SPHERICAL TANGIBLE USER INTERFACES IN MIXED REALITY

DISSERTATION

an der Fakultät für Mathematik, Informatik und Statistik
der Ludwig-Maximilians-Universität München

vorgelegt von

DAVID ENGLMEIER
M. Sc. Informatik

München, den 04.05.2021

Erstgutachter: Prof. Dr. Andreas Butz
Zweitgutachter: Prof. Dr. Tobias Höllerer
Drittgutachter: Prof. Dr. Dieter Schmalstieg

Tag der mündlichen Prüfung: 07.07.2021

ABSTRACT

The popularity of virtual reality (VR) and augmented reality (AR) has grown rapidly in recent years, both in academia and commercial applications. This is rooted in technological advances and affordable head-mounted displays (HMDs). Whether in games or professional applications, HMDs allow for immersive audio-visual experiences that transport users to compelling digital worlds or convincingly augment the real world.

However, as true to life as these experiences have become in a visual and auditory sense, the question remains how we can model interaction with these virtual environments in an equally natural way. Solutions providing intuitive tangible interaction would bear the potential to fundamentally make the mixed reality (MR) spectrum more accessible, especially for novice users. Research on tangible user interfaces (TUIs) has pursued this goal by coupling virtual to real-world objects. Tangible interaction has been shown to provide significant advantages for numerous use cases. Spherical tangible user interfaces (STUIs) present a special case of these devices, mainly due to their ability to fully embody any spherical virtual content. In general, spherical devices increasingly transition from mere technology demonstrators to usable multi-modal interfaces.

For this dissertation, we explore the application of STUIs in MR environments primarily by comparing them to state-of-the-art input techniques in four different contexts. Thus, investigating the questions of embodiment, overall user performance, and the ability of STUIs relying on their shape alone to support complex interaction techniques.

First, we examine how spherical devices can embody immersive visualizations. In an initial study, we test the practicality of a tracked sphere embodying three kinds of visualizations. We examine simulated multi-touch interaction on a spherical surface and compare two different sphere sizes to VR controllers. Results confirmed our prototype's viability and indicate improved pattern recognition and advantages for the smaller sphere.

Second, to further substantiate VR as a prototyping technology, we demonstrate how a large tangible spherical display can be simulated in VR. We show how VR can fundamentally extend the capabilities of real spherical displays by adding physical rotation to a simulated multi-touch surface. After a first study evaluating the general viability of simulating such a display in VR, our second study revealed the superiority of a rotating spherical display.

Third, we present a concept for a spherical input device for tangible AR (TAR). We show how such a device can provide basic object manipulation capabilities utilizing two different modes and compare it to controller techniques with increasing hardware complexity. Our results show that our button-less sphere-based technique is only outperformed by a mode-less controller variant that uses physical buttons and a touchpad.

Fourth, to study the intrinsic problem of VR locomotion, we explore two opposing approaches: a continuous and a discrete technique. For the first, we demonstrate a spherical locomotion device supporting two different locomotion paradigms that propel a user's first-person avatar accordingly. We found that a position control paradigm applied to a sphere performed mostly superior in comparison to button-supported controller interaction. For discrete locomotion, we evaluate the concept of a spherical world in miniature (SWIM) used for avatar teleportation in a large virtual environment. Results showed that users subjectively preferred the sphere-based technique over regular controllers and on average, achieved lower task times and higher accuracy.

To conclude the thesis, we discuss our findings, insights, and subsequent contribution to our central research questions to derive recommendations for designing techniques based on spherical input devices and an outlook on the future development of spherical devices in the mixed reality spectrum.

ZUSAMMENFASSUNG

Die Popularität von Virtual Reality (VR) und Augmented Reality (AR) hat in den letzten Jahren rasant zugenommen, sowohl im akademischen Bereich als auch bei kommerziellen Anwendungen. Dies ist in erster Linie auf technologische Fortschritte und erschwingliche Head-Mounted Displays (HMDs) zurückzuführen. Ob in Spielen oder professionellen Anwendungen, HMDs ermöglichen immersive audiovisuelle Erfahrungen, die uns in fesselnde digitale Welten versetzen oder die reale Welt überzeugend erweitern.

Doch so lebensecht diese Erfahrungen in visueller und auditiver Hinsicht geworden sind, so bleibt doch die Frage, wie die Interaktion mit diesen virtuