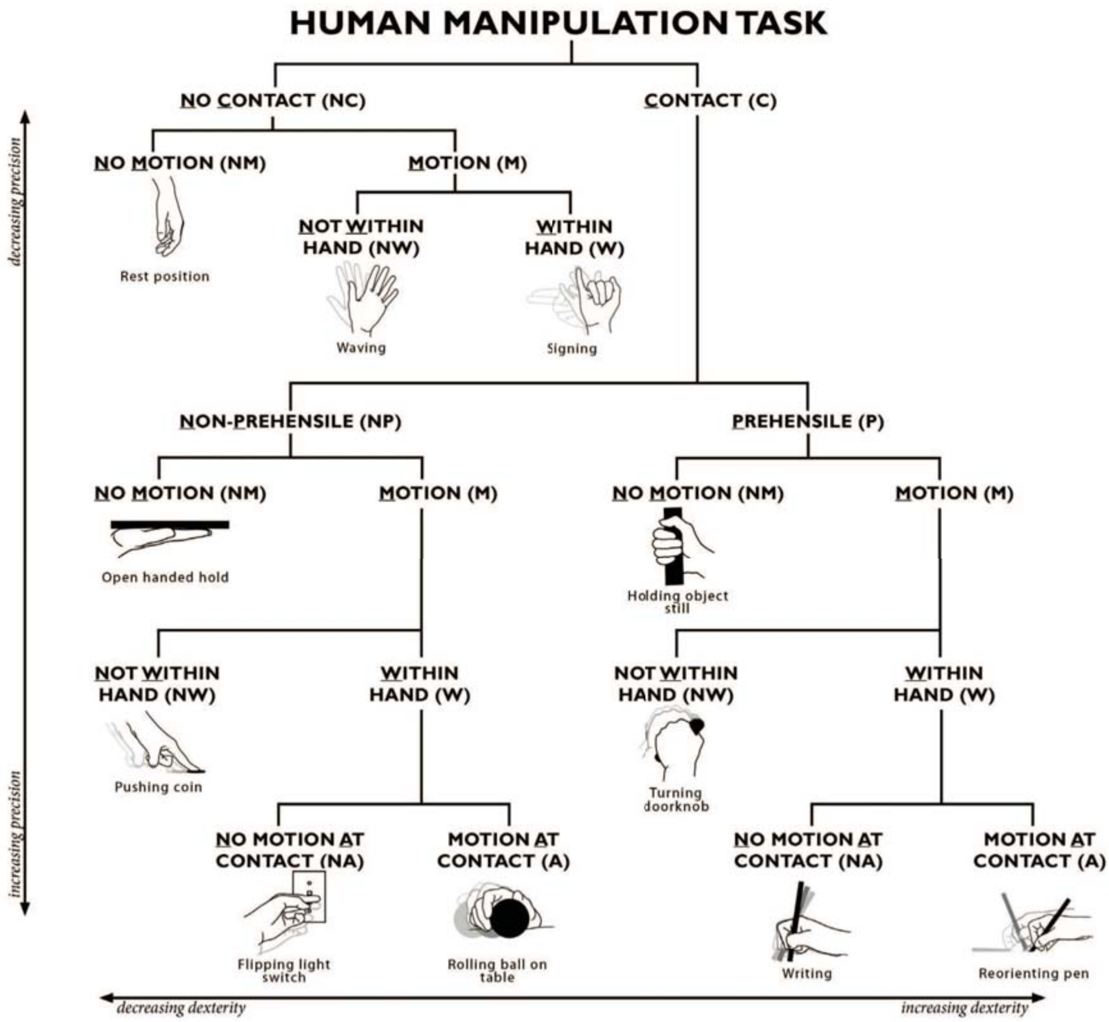


Figure 8.1: Hierarchical taxonomy of grasps by Bullock and Dollar [24].

Grasping TUIOs

With regard to (tabletop) TUIs, we find this taxonomy very useful. Trying to apply this taxonomy to TUIO handling in tabletop TUIs, we mostly find one class of human manipulation task: C-NP-M-W-A (cf. Fig. 8.1). In other words, TUIO handling in tabletop TUIs obviously involves contact with the TUIO (C), it is non-prehensile (NP), involves motion (M) within the hand (W) and involves motion on the tabletop surface (A). According to Napier, this classification path primarily resembles the power grasp. Of course, there are other grasp types that apply to TUIO handling. For instance, if the TUIOs are smaller like in the *Turtledove* system [140], we have a different handling: C-NP-M-NW. Another example for TUIO handling applies to the *Chopstix* system [16, p. 104–115]: C-P-M-W-NA. "Different object sizes further result in a different type of grip [127]. As a rule of thumb, square blocks with a width of 5 $\times$ 10 cm are easy to hold, a width of 5 cm supports a precision grip (pinching with thumb and one or two fingers) and a width of more than 10 cm requires a power grip with the entire hand. A token's weight can furthermore add meaning to the interaction-heaviness might indicate a more important and valuable object. A central affordance of physical objects is that they provide tactile feedback, supporting eyes-free control when performing fine-grained operations such as rotating the object, or moving two objects in relation to each other [102]. Moreover, an object's design can invite users to interact" [185].

The Speed-Accuracy Trade-off

Beside grasping, the manipulation of objects plays a major role, especially in tangible interaction. Fitts' Law [44] found favor with the communities in HCI and Ergonomics. This theorem is used to describe the speed-accuracy trade-off which occurs in interaction.

$$MT = a + b \cdot \log_2 \left(\frac{2A}{W} \right) \tag{8.1}$$

In formula 8.1 [128], MT is the predicted movement time, measured in seconds [s], W is the target width to be selected, A is the distance to the target. The constants a and b are determined through linear regression. In a nutshell, this model describes the relation between target size and distance and the difficulty in correctly selecting it with a pointing device (in a one-dimensional case). The smaller a target is and the further it is away from the current pointer position, the harder it is and the longer it takes to accurately select it.

Related Studies with Actuated TUIOs

In TUIs, many studies have been conducted, investigating interaction speed and result accuracy, such as [46]. With regard to actuated TUIs, Pedersen and Hornbæk described a comparative usability study in which they investigated differences in interaction speed and accuracy between non-actuated and their actuated TUIOs, the *Tangible Bots* [158]. The participants of their study preferred the active TUIOs over the passive ones. Furthermore, they found that the active TUIOs required less workload and that their participants reported that they have had more fun. The fine-grained rotation task benefited from actuation, whereas coarse planar movements were accomplished more effectively with the passive TUIOs.

Actuation Speeds of TUIOs in Literature

In Chapter 3, we already compared actuation specification of other actuated TUIOs found in literature, as given in Table 3.2. Additionally, Figure 8.6d visualizes these findings and compares these with the TAOs' current actuation capabilities. Though the *TangibleBots* by Pedersen and Hornbæk seem to base on the *3pi Robot*[1] capable of driving at 100 cm/s, the visual tracking might of the *TangibleBots* might be the limiting factor. More recently, *Acto* was published by Vonach et al. which claims to drive at up to 39 cm/s [204].

8.2 Basic Motion Properties of the Hand and the TAOs

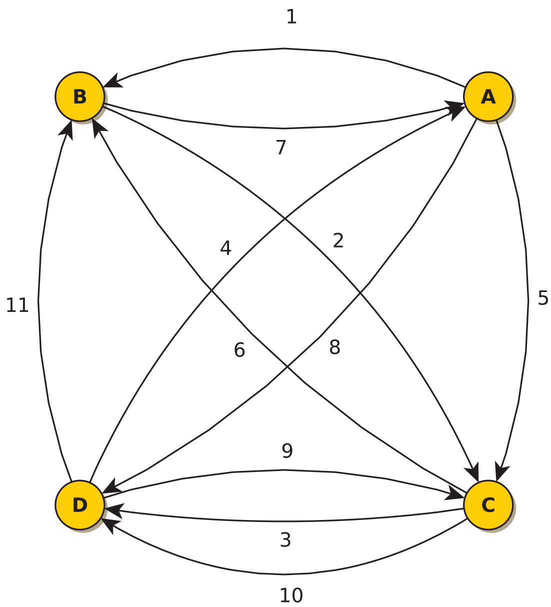
Speed is a very important key factor for effective manipulation of objects. In this section we describe our small pre-study to measure the speed of the human hand manipulating an object as an upper bound for actuated TUIOs. Furthermore, we measure the TAOs' velocity and compare the two measurements. As the TAOs should ideally be able to reproduce the human hand's speed, the human hand's manipulation speed serves as an upper boundary condition. Though we improved the TAOs' performance compared to earlier measurements [167, p. 70], we expect that they still cannot compete with the human hand.

Figure 8.2: Setting and preparation for the manipulation speed recording experiment.

(a) The MILab setup [136].

(b) Hand and TUIO equipped with Vicon markers.

Figure 8.3: The motion pattern for measuring the manipulation speed. The corners are labeled with upper case letters and the linear sub-trajectories of the pattern are labeled in their sequence of execution, starting in the upper right corner: $A \xrightarrow{1} B$, $B \xrightarrow{2} C$, $C \xrightarrow{3} D$, $D \xrightarrow{4} A$, $A \xrightarrow{5} C$, $C \xrightarrow{6} B$, $B \xrightarrow{7} A$, $A \xrightarrow{8} D$, $D \xrightarrow{9} C$, $C \xrightarrow{10} D$, $D \xrightarrow{11} B$.



Benchmarking the Human Hand

Apparatus

For the measurement of the human hand's manipulation speed, we used the *Vicon* motion capturing system installed in the institute's Manual Interaction Laboratory (MILab) (see Fig. 8.2a). The MILab [136] setup consists of a cage (length 2.1 m, width 1.3 m, height 2.1 m) that was equipped with fourteen *MX3+* cameras capturing at 200 frames per second. The glass table on which the experiment was carried out had a height of 1.0 m (a more detailed description can be found in [136]).

For our experiment, the hands of the participant and the object were equipped with reflective markers, as depicted in Fig. 8.2b. Three markers were fixed to each hand and the object in

[1] https://www.pololu.com/product/975

distinctive triangles (an isosceles and right-angled triangle on the object and scalene right-angled triangles on the hands; the right hand's triangle is mirrored on the left hand). In the recording software, all three triangles were defined as rigid bodies and labeled accordingly.

Procedure and Task

We decided on a pick-and-place task to measure the manipulation speed of the human hand manipulating an object. For this, we defined a special pattern, as depicted in Figure 8.3, that consists of multiple linear trajectories assembling a rectangle with its diagonals. This quadratical pattern was practiced multiple times before the actual experiment started. The four target positions (A, B, C and D) of the rectangular pattern were marked with reflective markers from underneath the MILab's tabletop glass surface. The experiment consists of three sessions in which the size of the rectangle is altered in terms of edge length (*a*) 50 cm, *b*) 25 cm and *c*) 5 cm). In each session the pattern is performed in three different ways: *a*) relaxed, *b*) fast and *c*) as precise as possible. All three modes are performed with the left and the right hand, resulting in six trials in each session. With this procedure, we hoped to get reliable results when combining the three performance modes for comparison with the TAOs.

Participant

Since this experiment is meant to be a pre-study to get a baseline for evaluating the TAOs, we had one participant, 28 years old and ambidextrous with preference for the left hand.

Results

We analyzed the trajectories with regard to the planar speed (without the z-axis; with $Z = 0$, respectively) for better comparability with the TAOs. The calculated instantaneous speed is summarized in Figure 8.4d. Within the three rectangle sizes, we found decreasing average speed with decreasing edge length of the pattern's rectangle. In the trials with the rectangle with 50 *cm* edge length, the average speed was $M = 73.86$ cm/s ($SD = 63.63$ cm/s, max $= 307.82$ cm/s). The trials where the rectangle had an edge length of 25 cm revealed an average speed of $M = 51.66$ cm/s ($SD = 40.06$ cm/s, max $= 182.33$cm/s). Finally, the average speed in the trials with a rectangle's edge length of 5 cm was $M = 18.29$ cm/s ($SD = 10.15$ cm/s, max $= 68.33$ cm/s). After combining all results, we got an average speed of $M = 55.51$ cm/s ($SD = 53.80$ cm/s).

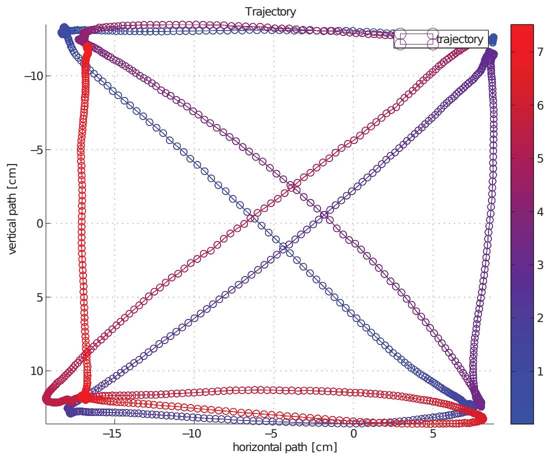
Applying linear regression on these data according to Fitts' Law results in $a \approx 8.27$ and $b \approx 0.25$ ($R^2 \approx 0.96$).

Figures 8.4a to 8.4c depict an example trajectory (25 cm edge length, left hand, relaxed). In Figure 8.4a the planar trajectory is plotted, while Figure 8.4b depicts the x and y components of the trajectory against time. The speed profile of the example trajectory is plotted in Figure 8.4c. Here we can easily identify the eleven linear trajectories and the turn points of the rectangular pattern.

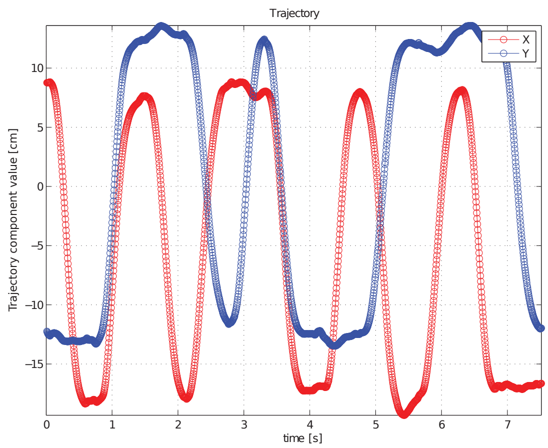
Discussion

The results basically reflect the general manipulation speed also found in literature, such as in the experiments by Maoz et al. [131]. The recorded trajectories exhibit the typical bell-shaped speed profile, as described by Flash and Hogan [48]. Furthermore, the decreasing speed with decreasing rectangle edge length basically correspond with Fitts' law. Though there was no explicit constraint for precision, the smaller rectangle size may be reinterpreted as a smaller target size which results in reduced speed. Also the distance to target is reduced, as well, which left the participant less room for acceleration. This can also be explained with the bell-shaped speed profile. The recorded data are not empirical, but they suffice for a

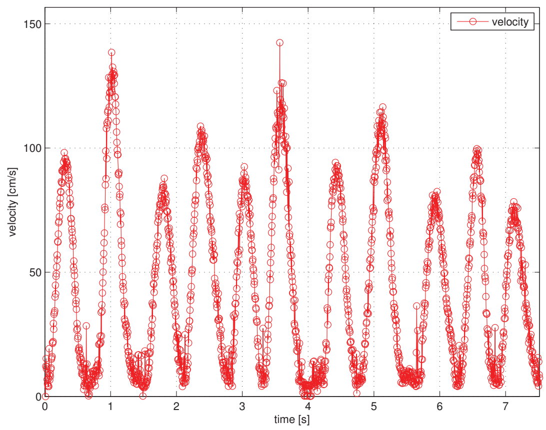
Figure 8.4: Three different visualizations of an example trajectory recorded during the experiment (25 cm rectangle edge length, left hand, relaxed). Also an overview with box plots of the speed in all three conditions of the experiment is given.



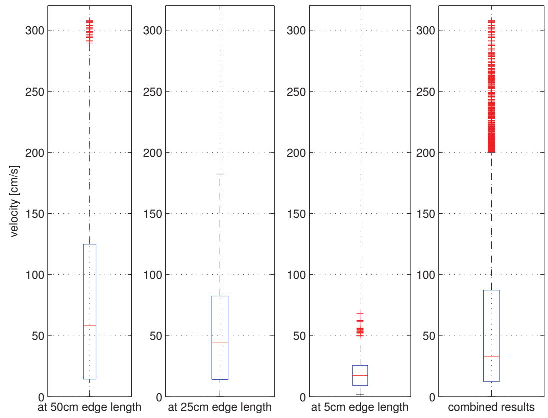
(a) An example trajectory of a TUIO being manipulated by a human hand, recorded with *Vicon*.



(b) The x and y components of the example trajectory plotted against time.



(c) The speed profile of the example trajectory (instantaneous manipulation speed over time).



(d) Overall distribution of speed of all conditions and combined over all trials.

first baseline for comparison with the TAOs' velocity.

Benchmarking the TAOs

Apparatus and Procedure

We created a similar procedure for evaluating the TAOs' velocity. We evaluated three TAOs on the tDesk, one after another. A special evaluation program requests the path-planning component to make the TAO move according to the same pattern as described above (see Fig. 8.3). When the TAO reaches a target position, the next target is requested instantaneously until the pattern is complete. A major difference here are the dimensions of the rectangular pattern. Due to the size of the interactive surface (56 cm × 42 cm), we decided on a different size and form factor. The upper left corner of the rectangular pattern was located at 14 cm, 10.5 cm and the lower right corner was located at 42 cm, 31.cm. This results in a width of 28 cm and a height of 21 cm for the pattern, while the pattern for evaluation of the human hand was quadratical. Figure 8.5 depicts a photo of a TAO being

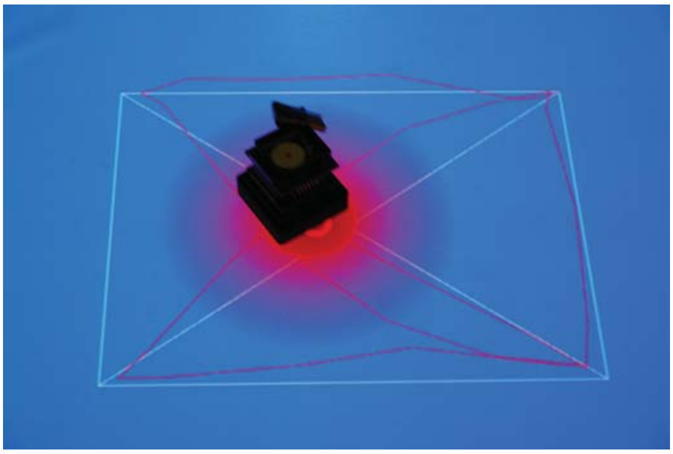


Figure 8.5: Picture taken during the evaluation of the TAOs. The rectangular pattern had a width of 28 cm and a height of 21 cm.

evaluated. Each of the three TAOs performed the pattern within three trials which results in nine trials for the whole evaluation. To obtain reliable results, the tracking component captured the TAOs' positions with a frame rate of 30 Hz. The evaluation component wrote log files with the positions of the TAOs at a fixed frame rate of 10 Hz with the time stamp for each position. Furthermore, the TAOs moved at maximum speed. In the other experiments described in this thesis, the TAOs were tracked at a frame rate of 15 Hz and a reduced speed of approximately three quarter of maximum speed.

Results

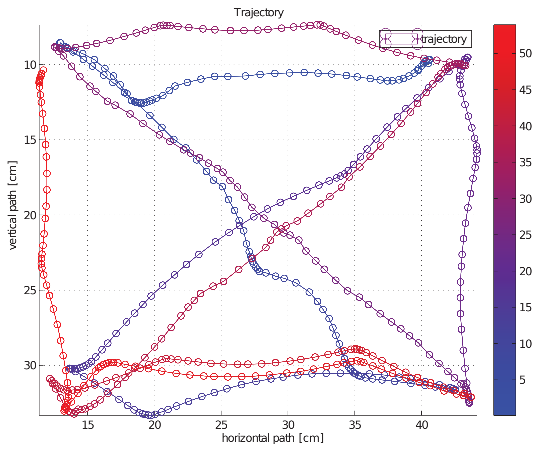
The Figures 8.6a to 8.6c depict an example trajectory a TAO performed during evaluation. As we can see, the TAOs performed not as accurately and smoothly as the human hand. The plotted trajectory and the x and y components plotted against time are more bumpy. Especially the speed profile is very noisy, but we can still distinguish the turn points at the target positions of the rectangular pattern (velocity of nearly zero in steps of about 5 seconds). The noisiness can be explained with drift caused by slight imprecision of the hand-assembled housings and mechanics. This could be overcome by implementing a control approach within the TAOs which is currently not possible due to technical limitations, such as the limited memory of the used *Arduino* platform. Figure 8.6d summarizes the results of the calculated velocities. We calculated the instantaneous velocities (frame-to-frame) to get an as accurate impression of the TAOs' velocity as possible. The average velocity of the TAOs was $M = 6.47$ cm/s ($SD = 3.69$ cm/s, max = 18.70 cm/s). For comparison, we repeated the evaluation driving the TAOs at normal speed. Here, they showed an average velocity of $M = 5.28$ cm/s ($SD = 2.30$ cm/s, max = 12.22).

Applying linear regression on these data according to Fitts' Law results in $a \approx 0.34$ and $b \approx 3.30$ ($R^2 \approx 0.99$). The rather large b value may be caused by some fishtailing movements, as visible in Figure 8.6a.

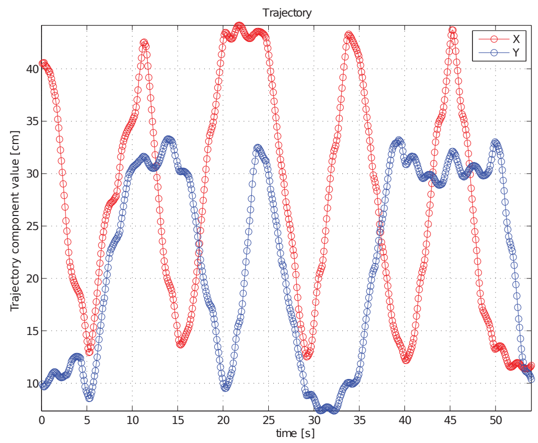
Discussion

An early prototype of the TAOs (using passive tracking with 10 Hz frame rate and old path-planning algorithm) had an average velocity of 1.56 cm/s and a maximum velocity of 3.44 cm/s [167, p. 70]. Against this background, we substantially improved the TAOs' performance – now they are over four times faster. Nonetheless, the TAOs are still not very precise along a longer trajectory (partially solved by introducing sub-targets). Furthermore,

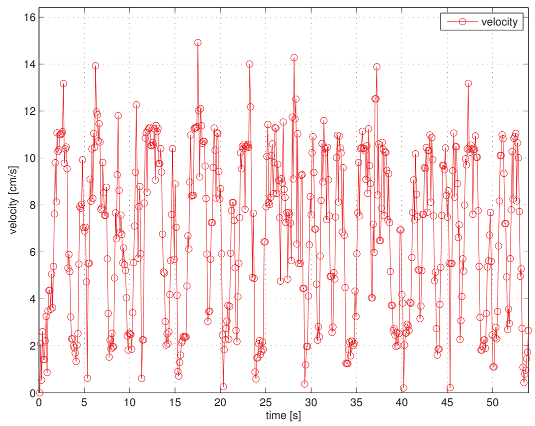
Figure 8.6: Three different visualizations of a TAO's example trajectory recorded during the benchmarking. Also an overview with box plots of the velocities in all trials is given compared to velocities found in literature.



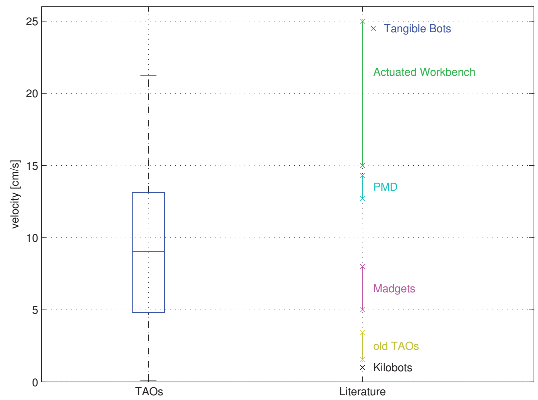
(a) A TAO's example trajectory recorded during the benchmarking.



(b) The x and y components of the TAO's example trajectory plotted against time.



(c) The speed profile of the TAO's example trajectory (instantaneous velocity over time).



(d) Overall distribution of the velocities in all trials in comparison to velocities reported in literature [152, 158, 167, 175, 176, 208].

a still missing control approach, such as PI(D) control, requires the TAOs to re-adjust their heading direction frequently which results in slightly nonuniform motion and noisy speed profiles.

Comparison

In comparison with the human hand, the performance of the TAOs leaves much room for improvement. Their maximum velocity roughly reaches the average speed of the human hand measured in the trials with 5 cm edge length of the rectangular pattern. On average, the human hand was about thrice as fast as the TAOs in this condition. In the 25 cm condition the hand was almost eight times faster and in the condition where the rectangular pattern had an edge length of 50 cm it was over ten times faster. Compared to the complete average of the combined results, the human hand is over eight times faster than the TAOs (M_{hand}

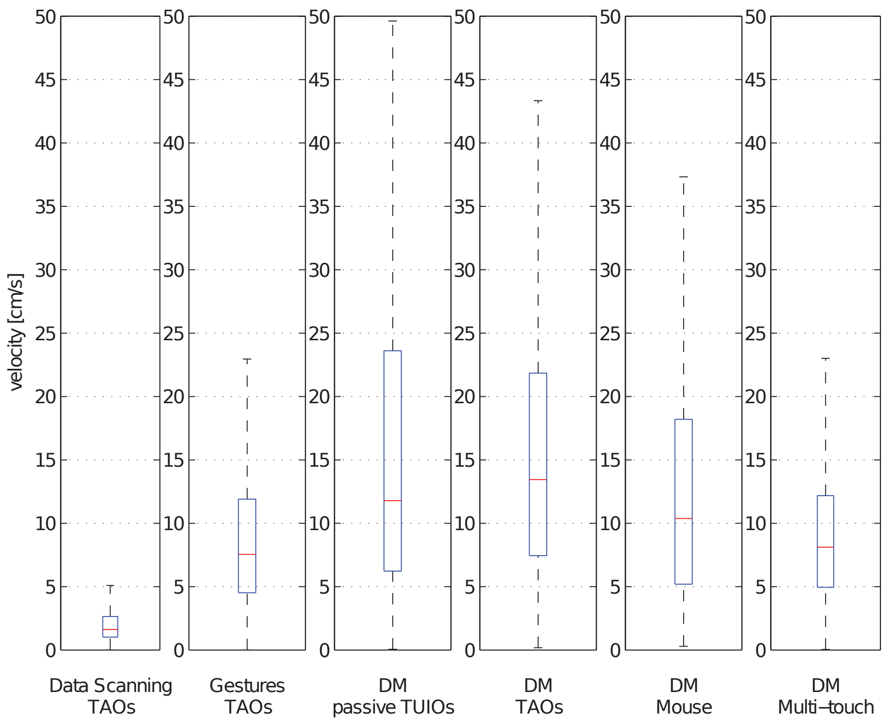


Figure 8.7: The analysis results of the interaction data recorded in the studies conducted in the course of this project (outliers were omitted in the box plots for better readability). The participants performed the fastest movements in data manipulation (DM) tasks.

= 55.51 cm/s, M_{TAO} = 6.47 cm/s). Furthermore, the TAOs do not exhibit the typical bell-shaped speed profile of the human hand (to have more realistic measures).

The described evaluation of the human hand and the TAOs revealed a wide gap in terms of speed and motion smoothness. In the experiment evaluating the hand's speed, the participant only had to move the object to predefined positions without any further challenge. This made the task rather artificial. Thus, we analyzed the interaction data from actual hands-on experiments with the TAOs conducted during this thesis with respect to human manipulation speed, as described in the next section.

8.3 The Human Hand Manipulating TUIOs

In each study we conducted in the course of this thesis, we recorded interaction data of the manipulated TAOs. In this section we evaluate these data to provide a better baseline for estimating the users' requirements for the TAOs in terms of manipulation speed. First, we smoothed the raw data to eliminate major jitter and noise caused by tracking inaccuracy. However, there remained jumps causing unrealistically high instantaneous speed. For this reason, we omit outliers in the plots and calculation of the maximum speed, as the box plots provide a reasonable impression of the velocity information. For better comparability, we calculated the instantaneous speed for each performed trajectory, as we did in the hand's and the TAOs' benchmarks above.

Scanning

In the *Blind Herder* study in which we evaluated the Interactive Auditory Scatter Plot (IAS), blindfolded participants used the TAOs and interactive Sonification to audio-haptically explore scatter plots without visual feedback (see [168] and Section 9.3 for more details). Here, the participants showed rather slow scanning behaviors manipulating the TAOs while listening to the resulting audio feedback in the closed-loop interaction. From the recorded interaction data, we extracted $N = 93$ trajectories that we used for the calculations. On average, the performed trajectories showed a manipulation speed of $M = 2.26$ cm/s ($SD = 2.58$ cm/s), as depicted in Figure 8.7 (first box plot). The TAOs are basically able to reproduce such scanning behavior.

Gestures

From the interaction data collected in the study for gathering user-defined gestures for our Embodied Social Networking client (ESN) client (see Chapter 4), $N = 474$ recorded gestures were used for speed analysis. Here, the participants were explicitly asked to perform their gestures with the TAOs rather slowly for better tracking results. As depicted in Figure 8.7 (second box plot), the analysis shows that the average speed of the performed gestures was $M = 13.551$ cm/s ($SD = 20.17$ cm/s). The TAOs should be able to reproduce most of the motions in real-time, but may have difficulties for speed of over 18 cm/s.

Data Manipulation

The last data set we analyzed was gathered in our comparative study in which $N = 80$ participants were asked to create a mind-map from given items with four different interface types (see Chapter 7). They manipulated the mind-map items either with the Mouse, through multi-touch, passive TUIOs or the TAOs, similar to the drag-and-drop paradigm. We analyzed the instantaneous manipulation speed of the performed trajectories in each condition, as described above.

Passive TUIOs

In the condition where the participants used the passive TUIOs for data manipulation, we extracted $N = 103$ trajectories usable for speed analysis. Here, the average instantaneous speed was $M = 20.18$ cm/s ($SD = 33.25$ cm/s).

TAOs

From the interaction data of the condition with the TAOs, we extracted $N = 82$ trajectories. Their analysis revealed an average instantaneous speed of $M = 18.85$ cm/s ($SD = 22.98$ cm/s). The TAOs were manipulated slightly slower than in the passive TUIOs condition.

Mouse and Multi-touch

Though the other two conditions (Mouse and multi-touch) do not directly relate to manipulation of TUIOs, we analyzed the data gathered in these conditions, as well. In the Mouse condition, we had $N = 66$ trajectories for analysis. The average instantaneous speed (of the Mouse pointer on the interactive surface) was $M = 12.91$ cm/s ($SD = 9.80$ cm/s). In the interaction data of the multi-touch condition, we found $N = 111$ usable trajectories. Their analysis revealed an average instantaneous speed of $M = 9.72$ cm/s ($SD = 7.99$ cm/s).

8.4 Discussion

In the first evaluation between the human hand's manipulation speed and the TAOs' velocity, we have seen that the TAOs are in an inferior position. They are not as fast as the human hand and their performance lacks smoothness. Nevertheless, also in literature there currently seems to be no actuated TUIO implementation that is able to fully reproduce the human hand's performance at all.

Comparison with Literature

Compared to the actuated TUIOs described in literature, the TAOs can compete with most of them (except the *Actuated Workbench* and the *Tangible Bots*), as depicted in Figure 8.6d. The electromagnetic *Actuated Workbench* produces slightly faster motion when the Manhattan motion algorithm is used instead of the smoother jet-based anti-aliasing motion control approach. In contrast to the electromagnetic *Actuated Workbench*, the *Tangible Bots* use the robotic approach for actuation. With a diameter of $\varnothing = 9.5$ cm they have more room to feature more powerful motors for faster actuation.

Reproducibility

From the analysis of the interaction data we recorded throughout multiple studies, there are applications where fast movement is not needed at all. The scanning motions performed by participants in the *Blind Herder* study would be easily reproducible by the TAOs. We explain the slower scanning motions with the demand of listening to the auditory feedback. This takes some time for interpretation which results in slower interaction. The trajectories performed by the participants in the gesture gathering study for the ESN client exhibit quicker motion, but they are still mostly reproducible, too (the participants were told not to move too quickly).

In the comparative study where the participants manipulated mind-map items, the situation is different. Here only the trajectories in the multi-touch and Mouse conditions are mostly reproducible while the trajectories recorded in the passive TUIOs and the TAOs conditions are not. Here the TAOs move too slowly. The difference between the conditions with TUIOs and the Mouse and multi-touch conditions is interesting. In case of the multi-touch interaction, this might be influenced by technical problems, some participants experienced during the trials. Another explanation for the slight drop in speed in the Mouse and multi-touch conditions can be the lack of a tangible representation. Here the participants could only rely on the graphical representation which may have had a slight lag. This lag requires the users to slow down their interaction to not make mistakes. In reverse, the tangible representation serves as a more natural means of interaction that has no lag and enables the users to perform faster than with pure non-tangible representations. This effect indicates that TUIOs in general might be more suitable for data manipulation than Mouse and multi-touch interaction. Nevertheless, this provocative hypothesis requires further investigation in future research.

Design Guidelines

Graspability and Shape of TUIOs

The hierarchical taxonomy of grasps by Bullock and Dollar [24] provides means for the classification of grasps. This taxonomy is flexible, extensible and provides all features that apply to the grasping and manipulation of TUIOs, too. Furthermore, it gives hints to the precision and dexterity of particular grasps.

The shape of the TUIOs depends on the particular application. For special purpose applications, it can be beneficial to have specially designed shapes to make the TUIOs more distinguishable. Furthermore, a special shape can support the non-tangible representation so that the users can better relate to them. In contrast to abstract shapes, more concrete shapes allow the users to better address them in a multi-user scenario, where the task demands discussion. Otherwise, abstract shapes can be specialized by the non-tangible representation, such as graphics. Abstract shapes can be used in different tasks, making the system applicable in more general-purpose tasks. Here, the cubical shape of the TAOs turned out to be a good compromise. Through the compatibility with the *TUImod* building blocks for TUIOs, they are modularly adjustable to the particular task, such as adding colored caps. These caps also feature distinguishable geometrical forms, such as circles and triangles. The latter provides the TAOs a direction used, for example, to represent the view of the camera TAO in the furniture placing application, described in Chapter 6. When no particular orientation of the TUIOs is needed, a round shape can also be useful.

Velocity Requirements: Upper and Lower Limits

Depending on the particular application, there is a demand for actuation technology that is able to produce motion comparable to the human hand, such as in remote collaboration applications (see Chap. 6) or replay of actions. Yet, there is no such actuation technology that can move TUIOs at an average velocity of about 55 cm/s, as we estimated in our evaluation of the human hand manipulation speed.

Fortunately, there are many applications for actuated TUIOs where velocities of $\approx$ 10 to 15 cm/s are absolutely sufficient. This is the case in applications where there is no need to reproduce human movement in real-time or when the interaction allows slight delays, such as when an arrangement of TUIOs is being restored (see Chap. 5).

For a complete coverage of all velocity requirements derived from applications, actuated TUIOs should be able to robustly produce motion velocities from 1 cm/s (as found for Data Scanning) up to 25 cm/s (as found for Data Manipulation). To be able to reproduce fast manipulation velocities as found in our pre-study in real-time, 300 cm/s might be a good target velocity for future development. However, such requirements demand great engineering skills and it might take some time for actuated TUIs to be developed with such capabilities.

Motion Dynamics

Though not implemented in this thesis, nor in literature, we find a human-like bell-shaped speed profile very useful for actuated TUIOs. It gives the users natural means for estimating a TUIO's trajectory and target. As an alternative for conveying this information to the users, we introduced a projected line from the TAO's current position and its target position during autonomous movement in our comparative study as a graphical workaround. Furthermore, the bell-shaped speed profile can be used for motion prediction in future research. Depending on the TUIOs' positions, such prediction can help overcome the lag of non-tangible representations.

8.5 Conclusion

In this chapter, we benchmarked both the human hand manipulating an object in a pick-and-place task and the TAOs in terms of instantaneous speed. Here, we identified the average speed of approximately 55 cm/s as the average speed, actuated TUIOs ideally should be able to move at. We found that neither the TAOs nor other actuated TUIOs documented in literature match the manipulation speed of the human hand. The argument that actuated TUIOs should ideally be equivalent to the human hand in their performance to provide full bi-directional interaction means is thereby not fulfilled, yet. Furthermore, we analyzed the interaction data gathered in studies conducted in the course of this thesis to derive speed requirements for actuated TUIOs. The results indicated that such high-performance requirements are only needed in rare cases, such as in reproduction of human motion. We also found indication for the benefits of TUIOs to facilitate the natural manipulation skills of the users. Finally we derived first design guidelines regarding the fundamental movement properties for actuated TUIOs.

9 What Else? A View Beyond the Scope

Give the pupils something to do, not something to learn; and the doing is of such a nature as to demand thinking; learning naturally results.

John Dewey,
Democracy and Education, 1916

Much more has happened in the course of this project – partly beyond the scope of this thesis. However, worth to mention because they demonstrate the flexibility and extensibility of the TAO architecture and broaden the view on the topic. Student groups supervised by the author and the author himself contributed to the TAOs system beyond this thesis' scope. The students' projects were part of a practical course, as a part of the Intelligent Systems Master's studies at Bielefeld University. These projects are briefly described in this chapter.

9.1 Assisting Furniture: The Interactive Mobile Seat

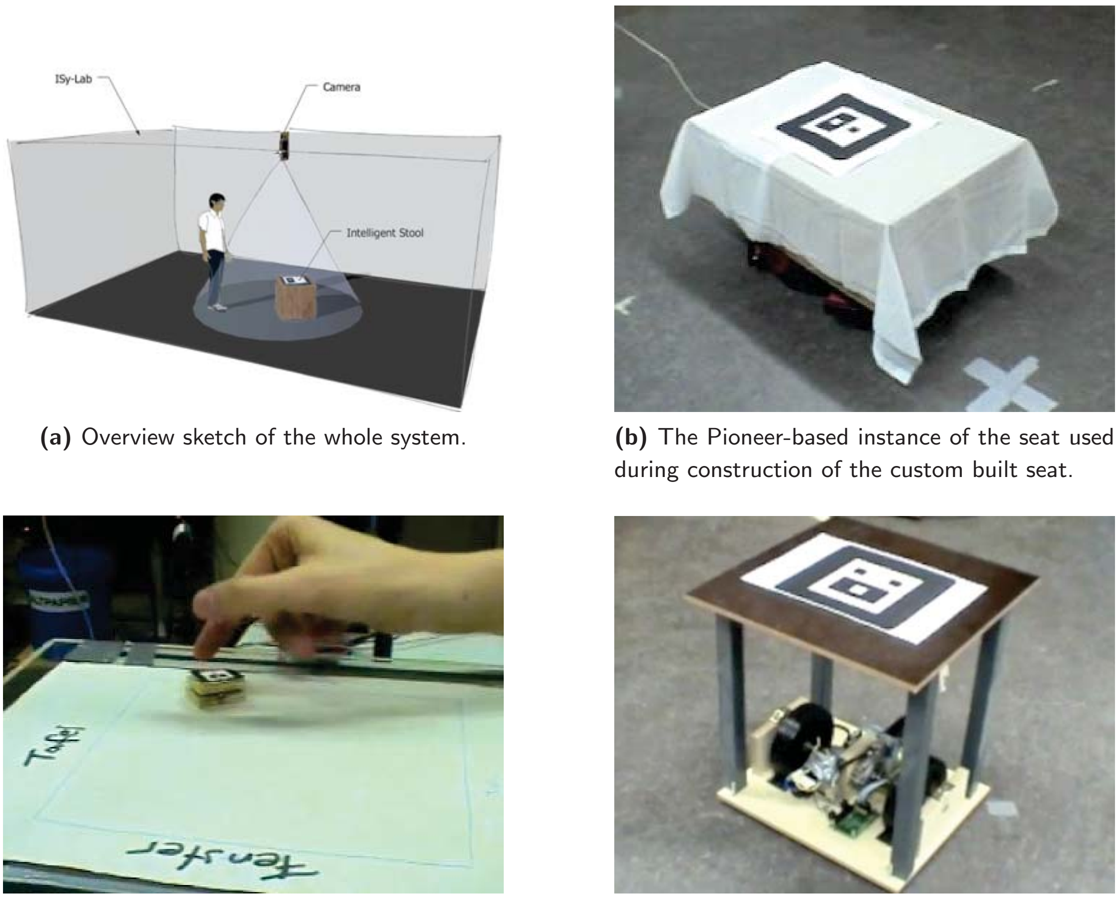
The first students' project to be presented here is the Interactive Mobile Seat (IMS). It is intended to assist disabled people in their living environment and to give them more freedom and independence. Technically inspired by the *Gotthard* project [61][1] and the *RobotStool* [148], the students designed and built the seat and its interface completely from scratch with the use of the TAO architecture.

Hardware Setup

The hardware setup basically consists of the tDesk and the custom built seat, shown in Figure 9.1d. The area of the room in which the seat operates was monitored by a ceiling mounted camera looking downwards (see Fig. 9.1a). The seat was equipped with a fiducial marker on top. It was the same marker type as it was used in the first prototypes of the TAOs (see Fig. 3.4a in Sec. 3.3). The tDesk was equipped with a map of the seat's operation area and another camera mounted above the tDesk observed the tDesk's interaction surface. The markers may be occluded by the users' hands, but in the interaction this did not turn out to be a problem in this particular application. A TUIO represents the seat in the map on the

[1] Unfortunately, the original website describing this project in detail is not available any more.

Figure 9.1: The Interactive Mobile Seat (IMS): System sketch and stills from the students' presentation movie showing the seat in action.



(a) Overview sketch of the whole system.

(b) The Pioneer-based instance of the seat used during construction of the custom built seat.

(c) The IMS's tabletop interface.

(d) The seat, built by the students (shown without the housings' sides).

tDesk. By relocating this representation, a (disabled) user can easily make the seat move, according to the position of the seat TUIO on the map. To reduce the dependencies between the construction of the seat and the interface design, a wired *Pioneer* robot platform was used as a placeholder during the design and building of the actual IMS (see Fig. 9.1b). The Pioneer platform should not be used to sit on, of course, so it was laid with tablecloth to make it serve as a coffee table for light objects.

Software Design

The students extended the basic TAO architecture, described in Section 3.3 without the display component, which was not yet existing during the IMS project. They added a component that interpreted the drive commands produced by the path-planning module to control the *Pioneer* platform. When the TUIO's position is changed by the user, an additional component processing the image of the overhead camera of the tDesk queries new navigational requests to the path-planning component controlling the seat.

Discussion and Outlook

The students presented a working prototype of the system that serves as a proof-of-concept. The system demonstrates another use-case of the TAO architecture in an application assisting disabled users.

A possible and obvious extension is the use of a TAO as a tangible representation of the seat on the tDesk. This TAO automatically moves if the actual seat is moved by a user to maintain the correct position of the seat's TUIO on the apartment's map, very much like in the remote collaborative application, presented in Chapter 6.

9.2 TAOgotchis: Embodied Tangible Agents

In the follow-up ISy project to the IMS, the same group of students contributed to the development of the active marker sensing for the TAOs allowing back-projection on the tDesk. A toy application was developed, during laying the foundations for the marker's PCB design and the tracking component, able to robustly recognize and track the new markers (see Sec. 3.3). This toy application deals with the embodiment of virtual agents, similar to the Tamagotchi toy. A Tamagotchi is a virtual pet that needs to be taken care of by the user by feeding it playing with it, just like a real pet. This idea was transferred to the TAOs, each of them embodying a Tamagotchi. As a result, the user (or player) has a little herd of so called TAOgotchis living on the tDesk, that needs to be taken care of.

Interaction Design and Implementation

Being a toy application, the TAOgotchi agents were implemented using a simple state machine approach with four states: *a*) *happy*, *b*) *hungry*, *c*) *bored* and *d*) *dead* (see Fig. 9.2). The states' transitions depend on two values representing the health of the TAOgotchis. When the *hunger* value exceeds a certain threshold, the TAOgotchi's state changes to the *hungry* state. Analogically, when the *bored* value exceeds its threshold, the TAOgotchi's state changes to *bored*. When both values have exceed their thresholds, the TAOgotchi dies and changes to the *dead* state. In the *happy* state, the TAOgotchis' TAOs perform a rather active random walk within their living area on the interaction surface of the tDesk. While in the *hungry* or *bored* state, they still perform a random walk behavior, but begin to stop more and more often and finally stop completely when in the *dead* state. It is the user's task to feed the TAOgothis and entertain them by placing them in a *feeding area* or *playground area* as part of the interactive surface and prevent them from dying. Here the *hungry* and *bored* values are reset to zero and the TAOgotchis change to the *happy* state, again. In the *happy* state, these values slowly increase by random amounts during the random walk behavior until they exceed their thresholds. The new markers and tracking was used in this project to graphically project the TAOgotchis' living, feeding and playground areas on the tDesk's surface.

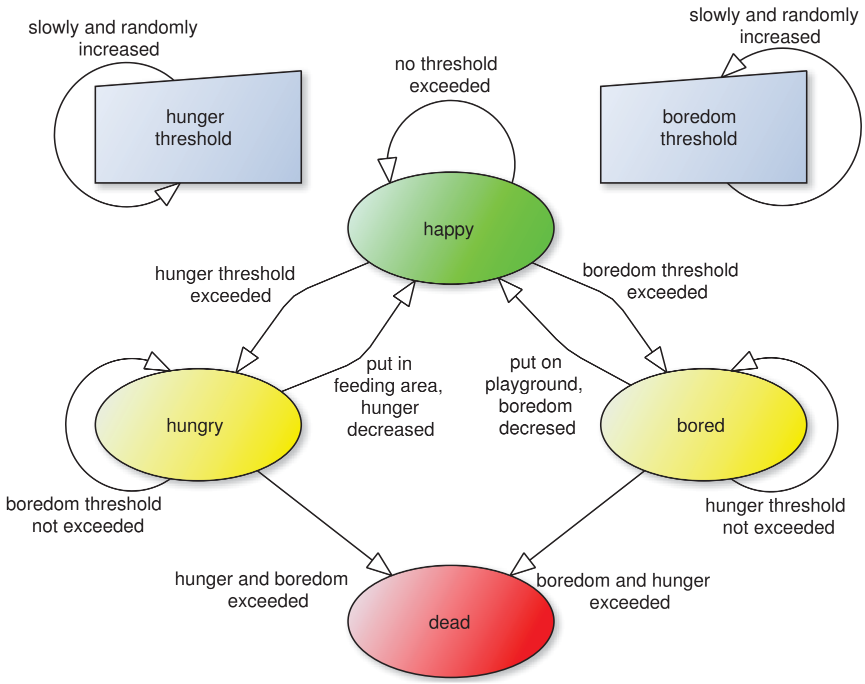


Figure 9.2: State graph of the TAO-gotchi state machine.

Discussion

While this toy application simply serves as a demonstration of the new active markers and their tracking, the idea of embodied tangible agents is still quite interesting. This rather simple simulation was not yet systematically evaluated in a study, but first users tended to ascribe the TAOgotchis a simple personality the users could easily relate to. They described these personalities with attributes, such as lazy, hyper-active or greedy. These personalities increase the users' affection to the TAOgotchis and facilitate interaction – at least until the users see through the simulation and it gets uninteresting. But the simulation can be extended in any order, e.g. by introducing more states and interaction possibilities or interaction between the TAOgotchis to demonstrate swarm behavior.

With the idea of the TAOs embodying agents, this project touches the field of Social Robotics. Fong et al. provide a good overview to this field [49]. According to Breazeal [22], the TAO-gotchis fulfill the criterion of being *socially evocative*. This class of social robots described by this criterion are "designed to encourage people to anthropomorphize the technology in order to interact with it, but goes no further. This is quite common in toys, where a nurture model is leveraged to yield an entertaining interaction." [22] In some more serious applications, such as *Spidey* [190], the idea of embodied agents that demonstrate some amount of personality can be useful to facilitate interaction, such in more complex games or artistic applications.

9.3 Audio-haptic Data Exploration: The Interactive Auditory Scatter-plot

Beyond vision, touch and hearing are natural means (not only for visually impaired users) to explore the environment that is in direct reach. In consequence, we used the TAOs to interactively provide a tactile display of the (rough) data distribution. Because they are not able to represent a detailed impression of the data due to their fixed size and shape, we utilized functional sound to convey further details. To allow the users of our system to gain a more detailed feeling about the data points in the scatter plot, we use a two-staged Sonification approach. Sonification basically denotes the process of making data audible – in contrast to visualization making data visually perceivable through diagrams and plots etc. An exhaustive textbook about Sonification is presented by Hermann et al. [69]. In our work we utilize the Parameter Mapping Sonification (PMSon) [69, p. 363] and the Model-based Sonification (MBS) [69, p. 408] techniques.

Interaction Design

Haptic Exploration

The interaction design is divided into three interaction stages.After the TAOs have reached the centroids' positions, the user manually scans the tDesk's interactive surface through touching to get a rough overview of the clusters' distribution. In this haptic exploration phase, the tactile borders of the interactive surface help the user to reference the TAOs' positions and their relative spatial formation.

Cluster Level Sonification

In the second stage of the interaction, the user already has a rough understanding of where major accumulations of data points are located. The Parameter Mapping Sonification (PMSon) now allows the user to inspect the clusters by scanning them one after another. This interaction allows to determine cluster borders and to estimate data point density.

Data Point Level Sonification

The second Sonification enables users to explore on the data point level. Since every data point has a virtual damped spring mass model attached in this Model-based Sonification (MBS) approach, each of them is directly audible. This local Data Sonogram is triggered by releasing a TAO at a particular position that the user finds interesting. The ability to listen to each data point allows the user to gain a detailed insight into the data distribution. Though it is hard (if not impossible) to remember single data points and their exact positions, this exploratory data analysis approach helps the users to gain a feeling for the data distribution.

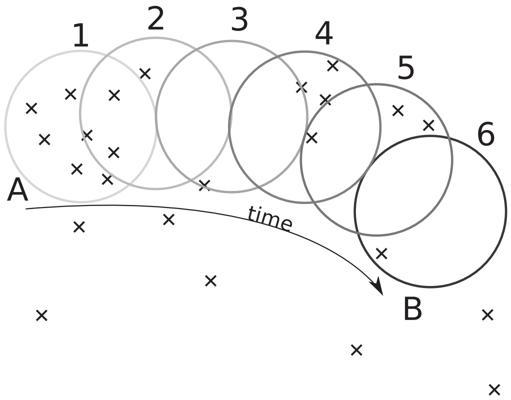
Extensions: Clustering and Interactive Sonification

In our system we use a combined audio-haptic approach for exploring a scatter plot that is non-visually spread across the tDesk's interactive surface. For a rough overview the TAOs can be used and for detailed interactive exploration we incorporate a two-staged Sonification approach. The tangibility of the TAOs is naturally given by design. The interesting regions in a scatter plot are those with a high data point density.

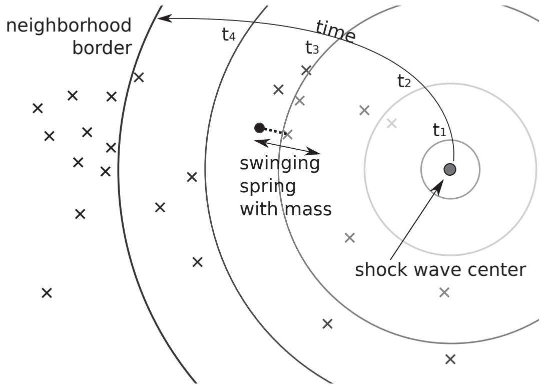
Clustering

To enable the TAOs to represent an overview of the data, we chose the K-Means cluster-

Figure 9.3: The two Sonification techniques used in the IAS for more detailed data exploration [168].



(a) Parameter Mapping Sonification: The circles depict the aura of TAOs. Moving a TAO from A to B results in a continuous Sonification of density as pitch, resulting in different pitch a positions 1 to 6.



(b) Local Data Sonograms: A virtual shock wave is evoked at the TAO's position and emerges until it reaches the neighborhood's border. During progressing through the data space each crossed data point generates a sound helping the user to estimate the data point's position.

ing algorithm [143] (following [15, p. 187-189]) to find such regions and their prototype vectors (centroids). As a convenient implementation, we utilize the *Open Source Clustering Software*[2] by Hoon et al. [74]. The output of this approach depends on the initialization of the centroids and may return a suboptimal result. To overcome this problem, the library provided by Hoon et al. repeats the described algorithm with multiple random initializations. It returns the result with the smallest J (within-cluster sum of distances between centroids and data points). Our clustering component uses this cluster library to analyze the data set according to the number of available TAOs (K). The clustering result is used to request the path-planning component to move the TAOs to the centroid positions. After the user stopped interacting with a particular TAO, this component also requests the path-planning component to make the TAO move back to its centroid. This behavior maintains the correctness of the haptic representation of the data.

Interactive Sonifications

Our interactive Sonification techniques are implemented using the *SuperCollider* programming language[3] for sound synthesis and interface with the rest of the system using the *OSC* network protocol.

Parameter Mapping Sonification

We use the PMSon for interactive auditory exploration of the data set. PMSon denotes an approach that maps properties of a data set, such as data value, to the auditory properties of the Sonification. In our application the local data density is mapped to pitch. Inspired by the *Sonic Scatter Plot* by Madhyastha [129] and the localized "aura" idea independently proposed by Ó Maidin and Fernström and Hermann et al. [68, 149], we implement a *Sonic Brushing* approach [69, p. 290]. Each TAO has a neighborhood limited by the radius r. The number of data points in a TAO's neighborhood is mapped to the pitch of a sawtooth wave

[2] `http://bonsai.hgc.jp/~mdehoon/software/cluster/`
[3] `http://supercollider.sourceforge.net/`

oscillator. Figure 9.3a graphically describes this interaction pattern.

Hermann describes Data Sonograms as a MBS [67]. As depicted in Figure 9.3b, a Data Sonogram is a Sonification technique that simulates a damped spring mass at each data point. A virtual shock wave that is emitted at a particular position slowly propagates through the data space and excites each hit data point to oscillate at a certain time. This oscillation is audible and makes spatial properties of the data points perceivable. In our approach this Data Sonogram is locally restricted to the TAO's neighborhood that also applies for the PMSon described above. This Sonification is triggered whenever the user releases a TAO at a particular position after scanning the data space with the PMSon. Local Data Sonograms

9.4 Future Directions: AHEAD, a Hybrid Multi-user Interface

The motivation behind our Active Home EntertAinment Desk (AHEAD) system was to investigate the combination possibilities of multi-touch interaction, passive TUIOs and the actuated TAOs in a hybrid multi-user interface. Co-supervised with René Tünnermann, AHEAD was a two-phase project comprehended by a student group within two semesters. Hence, the outcome was quite advanced and yields interesting future directions.

A multi-user interface was chosen as the application, interfacing with common home entertainment systems. AHEAD was intended to replace the large number of remote controls found in current living rooms and making the interaction with media data concise and consistent. It aims to support a group of users for example to organize their media files or decide which movies to watch on a movie night.

Related Work on Hybrid Interfaces and Tangible Media Control

Kirk et al. investigated the design space of hybrid interactive surfaces, featuring both (non-actuated) tangible and multi-touch interaction within one system. In their design considerations derived from two case studies, they highlight two general aspects of the design space: *a*) Choice of objects and *b*) emulation of the physical world. Within these two general aspects, they provide valuable considerations regarding the use of physical or digital objects, affordances and three-dimensional interaction [102]. Hybrid Interfaces

The *Tangible Bots* by Pedersen and Hornbæk can be classified as a hybrid interface, as well. Here, multi-touch interaction is used to group the actuated TUIOs to control them more effectively [158].

The *Physical Shortcuts for Media Remote Controls* by Ferscha et al. are motivated from the perspective of the requirements for in-hand manual interaction. Ferscha et al. analyze the requirements including aspects, such as grip-kinematics, and motivate their design and its affordances. Based on these implications they described the development of their cube-based tangible gesture-enabled system for remote media control [41]. Tangible Media Control

CRISTAL by Seifried et al. follows the multi-touch approach by using a large touch-enabled screen as a coffee table. They motivate their approach with the social aspects of the common living room and the need for collaborative control. Their video image-based interface is gesture-enabled and supports a variety of digital devices, including a television set, a digital picture frame, lights and even a vacuum cleaner robot [182].

System Design

In our AHEAD approach, we picked up the new idea of hybrid interfaces by Kirk et al. and added our TAOs as a third actuated means for hybrid interaction. To support the social use of digital media in the living room, such as digital pictures, videos and music, we followed the table-based approach, proposed by Seifried et al.

Interfacing with Home Entertainment Devices

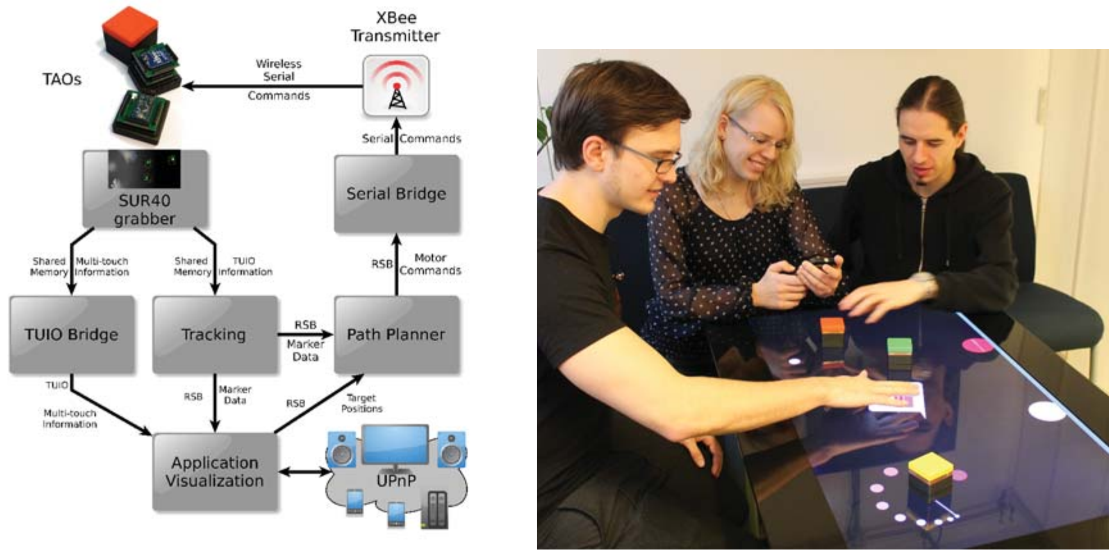
To generically support a large number of home entertainment devices, we utilized the Universal Plug and Play (UPnP) industrial standard. networked devices implementing this standard can be media storage or playback devices, such as network hard drives, media PCs, television sets or even smartphones and tablet PCs. UPnP allows simple and transparent interfacing with such devices in the same network.

Display

The students developed a new display component that interfaces with the UPnP stack and supports rotary GUI widgets with multi-touch interaction. The new display component queries the UPnP stack for available devices serving as media storage or media playback devices. These are graphically visualized on the interactive surface and can be assigned to TUIOs and TAOs as a tangible representation. Furthermore, TUIOs can serve as representations for playlists, which can be used to organize media files for later playback. The display component also allows starting and controlling the playback of media files by placing a playlist TUIO in close proximity to a TAO that represents a playback device. The playback is started by touching the graphical *play* button drawn near to the TAO. The TAO will then move slowly on a graphical bar to display the playback progress.

Interactive Table Hardware

The project was divided into two stages of development corresponding to the two semesters. The major difference between these two development iterations is the use of multi-touch hardware. In the first stage, a 22" multi-touch display by 3M was used. This display provides multi-touch interaction by capacitive sensing of the users' fingertips. Because visual tracking of the TUIOs and TAOs from underneath was not possible using this display, an overhead tracking approach with Bose/Chaudhuri/Hocquenghem (BCH) markers was used. Unfortunately, this tracking approach suffered from occlusions caused by the users' hands which disturbed the interaction with the system. Furthermore, the size of the screen hardly sufficed for multiple users. To solve these issues in the second stage, the AHEAD system was ported to the *SUR40* device by *Samsung*, featuring *Microsoft's PixelSense* technology. It uses optical sensing technology to track fingertips as they touch the display and provides an image of the interaction in the infrared band in which the TAOs' active markers operate. This allowed the use of the same technology – with minor adaptation – for sensing and tracking fingertips and the TUIOs and TAOs. The fingertip information was directly provided by the hardware and is transmitted to the display component via the *TUIO Protocol* as introduced by Kaltenbrunner et al. [91]. The tracking of the TAOs was only adapted not to recognize image artifacts of fingertips as false-positives.



(a) The overview of the software components and their relations.

(b) The AHEAD system being used.

Figure 9.4: The AHEAD system: Architecture overview and the running system.

PI-Control for the TAOs

To enable the TAOs to perform smooth and slow driving motions to represent the playback progress, Proportional–Integral (PI) control was introduced in the AHEAD project and included in the path-planning component. In a nutshell, a PI controller consists for two parts, a proportional and an integral part:

$$v_{\text{motor}}(t) = P(t) + I(t) \tag{9.1}$$

The proportional control part is simply a linear error function $e(t) = v_{\text{des}}(t) - v_{\text{act}}(t)$ that determines the difference between the desired and the actual speed:

$$P(t) = K_p \cdot e(t) \tag{9.2}$$

The integral part of the controller reduces the steady-state error of the proportional part:

$$I(t) = \frac{1}{T_I} \cdot \int_0^t e(t)dt \tag{9.3}$$

This control approach is a special case of PID control, with an additional derivative term for calculating the error of the process. We decided not to use the derivative term, because it did not turn out to improve the TAOs' motion notably in terms of smoothness. According to the basic software architecture described in Section 3.3, Figure 9.4a gives an overview of the additions made in this project and the components' relations and data flow.

Interaction Example

One natural setting for AHEAD is the living room. A group of users comes over for a movie night and everyone brings some movies he or she might like to watch with the group. Some bring them on a thumb drive or hard disk, others on their smartphone. The thumb drive or hard disk can be plugged in the host's media PC supporting the UPnP standard to make them available to the network. The users who brought their movies on their smartphone or tablet PC simply join the local WiFi network and start up a UPnP server application to make their media files available. The AHEAD system automatically queries the network for devices supporting the UPnP standard and visualizes them on the interactive surface. By putting TUIOs on top of the visualizations the users can then gain physical access to the data sources and playback devices. Every user also grabs an unassigned TUIO which serves as a representation for the user's playlist. These playlists can be filled with data by browsing the files graphically listed beside the data source TUIOs and dragging single files or selections with the fingertip from the source to the playlist TAO. The files may belong to a different user – mixing of media files from different sources is possible. When each user has finished building their personal playlist(s), the group can compare, see overlaps an jointly decide on a common playlist of movies to watch that night. At this stage, the collaborative decision making process can highly benefit from the possibility of using epistemic actions for rating and sorting the users' playlists (cf. [103, 105] and Sec. 2.4). The joint playlist then can be assigned to the TAO representing the television set by putting the playlist TUIO in the proximity of the TAO. By touching the *play* button graphically drawn near the TAO, the playback of the playlist starts immediately. Furthermore, volume control was included in the implementation. This feature is often offered by UPnP devices, such as the television set in our example. Volume control is bound to another TUIO that has a circular volume scale graphically drawn around its footprint. When there are multiple playback devices, the device's TAO standing closest to the volume control TUIO is affected by volume changes. By touching a certain volume level, the volume of the playback device can be adjusted. An additional graphical pointer shows the current volume of the next playback device. Figure 9.4b shows a snapshot of a small group of users interacting with the system.

Interaction Structure

In the described use-case, the interaction with our AHEAD system is designed to be structured into two stages, a single-user and a multi-user stage:

Single-user Tasks

Hence the organization of each user's playlist is a single-user use-case, mainly based on local multi-touch interactions. Browsing a media device's file list, media selection and assignment of media to a playlist is simply done by touching and dragging items with the finger.

Multi-user Interaction

When it comes to inter-group interaction the tangible features of the passive TUIOs and TAOs come in handy. It is easy for users to hand media sources over to other users, because the graspable nature support such physical interaction between the users. This would be not as easy as if there were only pure (graphical) non-tangible representations of the objects.

Discussion

Through the interaction approach provided by our system, the interaction with the media files and playback devices is uncoupled from the actual devices and becomes consistent across device borders. Furthermore, it offers the possibility to work collaboratively as each user has

equal access to the system. There is no need to pass remote controls around or to have one user control all devices and moderate the group discussion. Both of which can be annoying. The AHEAD system is very flexible and allows for even more different use cases. Beyond the presented use case, it can be used in almost every setting where groups of users interact with media data. For example, presenting holiday pictures along to music, distributing pictures to digital picture frames or, making slide presentations to a large audience, such as in meetings or class rooms. Even music and playlist organization of visitors of a party is possible.
As future work, a user study would be beneficial to measure the usability of the AHEAD system.[4]

9.5 Conclusion

These projects demonstrate the vast applicability of the TAOs and their architecture both within and beyond the borders of Tangible Interaction. Beside the IMS, a system rooted in the field of AAL, there are the TAOgothis, also touching the field of Social Robotics and finally AHEAD, merging Tangible Interaction (passive and actuated TUIOs) with Multi-touch Interaction. Here we also demonstrated three adapted menu metaphors for hybrid interfaces, as covered in Section 5.5. The use of functional sounds for Exploratory Data Analysis (EDA) in (actuated) TUIs was successfully demonstrated with the IAS. This shows the potential of our TAOs and their interoperability and extensibility.
In the end, the students working on these projects profited very much from working with the TAOs. They acquired new skills and learned to know new technology and tools they newer worked with before, such as CAD, PCB design, soldering and rapid-prototyping. They also learned how to use new high-end technology, such as the *Pioneer* robot platform or the *SUR40* multi-touch table. Last but not least it was great fun working with the students, guiding them and supporting them to bring in their own ideas in the frame of the given project topics.

[4] The lack of a user study unfortunately prevented the paper on the AHEAD system [169] from publication at the EICS symposium in 2012.

10 Lessons Learned: Summarizing the Guidelines

> Good design is also an act of communication between the designer and the user, except that all the communication has to come about by the appearance of the device itself. The device must explain itself.
>
> Donald Norman (2002), The Design of Everyday Things, Introduction to the 2002 Edition

In the course of this thesis we tackled various design aspects of our TAOs and tabletop TUIs in general. Within the chapters dealing with these aspects, we derived multiple design guidelines. In this chapter, we summarize our findings and put them in a larger frame. Though these guidelines were introduced within the frame of our TAOs, we give directions for transferring them to TUIs in general.

10.1 Initial Set of Design Guidelines for tabletop actuated TUIs

In this section we summarize and interweave the design guidelines we identified in the conceptual chapters. Developing our new interaction concepts, we also discussed design aspects, that are already dealt with in literature. We integrate these aspects, and mention further observations we made during the development. Figure 10.1 gives an overview for this section and guides with color codes through the covered aspects. When another aspect is referenced in the text, this color code is usedas well.

Interaction Structure

A general and understandable interaction structure is important to allow users to get the most out of the interaction with interactive systems without addistional explanation. Especially TUIs allow for free use and combination of the features provided by an interactive system. Good interaction design guides the users through the interaction without restraining them to few fixed interaction patterns. They should be allowed to develop their own patterns using the features they can easily understand and use [33]. The challenge is to design the features freely combinable, but independent from each other resulting in a lose interaction structure. This does not solely apply to the TAOs, but to TUIs and HCI in general.

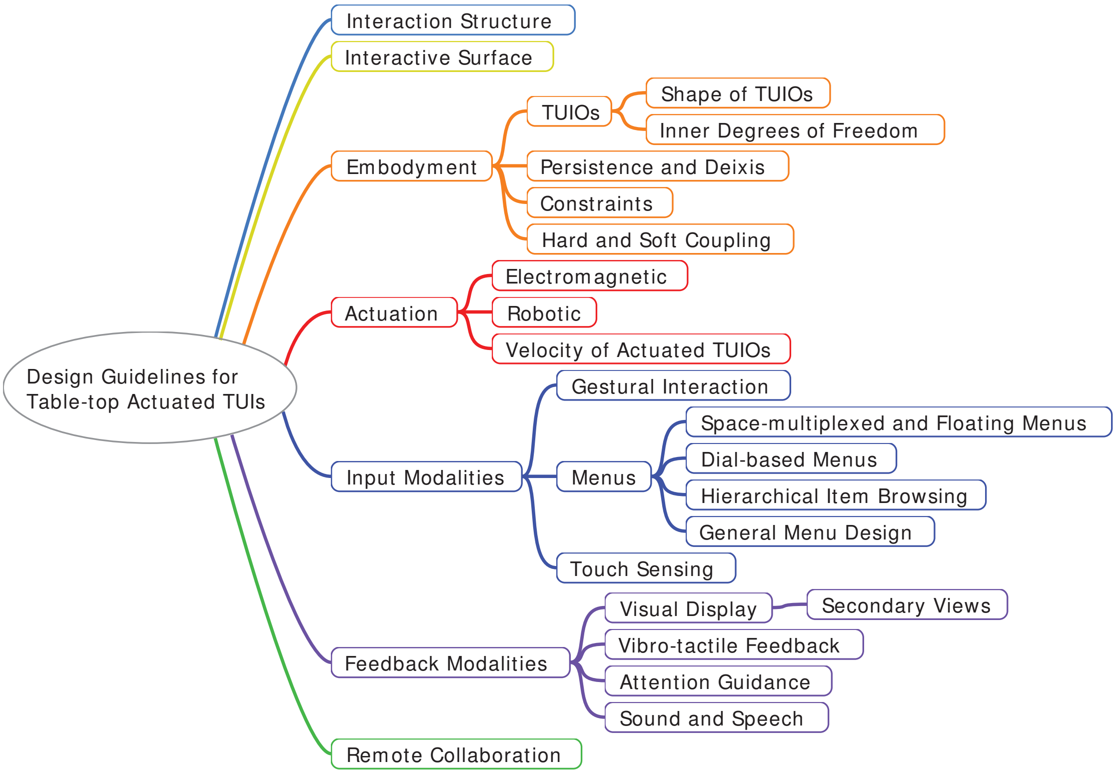


Figure 10.1: Overview of the collected design guidelines. The different aspects are color coded. The serven subsections in this chapter are color coded the same way for better orientation.

If a more structured interaction is needed for a certain task, a state machine approach has turned out to be a proper paradigm for modeling interaction. To guide the users through the interaction stages, the system should always give clues on the available interaction possibilities. Here different Feedback Modalities can be helpful to reflect these clues in different or even complementing ways.

Interactive Surface

The size of the interactive surface is often determined by technical constraints. A more user-centered approach to determine the size can be derived from the peripersonal [162] and interpersonal space [93, p. 209], as reviewed in Chapter 7. According to Previc, the peripersonal space is defined as the volume around the user, that is used for reaching and manipulating within the visual field of view. Kendon introduced the *formation* patterns for describing the orientation and grouping of humans in space. The *transitional segment* defined by Kendon is comparable to Previc's peripersonal space. The intersection of transitional segments of multiple users, Kendon calls *o-space*. The size of the these spaces depends on anthropometric parameters, such as the average length of the human arm (approximately 58 cm for adults), which also influences ergonomics. For the interactive surface, this means that its size is determined by the number of potential users and resulting *o-space*.

Embodyment

TUIOs

Our TAOs turned out to have a well-fitting size and shape. Their cubical form with and edge length of 5 cm was easily graspable by all our participants – even for the youngest with an age of 12 years. In literature similar sizes can be found – sometimes slightly larger, sometimes smaller (cf. [185, p. 104]; touched in Chapter 8).

One important factor here, is the number of available TUIOs and how they should be manipulated. For a rather large number of TUIOs one could consider to use smaller forms, especially when properties, such as orientation and identification may play a minor role. Of course, when it comes to actuation and further enhancements, size is often determined by technical constraints again, as discussed in Chapter 3.

Shape of TUIOs

The shape of the TUIOs depends on the particular application. For general-purpose applications, abstract shapes provide tangible representations for many kinds of tasks. Cubical or round shapes work out well, depending on the size of the TUIOs and whether there is a need for representing orientation. The addition of non-tangible representations using additional Feedback Modalities, such as graphics can help making the TUIOs distinguishable and better addressable. For special-purpose applications, more concrete shapes should be favored over abstract shapes. Having additional tangible features that support the physical representation helps the users to better relate to the represented data. Such representations are even better distinguishable and addressable in multi-user tasks that demand discussion between the users. When favoring multi-purpose applications, the TUIOs should have a more abstract shape to be able to represent all kinds of data.

Inner Degrees of Freedom

For some tasks it can be beneficial to have TUIOs with inner degrees of freedom. We used this idea in our menu metaphor for altering and selecting parameters of the represented data. In the case of the mTAOs we added an actuated dial for implementing our menu, as presented in Chapter 5. Other systems, such as the *Madgets* [208] or the *tangible workbench* [97] implement inner degrees, as well. Weiss et al. added controllable widgets to their magnetic actuated TUIOs, allowing bi-directional inner degrees, similar to our dial. Kienzl et al. added inner degrees to their completely passive TUIOs, as well. They cleverly implemented the monitoring of these inner degrees through the fiducial markers of their TUIOs that change when the users manipulate them.

Persistence and Deixis

Behaviors, such as the automatic homing of the TAOs, described in Section 9.3, help to preserve the consistency and correctness of the spatial representation of the data. This is important, especially for non-visual exploration and manipulation of data. Non-visual not only refers to visually impaired users, but also applies to eyes-free interaction when users pay attention to other aspects of the system, such as additional views, as described in Chapter 6. A persistent and thereby consistent physical data representation helps the users and provides robust anchor points for deictic gesticulation fostering collaboration.

Contraints

Our constraints concept allows to interactively define and preserve these relations during interaction. Persistent data representation even during interaction allows for spatial deixis. Especially in multi-user scenarios, such as the mind-mapping task in our comparative study, this is important and serves as a common ground for discussion. In Chapter 7, we coped with relations and constraints between manipulated data represented by the TAOs.

Hard and Soft Coupling between TUIOs and Data

Connected with embodiment is the coupling between the TUIOs and the represented data. It can be implemented in two ways, as discussed in Chapters 6 and 7. Either the represented data is permanently tied to the TUIOs, or the users are able to break the coupling and recouple data and TUIOs like they want to, similar to the container concept [197], as described in Section 2.3. The choice for soft coupling seems inevitable when there are more data items than TUIOs available. Otherwise, the strong bounds of hard coupling between data and TUIOs supports the natural perception of the embodiment and thereby the persistence of the represented data.

Actuation

Actuation is a key feature for enabling TUIs to support bi-directional interaction [175]. The two major actuation technologies found in literature are electromagnetic actuation and small-sized mobile robotic platforms.

Electromagnetic

Electromagnetic actuation requires a sophisticated hardware design. A large grid of electromagnets built into the interactive surface and an advanced controlling approach (regarding hardware and software) is needed to actuate magnetic objects. This technology allows actuation and applying perceivable forces to the TUIOs even if a user has slightly lifted them from the surface. The *Actuated Workbench* by Pangaro et al. [152] and the *PICO* system by Patten and Ishii [154] only use one magnetic anchor point for moving the TUIOs on the interactive surface. This makes the control of the orientation of the TUIOs impossible for the systems. This problem is solved by Weiss et al. in their *Madgets* project [208]. Using multiple anchor points for actuation, they are able to control planar and rotational movement simultaneously, resulting in a holonomic movement. Furthermore, they added inner degrees of freedom to their TUIOs that assemble actuated general-purpose widgets, such as buttons, dials and sliders. The electromagnetic control approach even allowed them to implement further feedback modalities, such as force feedback, including resistance, vibration and dynamic notches, such as steps in a scale. Beyond this, they presented an induction driven LED, audio feedback with a mechanic bell and a simple motor *Madget*.

Robotic

The robotic approach is completely different. The interactive surface basically consists of a (projectable) glass surface or display and (visual) tracking. The robotic TUIOs can have a rather simple design in terms of hardware and firmware. The tracking and control of them is often implemented in software running completely on the controlling host computer. However, this approach has some disadvantages compared to electromagnetic actuation. As soon as a user lifts a TUIO from the interactive surface, there can be no force applied through the actuation mechanism. A differential drive is the common choice allowing to move and rotate the TUIOs. Unfortunately, a holonomic movement like in the electromagnetic approach is not possible. This would demand a special holonomic drive design which greatly increases the complexity of the mechanics and control. Additional features, such as inner degrees of freedom or sensors, can easily be implemented.

Velocity of Actuated TUIOs

Ideally, actuated TUIOs should be able to reproduce human hand motions manipulating a TUIO in real-time to provide the same means for manipulation input and actuation output. As we have seen in Chapter 8, there is no actuation technology with such capabilities, yet. Nonetheless, the motion velocity of most actuation technologies (approx. 10 cm/s) is sufficient for most applications, as long as there is no demand for high-speed actuation where human manipulation should to be reproduced in real-time.

Input Modalities

Gestural Interaction

Due to the lack of well-known dynamic GUI widgets, such as buttons and drop-down menus and so forth in TUIs, the ability to trigger actions demands adaption of such interaction patterns. From multi-touch applications, gestural interaction is already wide-spread to directly manipulate, move, scroll or zoom displayed information. Gestural interaction can also be used for triggering actions, like it has been used in few GUI applications. In Chapter 4, we discussed gathering of user-defined gestures for triggering actions for our ESN client. Implementing gesture recognition in the final system yields new problems. The already mentioned state machine approach helps to implement context sensitive activation of multiple gestures for different actions. System and interaction designers need to consider how to inform the users of the available gestures and their effects. Here, a graphical projection of the available gestures and actions can support the users, as well as verbal presentation of these informations. Especially for systems aiming at visually impaired users this can be beneficial. Yuan et al. [219] investigated the preferences of visually impaired users of touch-based interfaces and provides worthy directions here.

Menus

In Chapter 5 we reviewed the use of menus and their application in TUIs. This differs quite a lot from the menus known from GUIs. We highlighted strengths and limitations of the different approaches and proposed our tangible actuated menu metaphor. We demonstrated this approach in a generic application for enhancing existing TUIs with a saving and restoring mechanism. In Chapter 6, we extended our menu approach by improving the design of the graphical presentation of the menu in a remote collaboration application. The choice for a particular menu implementation highly depends on the number of needed menu items. For up to ten menu items, all reviewed menu styles are applicable.

We identified three general menu styles: *a*) space-multiplexed menus, *b*) dial-based menus and *c*) hierarchical item browsing and selection.

Space-multiplexed and Floating Menus

Space-multiplexed (floating) menus have a rather simple implementation using a graphical representation and are easy to use. However, they are often space consuming and the number of items is limited by the available space. They are often aligned in one direction and their interaction frame is locally bound to the interactive surface, which often results in unequal reachability in multi-user scenarios. Furthermore, they require visual monitoring, since there is no physical feedback on the menu items in this approach. Floating menus are an improvement towards dynamic and adaptable space-multiplexed menus that are relocatable because they are bound to the TUIOs.

Dial-based Menus

Dial-based menus often have a persistent physical representation (except for hybrid multi-touch implementations) and their interaction frame is bound to the object of interaction. With increasing number of menu items, there is a trade off between interaction speed and accuracy (especially for actuated menus). Furthermore, depending on the implementation this menu style can suffers from the nulling problem, described by Buxton [27]. When the menu allows multiple revolutions, there is no perceivable start or endpoint which the users could use for orientation.

Hierarchical Item Browsing

Finally, the hierarchical item browsing and selection style allows complex and large menu structures, but this on the contrary can require longer interaction time which is tedious when the menu is often needed to fulfill a certain task.

General Menu Design

Tangible menu implementations should support multiple feedback modalities to enable rich interaction. First of all, a persistent physical embodiment which physically represents the state of the menu is very supportive for the users. It allows eyes-free navigation of the menu, while monitoring the result of the selection on a secondary view. Here speech output can be beneficial, as spoken menu items help the users to understand them when their meaning is not directly self-explanatory from the graphical presentation. This is especially the case when text is used to reflect the menu items' meaning. A well designed graphical representation of the menu items is understandable even if rendered upside-down. Since menus may be required only sometimes during interaction, the graphical representation can be faded out when the menu is not used, freeing projection space for the rendering of the actual task. Especially for space-multiplexed menus, unused menu items can be removed according to the context of the task, which simplifies the menu navigation for the users and decrease their space consumption.

Touch Sensing

The use of touch sensing at the TUIOs, as described in Chapter 7, opens up further possibilities for interaction design. In our comparative study, we used this feature to enable the participants to interactively define constraints between TAOs, but the field of applications is wider: Knowing when a user touches a TUIO can be a valuable information. For instance, when a user touches a TUIO without manipulating it, this may indicate uncertainty about the available interaction possibilities. The system could display available gestures and functions to support the users. Multiple touch sensors can be used to sense multiple touch points on the TUIOs. Beyond this, touch sensing in TUIOs is rather new and rarely used. It requires further investigation and exploration for new interaction patterns.

Feedback Modalities

The use of multiple feedback modalities has been presented in previous work. Graphical display is already a standard feedback method and the large number of musical application obviously incorporate the production of sound.

Visual Display

Regarding the visual display on the interactive surface of a tabletop TUI, there are few rather obvious things to keep in mind. Depending on the number of simultaneous users, the display should be rotation invariant, allowing users to stand around the tabletop surface, instead of at one side. In single-user scenarios (which we mainly focused on during this thesis), the display can be oriented to one side of the table. In Chapter 5 we discussed user-oriented design considerations for orientable and rotation invariant display of menus. Textual menu items are only suitable for single-user scenarios where the orientation of the menu does not affect the state of the data. Graphical menu items with pictures or icons may help to overcome the orientation problem in multi-user scenarios or when the orientation of menu TAO affects the represented data. The same problem affects gestural interaction, as discussed in Chapter 4. Furthermore, we have seen that the size of the projected interactive area and the size of the projected media also play an important role for the users.

Secondary Views

Depending on the task it can be useful to have additional views accompanying the view of the interactive surface. As pointed out by Patten et al. [157], this has to be considered carefully. In many cases, it is possible to have additional information about the represented data directly rendered at the TUIOs' position. Only when this is impossible, additional views are an option. For instance, this was the case for our furniture placing application. Since the view of the interactive surface gives a bird-eye view of the map of the apartment to be arranged with pieces of furniture, the interactive perspective view of the room was implemented using an additional display. Another example would be a video conferencing link, as proposed for this application. Adding a further display for the video conferencing would suffice on the first sight. A more creative and perhaps more supportive implementation would be possible when both the local and the distant users have their own TUIO representation. Then the distant user's video could be rendered in the perspective view at the position of the TUIO's position in the room. There is the problem that the remote video in the perspective view cannot be seen when the local user's TUIO is not facing the position of the remote user's TUIO. It can be overcome by rendering the video on the interactive surface beside the remote users' TUIOs or by embedding a display into the TUIOs themselves.

Vibro-tactile Feedback

Complementary to touch sensing is vibro-tactile feedback. Also this feedback modality is rather new in TUIOs and not yet exhaustively investigated in this context. Nonetheless, it is useful to eyes-free inform the users about certain states of the represented data, as described in Chapter 6. In our case, we used vibro-tactile feedback to alert the users, which even supports the deixis of the system, as discussed earlier. In contrast to this alerting characteristic, this feedback modality can be used to convey information about the represented data. For instance, the IAS could be extended with vibro-tactile feedback to reflect the mapped data density to the vibration intensity. Addressing multiple senses can be beneficial for the users, since they can concentrate on the modality that they find most useful.

Attention Guidance

Due to their alarming characteristic, vibro-tactile and audio feedback are very useful to guide the users' (visual) attention, as discussed in Chapter 6. This is useful in scenarios where the users have to share attention between multiple views or manipulate the TUIOs eyes-free. This aspect informs the users *at hand* where something important is happening.

Sound and Speech

The use of sound beyond musical applications is rather rare in TUIs. Nonetheless, we have seen that sonification used with tangible interaction may help visually impaired (blindfolded users in our study scenario) to better understand data, covered in Section 9.3. Generally functional sound and speech output enable users to eyes-free manipulate data while paying attention to other aspects of the system, as discussed in Chapter 6. Here, users can navigate the speech-augmented menu while monitoring the effect on the simulated data on an additional view.

Remote Collaboration

Remote collaboration is one major application for actuated TUIs and heavily relies on the actuation capabilities of the system. Already in 1998 Brave et al. presented the first actuated tabletop TUI *PSyBench* and proposed remote collaboration as a major application. In Chapter 6 we discussed the minimal amount of information needed to synchronize two tDesks over the Internet. We also highlighted the influence of soft coupling between the TAOs and their represented data, which we utilized in Chapter 7. This demands more information to be exchanged between the systems to support the coupling capabilities. Furthermore, additional communication channels, such as audio and video conferencing greatly supports the remote collaborative task accomplishment.

Since the TAOs are not as quick as the users manipulating them, the distant side benefits from a visualization of the navigation process. For instance, this helps not to unintentionally intercept a moving TAO. For this we added a projected red glare around a moving TAO to reflect the state of being moved on the distant side (see Chapter 6). An additional line running from the TAO's current position to its target position also helps the users to better understand the movement process. The users already have an idea of the final position of the moving TAOs and can work on these informations more effectively (see Chapter 7).

11 Reviewing Systems and Concepts Towards Future Perspectives

There's a way to do it better–find it.

Thomas Edison

Throughout the course of this thesis, we mainly viewed the systems demonstrators from a conceptual point of view. This often lead the actual applications and their technical improvements and potentials to somehow take a back seat. In this chapter we want to briefly summarize the system demonstrators and their central concepts to put them into a larger context. In this context we want to present prospects for future developments of actuated TUIs and use this opportunity to integrate further ideas we had for the TAOs. On the quest towards applications widening the use of the TAOs, some of these ideas were picked up in student projects that served as a playground for these ideas.

11.1 System Demonstrator Summary

This section briefly summarizes the system demonstrators that were developed throughout the course of this thesis in chronological order.

Embodied Social Networking

The ESN client (cf. Section 4.4 and [172]) is a good example for a fully integrated actuated application for social networking. For this application we added the graphical display component with graphical widgets for text output and input (via keyboard). The TAOs represent the messages and postings within the social network. Their actuation is used to reflect the messages' states. New messages and postings enqueue into respective queues to the left and the right and thus naturally represent their chronological sequence. Between the queues, the user has space for interacting with the messages by triggering different actions via gestures. The interaction structure was modeled using a state machine approach where gestural input triggered the different actions.

Saving and Restoring Mechanism

As a generic approach for augmenting existing (passive) TUIs with a saving and restoring mechanism (cf. Section 5.5 and [173]). As many existing tabletop TUIs rely on the *TUIO*

Protocol [91], the TAO system was extended to produce suitable output to provide an interface for the TUI to be augmented. Thus, the TUI does not need to be altered while the TAO system takes care of the TUIO arrangement and interaction management. As a demonstrator for this generic application, we utilized the *Soundblox* engine [19].

Remote Collaborative Interior Design

Though our remote collaborative interior design application covered in Section 6.3 and [170] was mainly intended as a stress test for our TAO architecture as a highly integrated multi-modal interface, it clearly contributed on remote collaboration design for actuated TUIs. We integrated multiple additional features simultaneously, such as the actuated dial with speech output, constraints, vibro-tactile feedback indicating collisions of virtual models and secondary views. All these features relied on the arrangement of the TAOs and their dial states. This resulted in a feature-rich distributed application that only used the synchronized physical states of the TAOs to reproduce all user-relevant interaction information. To synchronize two instances of this application over the Internet, we created an XMPP interface that transmits only the TAOs' states in real-time.

Mind-mapping

The mind-mapping application presented in Section 7.2 only served the purpose of our comparative study where seven given mind-map items were used.
Nonetheless, it provides already great potential for a fully featured application for the TAOs. By incorporating the graphical widgets for text input and output introduced in the ESN it would enable the users to create their own mind-map items as they put TAOs on the interactive surface. These new mind-map items can then be connected to meaningful mind-maps as already implemented. Furthermore, the actuated dial could be used to allow for altering the items and to save and restore the mind-maps.

System Demonstrators Beyond the Scope

Interactive Auditory Scatter-plot The Interactive Auditory Scatter-plot (cf. Section 9.3 and [168]) was developed and improved during the definition phase of this thesis. The lack of graphical display inspired us to investigate the use of functional sounds with the TAOs in an EDA application, targeting visually impaired users. We created a system that interfaces with two Sonifications [112] implemented in SuperCollider [213]. Both Sonifications render the data density of 2-dimensional scatter-plots to an auditory data stream. Beyond artistic music creation, the use of functional sound is a useful addition to feedback modalities that supports data exploration. The TAOs also keep the haptic data display consistent as they home back into the cluster centers of highest data density, providing a coarse tangible overview of the data distribution.
Interactive Mobile Seat To explore the possibilities in integrating other robot platforms into the TAO platform, the IMS was created (as covered in Section 9.1). A *Pioneer* robot

platform controlled by the *Player/Stage* software environment [55] was integrated into our TAO architecture including path planning and control. It served as an intermediate solution for the creation of a robotic mobile seat that was built from scratch by the students participating in this project. Finally, both platforms were controllable by a (passive) tabletop TUI that allowed the user to re-position the seat within a living environment.

TAOgotchis The same student group that worked in the IMS also worked within the TAOgotchis project (see Section 9.2). This was a good example for a game like application for the TAOs and by the way introduced the idea of embodied agents to actuated TUIs. During this project the concept of state machines for interaction modeling was considered and used to implement the basic functionalities of the TAOgotchis.

Active Home Entertainment Desk The AHEAD system (cf. Section 9.4) was a two staged student project. Inspired by the work of Seifried et al. [182], we wanted to create a media control and organization system for the TAOs that seamlessly integrates into established standards, such as *UPnP AV* or *Digital Living Network Alliance (DLNA)*. Furthermore, it was an attempt towards hybrid user interfaces integrating passive and active TUIOs with multi-touch interaction. For this, in the first stage a multi-touch display was utilized and a marker-based over-head tracking approach was established and the *UPnP AV/DLNA* interface was integrated into the TAO architecture. In the second stage of the project, the code base was ported to a *Samsung SUR40* device featuring Microsoft's *PixelSense* technology. This allowed us to move back from over-head tracking of the TUIOs to tracking from below using the active markers of the TAOs without any occlusions. From the beginning, the AHEAD system demonstrator was intended as a multi-user interface that supports groups of users to collaboratively organize and run a movie night.

11.2 Concept Overview

Within the field of applications as proposed by Shaer and Hornecker [185] we systematically review the main concepts covered and used in our system demonstrators and highlight further possible application fields for the concepts. In Table 11.1 we created an application-concept matrix that helps us to systematically examine each combination and its potentials. In this overview we mark combinations already addressed with the TAOs (marked with letter X) and indicate where we see potential for future developments (marked with letter P). Of course, this matrix is not necessarily complete as new fields of applications or possible concepts may emerge (we already added the categories 'Assisting Systems' and 'Monitoring and Control' which we examine in Section 11.3 in more detail). Also combinations that were not considered with high potential may inspire others with new ideas we did not yet imagined. Furthermore, the categories are not exclusive as systems may fall into multiple fields of applications.

Functional Sounds

The concept of functional sounds was addressed in our IAS application which mainly falls into the application fields information visualization and assisting systems. It renders 2-dimensional information in an auditory way, assisting visually-impaired users in EDA tasks. The application field reminders and tags might benefit from this concept, as it provides

Table 11.1: Our application-concept matrix according to the application fields [185]. We added the fields 'Assisting Systems' and 'Monitoring' and marked combinations we addressed with the TAOs with the letter X and those where we see greater potential for future developments with the letter P. Gestural interaction plays a special role as it is one major aspect in hybrid systems which resemble an additional concept for potential future development (marked with letter H).

	Learning	Problem Solving and Planning	Information Visualization	Programming	Entertainment and Play	Music and Performance	Communication	Reminders and Tags	Assisting Systems	Monitoring and Control
Functional Sounds	P		X					P	X	P
Persistence	P	X	X	P	P	P	X		X	P
Gestural Interaction	H	H	H		X	H	X		H	H
Actuated Dial		X		P	P	P			P	P
Save and Restore		X	X	P	P	P		P	P	
Remote Collaboration	P	X		P	P		X		P	P
Vibro-tactile Feedback		X	P				X	P	P	P
Touch Sensing		X			P	P				
Constraints	P	X	P	P	P	P	X		P	P

auditory alarming qualities and could be used in calendar applications, search, and monitoring tasks. As already contemplated in our IAS application, functional sounds can be used to convey information which can support educational systems and learning.

Persistence

Persistence is a central concept in TUIs and greatly benefits from actuated TUIOs. This makes it applicable in many application categories, as we did with our remote collaborative interior design application falling into the problem solving and planning category. Also the IAS benefits from persistence, as the TAOs home back to their cluster centers keeping the haptic display consistent. Additionally, our ESN profited from persistence. As the TAOs enqueue into message queues, they provide an overview of incoming messages and postings on the first glance. Persistence can contribute to almost all other application fields and increase support for collaboration in multi-user scenarios. Persistent TUIs foster collaboration as they provide physical anchors for discussions and gesticulation. Also in programming and monitoring tasks actuation contributes persistence.

Gestural Interaction

In the ESNs (falling into the communication category) gestural interaction was the central interaction concept for triggering actions. Also in the hybrid AHEAD system multi-touch gestures were used. In our opinion, hybrid systems themselves provide high potential for future developments and may fall in almost all application categories. We mark this special case with letter H in Table 11.1.

Actuated Dial

Our actuated dial was used in the mTAOs for the remote collaborative interior design application which falls into the problem solving and planning category. Furthermore, the mTAOs were used in the generic saving and restoring mechanism which resembles a concept of its own. This actuated inner degree of freedom can find potential application in many categories as it provides an additional mean of instant parameter control. Beside the already addressed category for problem solving and planning, the most promising categories for future potentials are programming, entertainment and play, music and performance and assisting systems. In monitoring applications the mTAOs can serve as indicators for orientation related states, e.g. wind direction in a wind park monitoring application.

Saving and Restoring

The already mentioned saving and restoring mechanism was introduced as a generic application for enhancing existing TUIs with these features. Our demonstrator using the *Soundblox* engine [19] might fall into the problem solving and planning and information visualization categories. This concept can find potential application where data is created and / or organized by the users, such as programming, entertainment and play, music and performance, reminders and tags, and assisting systems.

Remote Collaboration

The concept remote collaboration is already an established concept in actuated TUIs. Our interior design demonstrator made heavy use of this concept and extended it to synchronizing the mTAOs' actuated dials. This demonstrator falls into the problem solving and planning category and mutually belongs to the communication applications. Thus, all applications supporting collaboration between multiple users can make use of this concept to allow for distributed collaboration applications, such as in learning, programming, entertainment and play, assisting systems, and monitoring categories.

Vibro-tactile Feedback

As we have seen, vibro-tactile feedback provides an additional output channel for the TAOs and was used in our remote collaborative interior design application falling into the categories problem solving and planning and communication. Beyond the use as alarming attention guidance, this concept can be used in information visualization applications, for reminders and tags and assisting systems. In (contact-based) monitoring tasks, vibro-tactile feedback provides an additional information channel for continuous and discrete information.

Touch Sensing

Touch sensing was used with the TAOs in the mind-mapping application (problem solving and planning category) to interactively alter constraints and relations between multiple TAOs to move them simultaneously while manipulating only one TAO. Touch sensing can provide and instant mean for direct input which can be beneficial in application categories, such as entertainment and play and music and performance.

Constraints

The constraints and relations concept was used in the two collaborative applications interior design and mind-mapping. This concept improves the persistence of TUIOs and can thereby contribute in many application fields, such as learning, information visualization, programming, entertainment and play, music and performance, assisting systems, and monitoring tasks.

11.3 Future Perspectives for TUIs and their Design

Before we pioneer future perspectives for TUIs and their design in more concrete directions, let us reconsider the initial vision for this thesis (see Section 1). We had (actuated) TUIs in mind that seamlessly blend into everyday environments and tasks. Of course, this goal was too far for one single PhD project, thus we focused on concepts that contribute to this vision, such as implementing mechanisms for triggering a wider pallet of actions.
In this section we identify still missing concepts that help making this vision reachable. We highlight further possible extensions and improvements for the TAOs, followed by further application possibilities and use cases.

Further Extensions and Conceptual Improvements

Gestural Interaction

The first potential improvement is the already addressed gestural interaction concept. This can be vastly improved by incorporating IMUs into the TAOs and using more capable gesture recognition methods. The use of IMUs – mostly incorporating gyroscopes and magnetometers – would allow for 3-dimensional gestures with all 6 degrees of freedom. Not just a new gesture recognition algorithm is challenging, but also the increased amount of real-time data streams of position and orientation data in high temporal resolution. Switching to a different communication standard that is more capable thant the used *XBee* modules seems inevitable. Overcoming these challenges, such improved gestural interaction possibilities can greatly improve TUIs in general.

User Detection and Tracking

To foster multiple-user scenarios, user detection and tracking means can contribute in future developments. First approaches have already been demonstrated in multiple publications [3, 107, 181, 207]. Such extensions allow the systems to orient towards the users and help organizing each user's particular tasks.

Grahpical Widgets

The integration of further graphical widgets provide known interaction means to the users and widen the possible use-cases towards general-purpose applications. Especially in hybrid systems graphical widgets virtually attached to the TAOs instantly add further interaction degrees. For instance, a color chooser widget can contribute in 'smart home' applications (see below) with an interface similar to our interior design application where the TAOs represent lights.

Map Rendering and Tiling Engine

Beyond widgets, many tabletop games and Geographic Information Systems (GISs) dealing with monitoring and planning tasks heavily rely on large graphical maps. Here, map rendering and tiling engines in particular can widen this field of applications as they provide a general-purpose framework for managing this kind of information.

Physical Widgets

In addition to graphical widgets for hybrid interfaces, more physical widgets, such as buttons and sliders, etc. contribute further physical inner degrees of freedom for data manipulation, as proposed by Weiss et al. [208]. Here, the robotic actuation approach for active TUIOs may ease the implementation of such widgets; imagine a TAO with four sliders (one at each sides).

Embedded Display and Audio

Similarly to the mentioned physical widgets or vibro-tactile feedback, the incorporation of visual and auditory displays into the TAOs provide additional feedback channels and reduce the abstractness of the cubical TAOs. Such implementations were already demonstrated [139, 204]. An additional display could contribute to monitoring applications or remote collaborative applications and games where (interaction) parties are represented by TAOs. A small-sized picture or even live video could be show on the representative TAO.

Speech Recognition

One major disadvantage of TUIs in general is the necessity of a keyboard when it comes to text processing which largely limits the applicability of TUIs in many general-purpose applications. As speech recognition is greatly emerging in consumer products lately, the barrier of using this input modality is low both in terms of user acceptance and integration effort as there are sophisticated APIs and services. Thus, communication applications like our ESN client can benefit from such extensions. Recognition results improve as well, as recent developments in machine learning techniques may even allow for dictation of longer text passages without training.

Active Manipulation of passive TUIOs

A building block contributing to hybrid interfaces in the means of integrating passive and active TUIOs is the concept of active manipulation of passive TUIOs by the TAOs. By incorporating a swarm concept for the active TAOs they can be enabled to autonomously manipulate passive objects and TUIOs to integrate both object types into one active TUI. This allows to use passive TUIOs for tasks where the system rarely needs to adjust their position and spare the TAOs for active tasks. In blended everyday working scenarios, the TAOs could be of assistance beyond the TUI, by cleaning up and organizing the desk.

Actuated Physical Avatars

Though definitely leaving the field of applications for TUIs, the field of social robotics that lately emerges into consumer products, such as *Jibo* [164] provides inspiration for the TAOs. Such robots embody assistance agents like Apple's *Siri* or Amazon's *Alexa* and mark the next level in consumer robotics. Adapting this concept to the TAOs would allow them to act as robotic companions. A simple but expressive actuated character like the one presented with the *Cero* robot [184] could be addressed with speech commands via speech recognition and assist in everyday tasks. In (remote) communication scenarios such companion robots could increase the awareness for interaction partners by providing a more physical anchor than a photo on an embedded display could.

Further Applications

Beyond these additional extensions with their already mentioned potential applications, we would like to use the opportunity to present further fields of applications we had in mind. As mentioned above, we have monitoring and control, and assisting systems in mind. Furthermore, we will add an additional interaction possibility within the frame of collaborative applications and conclude this chapter with picturing our idea of an integrated hybrid multi-purpose user interface incorporating conventional, multi-touch and (active) tangible interaction.

Monitoring, Assistance and Therapy Systems

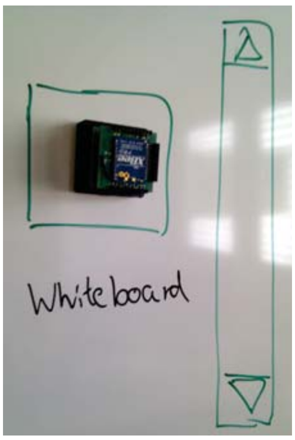
As an example for monitoring applications, we have smart home control in mind. Smart home applications deal with a large amount of real-time data, including lighting, heating,

appliance control and a manifold of sensors, such as smoke detectors or power consumption, controlled by predefined rules. We can also think of incorporating active furniture as we addressed with the IMS project and media control as proposed with the AHEAD system. TUIs can provide a suitable way to monitor, control and manage all these data and the respective appliances by representing the current state of the whole living environment at a glance. Also communication and remote presence functionalities could be integrated in such scenarios, connecting multiple homes of family members and friends.
By this, an integrated and versatile application is scripted that increases comfort for their residents, including support for disabled and elderly users, as proposed by the field of AAL.
Apart from such monitoring and control tasks, TUIs can be supportive in therapy applications. As already proposed in [173], the mTAOs can form a system for assisting in therapy sessions using the Family-System-Test (FAST) for measuring family relations [53]. Here, the saving and restoring mechanism and the actuated dial are the key concepts for the implementation. In rehabilitation, the TAOs can provide a playful mean for occupational therapy. Within a game scenario the TAOs could train the dexterity of stroke patients and automatically measure the therapy progress under supervision of a therapist.

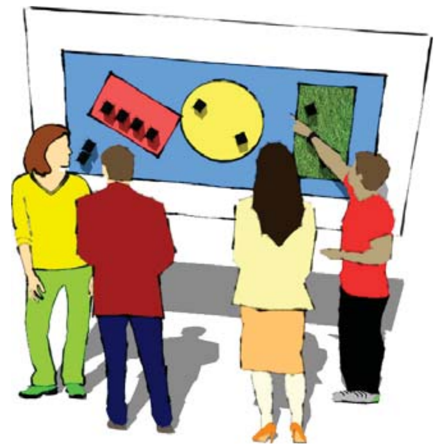
Vertical Actuated TUIs

Another idea we had in mind for the TAOs, but was neglected as we focused on horizontal tabletop applications for actuated TUIs, were vertical actuated TUIs, as illustrated in Figure 11.1. Inspired by the *Senseboard* by Jacob et al. we dreamt of applications for organization tasks, and teaching and learning.
Very recently, Bader et al. presented their *Self-Actuated Displays for Vertical Surfaces* [6] that comes quite close to our vision: They attached magnets to a *3pi robot* platform to

Figure 11.1: Two pictures proposing the use of the TAOs in horizontal actuated TUIs.



(a) Mock-up of TAO at a horizontal white board. It uses permanent magnets to hold to the surface (Photo taken in 2010).



(b) Illustration of a horizontal TUI for co-located collaboration and teaching.

make it hold on a whiteboard. Furthermore they added housing components for a pen, an eraser, additional batteries and a small tablet PC for display. Bader et al. proposed four scenarios, covering assistance in a kitchen environment, teaching and self-learning applications in classroom and museum scenarios and an office situation for automatically adjusting displays for remote communication.

Tangible Hybrid Desktop Environment

Through our own experience, we find the direction for applications of TUIs as stated by Fitzmaurice and Buxton still valid: "The ultimate benefit may be to have a collection of strong specific devices creating a strong general system" [46]. This statement absolutely supports our own vision, as we imagine a general-purpose tangible (or even hybrid) desktop environment that seamlessly blends into everyday environments and tasks.

Passive and active TUIs and multi-touch interaction provide such strong specific interfaces but there are still applications where Mouse and keyboard work best, such as text processing or creating graphics. The demonstrated and proposed extensions and concepts already contribute many useful means to push and integrate these towards a more general hybrid interface. But there are still building blocks missing to create the ultimate general system with strong specific devices.

A desktop environment that features all the addressed application fields should thus support Mouse and keyboard and hybrid passive and active TUIOs with multi-touch facilities, as illustrated in Figure 11.2. To seamlessly blend all interfaces, support for parallel application execution and live task switching between different applications is necessary. These task switching capabilities should be equally supported by all interface types. Where possible, the system should also support device switching within a certain task to make the interface completely task-transparent. In conclusion, the user can naturally decide which interface suits best for each specific task.

Figure 11.2: Illustration of a tangilbe hybrid desktop environment.

12 Conclusion: Contributions and Research Perspectives

In times of increasing connectedness and virtualization of information, the TAOs provide new means for making information graspable again. We believe that the use of TUIs may not only be appealing for the user, but also generally more inspiring than GUIs, because of their embodiment and the possibility to embed these interfaces into the user's everyday environment using the same properties and modalities. The more direct way of interaction can decrease the cognitive load so that users can better concentrate on the actual task and perhaps the embodiment of such systems may cognitively stimulate users to contemplate ideas that they may not have using ordinary GUI-based systems.

Our work copes with various aspects of actuated tabletop TUIs. Though it is a more technical and evaluation driven work, we gave a general overview of TUIs and introduces the theoretical background of the field. We motivated and described our TAOs architecture which lay the foundations for our research.

Addressed Application Domains

With our applications for the TAOs we addressed multiple of the application domains for TUIs, as identified by Shaer and Hornecker.

The ESN client, presented in Chapter 4, addresses the social communication domain as it provides a tangible actuated interface to social networks.

Multiple application domains are addressed by our remote collaborative furniture placing application, discussed in Chapter 6. First of all, it obviously falls into the social communication domain, as it allows distant users to work together. The second addressed domain is the problem solving and planning domain. The distant users can collaboratively work on the same task, planning the interior design of an apartment.

Though the mind-mapping application was used in the comparative study (see Chap. 7) to evaluate different kinds of interfaces, it is a useful application that falls into the learning domain. It allows groups of users to collaboratively elaborate on a particular topic and to learn from each other. Furthermore, the task of creating mind-maps, this application partially touches the problem solving and planning domain.

Being meant as a toy application, the TAOgotchis, as discussed in Chapter 9, are covered by the entertainment, play and edutainment domain.

Another example for this application domain is our AHEAD application, discussed in the same chapter. It interfaces with home entertainment devices and allows groups of users to collaboratively organize a movie night. This organization task also addresses the problem solving and planning domain.

Our IAS, described in Chapter 9.3, falls into the learning and the information visualization domain. It provides means for exploratory data analysis and aims to help visually impaired users to learn about data usually visualized using scatter plots. Interactive sonification and haptic exploration are non-visual displays of data and thereby visualization techniques in a broader view. Consequently, this application falls into the information visualization domain.

New Application Domains

Applications that do not fall into any of the domains identified by Shaer and Hornecker are the IMS, described in Chapter 9. The IMS is half assisting system, half TUI. Its mobile robot resembling an autonomous seating, whereas its TUI enables handicapped users to control the seating and move it without external help. The IAS is another example that would fit into this domain, since it enables visually-impaired users to non-visually explore data usually presented graphically. We propose the application domain of *Assistive TUIs*.

Furthermore, with the presented AHEAD system and the perspective highlighted in Chapter 11, we also propose the application field of 'Monitoring and Control'.

Answering the Research Questions and Filling the Gaps

Our studies and evaluations allowed us to answer our research questions, stated in the introduction chapter.

In our gestural interaction study we identified two classes of gestures in terms of complexity. One simple class with abstract single- and two-stroke gestures and more symbolic gestures inspired by letters and symbols. We found out that a questionnaire-based study design only produces first directions for gestures, but a real-life study with the actual system is more effective for gathering well-fitting gestures.

We identified three different types of menu styles in TUIs. After reviewing their strengths and limitations, we proposed our tangible menu metaphor based on an actuated dial, that is applicable in most use cases with up to approximately ten menu items.

Beside the embodied interaction and the visual domain, mostly covered in literature, we combined our additional concepts into a system with rich interaction possibilities. In our remote collaboration application we demonstrated the benefits, such a combined approach has and how they complement each other.

Our comparative study showed a preference of the participants towards the TAOs and the TUIOs. In the study design we also compared Mouse and multi-touch interaction within the same system design and task setting. We transferred and adapted interaction measures to investigate interaction qualities that extend the methods used in literature.

We identified boundary conditions and requirements for actuated TUIs in terms of speed or velocity. Comparing our results from the benchmarks of the human hand's manipulation speed and the TAOs' velocity, we found that the TAOs are partially unable to reproduce movements of a TUIO manipulated by a human. The TAOs but also most actuated TUIs described in literature are roughly ten times slower as the human hand, depending on the task and the needed precision.

Design Guidelines

The design guidelines we derived in the core chapters integrate the aspects and their interplay with common design approaches for TUIs, observed and developed throughout this project. These guidelines serves as a foundation for further design investigations and are applicable for a large range of tabletop TUIs.

Towards Systematical Evaluation of TUIs

With our comparative collaboration study, we presented adapted interaction measures that were transferred to the field of (actuated) TUIs. These measures may help comparing different interface styles with regard to social interaction beyond performance measures and questionnaires. At that time, this was the fist attempt to compare four different interaction styles at once. However, the hoped-for large differences were not found, thus future studies are needed. Nonetheless, the measures may serve as foundations and precursors for such systematical evaluation of TUIs that allow empirical proving of the theories on tangible interaction.

We hope that both the new interaction measures for evaluation and the design framework become more and more important regarding the increasing sophistication of TUIs.

Into the Frameworks

With regard to the map of frameworks, proposed by Mazalek et al., our work can be integrated into different areas of their map. In general, our work definitely contributes to the *building technologies* area as it provides an implementation of a sophisticated actuated TUI. Our review of available actuation technologies and the identification of boundary conditions and requirements for actuation adds to the *abstracting technology* area. The *building interactions* area is addresses by nearly all our applications because they include new interaction concepts for actuated TUIs, identified as gaps in the introduction chapter. Through our design guidelines, many facets of the *designing* column of the frameworks map are covered, such as the *technologies*, *interactions*, *physicality* and even the *domains* facets. Since our design guidelines are user-centric oriented they also touch the *experiences* facet.

12.1 Outlook and Future Work

In a course of three and a half years, many results and insights have been collected and further questions and issues have been raised. The adapted evaluation measures we described extend the evaluation methods for tabletop TUIs and disclose new research possibilities with more detailed and accurate measures.

With the current design of the TAOs we reached the bounds of possibility at some points. Over the years, the technicals requirements for the TAOs vastly increased so that a redesign of them is needed to feature all our described interaction concepts at the same time. Incorporating a more sophisticated and versatile microcontroller platform, within the TAOs may even more increase the pallet of possible applications and evaluations. Nevertheless, our combinatory and integrative approach leads to rich interactions for actuated TUIs. We strongly believe that this approach will help to pull TUIs out of the niche of special-purpose applications. Also the design and development of TUIs needs to become more simple to quickly create sophisticated applications. Here, the *TuiML* approach [186] can point out a reasonable implementation style. One day actuated TUIs will be embedded into our everyday live. Whether at work or at home, this approach will be applicable in many situations combining aspects of actuated TUIs, GUIs and multi-touch interaction and even full-body interaction. This possibility of choosing and combining different interaction approaches will enable users to find their personal way of interaction.

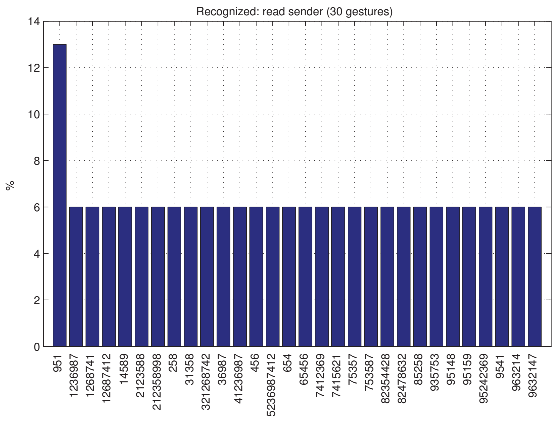
Study Related Information and Further Results

A

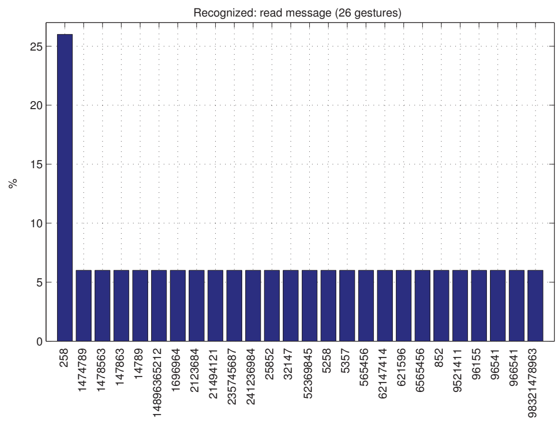
A.1 Hands-on Gesture Study

Frequencies of Recognized Gestures

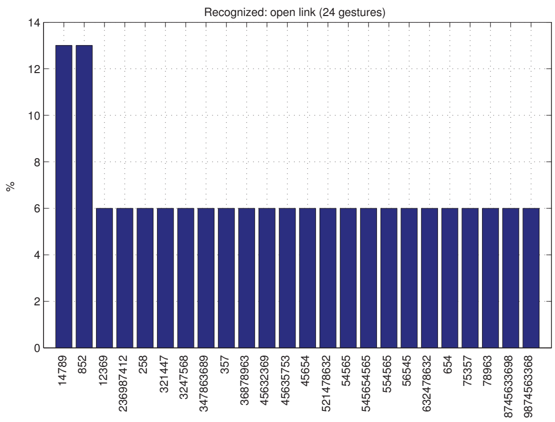
Figure A.1: Recognized gesture frequencies (part 1/3)



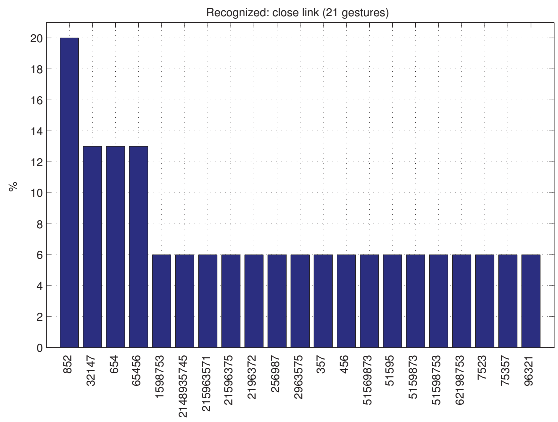
(a) read sender



(b) read message

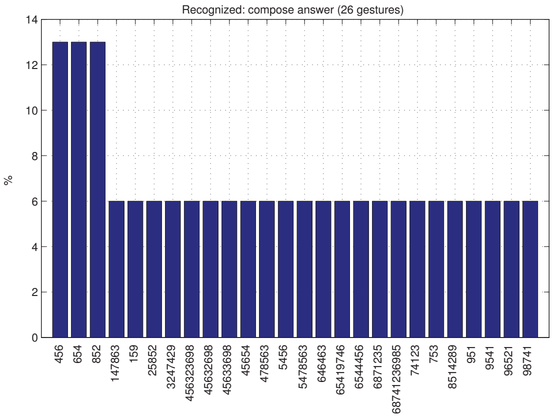


(c) open link

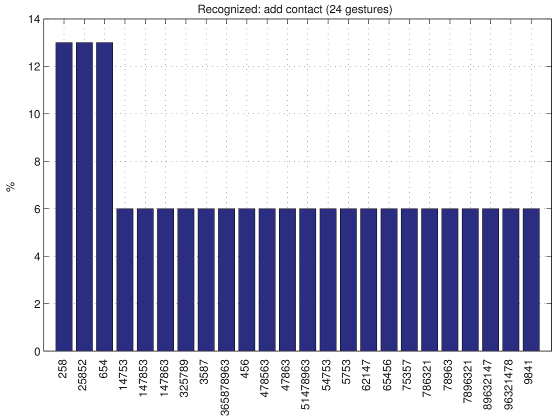


(d) close link

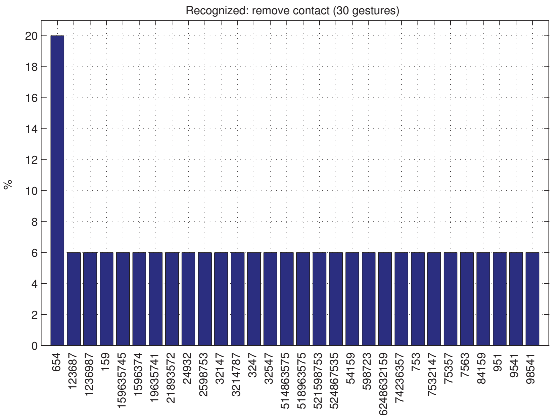
Figure A.2: Recognized gesture frequencies (part 2/3)



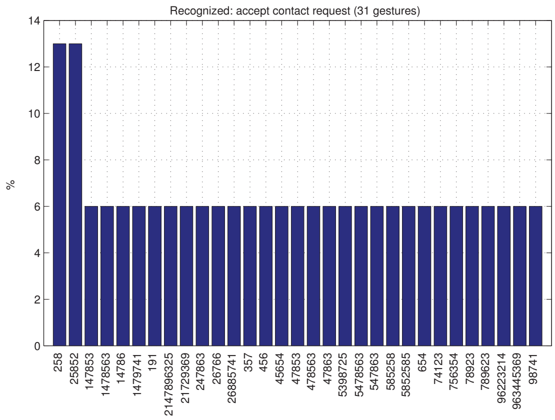
(a) compose answer



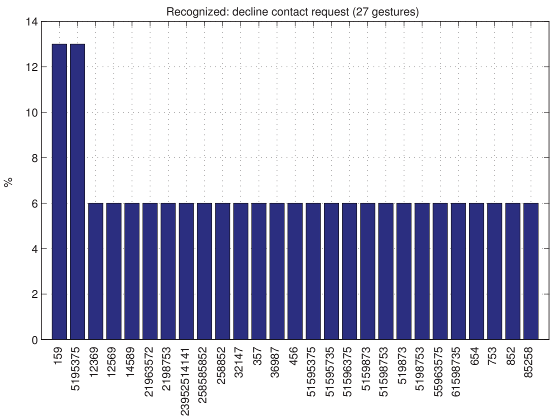
(b) add contact



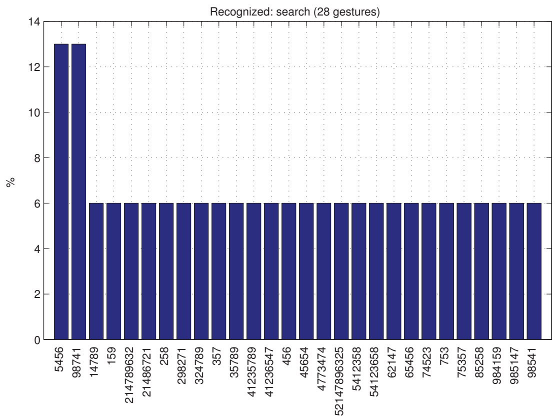
(c) remove contact



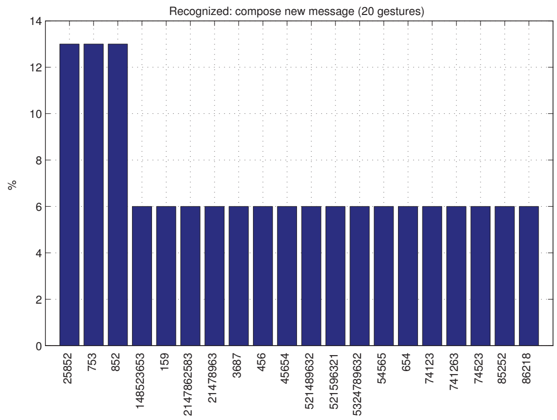
(d) accept contact request



(e) decline contact request



(f) search

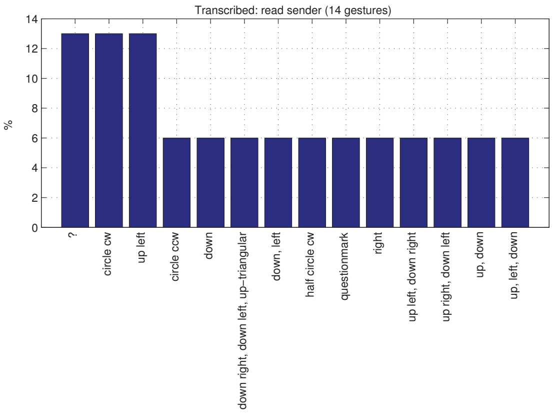


(a) compose message

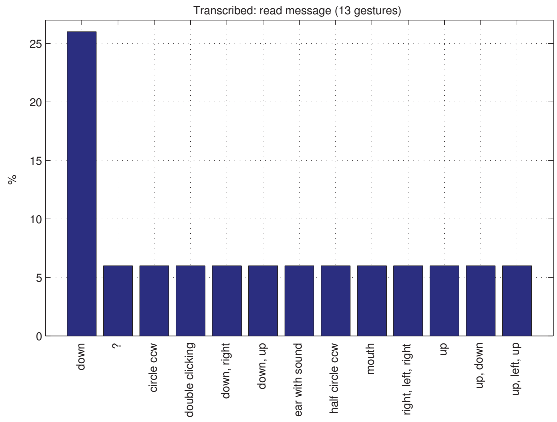
Figure A.3: Recognized gesture frequencies (part 3/3)

Frequencies of Transcribed Gestures

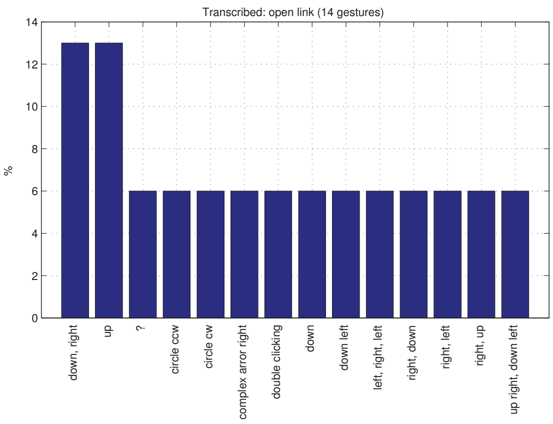
Figure A.4: Transcribed gesture frequencies (part 1)



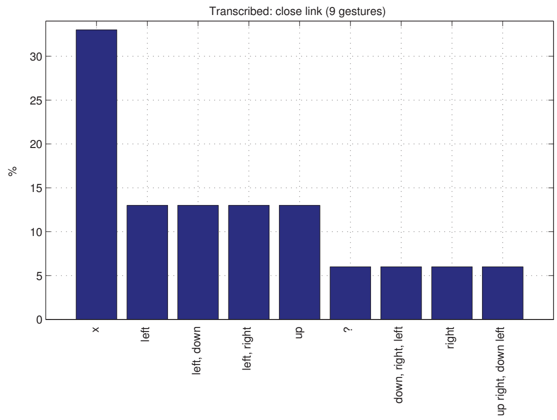
(a) read sender



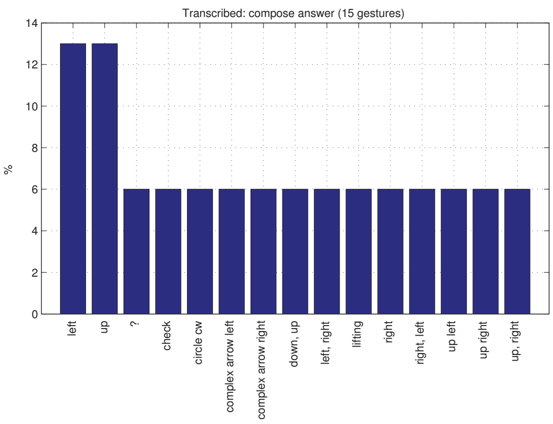
(b) read message



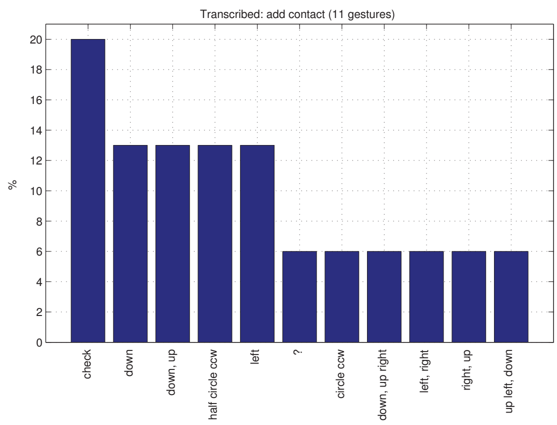
(c) open link



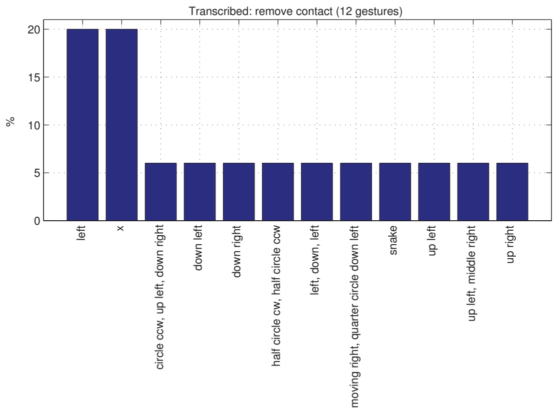
(d) close link



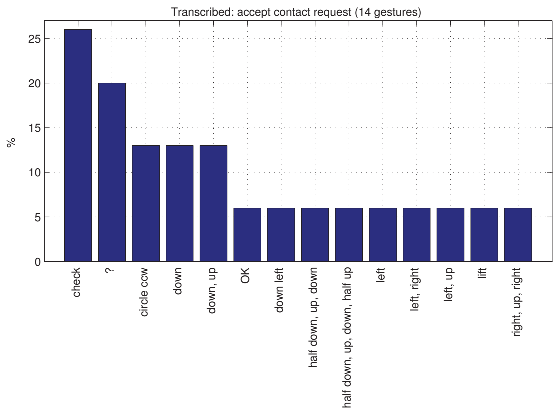
(e) compose answer



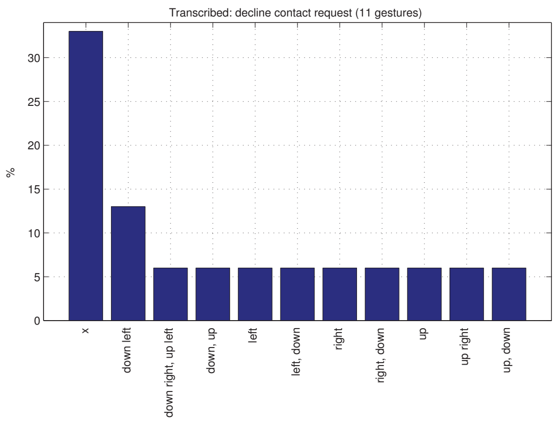
(f) add contact



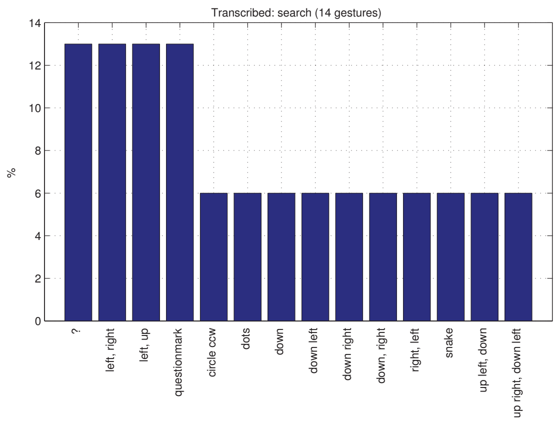
(a) remove contact



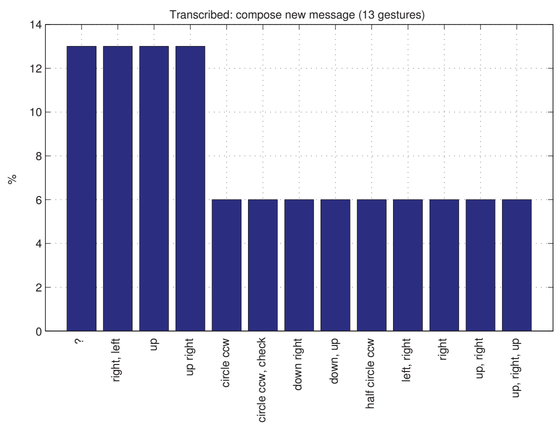
(b) accept contact request



(c) decline contact request



(d) search



(e) compose message

Figure A.5: Transcribed gesture frequencies (part 2)

Questionnaire Items

1. Age
2. Sex
3. Handedness [right / left / both/different]
4. Occupation
5. Highest educational degree
6. Major subject (as student)
7. Have you heard of this project before?
8. Have you participated in an earlier study (of this project)?
9. Which one(s)?
10. Do you know mouse or finger gestures? [yes / no / unsure]
11. Do you use them? [yes / no]
12. With what programs or devices do you use them?
13. Do you know social networks? [yes / no]
14. Do you use them? [yes / no]
15. Why do you use social networks?
16. Why don't you use social networks?
17. Can you imagine to use such a system on your desk? [yes / no / unsure]
18. Would you prefer a standardized or a personalized gesture set? [personalized / standardized / unsure]

Comments

A.2 Comparative Study

Questionnaire

Pre-questions

1. Age
2. Sex
3. Handedness [right / left / both]
4. Did you know your trial partner before? [good / a little / not at all]
5. Occupation
6. Highest educational degree
7. Major subject (as student)
8. Have you heard of this project before? [yes / no]
9. Have you attended in an earlier study (of this project)? [yes / no]
10. Which one(s)?

Own Items

1. Working with the system was fun.
2. I would like to work longer with the system.
3. Working with my trial partner was productive.
4. Working with the system was motivating.
5. The use of the system was interesting.
6. The use of the system was inspiring.
7. The system has distracted me from the actual task. (recoded)
8. The task was too hard. (recoded)
9. The usage of the system was difficult to learn. (recoded)
10. The system is unsuitable for the task. (recoded)
11. I would like to use the system more frequently.
12. I would like to have such a system at my office / home.
13. I can imagine to use this system for other tasks.
14. The design of the system (presentation, shapes, colors, etc.) was appealing.
15. The system worked the way I expected.
16. I would like to redesign the system, if I could. (recoded)
17. The system has facilitated the collaboration with my trial partner.
18. I had to deal with similar tasks before.
19. The system hindered me from effectively working with my trial partner. (recoded)
20. I think working with my partner was very cooperative.
21. I think the communication between my partner and me was very good.
22. I like our result of the task very much.
23. I work with computers almost every day.
24. In my occupation I am used to work with computers.
25. I can write computer programs.
26. In private live I enjoy using computers.

SUS Items

1. I think that I would like to use this system frequently
2. I found the system unnecessarily complex
3. I thought the system was easy to use

4. I think that I would need the support of a technical person to be able to use this system
5. I found the various functions in this system were well integrated
6. I thought there was too much inconsistency in this system
7. I would imagine that most people would learn to use this system very quickly
8. I found the system very cumbersome to use
9. I felt very confident using the system
10. I needed to learn a lot of things before I could get going with this system

Comments

Results

Questionnaire

Index	Mean M				Standard deviation SD			
Condition	1	2	3	4	1	2	3	4
System usability	4.89	4.69	5.01	5.74	1.05	1.23	1.40	0.89
Collaboration	5.57	4.84	5.49	5.46	0.99	1.37	1.18	0.98
Task	6.21	5.76	5.25	5.58	0.78	1.00	1.39	0.90
User type	5.79	5.90	5.05	5.79	1.15	0.96	1.99	1.18
Other tasks	5.10	5.35	5.10	5.15	1.33	1.76	1.80	1.50
System design	4.25	4.35	4.50	5.25	1.59	1.63	2.04	1.41
Expected system behavior	5.25	4.35	5.15	5.10	1.71	1.57	1.14	1.07
Redesign	3.60	4.95	4.20	4.20	2.14	1.43	1.67	1.54
Task familiarity	3.65	3.60	2.00	3.65	2.30	2.21	1.52	2.30
Result	5.50	5.05	5.70	5.40	1.32	1.93	1.08	1.70
SUS	77.13	78.25	72.63	77.38	16.69	12.93	15.72	9.30

Table A.1: Descriptive statistics for the questionnaire indexes.

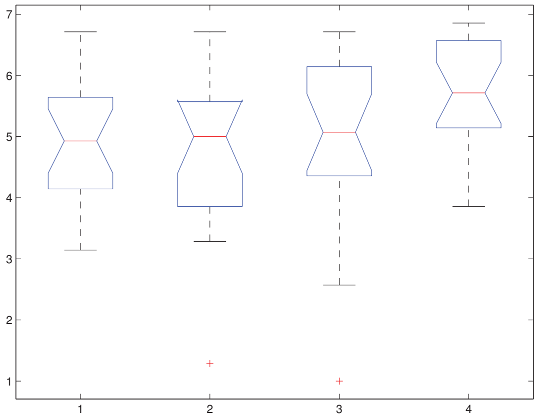
Index	$F(3, 76)$-value	p-value	η_p^2-value
System usability	3.07	0.03	0.06
Collaboration	1.74	0.17	0.03
Task	2.97	0.04	0.06
User type	1.62	0.19	0.03
Other tasks	0.11	0.95	< 0.01
System design	1.45	0.23	0.03
Expected system behavior	1.74	0.17	0.03
Redesign	2.07	0.11	0.04
Task familiarity	3.00	0.04	0.06
Result	0.62	0.60	0.01
SUS	0.66	0.58	0.01

Table A.2: Complete ANOVA results for the questionnaire indexes.

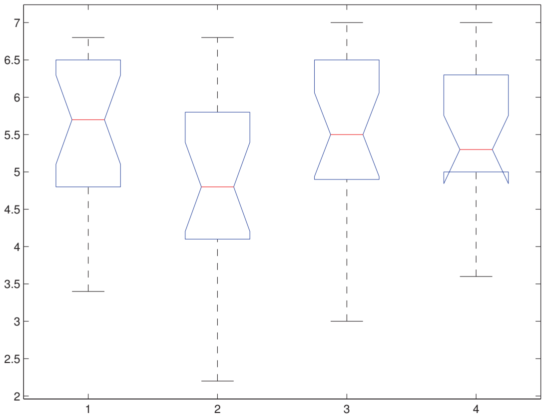
Table A.3: Complete results for the post-hoc analysis of the questionnaire indexes.

Index	Compared conditions	*p*-value
System usability	1 – 2	0.560
	1 – 3	0.697
	1 – 4	0.012
	2 – 3	0.332
	2 – 4	0.002
	3 – 4	0.032
Collaboration	1 – 2	0.033
	1 – 3	0.811
	1 – 4	0.744
	2 – 3	0.056
	2 – 4	0.069
	3 – 4	0.929
Task	1 – 2	0.179
	1 – 3	0.005
	1 – 4	0.059
	2 – 3	0.127
	2 – 4	0.573
	3 – 4	0.330
User type	1 – 2	0.765
	1 – 3	0.053
	1 – 4	1.000
	2 – 3	0.027
	2 – 4	0.765
	3 – 4	0.053

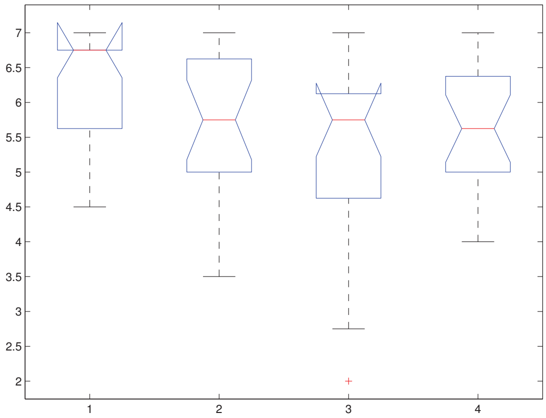
Signle-item index	Compared conditions	*p*-value
Other tasks	1 – 2	0.608
	1 – 3	1.000
	1 – 4	0.918
	2 – 3	0.608
	2 – 4	0.682
	3 – 4	0.918
System design	1 – 2	0.855
	1 – 3	0.647
	1 – 4	0.071
	2 – 3	0.784
	2 – 4	0.103
	3 – 4	0.173
Expected system behavior	1 – 2	0.046
	1 – 3	0.822
	1 – 4	0.735
	2 – 3	0.075
	2 – 4	0.095
	3 – 4	0.910
Redesign	1 – 2	0.018
	1 – 3	0.283
	1 – 4	0.283
	2 – 3	0.181
	2 – 4	0.181
	3 – 4	1.000
Task familiarity	1 – 2	0.939
	1 – 3	0.013
	1 – 4	1.000
	2 – 3	0.016
	2 – 4	0.939
	3 – 4	0.013
Result	1 – 2	0.347
	1 – 3	0.675
	1 – 4	0.834
	2 – 3	0.176
	2 – 4	0.464
	3 – 4	0.530
SUS	1 – 2	0.809
	1 – 3	0.335
	1 – 4	0.957
	2 – 3	0.229
	2 – 4	0.850
	3 – 4	0.309



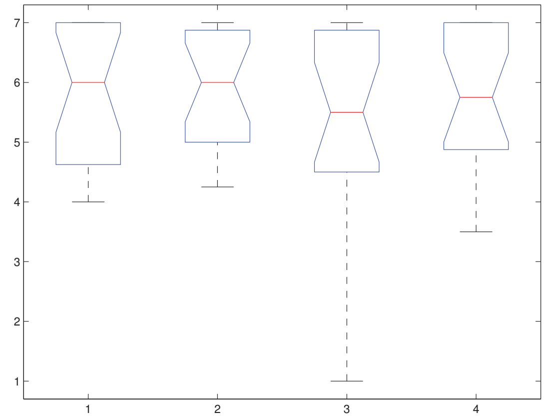
(a) System usability.



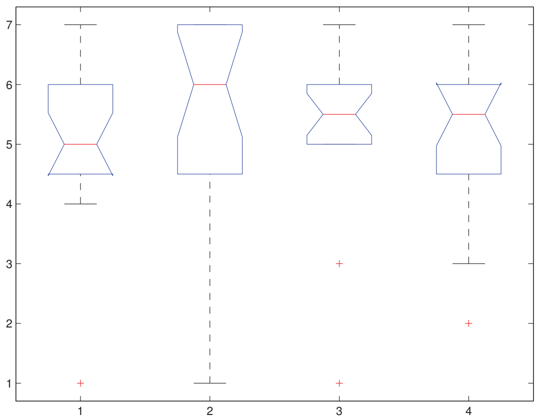
(b) Collaboration.



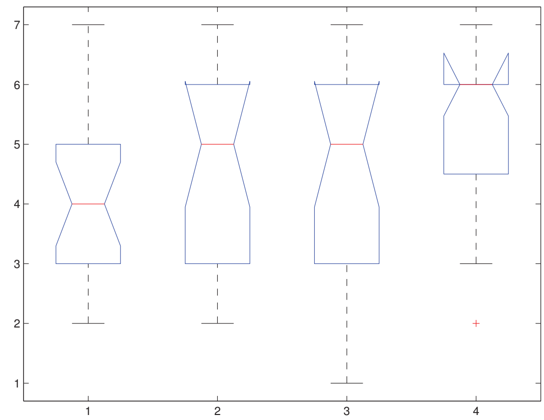
(c) Task.



(d) User type.



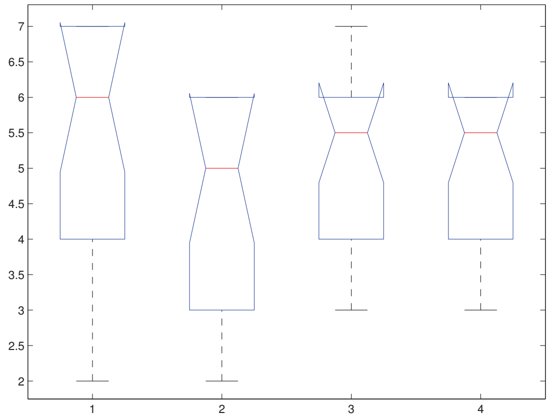
(e) Other tasks.



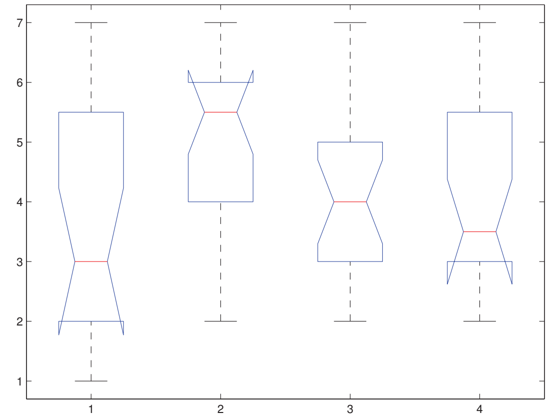
(f) System design.

Figure A.6: Visualized descriptive statistics of the indexes (part 1).

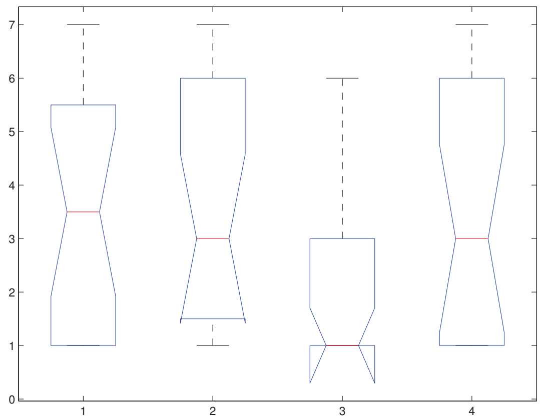
Figure A.7: Visualized descriptive statistics of the indexes (part 2).



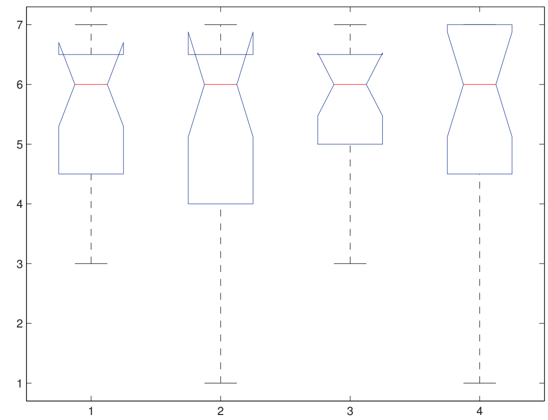
(a) Expected system behavior.



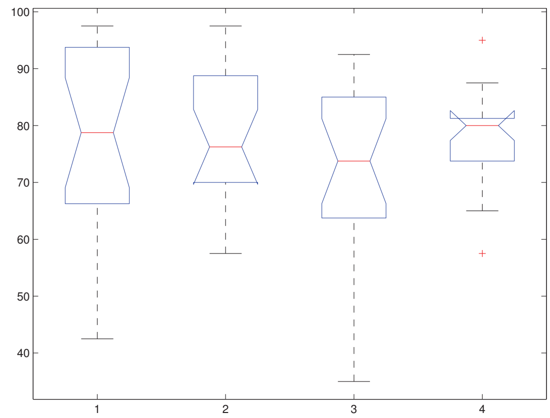
(b) Redesign.



(c) Task familiarity.



(d) Result.



(e) *SUS*.

Interaction Measures

Interaction measure	**Mean** *M*			
Condition	1	2	3	4
Utterances sum	57.01	42.92	57.47	63.67
Interaction mean	0.80	2.17	2.05	1.78
Interaction sum	32.61	47.62	49.13	40.90
Overlap mean (task+interaction)	0.35	0.69	0.83	0.78
Overlap sum (task+interaction)	4.82	5.65	8.51	8.20
Overlap mean (interaction+interaction)	0.00	3.32	4.01	2.57
Interaction space	0.33	0.50	0.45	0.39
Intersection	0.14	0.30	0.24	0.18
Turn taking (speech)	41.00	31.00	36.40	39.50
Turn taking (interaction)	1.78	7.90	6.40	6.10
	Standard deviation *SD*			
Utterances sum	35.65	20.03	27.40	32.77
Interaction mean	0.49	1.16	0.83	0.71
Interaction sum	27.98	23.85	20.94	19.61
Overlap mean (task+interaction)	0.26	0.38	0.43	0.35
Overlap sum (task+interaction)	7.49	4.60	6.64	5.88
Overlap mean (interaction+interaction)	0.00	5.14	2.96	3.62
Interaction space	0.13	0.10	0.07	0.74
Intersection	0.18	0.15	0.07	0.10
Turn taking (speech)	15.84	10.21	14.80	10.28
Turn taking (interaction)	0.83	4.15	2.07	2.85

Table A.4: Descriptive statistics for the interaction measures.

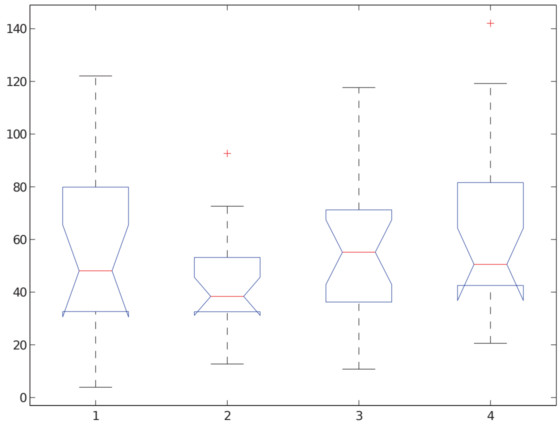
Interaction Measure	$F(3, 74)$-value	p-value	η_p^2-value
Utterances sum	1.78	0.158	0.035
Interaction mean	10.23	< 0.01	0.171
Interaction sum	1.99	0.123	0.039
Overlap mean (task+interaction)	6.79	< 0.01	0.12
Overlap sum (task+interaction)	1.68	0.178	0.033
Overlap mean (interaction+interaction)	2.30	0.095	0.152
Interaction space	5.51	0.003	0.047
Intersection	2.97	0.045	0.014
Turn taking (speech)	1.13	0.349	0.034
Turn taking (interaction)	8.30	< 0.01	0.032

Table A.5: Complete ANOVA results for the interaction measures.

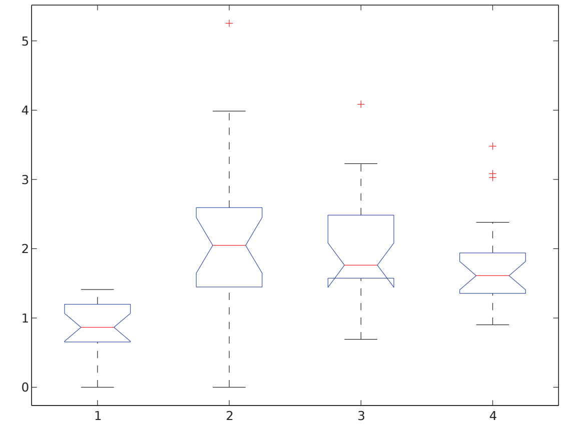
Table A.6: Complete results for the post-hoc analysis of the interaction measures.

Measure	Compared conditions	*p*-value	Measure	Compared conditions	*p*-value
Utterances sum	1 – 2	0.457	Overlap mean (inter. + inter.)	1 – 2	0.243
	1 – 3	1.000		1 – 3	0.009
	1 – 4	0.897		1 – 4	0.184
	2 – 3	0.404		2 – 3	0.982
	2 – 4	0.124		2 – 4	0.981
	3 – 4	0.909		3 – 4	0.765
Interaction mean	1 – 2	< 0.001	Interaction space	1 – 2	0.033
	1 – 3	< 0.001		1 – 3	0.125
	1 – 4	0.003		1 – 4	0.632
	2 – 3	0.967		2 – 3	0.594
	2 – 4	0.465		2 – 4	0.060
	3 – 4	0.749		3 – 4	0.280
Interaction sum	1 – 2	0.200	Intersection	1 – 2	0.171
	1 – 3	0.134		1 – 3	0.425
	1 – 4	0.690		1 – 4	0.918
	2 – 3	0.997		2 – 3	0.615
	2 – 4	0.796		2 – 4	0.178
	3 – 4	0.677		3 – 4	0.445
Overlap mean (task + inter.)	1 – 2	0.022	Turn taking (speech)	1 – 2	0.349
	1 – 3	0.001		1 – 3	0.866
	1 – 4	0.002		1 – 4	0.994
	2 – 3	0.626		2 – 3	0.788
	2 – 4	0.864		2 – 4	0.467
	3 – 4	0.974		3 – 4	0.950
Overlap sum (task + inter.)	1 – 2	0.976	Turn taking (interaction)	1 – 2	0.005
	1 – 3	0.268		1 – 3	< 0.001
	1 – 4	0.344		1 – 4	0.004
	2 – 3	0.469		2 – 3	0.739
	2 – 4	0.567		2 – 4	0.467
	3 – 4	0.999		3 – 4	0.950

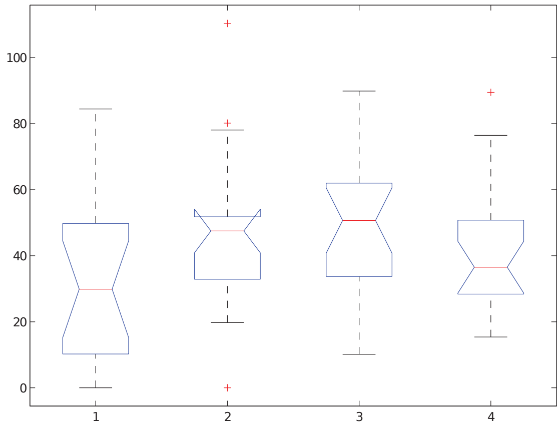
Figure A.8: Visualized descriptive statistics of the interaction measures (part 1/2).



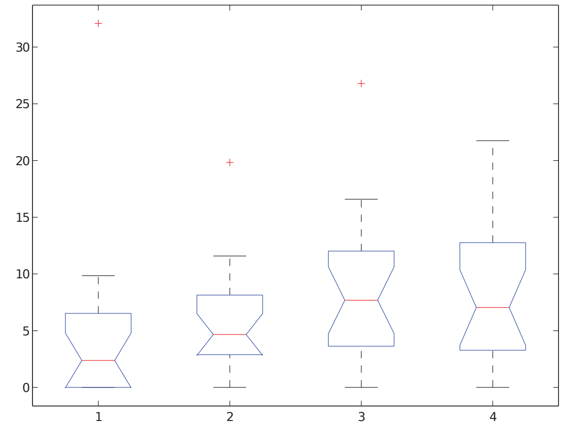
(a) Summed utterance duration.



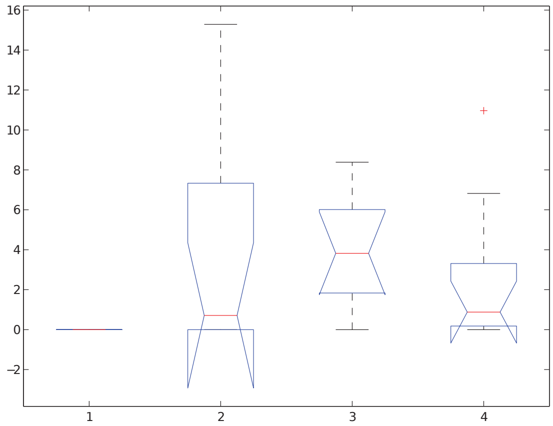
(b) Average interaction duration.



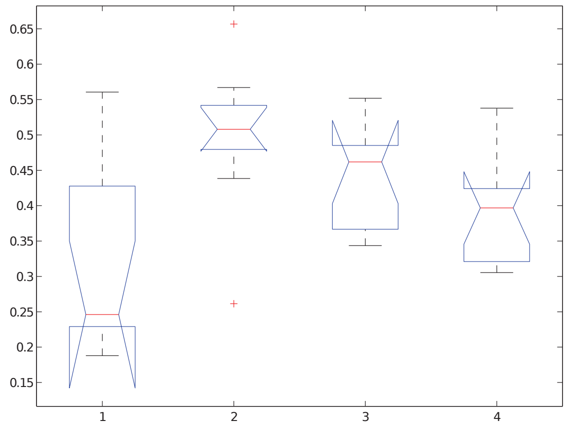
(c) Summed interaction duration.



(d) Summed overlap duration between utterance and interaction.

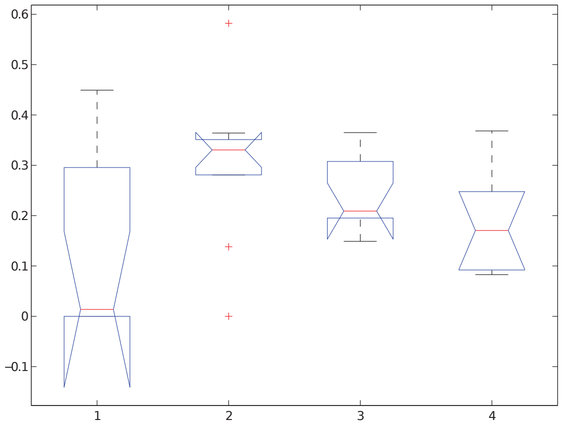


(e) Summed overlap between participants' interaction duration.

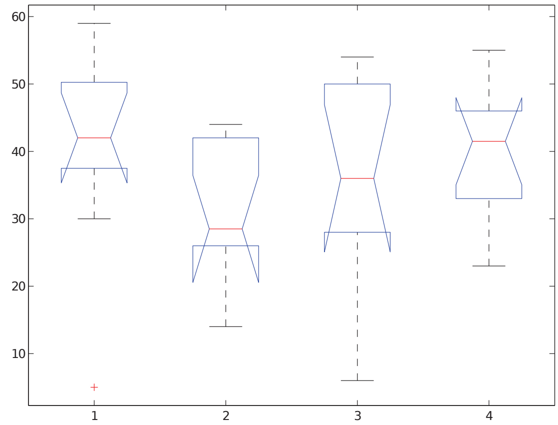


(f) Interaction space.

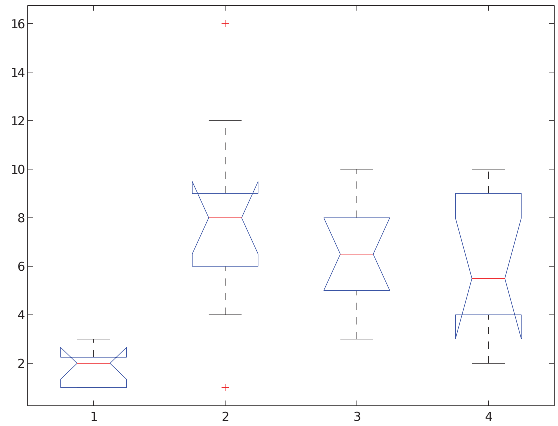
Figure A.9: Visualized descriptive statistics of the interaction measures (part 2/2).



(a) Interaction space intersection.



(b) Turn taking in speech.



(c) Turn taking in interaction.

Further Observations

Index	**Mean** M			
Condition	1	2	3	4
Learning phase duration	149.00	314.11	266.89	346.60
	Standard deviation SD			
Learning phase duration	52.609	216.116	246.799	118.130

Table A.7: Descriptive statistics for the learning phase duration.

Measure	$F(3, 33)$-value	p-value	η_p^2-value
Learning phase duration	2.27	0.099	0.093

Table A.8: ANOVA results for the learning phase duration.

Measure	**Compared conditions**	p**-value**
Learning phase duration	1 – 2	0.207
	1 – 3	0.490
	1 – 4	0.085
	2 – 3	0.939
	2 – 4	0.977
	3 – 4	0.755

Table A.9: Post-hoc analysis results of the learning phase duration.

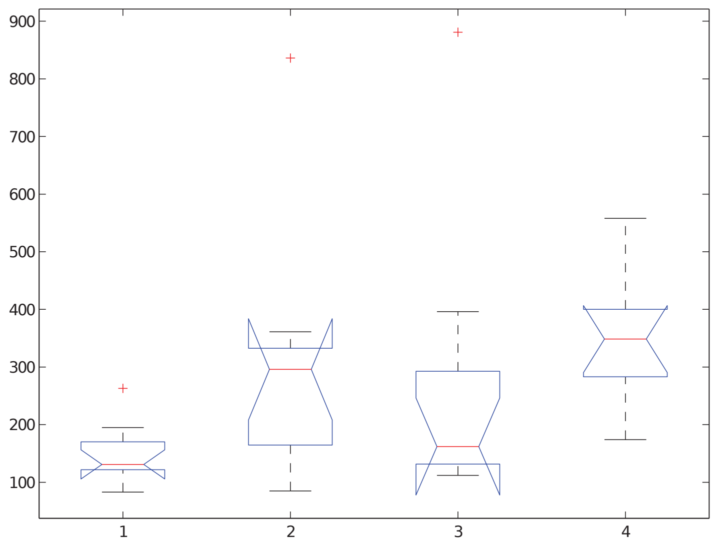


Figure A.10: Summed duration of learning phases.

List of Abbreviations

AAL Ambient Assisted Living

ABS acrylonitrile-butadiene-styrene

AHEAD Active Home EntertAinment Desk

AMIRE International Symposium on Autonomous Minirobots for Research and Edutainment

ANOVA Analysis of variance

API Application Programming Interface

AR Augmented Reality

BCH Bose/Chaudhuri/Hocquenghem

CAD Computer Aided Design

CCV Community Core Vision

CLI Command Line Interface

CRT Cathode Ray Tube

CSCW Computer Supported Cooperative Work

DLNA Digital Living Network Alliance

EDA Exploratory Data Analysis

EEG Electroencephalogram

EICS Symposium on Engineering Interactive Computing Systems

ESN Embodied Social Networking client

FAST Family-System-Test

FTIR Frustrated Total Internal Reflection

gDesk Gesture Desk

GDL	Gesture Definition Language
GIS	Geographic Information System
GUI	Graphical User Interface
HCI	Human Computer Interaction
HCII	International Conference on Human-Computer Interaction
HDV	Haptic Data Visualization
HMM	Hidden Markov Model
HSD	Honestly Significant Difference
HUD	Head-up Display
IAS	Interactive Auditory Scatter Plot
IC	Integrated Circuit
ICAD	International Conference on Auditory Display
ICL	Image Component Library
IMS	Interactive Mobile Seat
IMU	Inertial Measurement Unit
IPC	Inter-Process Communication
LED	Light-emitting Diode
MILab	Manual Interaction Laboratory
MBS	Model-based Sonification
MCRpd	Model Controller Representation (physical and digital)
MRI	Mixed-Reality Interface
MUI	Malleable User Interface
MVC	Model View Controller
MVP	Model-View-Presenter
mTAO	Menu TAO
MW	Middleware
OSC	Open Sound Control

PARC Palo Alto Research Center

PCB Printed Circuit Board

PICO Physical Intervention in Computational Optimization

PI Proportional–Integral

PID Proportional–Integral–Derivative

PMD Planar Manipulator Display

PMSon Parameter Mapping Sonification

PSyBench Physically Synchronized Bench

PWM Pulse Width Modulation

RATI Remote Active Tangible Interactions

RBI Reality-based Interaction

RFID Radio Frequency Identification

RMS Root Mean Square

ROS Robot Operating System

RSB Robotic Service Bus

SETO SuperCollider Environment for Tangible Objects

SOM Self-organizing Map

SRI Stanford Research Institute

SRM Saving and Restoring Mechanism

StPr Student Project

SUS System Usability Scale

TAO Tangible Active Object

tDesk Tangible Desk

TEI International Conference on Tangible, Embedded and Embodied Interaction

TDI Tangible Desk Interaction

TDS Tangible Data Scanning

TI-Son Tangible Interactive Sonification

TRecS Tangible Reconfigurable System

TTS Text-To-Speech

TUI Tangible User Interface

TUIML Tangible User Interface Modeling Language

TUIMS Tangible User Interface Management System

TUIO Tangible User Interface Object

UI User Interface

UIDL User Interface Description Language

UPM Universal Planar Manipulator

UPnP Universal Plug and Play

VoIP Voice over IP

WIMP Windows, Icons, Menus, Pointer

WP Work Package

XCF XML enabled Communication Framework

XML Extensible Markup Language

XMPP Extensible Messaging and Presence Protocol

List of Figures

List of Tables

References

[1] Alon, J., Athitsos, V., Yuan, Q., and Sclaroff, S. “A unified framework for gesture recognition and spatiotemporal gesture segmentation.” In: *IEEE transactions on pattern analysis and machine intelligence* 31.9 (Sept. 2009), pp. 1685–99. ISSN: 0162-8828. DOI: 10.1109/TPAMI.2008.203.

[2] Angelini, L., Lalanne, D., Hoven, E., Khaled, O., and Mugellini, E. “Move, Hold and Touch: A Framework for Tangible Gesture Interactive Systems”. In: *Machines* 3.3 (Aug. 2015), pp. 173–207. ISSN: 2075-1702. DOI: 10.3390/machines3030173.

[3] Annett, M. and Grossman, T. “Medusa: a proximity-aware multi-touch tabletop”. In: *Proceedings of the 24th annual ACM symposium on User interface software and technology*. Oct. 2011, pp. 337–346. ISBN: 9781450307161. DOI: 10.1145/2047196.2047240.

[4] Anthony, L. and Wobbrock, J. O. “A Lightweight Multistroke Recognizer for User Interface Prototypes”. In: *Proceedings of Graphics Interface 2010*. GI ’10. Ottawa, Ontario, Canada: Canadian Information Processing Society, May 2010, pp. 245–252. ISBN: 978-1-56881-712-5.

[5] Antle, A. N. “The CTI framework: Informing the Design of Tangible Systems for Children”. In: *Proceedings of the 1st international conference on Tangible and embedded interaction - TEI ’07*. New York, New York, USA: ACM Press, Feb. 2007, p. 195. ISBN: 9781595936196. DOI: 10.1145/1226969.1227010.

[6] Bader, P., Schwind, V., Pohl, N., Henze, N., Wolf, K., Schneegass, S., and Schmidt, A. “Self-Actuated Displays for Vertical Surfaces”. In: *Human-Computer Interaction – INTERACT 2015*. Ed. by Abascal, J., Barbosa, S., Fetter, M., Gross, T., Palanque, P., and Winckler, M. Vol. 9299. Lecture Notes in Computer Science. Cham: Springer International Publishing, Aug. 2015, pp. 282–299. ISBN: 978-3-319-22722-1. DOI: 10.1007/978-3-319-22723-8.

[7] Ballagas, R., Ringel, M., Stone, M., and Borchers, J. “iStuff: a physical user interface toolkit for ubiquitous computing environments”. In: *Proceedings of the conference on Human factors in computing systems - CHI ’03*. New York, New York, USA: ACM Press, Apr. 2003, p. 537. ISBN: 1581136307. DOI: 10.1145/642611.642705.

[8] Banzi, M. *Getting Started with Arduino*. Make Books - Imprint of: O’Reilly Media, Oct. 2008. ISBN: 0596155514, 9780596155513.

[9] Bates, S. and Cozby, P. *Methods in Behavioral Research*. 11th Edition. McGraw-Hill Education, 2012. ISBN: 0077861892.

[10] Bellotti, V., Back, M., Edwards, W. K., Grinter, R. E., Henderson, A., and Lopes, C. "Making Sense of Sensing Systems: Five Questions for Designers and Researchers". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '02. Minneapolis, Minnesota, USA: ACM, Apr. 2002, pp. 415–422. ISBN: 1-58113-453-3. DOI: 10.1145/503376.503450.

[11] Bencina, R., Kaltenbrunner, M., and Jorda, S. "Improved Topological Fiducial Tracking in the reacTIVision System". In: *Computer Vision and Pattern Recognition - Workshops, 2005. CVPR Workshops. IEEE Computer Society Conference on*. Vol. 3. Ieee, June 2005, pp. 99–99. ISBN: 0-7695-2372-2. DOI: 10.1109/CVPR.2005.475.

[12] Benford, S., Schnädelbach, H., Koleva, B., Anastasi, R., Greenhalgh, C., Rodden, T., Green, J., Ghali, A., Pridmore, T., Gaver, B., Boucher, A., Walker, B., Pennington, S., Schmidt, A., Gellersen, H., and Steed, A. "Expected, Sensed, and Desired: A Framework for Designing Sensing-based Interaction". In: *ACM Trans. Comput.-Hum. Interact.* 12.1 (Mar. 2005), pp. 3–30. ISSN: 1073-0516. DOI: 10.1145/1057237.1057239.

[13] Bianchi, A., Oakley, I., Lee, J. K., Kwon, D. S., and Kostakos, V. "Haptics for Tangible Interaction: A Vibro-tactile Prototype". In: *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '11. Funchal, Portugal: ACM, Jan. 2011, pp. 283–284. ISBN: 978-1-4503-0478-8. DOI: 10.1145/1935701.1935764.

[14] Biocca, F, Harms, C, and Gregg, J. "The Networked Minds Measure of Social Presence: Pilot Test of the Factor Structure and Concurrent Validity". In: *4th annual International Workshop on Presence*. Philadelphia, PA, May 2001.

[15] Bishop, C. M. *Neural networks for pattern recognition*. Oxford, UK: Clarendon Press, 1995. ISBN: 0 19 853864 2.

[16] Bovermann, T. "Tangible Auditory Interfaces". PhD thesis. Bielefeld University, Dec. 2009, p. 214.

[17] Bovermann, T. and Hermann, T. "A Tangible Environment for Ambient Data Representation". In: *First International Workshop on Haptic and Audio Interaction Design*. Glasgow, U.K., Aug. 2006, pp. 26–30.

[18] Bovermann, T., Hermann, T., and Ritter, H. "AudioDB: Get in Touch with Sounds". In: *Proceedings of the 14th International Conference on Auditory Display*. Ed. by Katz, B. June 2008.

[19] Bovermann, T., Lensch, B., Tünnermann, R., Lensch, J., Hahne, S., Stein, N., and Kuleß a, T. *AudioDome SoundBlox — Tangible Auditory Interfaces.* Apr. 2010. URL: http://tangibleauditoryinterfaces.de/index.php/tai-applications/audiodome-soundblox/.

[20] Bovermann, T., Kõiva, R., Hermann, T., and Ritter, H. "TUImod: Modular objects for tangible user interfaces". In: *Proceedings of the 2008 Conference on Pervasive Computing*. Mar. 2008.

[21] Brave, S., Ishii, H., and Dahley, A. "Tangible interfaces for remote collaboration and communication". In: *Proceedings of the 1998 ACM conference on Computer supported cooperative work*. New York, New York, USA: ACM, Nov. 1998, pp. 169–178. ISBN: 1581130090. DOI: 10.1145/289444.289491.

[22] Breazeal, C. "Toward sociable robots". In: *Robotics and Autonomous Systems* 42.3-4 (Mar. 2003), pp. 167–175. ISSN: 09218890. DOI: 10.1016/S0921-8890(02)00373-1.

[23] Brooke, J. "SUS-A quick and dirty usability scale". In: *Usability Evaluation In Industry*. Ed. by Jordan, P. W., Thomas, B., Weerdmeerster, B. A., and McClelland, I. L. 1996. ISBN: 0748404600.

[24] Bullock, I. M. and Dollar, A. M. "Classifying human manipulation behavior". In: *IEEE International Conference on Rehabilitation Robotics* (Jan. 2011). ISSN: 1945-7901. DOI: 10.1109/ICORR.2011.5975408.

[25] Buxton, B. "Multi-touch systems that i have known and loved". In: *Microsoft Research* (Jan. 2007).

[26] Buxton, W. and Myers, B. "A Study in Two-handed Input". In: *SIGCHI Bulletin* 17.4 (Apr. 1986), pp. 321–326. ISSN: 0736-6906. DOI: 10.1145/22339.22390.

[27] Buxton, W. "Human-computer Interaction". In: ed. by Preece, J. Upper Saddle River, NJ, USA: Prentice Hall Press, May 1990. Chap. There's More to Interaction Than Meets the Eye: Some Issues in Manual Input, pp. 122–137. ISBN: 0-13-444910-X.

[28] Carvalho, D., Bessa, M., and Magalhães, L. "Different interaction paradigms for different user groups". In: *Proceedings of the XV International Conference on Human Computer Interaction - Interacción '14*. New York, New York, USA: ACM Press, Sept. 2014, pp. 1–6. ISBN: 9781450328807. DOI: 10.1145/2662253.2662293.

[29] Catalá, A., Garcia-Sanjuan, F., Jaen, J., and Mocholi, J. A. "TangiWheel: A Widget for Manipulating Collections on Tabletop Displays Supporting Hybrid Input Modality". In: *Journal of Computer Science and Technology* 27.4 (2012), pp. 811–829. ISSN: 1000-9000. DOI: 10.1007/s11390-012-1266-4.

[30] Couture, N., Rivière, G., and Reuter, P. "GeoTUI: a tangible user interface for geoscience". In: *Proceedings of the 2nd international conference on Tangible and embedded interaction*. New York, New York, USA: ACM, Feb. 2008, pp. 89–96. ISBN: 9781605580043. DOI: 10.1145/1347390.1347411.

[31] Cruz-Neira, C., Sandin, D. J., and DeFanti, T. A. "Surround-Screen Projection-Based Virtual Realityy: The Design and Implementation of the CAVE". In: *Proceedings of the 20th annual conference on Computer graphics and interactive techniques - SIGGRAPH '93*. New York, New York, USA: ACM Press, Sept. 1993, pp. 135–142. ISBN: 0897916018. DOI: 10.1145/166117.166134.

[32] Dawin, J. J. R., Hartwig, D., Kudenko, A., and Riedenklau, E. *TRecS: Ein tangibles, rekonfigurierbares System zur explorativen Datenanalyse*. Tech. rep. Bielefeld: Bielefeld University, Faculty of Technology, 2007.

[33] Dourish, P. *Where the action is: the foundations of embodied interaction*. MIT Press, 2004. ISBN: 9780262254151.

[34] Edge, D. and Blackwell, A. F. "Peripheral Tangible Interaction by Analytic Design". In: *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction*. TEI '09. Cambridge, United Kingdom: ACM, Feb. 2009, pp. 69–76. ISBN: 978-1-60558-493-5. DOI: 10.1145/1517664.1517687.

[35] Edge, D. and Blackwell, A. "Correlates of the cognitive dimensions for tangible user interface". In: *Journal of Visual Languages & Computing* 17.4 (Aug. 2006), pp. 366–394. ISSN: 1045926X. DOI: 10.1016/j.jvlc.2006.04.005.

[36] Erp, J. B. van, Willemse, C. J., Janssen, J. B., and Toet, A. "Sensators: active multisensory tangible user interfaces". In: Lecture notes in computer science 8619 (June 2014), pp. 485–487.

[37] Erp, J. B. van, Toet, A., Meijer, K., Janssen, J., and Jong, A. de. "Subjective User Experience and Performance with Active Tangibles on a Tabletop Interface". In: *Distributed, Ambient, and Pervasive Interactions*. Ed. by Streitz, N. and Markopoulos, P. Vol. 9189. Lecture Notes in Computer Science. Cham: Springer International Publishing, July 2015, pp. 212–223. ISBN: 978-3-319-20803-9. DOI: 10.1007/978-3-319-20804-6.

[38] Erp, J. B. van, Toet, A., and Janssen, J. B. "Uni-, bi- and tri-modal warning signals: Effects of temporal parameters and sensory modality on perceived urgency". In: *Safety Science* 72 (Feb. 2015), pp. 1–8. ISSN: 09257535. DOI: 10.1016/j.ssci.2014.07.022.

[39] Faul, F., Erdfelder, E., Buchner, A., and Lang, A.-G. "Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses." In: *Behavior research methods* 41.4 (Nov. 2009), pp. 1149–60. ISSN: 1554-3528. DOI: 10.3758/BRM.41.4.1149.

[40] Fernaeus, Y., Tholander, J., and Jonsson, M. "Beyond representations: Towards an action-centric perspective on tangible interaction". In: *International Journal of Arts and Technology* 1.3/4 (2008), pp. 249–267. DOI: 10.1504/IJART.2008.022362.

[41] Ferscha, A., Vogl, S., Emsenhuber, B., and Wally, B. "Physical shortcuts for media remote controls". In: *Proceedings of the 2nd international conference on INtelligent TEchnologies for interactive enterTAINment*. Jan. 2008, p. 9. ISBN: 978-963-9799-13-4.

[42] Fiala, M. "ARTag, a Fiducial Marker System Using Digital Techniques". In: *IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR'05)*. Vol. 2. IEEE, June 2005, pp. 590–596. ISBN: 0-7695-2372-2. DOI: 10.1109/CVPR.2005.74.

[43] Fishkin, K. K. "A taxonomy for and analysis of tangible interfaces". In: *Personal and Ubiquitous Computing* 8.5 (July 2004). ISSN: 1617-4909. DOI: 10.1007/s00779-004-0297-4.

[44] Fitts, P. M. "The information capacity of the human motor system in controlling the amplitude of movement." In: *Journal of Experimental Psychology* 47 (Sept. 1954), pp. 381–391. ISSN: 1939-2222. DOI: 10.1037/0096-3445.121.3.262.

[45] Fitzmaurice, G. W. "Graspable User Interfaces". PhD thesis. 1996. ISBN: 0-612-18871-X.

[46] Fitzmaurice, G. W. and Buxton, W. "An Empirical Evaluation of Graspable User Interfaces: towards specialized, space-multiplexed input". In: *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems*. ACM New York, NY, USA, Mar. 1997, pp. 43–50. ISBN: 0-89791-802-9. DOI: 10.1145/258549.258578.

[47] Fitzmaurice, G. W., Ishii, H., and Buxton, W. A. S. "Bricks: Laying the Foundations for Graspable User Interfaces". In: *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI '95*. New York, New York, USA: ACM Press, May 1995, pp. 442–449. ISBN: 0201847051. DOI: 10.1145/223904.223964.

[48] Flash, T and Hogan, N. "The coordination of arm movements: an experimentally confirmed mathematical model". In: *Journal of Neuroscience* 5.7 (July 1985), pp. 1688–1703. ISSN: 1529-2401.

[49] Fong, T, Nourbakhsh, I., and Dautenhahn, K. "A survey of socially interactive robots". In: *Robotics and autonomous systems* 42.3-4 (Mar. 2003), pp. 143–166. ISSN: 0921-8890. DOI: 10.1016/S0921-8890(02)00372-X.

[50] Freeman, D. and Benko, H. "ShadowGuides: Visualizations for In-Situ Learning of Multi-Touch and Whole-Hand Gestures". In: *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces*. ACM New York, NY, USA, Nov. 2009, pp. 165–172. ISBN: 9781605587332. DOI: 10.1145/1731903.1731935.

[51] Fritsch, J. and Wrede, S. "An Integration Framework for Developing Interactive Robots". In: *Springer Tracts in Advanced Robotics*. Ed. by Brugali, D. Vol. 30. Springer Tracts in Advanced Robotics. Berlin, Heidelberg: Springer Berlin Heidelberg, 2007, pp. 291–305. ISBN: 978-3-540-68949-2. DOI: 10.1007/978-3-540-68951-5.

[52] Furuhira, A., Marais, W., and Thomas, B. "Supporting remote tangible robotic entertainment". In: *Proceedings of the 2008 International Conference in Advances on Computer Entertainment Technology - ACE '08*. New York, New York, USA: ACM Press, Dec. 2008, p. 412. ISBN: 9781605583938. DOI: 10.1145/1501750.1501862.

[53] Gehring, T. M. and Wyler, I. L. "Family-system-test (FAST): A three dimensional approach to investigate family relationships". In: *Child Psychiatry & Human Development* 16.4 (June 1986), pp. 235–248. ISSN: 0009-398X. DOI: 10.1007/BF00706480.

[54] Gelineck, S, Overholt, D, Büchert, M, and Andersen, J. "Towards an Interface for Music Mixing based on Smart Tangibles and Multitouch". In: *Proceedings of the 13th International Conference on New Interfaces for Musical Expression*. Daejeon, Korea, May 2013.

[55] Gerkey, B, Vaughan, R., and Howard, A. "The Player/Stage Project: Tools for Multi-Robot and Distributed Sensor Systems". In: *Proceedings of the International Conference on Advanced Robotics (ICAR 2003)*. June 2003.

[56] Goldin-Meadow, S. *Hearing gesture: How our hands help us think*. Harvard University Press, Oct. 2005. ISBN: 0674018370.

[57] Greenberg, S. and Fitchett, C. "Phidgets: easy development of physical interfaces through physical widgets". In: *Proceedings of the 14th annual ACM symposium on User interface software and technology - UIST '01*. New York, New York, USA: ACM Press, Nov. 2001, p. 209. ISBN: 158113438X. DOI: 10.1145/502348.502388.

[58] Guerra, P. "RemoteBunnies: Multi-agent Phenomena Mapping Between Physical Environments". In: *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction*. TEI '13. Barcelona, Spain: ACM, Feb. 2013, pp. 347–348. ISBN: 978-1-4503-1898-3. DOI: 10.1145/2460625.2460687.

[59] Guiard, Y. "Asymmetric division of labor in human skilled bimanual action: The kinematic chain as a model". In: *Journal of Motor Behavior* (Feb. 1987). DOI: 10.1080/00222895.1987.10735426.

[60] Hall, E. T. *The hidden dimension*. 1969.

[61] Hall, K. *Smart Stool robot listens to you babble and then tells rest of the room — DVICE*. 2007. URL: http://www.dvice.com/archives/2007/10/smart-stool-robot-listens-to-y.php.

[62] Han, J. Y. "Low-cost multi-touch sensing through frustrated total internal reflection". In: *Proceedings of the 18th annual ACM symposium on User interface software and technology - UIST '05*. UIST '05. New York, New York, USA: ACM Press, Oct. 2005, pp. 115–118. ISBN: 1595932712. DOI: 10.1145/1095034.1095054.

[63] Hartmann, B., Klemmer, S. R., Bernstein, M., Abdulla, L., Burr, B., Robinson-Mosher, A., and Gee, J. "Reflective physical prototyping through integrated design, test, and analysis". In: *Proceedings of the 19th annual ACM symposium on User interface software and technology - UIST '06*. New York, New York, USA: ACM Press, Oct. 2006, p. 299. ISBN: 1595933131. DOI: 10.1145/1166253.1166300.

[64] Hauber, J, Regenbrecht, H, and Hills, A. "Social presence in two-and three-dimensional videoconferencing". In: *8th Annual International Workshop on Presence*. 2005, pp. 189–198. DOI: 10.1234/12345678.

[65] He, X., Yung, N. N. H. C., and Chen He, X. "Corner detector based on global and local curvature properties". In: *Optical Engineering* 47.5 (May 2008), p. 057008. ISSN: 00913286. DOI: 10.1117/1.2931681.

[66] Hermann, T., Bovermann, T., Riedenklau, E., and Ritter, H. "Tangible computing for interactive sonification of multivariate data". In: *Proceedings of the 2nd Interactive Sonification Workshop*. 2007.

[67] Hermann, T. "Sonification for Exploratory Data Analysis". PhD thesis. Bielefeld University, Feb. 2002.

[68] Hermann, T., Henning, T., Ritter, H., Camurri, A., and Volpe, G. "Gesture Desk–An Integrated Multi-modal Gestural Workplace for Sonification". In: *Gesture-Based Communication in Human-Computer Interaction*. Ed. by Camurri, A. and Volpe, G. Vol. 2915. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer Berlin Heidelberg, Apr. 2004, pp. 103–104. ISBN: 978-3-540-21072-6. DOI: 10.1007/978-3-540-24598-8_34.

[69] Hermann, T., Hunt, A., and Neuhoff, J. G., eds. *The Sonification Handbook*. Berlin, Germany: Logos Verlag Berlin GmbH, 2011. ISBN: 978-3-8325-2819-5.

[70] Hinckley, K., Pausch, R., Goble, J. C., and Kassell, N. F. "A survey of design issues in spatial input". In: *Proceedings of the 7th annual ACM symposium on User interface software and technology - UIST '94*. New York, New York, USA: ACM Press, Nov. 1994, pp. 213–222. ISBN: 0897916573. DOI: 10.1145/192426.192501.

[71] Hindmarsh, J. and Heath, C. "Embodied reference: A study of deixis in workplace interaction". In: *Journal of Pragmatics* 32.12 (Nov. 2000), pp. 1855–1878. ISSN: 03782166. DOI: 10.1016/S0378-2166(99)00122-8.

[72] Holmes, N. P. and Spence, C. "The body schema and the multisensory representation(s) of peripersonal space." In: *Cognitive processing* 5.2 (June 2004), pp. 94–105. ISSN: 1612-4782. DOI: 10.1007/s10339-004-0013-3.

[73] Holmquist, L., Redström, J., and Ljungstrand, P. "Token-Based Access to Digital Information". In: *Handheld and Ubiquitous Computing*. Ed. by Gellersen, H.-W. Vol. 1707. Lecture Notes in Computer Science. Springer Berlin Heidelberg, Nov. 1999, pp. 234–245. ISBN: 978-3-540-66550-2. DOI: 10.1007/3-540-48157-5_22.

[74] Hoon, M. J. L. de, Imoto, S, Nolan, J, and Miyano, S. "Open source clustering software." In: *Bioinformatics (Oxford, England)* 20.9 (June 2004), pp. 1453–4. ISSN: 1367-4803. DOI: 10.1093/bioinformatics/bth078.

[75] Horn, M. S., Solovey, E. T., Crouser, R. J., and Jacob, R. J. "Comparing the use of tangible and graphical programming languages for informal science education". In: *Proceedings of the 27th international conference on Human factors in computing systems - CHI 09*. New York, New York, USA: ACM Press, Apr. 2009, p. 975. ISBN: 9781605582467. DOI: 10.1145/1518701.1518851.

[76] Hornecker, E. and Buur, J. "Getting a Grip on Tangible Interaction: A Framework on Physical Space and Social Interaction". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '06. Montréal, Québec, Canada: ACM, Apr. 2006, pp. 437–446. ISBN: 1-59593-372-7. DOI: 10.1145/1124772.1124838.

[77] Hornecker, E., Marshall, P., Dalton, N. S., and Rogers, Y. "Collaboration and Interference: Awareness with Mice or Touch Input". In: *Proceedings of the ACM 2008 conference on Computer supported cooperative work - CSCW '08*. New York, New York, USA: ACM Press, Nov. 2008, p. 167. ISBN: 9781605580074. DOI: 10.1145/1460563.1460589.

[78] Hoshi, T., Takahashi, M., Nakatsuma, K., and Shinoda, H. "Touchable holography". In: *ACM SIGGRAPH 2009 Emerging Technologies on - SIGGRAPH '09*. New York, New York, USA: ACM Press, Aug. 2009, pp. 1–1. ISBN: 9781605588339. DOI: 10.1145/1597956.1597979.

[79] Hoven, E. van den and Eggen, B. "Tangible Computing in Everyday Life: Extending Current Frameworks for Tangible User Interfaces with Personal Objects". In: *Ambient Intelligence*. Ed. by Markopoulos, P., Eggen, B., Aarts, E., and Crowley, J. Vol. 3295. Lecture Notes in Computer Science. Springer Berlin Heidelberg, 2004, pp. 230–242. ISBN: 978-3-540-23721-1. DOI: 10.1007/978-3-540-30473-9_22.

[80] Hoven, E. van den and Mazalek, A. "Grasping gestures: Gesturing with physical artifacts". In: *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* 25 (Special Issue 03 Aug. 2011), pp. 255–271. ISSN: 1469-1760. DOI: 10.1017/S0890060411000072.

[81] Igoe, T. *Making Things Talk: Practical Methods for Connecting Physical Objects*. O'Reilly Media, Sept. 2007. ISBN: 9780596510510.

[82] Ishii, H. and Ullmer, B. A. "Tangible bits: towards seamless interfaces between people, bits and atoms". In: *Proceedings of the SIGCHI conference on Human factors in computing systems*. New York, New York, USA: ACM, Mar. 1997, pp. 234–241. ISBN: 0897918029. DOI: 10.1145/258549.258715.

[83] Jacob, R. J. K. and Sibert, L. E. "The Perceptual Structure of Multidimensional Input Device Selection". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '92. Monterey, California, USA: ACM, June 1992, pp. 211–218. ISBN: 0-89791-513-5. DOI: 10.1145/142750.142792.

[84] Jacob, R. J. K., Ishii, H., Pangaro, G., and Patten, J. "A Tangible Interface for Organizing Information Using a Grid". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '02. Minneapolis, Minnesota, USA: ACM, Apr. 2002, pp. 339–346. ISBN: 1-58113-453-3. DOI: 10.1145/503376.503437.

[85] Jacob, R. J., Girouard, A., Hirshfield, L. M., Horn, M. S., Shaer, O., Solovey, E. T., and Zigelbaum, J. "Reality-based Interaction: A Framework for post-WIMP Interfaces". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '08. Florence, Italy: ACM, Apr. 2008, pp. 201–210. ISBN: 978-1-60558-011-1. DOI: 10.1145/1357054.1357089.

[86] Jarvis, R. A. "On the identification of the convex hull of a finite set of points in the plane". In: *Information Processing Letters* 2.1 (Mar. 1973), pp. 18–21. ISSN: 00200190. DOI: 10.1016/0020-0190(73)90020-3.

[87] Johnson, M. P., Wilson, A., Blumberg, B., Kline, C., and Bobick, A. "Sympathetic Interfaces: Using a Plush Toy to Direct Synthetic Characters". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '99. Pittsburgh, Pennsylvania, USA: ACM, May 1999, pp. 152–158. ISBN: 0-201-48559-1. DOI: 10.1145/302979.303028.

[88] Jordá, S. "On stage: the reactable and other musical tangibles go real". In: *International Journal of Arts and Technology* (2008), 268–287. DOI: 10.1504/IJART.2008.022363.

[89] Jordà, S., Geiger, G., Alonso, M., and Kaltenbrunner, M. "The reacTablee: Exploring the Synergy between Live Music Performance and Tabletop Tangible Interfaces". In: *Proceedings of the 1st international conference on Tangible and embedded interaction - TEI '07*. New York, New York, USA: ACM Press, Feb. 2007, p. 139. ISBN: 9781595936196. DOI: 10.1145/1226969.1226998.

[90] Kaltenbrunner, M. and Bencina, R. "reacTIVision: a computer-vision framework for table-based tangible interaction". In: *Proceedings of the 1st international conference on Tangible and embedded interaction - TEI '07*. New York, New York, USA: ACM Press, Feb. 2007, p. 69. ISBN: 9781595936196. DOI: 10.1145/1226969.1226983.

[91] Kaltenbrunner, M., Bovermann, T., Bencina, R., and Costanza, E. "TUIO: A protocol for table-top tangible user interfaces". In: *Proceedings of the The 6th International Workshop on Gesture in Human-Computer Interaction and Simulation*. May 2005.

[92] Kato, H. and Billinghurst, M. "Marker Tracking and HMD Calibration for a Video-Based Augmented Reality Conferencing System". In: (Oct. 1999), p. 85. DOI: 10.1109/IWAR.1999.803809.

[93] Kendon, A. *Conducting Interaction: Patterns of behavior in focused encounters*. 1990. ISBN: 0521389380.

[94] Kenny, D. A. and Kashy, D. A. "Enhanced co-orientation in the perception of friends: A social relations analysis." In: *Journal of Personality and Social Psychology* 67.6 (Dec. 1994), pp. 1024–1033. ISSN: 1939-1315. DOI: 10.1037/0022-3514.67.6.1024.

[95] Kettler, A., Szymanski, M., Liedke, J., and Wörn, H. "Introducing Wanda-A new robot for research, education, and Arts". In: *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. Oct. 2010, pp. 4181 –4186. ISBN: 978-1-4244-6674-0. DOI: 10.1109/IROS.2010.5649564.

[96] Khandkar, S. H. and Maurer, F. "A Domain Specific Language to Define Gestures for Multi-touch Applications". In: *Proceedings of the 10th Workshop on Domain-Specific Modeling*. DSM '10. Reno, Nevada: ACM, Oct. 2010, 2:1–2:6. ISBN: 978-1-4503-0549-5. DOI: 10.1145/2060329.2060339.

[97] Kienzl, T., Marsche, U., Kapeller, N., and Gokcezade, A. "tangible workbench "TW": with changeable markers". In: *ACM SIGGRAPH 2008 new tech demos on - SIGGRAPH '08*. New York, New York, USA: ACM Press, Aug. 2008, pp. 1–1. DOI: 10.1145/1401615.1401652.

[98] Kim, M. J. and Maher, M. L. "The impact of tangible user interfaces on spatial cognition during collaborative design". In: *Design Studies* 29.3 (May 2008), pp. 222–253. ISSN: 0142694X. DOI: 10.1016/j.destud.2007.12.006.

[99] Kimura, H., Okuda, Y., and Nakajima, T. "CookieFlavors: Rapid Composition Framework for Tangible Media". In: *Proceedings of the The 2007 International Conference on Next Generation Mobile Applications, Services and Technologies*. IEEE Computer Society, Sept. 2007, pp. 100–109. ISBN: 0-7695-2878-3.

[100] King, J., Bose, R., Yang, H.-I., Pickles, S., and Helal, A. "Atlas: A service-oriented sensor platform: Hardware and middleware to enable programmable pervasive spaces". In: *31st IEEE Conference on Local Computer Networks, Proceedings*. Nov. 2006, pp. 630 –638. ISBN: 1-4244-0418-5. DOI: 10.1109/LCN.2006.322026.

[101] Kirk, D., Izadi, S., Hilliges, O., Banks, R., Taylor, S., and Sellen, A. "At home with surface computing?" In: *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI '12*. New York, New York, USA: ACM Press, May 2012, p. 159. ISBN: 9781450310154. DOI: 10.1145/2207676.2207699.

[102] Kirk, D., Sellen, A., Taylor, S., Villar, N., and Izadi, S. "Putting the Physical into the Digital: Issues in Designing Hybrid Interactive Surfaces". In: *Proceedings of the 23rd British HCI Group Annual Conference on People and Computers: Celebrating People and Technology*. BCS-HCI '09. Cambridge, United Kingdom: British Computer Society, Sept. 2009, pp. 35–44.

[103] Kirsh, D. "On distinguishing epistemic from pragmatic action". In: *Cognitive Science* 18.4 (Dec. 1994), pp. 513–549. ISSN: 03640213. DOI: 10.1016/0364-0213(94)90007-8.

[104] Klemmer, S. R. S., Li, J., Lin, J., and Landay, J. A. "Papier-Mâché: Toolkit Support for Tangible Input". In: *Proceedings of the 2004 conference on Human factors in computing systems - CHI '04*. New York, New York, USA: ACM Press, Apr. 2004, pp. 399–406. ISBN: 1581137028. DOI: 10.1145/985692.985743.

[105] Klemmer, S. R., Hartmann, B., and Takayama, L. "How Bodies Matter: Five Themes for Interaction Design". In: *Proceedings of the 6th ACM conference on Designing Interactive systems - DIS '06*. New York, New York, USA: ACM Press, June 2006, p. 140. ISBN: 1595933670. DOI: 10.1145/1142405.1142429.

[106] Kline, R. B. *Becoming a behavioral science researcher: A guide to producing research that matters*. 2008. ISBN: 1606235966.

[107] Klinkhammer, D., Nitsche, M., Specht, M., and Reiterer, H. "Adaptive personal territories for co-located tabletop interaction in a museum setting". In: *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces - ITS '11*. New York, New York, USA: ACM Press, Nov. 2011, p. 107. ISBN: 9781450308717. DOI: 10.1145/2076354.2076375.

[108] Klompmaker, F., Nebe, K., and Fast, A. "dSensingNI: A Framework for Advanced Tangible Interaction Using a Depth Camera". In: *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction*. TEI '12. Kingston, Ontario, Canada: ACM, Feb. 2012, pp. 217–224. ISBN: 978-1-4503-1174-8. DOI: 10.1145/2148131.2148179.

[109] Kojima, M., Sugimoto, M., Nakamura, A., Tomita, M., Inami, M., and Nii, H. "Augmented Coliseum: An Augmented Game Environment with Small Vehicles". In: *First IEEE International Workshop on Horizontal Interactive Human-Computer Systems (TABLETOP '06)*. IEEE, Jan. 2006, pp. 3–8. ISBN: 0-7695-2494-X. DOI: 10.1109/TABLETOP.2006.3.

[110] Koleva, B, Benford, S, Ng, K., and Rodden, T. "A Framework for Tangible User Interfaces". In: *Physical Interaction (PI03), Workshop on Real World User Interfaces, Mobile HCI Conf.* Udine, Italy, Sept. 2003.

[111] Kornienko, S. U. o. S., Szymanski, M. U. o. K., and Estane, R. U. o. K. *Swarmrobot - Open-source micro-robotic project*. URL: http://www.swarmrobot.org/.

[112] Kramer, G., ed. *Auditory Display: Sonification, Audification and Auditory Interfaces*. Boston, MA, USA: Addison-Wesley Longman Publishing Co., Inc., Jan. 2000. ISBN: 0201626039.

[113] Kratz, S. and Rohs, M. "A $3 Gesture Recognizer: Simple Gesture Recognition for Devices Equipped with 3D Acceleration Sensors". In: *Proceedings of the 15th International Conference on Intelligent User Interfaces*. IUI '10. Hong Kong, China: ACM, Feb. 2010, pp. 341–344. ISBN: 978-1-60558-515-4. DOI: 10.1145/1719970.1720026.

[114] Kratz, S. and Rohs, M. "Protractor3D: A Closed-form Solution to Rotation-invariant 3D Gestures". In: *Proceedings of the 16th International Conference on Intelligent User Interfaces*. IUI '11. Palo Alto, CA, USA: ACM, Feb. 2011, pp. 371–374. ISBN: 978-1-4503-0419-1. DOI: 10.1145/1943403.1943468.

[115] Krzywinski, A., Mi, H., Chen, W., and Sugimoto, M. "RoboTable: a tabletop framework for tangible interaction with robots in a mixed reality". In: *Proceedings of the International Conference on Advances in Computer Enterntainment Technology - ACE '09*. New York, New York, USA: ACM, Oct. 2009, pp. 107–114. ISBN: 9781605588643. DOI: 10.1145/1690388.1690407.

[116] Kuhn, H. W. "The Hungarian method for the assignment problem". In: *Naval Research Logistics Quarterly* 2.1-2 (Mar. 1955), pp. 83–97. ISSN: 00281441. DOI: 10.1002/nav.3800020109.

[117] Kumpf, A. "Trackmate: Large-scale accessibility of tangible user interfaces". MA thesis. July 2009.

[118] Kuutti, K. "Activity theory as a potential framework for human-computer interaction research". In: *Context and Consciousness: Activity Theory and Human-Computer Interaction*. Massachusetts Institute of Technology, Dec. 1995, pp. 17–44. ISBN: 0-262-14058-6.

[119] Latombe, J.-C. 1991. ISBN: 0792391292.

[120] Lee, J., Olwal, A., Ishii, H., and Boulanger, C. "SpaceTop: Integrating 2D and Spatial 3D Interactions in a See-through Desktop Environment". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '13*. New York, New York, USA: ACM Press, Apr. 2013, p. 189. ISBN: 9781450318990. DOI: 10.1145/2470654.2470680.

[121] Lee, J. C., Avrahami, D., Hudson, S. E., Forlizzi, J., Dietz, P. H., and Leigh, D. "The calder toolkit: wired and wireless components for rapidly prototyping interactive devices". In: *Proceedings of the 2004 conference on Designing interactive systems processes, practices, methods, and techniques - DIS '04*. New York, New York, USA: ACM Press, Aug. 2004, p. 167. ISBN: 1581137877. DOI: 10.1145/1013115.1013139.

[122] Li, Y. "Protractor: A Fast and Accurate Gesture Recognizer". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '10. Atlanta, Georgia, USA: ACM, Apr. 2010, pp. 2169–2172. ISBN: 978-1-60558-929-9. DOI: 10.1145/1753326.1753654.

[123] Lloyd, D. M. "The space between us: a neurophilosophical framework for the investigation of human interpersonal space." In: *Neuroscience and biobehavioral reviews* 33.3 (Mar. 2009), pp. 297–304. ISSN: 0149-7634. DOI: 10.1016/j.neubiorev.2008.09.007.

[124] López de Ipiña, D., Mendonça, P. R. S., and Hopper, A. "TRIP: A Low-Cost Vision-Based Location System for Ubiquitous Computing". In: *Personal and Ubiquitous Computing* 6.3 (May 2002), pp. 206–219. ISSN: 1617-4909. DOI: 10.1007/s007790200020.

[125] Lü, H. and Li, Y. "Gesture Coder: A Tool for Programming Multi-touch Gestures by Demonstration". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '12. Austin, Texas, USA: ACM, May 2012, pp. 2875–2884. ISBN: 978-1-4503-1015-4. DOI: 10.1145/2207676.2208693.

[126] Lucchi, A., Jermann, P., Zufferey, G., and Dillenbourg, P. "An Empirical Evaluation of Touch and Tangible Interfaces for Tabletop Displays". In: *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '10. Cambridge, Massachusetts, USA: ACM, Jan. 2010, pp. 177–184. ISBN: 978-1-60558-841-4. DOI: 10.1145/1709886.1709917.

[127] MacKenzie, C. L. and Iberall, T. *The Grasping Hand*. Vol. 104. Advances in psychology. Amsterdam, Netherlands, 1994. ISBN: 0080867588.

[128] MacKenzie, I. S. "Fitts' Law as a Research and Design Tool in Human-Computer Interaction". In: *Human-Computer Interaction* 7.1 (Mar. 1992), pp. 91–139. ISSN: 0737-0024. DOI: 10.1207/s15327051hci0701_3.

[129] Madhyastha, T. M. "A Portable System for Data Sonification". MA thesis. Champaign, IL, USA, 1992.

[130] Magerkurth, C., Cheok, A. D., Mandryk, R. L., and Nilsen, T. "Pervasive games". In: *Computers in Entertainment* 3.3 (July 2005), p. 4. ISSN: 15443574. DOI: 10.1145/1077246.1077257.

[131] Maoz, U., Berthoz, A., and Flash, T. "Complex unconstrained three-dimensional hand movement and constant equi-affine speed." In: *Journal of neurophysiology* 101.2 (Feb. 2009), pp. 1002–1015. ISSN: 0022-3077. DOI: 10.1152/jn.90702.2008.

[132] Marco, J., Cerezo, E., and Baldassarri, S. "ToyVision: A Toolkit for Prototyping Tabletop Tangible Games". In: *Proceedings of the 4th ACM SIGCHI Symposium on Engineering Interactive Computing Systems*. EICS '12. Copenhagen, Denmark: ACM, June 2012, pp. 71–80. ISBN: 978-1-4503-1168-7. DOI: 10.1145/2305484.2305498.

[133] Marrin, T. "Possibilities for the Digital Baton As a General-purpose Gestural Interface". In: *CHI '97 Extended Abstracts on Human Factors in Computing Systems*. CHI EA '97. Atlanta, Georgia: ACM, Mar. 1997, pp. 311–312. ISBN: 0-89791-926-2. DOI: 10.1145/1120212.1120409.

[134] Marshall, M., Carter, T., Alexander, J., and Subramanian, S. "Ultra-tangibles: creating movable tangible objects on interactive tables". In: *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI '12*. New York, New York, USA: ACM Press, May 2012, p. 2185. ISBN: 9781450310154. DOI: 10.1145/2207676.2208370.

[135] Martinussen, E. S. and Arnall, T. "Designing with RFID". In: *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction - TEI '09*. New York, New York, USA: ACM Press, Feb. 2009, p. 343. ISBN: 9781605584935. DOI: 10.1145/1517664.1517734.

[136] Maycock, J., Dornbusch, D., Elbrechter, C., Haschke, R., Schack, T., and Ritter, H. "Approaching Manual Intelligence". In: *KI - Künstliche Intelligenz* 24.4 (Aug. 2010), pp. 287–294. ISSN: 0933-1875. DOI: 10.1007/s13218-010-0064-9.

[137] Mazalek, A., Hoven, E. van den, and Hoven, E. "Framing tangible interaction frameworks". In: *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* 23.03 (June 2009). ISSN: 0890-0604. DOI: 10.1017/S0890060409000201.

[138] Mazalek, A., Shaer, O., Ullmer, B. A., and Konkel, M. K. "Tangible Meets Gestural: Gesture Based Interaction with Active Tokens". In: *ACM CHI 2014 Workshop on Gesture-based Interaction Design, ACM CHI*. 2014.

[139] Merrill, D., Sun, E., and Kalanithi, J. "Sifteo Cubes". In: *CHI '12 Extended Abstracts on Human Factors in Computing Systems*. CHI EA '12. Austin, Texas, USA: ACM, May 2012, pp. 1015–1018. ISBN: 978-1-4503-1016-1. DOI: 10.1145/2212776.2212374.

[140] Metz, O., Leichsenring, C., Tünnermann, R., Hermann, T., and Bovermann, T. "Turtledove: a tangible grain interface for image organization". In: *CHI '12 Extended Abstracts on Human Factors in Computing Systems*. ACM New York, NY, USA, May 2012, pp. 1943–1948. ISBN: 978-1-4503-1016-1. DOI: 10.1145/2223656.2223733.

[141] Micire, M., Desai, M., Courtemanche, A., Tsui, K. M., and Yanco, H. A. "Analysis of Natural Gestures for Controlling Robot Teams on Multi-touch Tabletop Surfaces". In: *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces*. ITS '09. Banff, Alberta, Canada: ACM, Nov. 2009, pp. 41–48. ISBN: 978-1-60558-733-2. DOI: 10.1145/1731903.1731912.

[142] Milosevic, B, Farella, E, and Benini, L. "Continuous gesture recognition for resource constrained smart objects". In: *Proceedings of the 4th International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies*. Oct. 2010. ISBN: 978-1-61208-100-7.

[143] Moody, J. and Darken, C. J. "Fast Learning in Networks of Locally-Tuned Processing Units". In: *Neural Computation* 1.2 (June 1989), pp. 281–294. ISSN: 0899-7667. DOI: 10.1162/neco.1989.1.2.281.

[144] Morris, M. R. M., Wobbrock, J. O. J., and Wilson, A. A. D. "Understanding users' preferences for surface gestures". In: *Proceedings of Graphics Interface*. Canadian Information Processing Society Toronto, Canada, May 2010, pp. 261–268. ISBN: 978-1-56881-712-5.

[145] Müller-Tomfelde, C., Inami, M., Sugimoto, M., Thomas, B. H., and Richter, J. "Active Tangible Interactions". In: *Tabletops - Horizontal Interactive Displays*. Ed. by Müller-Tomfelde, C. Human-Computer Interaction Series. London: Springer London, Mar. 2010, pp. 171–187. ISBN: 978-1-84996-112-7. DOI: 10.1007/978-1-84996-113-4.

[146] Napier, J. R. "The prehensile movements of the human hand". In: *Journal of Bone and Joint Surgery* (Nov. 1956).

[147] Nguyen, N. and Wachsmuth, I. "From Body Space to Interaction Space: Modeling Spatial Cooperation for Virtual Humans". In: *The 10th International Conference on Autonomous Agents and Multiagent Systems - Volume 3*. AAMAS '11. Taipei, Taiwan: International Foundation for Autonomous Agents and Multiagent Systems, May 2011, pp. 1047–1054. ISBN: 0-9826571-7-X, 978-0-9826571-7-1.

[148] Norris, S. *RobotStool - Furniture. On-Demand.* 2008. URL: http://www.norrislabs.com/Projects/RoboStool/index.html.

[149] Ó Maidin, D and Fernström, M. "The best of two worlds: Retrieving and browsing". In: *Proceedings of the COST G-6 Conference on Digital Audio Effects (DAFX-00)*. Verona, Italy, Dec. 2000, pp. 131–134.

[150] O'Malley, C and Fraser, D. *Literature review in learning with tangible technologies*. 2004. ISBN: 0-9548594-2-1.

[151] O'Sullivan, D. and Igoe, T. *Physical computing: sensing and controlling the physical world with computers*. Thomson Course Technology PTR, Jan. 2004. ISBN: 159200346X.

[152] Pangaro, G., Maynes-Aminzade, D., and Ishii, H. "The Actuated Workbench: Computer-Controlled Actuation in Tabletop Tangible Interfaces". In: *Proceedings of the 15th annual ACM symposium on User interface software and technology*. New York, New York, USA: ACM, Oct. 2002, pp. 181–190. ISBN: 1581134886. DOI: 10.1145/571985.572011.

[153] Paradiso, J. and Pardue, L. "Electromagnetic tagging for electronic music interfaces". In: *Journal of New Music Research* 32.4 (2003), pp. 395–409. DOI: 10.1076/jnmr.32.4.395.18858.

[154] Patten, J. and Ishii, H. "Mechanical constraints as computational constraints in tabletop tangible interfaces". In: *Proceedings of the SIGCHI conference on Human*. New York, New York, USA: ACM Press, Apr. 2007, p. 809. ISBN: 9781595935939. DOI: 10.1145/1240624.1240746.

[155] Patten, J., Recht, B., and Ishii, H. "Audiopad: A Tag-based Interface for Musical Performance". In: *Proceedings of the 2002 Conference on New Interfaces for Musical Expression*. NIME '02. Dublin, Ireland: National University of Singapore, May 2002, pp. 1–6. ISBN: 1-87465365-8.

[156] Patten, J., Recht, B., and Ishii, H. "Interaction Techniques for Musical Performance with Tabletop Tangible Interfaces". In: *Proceedings of the 2006 ACM SIGCHI International Conference on Advances in Computer Entertainment Technology*. ACE '06. Hollywood, California, USA: ACM, June 2006. ISBN: 1-59593-380-8. DOI: 10.1145/1178823.1178856.

[157] Patten, J., Ishii, H., Hines, J., and Pangaro, G. "Sensetable: A Wireless Object Tracking Platform for Tangible User Interfaces". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '01. Seattle, Washington, USA: ACM, Mar. 2001, pp. 253–260. ISBN: 1-58113-327-8. DOI: 10.1145/365024.365112.

[158] Pedersen, E. W. and Hornbæk, K. "Tangible Bots: Interaction with Active Tangibles in Tabletop Interfaces". In: *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI '11*. New York, New York, USA: ACM Press, May 2011, p. 2975. ISBN: 9781450302289. DOI: 10.1145/1978942.1979384.

[159] Pedersen, E. W. and Hornbæk, K. "mixiTUI: a tangible sequencer for electronic live performances". In: *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction - TEI '09*. New York, New York, USA: ACM Press, Feb. 2009, p. 223. ISBN: 9781605584935. DOI: 10.1145/1517664.1517713.

[160] Piekarski, W. and Thomas, B. H. "Through-Walls Collaboration". In: *IEEE Pervasive Computing* 8.3 (July 2009), pp. 42–49. ISSN: 1536-1268. DOI: 10.1109/MPRV.2009.59.

[161] Previc, F. H. "Functional specialization in the lower and upper visual fields in humans: Its ecological origins and neurophysiological implications". In: *Behavioral and Brain Sciences* 13.3 (1990), pp. 519–542. DOI: 10.1017/S0140525X00080018.

[162] Previc, F. H. "The neuropsychology of 3-D space." In: *Psychological Bulletin* 124 (2 Sept. 1998). DOI: 10.1037/0033-2909.124.2.123.

[163] Quigley, M, Faust, J, Foote, T, and Leibs, J. "ROS: an open-source Robot Operating System". In: *ICRA workshop on open source software* 3.3.2 (May 2009).

[164] Rane, P., Mhatre, V., and Kurup, L. "Study of a Home Robot: JIBO". In: *International Journal of Engineering Research & Technology (IJERT)* 3.10 (Oct. 2014), pp. 490–493. ISSN: 2278-0181.

[165] Rasmussen, M. K., Pedersen, E. W., Petersen, M. G., and Hornbæk, K. "Shape-changing interfaces". In: *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI '12*. New York, New York, USA: ACM Press, May 2012, p. 735. ISBN: 9781450310154. DOI: 10.1145/2207676.2207781.

[166] Richter, J., Thomas, B. B. H., Sugimoto, M., and Inami, M. "Remote active tangible interactions". In: *Proceedings of the 1st international conference on Tangible and embedded interaction*. New York, New York, USA: ACM, Feb. 2007, pp. 39–42. ISBN: 9781595936196. DOI: 10.1145/1226969.1226977.

[167] Riedenklau, E. "TAOs - Tangible Active Objects for table-top interaction". MA thesis. June 2009.

[168] Riedenklau, E, Hermann, T., and Ritter, H. "Tangible Active Objects and interactive sonification as a scatter plot alternative for the visually impaired". In: *Proceedings of the 16th International Conference on Auditory Display*. June 2010. ISBN: 0-9670904-3-1.

[169] Riedenklau, E., Tünnermann, R., Carlmeyer, B., Richter, V., Schöpping, T., Hermann, T., and Ritter, H. "AHEAD: Combining Multi-touch Interaction, Tangible Objects and Robots into a Hybrid Multi-user Interface for Controlling Home Entertainment Systems". unpublished.

[170] Riedenklau, E., Hermann, T., and Ritter, H. "An integrated multi-modal actuated tangible user interface for distributed collaborative planning". In: *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction - TEI '12*. New York, New York, USA: ACM Press, Feb. 2012, p. 169. ISBN: 9781450311748. DOI: 10.1145/2148131.2148167.

[171] Riedenklau, E., Hermann, T., and Ritter, H. "Begreifbare sich bewegende Objekte in Tisch-basierten Interaktionsszenarien Actuated tangible objects in table-top interactions". In: *i-com* (Aug. 2012). Ed. by Hornecker, E., Habakuk Israel, J., Brade, M., and Kammer, D. DOI: 10.1524/icom.2012.0021.

[172] Riedenklau, E., Petker, D., Hermann, T., and Ritter, H. "Embodied Social Networking with Gesture-enabled Tangible Active Objects". In: *Proceedings of 6th International Symposium on Autonomous Minirobots for Research and Edutainment (AMIRE)*. Ed. by Rückert, U., Sitte, J., and Werner, F. May 2011. DOI: 10.1007/978-3-642-27482-4.

[173] Riedenklau, E., Hermann, T., Ritter, H., and Jacko, J. "Saving and restoring mechanisms for tangible user interfaces through tangible active objects". In: *Human-Computer Interaction. Interaction Techniques and Environments*. Ed. by Jacko, J. A. Vol. 6762. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer Berlin Heidelberg, July 2011, pp. 110–118. ISBN: 978-3-642-21604-6. DOI: 10.1007/978-3-642-21605-3.

[174] Rogers, Y. and Muller, H. "A framework for designing sensor-based interactions to promote exploration and reflection in play". In: *International Journal of Human-Computer Studies* 64.1 (Jan. 2006), pp. 1–14. ISSN: 10715819. DOI: 10.1016/j.ijhcs.2005.05.004.

[175] Rosenfeld, D., Zawadzki, M., Sudol, J., and Perlin, K. "Physical objects as bidirectional user interface elements". In: *IEEE Computer Graphics and Applications* 24.1 (Jan. 2004), pp. 44–49. ISSN: 0272-1716. DOI: 10.1109/MCG.2004.1255808.

[176] Rubenstein, M., Ahler, C., and Nagpal, R. "Kilobot: A low cost scalable robot system for collective behaviors". In: *Robotics and Automation (ICRA), 2012 IEEE International Conference on*. 2012, pp. 3293–3298. DOI: 10.1109/ICRA.2012.6224638.

[177] Sacks, H., Schegloff, E. A., and Jefferson, G. "A Simplest Systematics for the Organization of Turn-Taking for Conversation." In: *Language* 50.4 (Dec. 1974), pp. 696–735.

[178] Sapounidis, T. and Demetriadis, S. "Tangible versus graphical user interfaces for robot programming: exploring cross-age children's preferences". In: *Personal and Ubiquitous Computing* (Mar. 2013). ISSN: 1617-4909. DOI: 10.1007/s00779-013-0641-7.

[179] Schack, T. and Ritter, H. "The cognitive nature of action - functional links between cognitive psychology, movement science, and robotics." In: *Progress in brain research* 174 (Jan. 2009), pp. 231–50. ISSN: 1875-7855. DOI: 10.1016/S0079-6123(09)01319-3.

[180] Schlesinger, G. "Der mechanische Aufbau der künstlichen Glieder (the mechanical building of artifical limbs)". In: *Ersatzglieder und Arbeitshilfen für Kriegsbeschadigte und Unfallverletzte*. 1919, pp. 321–699. ISBN: 978-3-662-33009-8.

[181] Scott, S. D., Carpendale, M. S. T., and Inkpen, K. M. "Territoriality in Collaborative Tabletop Workspaces". In: *Proceedings of the 2004 ACM Conference on Computer Supported Cooperative Work*. CSCW '04. Chicago, Illinois, USA: ACM, Nov. 2004, pp. 294–303. ISBN: 1-58113-810-5. DOI: 10.1145/1031607.1031655.

[182] Seifried, T., Haller, M., Scott, S. D. S., Perteneder, F., Rendl, C., Sakamoto, D., and Inami, M. "CRISTAL: a collaborative home media and device controller based on a multi-touch display". In: *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces - ITS '09*. New York, New York, USA: ACM Press, Nov. 2009, p. 33. ISBN: 9781605587332. DOI: 10.1145/1731903.1731911.

[183] Seitz, J. A. "The bodily basis of thought". In: *New Ideas in Psychology* 18.1 (Apr. 2000), pp. 23–40. ISSN: 0732118X. DOI: 10.1016/S0732-118X(99)00035-5.

[184] Severinson-Eklundh, K., Green, A., and Hüttenrauch, H. "Social and collaborative aspects of interaction with a service robot". In: *Robotics and Autonomous Systems* 42.3-4 (Mar. 2003), pp. 223–234. ISSN: 09218890. DOI: 10.1016/S0921-8890(02)00377-9.

[185] Shaer, O. and Hornecker, E. "Tangible User Interfaces: Past, Present, and Future Directions". In: *Foundations and Trends® in Human–Computer Interaction* 3.1-2 (2009), pp. 1–137. ISSN: 1551-3955. DOI: 10.1561/1100000026.

[186] Shaer, O. and Jacob, R. J. "A specification paradigm for the design and implementation of tangible user interfaces". In: *ACM Transactions on Computer-Human Interaction* 16.4 (Nov. 2009), pp. 1–39. ISSN: 10730516. DOI: 10.1145/1614390.1614395.

[187] Shaer, O., Leland, N., Calvillo-Gamez, E., and Jacob, R. "The TAC paradigm: specifying tangible user interfaces". In: *Personal and Ubiquitous Computing* 8.5 (July 2004), pp. 359–369. ISSN: 1617-4909.

[188] Sharlin, E., Watson, B., Kitamura, Y., Kishino, F., and Itoh, Y. "On tangible user interfaces, humans and spatiality". In: *Personal and Ubiquitous Computing* 8.5 (July 2004), pp. 338–346. ISSN: 1617-4909. DOI: 10.1007/s00779-004-0296-5.

[189] Sheridan, J. and Kortuem, G. "Affordance-Based Design of Physical Interfaces for Ubiquitous Environments". In: *Ubiquitous Computing Systems*. Ed. by Youn, H. Y., Kim, M., and Morikawa, H. Vol. 4239. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer Berlin Heidelberg, 2006, pp. 183–199. ISBN: 978-3-540-46287-3. DOI: 10.1007/11890348.

[190] Somanath, S., Sharlin, E., and Sousa, M. C. "Integrating a robot in a tabletop reservoir engineering application". In: *Proceedings of the 8th ACM/IEEE international conference on Human-robot interaction*. IEEE Press Piscataway, NJ, USA, Mar. 2013, pp. 229–230. ISBN: 978-1-4673-3055-8.

[191] Somanath, S., Sharlin, E., and Sousa, M. C. *Spidey: a Robotic Tabletop Assistant*. Tech. rep. c. University of Calgary, Feb. 2012, pp. 1–2.

[192] Taylor, C. L. and Schwarz, R. J. "The anatomy and mechanics of the human hand." In: *Artificial limbs* 2.2 (May 1955), pp. 22–35.

[193] Tuddenham, P., Kirk, D., and Izadi, S. "Graspables Revisited: Multi-touch vs. Tangible Input for Tabletop Displays in Acquisition and Manipulation Tasks". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '10. Atlanta, Georgia, USA: ACM, Apr. 2010, pp. 2223–2232. ISBN: 978-1-60558-929-9. DOI: 10.1145/1753326.1753662.

[194] Ullmer, B. A. and Ishii, H. "Emerging frameworks for tangible user interfaces". In: *IBM Systems Journal* 39.3.4 (Apr. 2001), pp. 915–931. ISSN: 0018-8670. DOI: 10.1147/sj.393.0915.

[195] Ullmer, B. A. and Ishii, H. "The metaDESK: models and prototypes for tangible user interfaces". In: *Proceedings of the 10th annual ACM symposium on User interface software and technology*. ACM New York, NY, USA, Oct. 1997, pp. 223–232. ISBN: 0-89791-881-9. DOI: 10.1145/263407.263551.

[196] Ullmer, B. A. "Tangible interfaces for manipulating aggregates of digital information". PhD thesis. Sept. 2002.

[197] Ullmer, B. A. and Ishii, H. "mediaBlocks: physical containers, transports, and controls for online media". In: *Computer Graphics Proceedings (SIGGRAPH'98)*. 1998.

[198] Ullmer, B. A., Ishii, H., and Jacob, R. J. K. "Token+constraint systems for tangible interaction with digital information". In: *ACM Transactions on Computer-Human Interaction* 12.1 (Mar. 2005), pp. 81–118. ISSN: 10730516. DOI: 10.1145/1057237.1057242.

[199] Underkoffler, J. and Ishii, H. "Urp: A Luminous-tangible Workbench for Urban Planning and Design". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '99. Pittsburgh, Pennsylvania, USA: ACM, May 1999, pp. 386–393. ISBN: 0-201-48559-1. DOI: 10.1145/302979.303114.

[200] Uray, P., Kienzl, D. T., and Marsche, D. U. "MRI: a mixed reality interface for the masses". In: *ACM SIGGRAPH 2006 Emerging technologies on - SIGGRAPH '06*. New York, New York, USA: ACM Press, July 2006, p. 24. ISBN: 1595933646. DOI: 10.1145/1179133.1179158.

[201] Valdes, C., Eastman, D., Grote, C., Thatte, S., Shaer, O., Mazalek, A., Ullmer, B. A., and Konkel, M. K. "Exploring the Design Space of Gestural Interaction with Active Tokens Through User-defined Gestures". In: *Proceedings of the 32Nd Annual ACM Conference on Human Factors in Computing Systems*. CHI '14. Toronto, Ontario, Canada: ACM, Apr. 2014, pp. 4107–4116. ISBN: 978-1-4503-2473-1. DOI: 10.1145/2556288.2557373.

[202] Vaucelle, C. and Ishii, H. "Picture This!: Film Assembly Using Toy Gestures". In: *Proceedings of the 10th International Conference on Ubiquitous Computing*. UbiComp '08. Seoul, Korea: ACM, Sept. 2008, pp. 350–359. ISBN: 978-1-60558-136-1. DOI: 10.1145/1409635.1409683.

[203] Villar, N. and Gellersen, H. "A malleable control structure for softwired user interfaces". In: *Proceedings of the 1st international conference on Tangible and embedded interaction - TEI '07*. New York, New York, USA: ACM Press, Feb. 2007, p. 49. ISBN: 9781595936196. DOI: 10.1145/1226969.1226980.

[204] Vonach, E., Gerstweiler, G., and Kaufmann, H. "ACTO". In: *Proceedings of the Ninth ACM International Conference on Interactive Tabletops and Surfaces - ITS '14*. New York, New York, USA: ACM Press, Nov. 2014, pp. 259–268. ISBN: 9781450325875. DOI: 10.1145/2669485.2669522.

[205] Vyas, D., Poelman, W., Nijholt, A., and De Bruijn, A. "Smart material interfaces: a new form of physical interaction". In: *CHI '12 Extended Abstracts on Human Factors in Computing Systems*. ACM New York, NY, USA, May 2012, pp. 1721–1726. ISBN: 978-1-4503-1016-1. DOI: 10.1145/2223656.2223699.

[206] Wagner, D and Schmalstieg, D. "ARToolKitPlus for Pose Tracking on Mobile Devices". In: *Proceedings of 12th Computer Vision Winter Workshop 2007*. Ed. by Grabner, M. and Grabner, H. Feb. 2007.

[207] Walther-Franks, B., Teichert, J., Krause, M., and Herrlich, M. "User Detection for a Multi-touch Table via Proximity Sensors". In: *Proceedings of the IEEE Tabletops and Interactive Surfaces*. Jan. 2008.

[208] Weiss, M., Schwarz, F., Jakubowski, S., and Borchers, J. "Madgets: Actuated Widgets on Interactive Tabletops". In: *Proceedings of the 23nd annual ACM symposium on User interface software and technology - UIST '10*. New York, New York, USA: ACM Press, Oct. 2010, p. 293. ISBN: 9781450302715. DOI: 10.1145/1866029.1866075.

[209] Weiss, M., Wagner, J., Jansen, Y., Jennings, R., Khoshabeh, R., Hollan, J. D., and Borchers, J. "SLAP Widgets: Bridging the Gap Between Virtual and Physical Controls on Tabletops". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '09. Boston, MA, USA: ACM, Apr. 2009, pp. 481–490. ISBN: 978-1-60558-246-7. DOI: 10.1145/1518701.1518779.

[210] Wensveen, S. A. G., Djajadiningrat, J. P., and Overbeeke, C. J. "Interaction frogger: a design framework to couple action and function through feedback and feedforward". In: *Proceedings of the 2004 conference on Designing interactive systems processes, practices, methods, and techniques - DIS '04*. New York, New York, USA: ACM Press, Aug. 2004, p. 177. ISBN: 1581137877. DOI: 10.1145/1013115.1013140.

[211] Wienke, J. and Wrede, S. "A middleware for collaborative research in experimental robotics". In: *2011 IEEE/SICE International Symposium on System Integration (SII)*. IEEE, Dec. 2011, pp. 1183–1190. ISBN: 978-1-4577-1524-2. DOI: 10.1109/SII.2011.6147617.

[212] Wigdor, D., Penn, G., Ryall, K., Esenther, A., and Shen, C. "Living with a tabletop: Analysis and observations of long term office use of a multi-touch table". In: *Tabletop 2007 - 2nd Annual IEEE International Workshop on Horizontal Interactive Human-Computer Systems*. 2007, pp. 60–67.

[213] Wilson, S., Cottle, D., and Collins, N. *The SuperCollider Book*. The MIT Press, 2011. ISBN: 0262232693, 9780262232692.

[214] Wobbrock, J. O., Wilson, A. D., and Li, Y. "Gestures Without Libraries, Toolkits or Training: A $1 Recognizer for User Interface Prototypes". In: *Proceedings of the 20th Annual ACM Symposium on User Interface Software and Technology*. UIST '07. Newport, Rhode Island, USA: ACM, Oct. 2007, pp. 159–168. ISBN: 978-1-59593-679-0. DOI: 10.1145/1294211.1294238.

[215] Wobbrock, J. O., Aung, H. H., Rothrock, B., and Myers, B. A. "Maximizing the Guessability of Symbolic Input". In: *CHI '05 Extended Abstracts on Human Factors in Computing Systems*. CHI EA '05. Portland, OR, USA: ACM, Apr. 2005, pp. 1869–1872. ISBN: 1-59593-002-7. DOI: 10.1145/1056808.1057043.

[216] Wobbrock, J. O., Morris, M. R., and Wilson, A. D. "User-defined gestures for surface computing". In: *Proceedings of the 27th international conference on Human factors in computing systems - CHI '09*. New York, New York, USA: ACM Press, Apr. 2009, p. 1083. ISBN: 9781605582467. DOI: 10.1145/1518701.1518866.

[217] Wright, M., Freed, A., and Momeni, A. "OpenSound Control: State of the Art 2003". In: *Proceedings of the 2003 Conference on New Interfaces for Musical Expression*. NIME '03. Montreal, Quebec, Canada: National University of Singapore, May 2003, pp. 153–160.

[218] Yu, N.-H., Chan, L.-W., Lau, S. Y., Tsai, S.-S., Hsiao, I.-C., Tsai, D.-J., Hsiao, F.-I., Cheng, L.-P., Chen, M., Huang, P., and Hung, Y.-P. "TUIC: Enabling Tangible Interaction on Capacitive Multi-touch Displays". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '11. Vancouver, BC, Canada: ACM, May 2011, pp. 2995–3004. ISBN: 978-1-4503-0228-9. DOI: 10.1145/1978942.1979386.

[219] Yuan, Y, Liu, Y, and Barner, K. "Tactile gesture recognition for people with disabilities". In: *IEEE International Conference on Acoustics, Speech, and Signal Processing, 2005. Proceedings. (ICASSP '05)*. Mar. 2005, pp. 461–464. ISBN: 0780388747. DOI: 10.1109/ICASSP.2005.1416340.

[220] Zhang, J. "Representations in distributed cognitive tasks". In: *Cognitive Science* 18.1 (Mar. 1994), pp. 87–122. ISSN: 03640213. DOI: 10.1016/0364-0213(94)90021-3.

[221] Zhang, J. "The nature of external representations in problem solving". In: *Cognitive Science* 21.2 (June 1997), pp. 179–217. ISSN: 03640213. DOI: 10.1016/S0364-0213(99)80022-6.

[222] Zuckerman, O., Arida, S., and Resnick, M. "Extending Tangible Interfaces for Education: Digital Montessori-inspired Manipulatives". In: *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI '05*. New York, New York, USA: ACM Press, Apr. 2005, p. 859. ISBN: 1581139985. DOI: 10.1145/1054972.1055093.

Related References by the Author

[32] Dawin, J. J. R., Hartwig, D., Kudenko, A., and Riedenklau, E. *TRecS: Ein tangibles, rekonfigurierbares System zur explorativen Datenanalyse*. Tech. rep. Bielefeld: Bielefeld University, Faculty of Technology, 2007.

[66] Hermann, T., Bovermann, T., Riedenklau, E., and Ritter, H. "Tangible computing for interactive sonification of multivariate data". In: *Proceedings of the 2nd Interactive Sonification Workshop*. 2007.

[167] Riedenklau, E. "TAOs - Tangible Active Objects for table-top interaction". MA thesis. June 2009.

[168] Riedenklau, E, Hermann, T., and Ritter, H. "Tangible Active Objects and interactive sonification as a scatter plot alternative for the visually impaired". In: *Proceedings of the 16th International Conference on Auditory Display*. June 2010. ISBN: 0-9670904-3-1.

[172] Riedenklau, E., Petker, D., Hermann, T., and Ritter, H. "Embodied Social Networking with Gesture-enabled Tangible Active Objects". In: *Proceedings of 6th International Symposium on Autonomous Minirobots for Research and Edutainment (AMIRE)*. ed. by Rückert, U., Sitte, J., and Werner, F. May 2011. DOI: 10.1007/978-3-642-27482-4.

[173] Riedenklau, E., Hermann, T., Ritter, H., and Jacko, J. "Saving and restoring mechanisms for tangible user interfaces through tangible active objects". In: *Human-Computer Interaction. Interaction Techniques and Environments*. Ed. by Jacko, J. A. Vol. 6762. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer Berlin Heidelberg, July 2011, pp. 110–118. ISBN: 978-3-642-21604-6. DOI: 10.1007/978-3-642-21605-3.

[170] Riedenklau, E., Hermann, T., and Ritter, H. "An integrated multi-modal actuated tangible user interface for distributed collaborative planning". In: *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction - TEI '12*. New York, New York, USA: ACM Press, Feb. 2012, p. 169. ISBN: 9781450311748. DOI: 10.1145/2148131.2148167.

[171] Riedenklau, E., Hermann, T., and Ritter, H. "Begreifbare sich bewegende Objekte in Tisch-basierten Interaktionsszenarien Actuated tangible objects in table-top interactions". In: *i-com* (Aug. 2012). Ed. by Hornecker, E., Habakuk Israel, J., Brade, M., and Kammer, D. DOI: 10.1524/icom.2012.0021.

[169] Riedenklau, E., Tünnermann, R., Carlmeyer, B., Richter, V., Schöpping, T., Hermann, T., and Ritter, H. "AHEAD: Combining Multi-touch Interaction, Tangible Objects and Robots into a Hybrid Multi-user Interface for Controlling Home Entertainment Systems". unpublished.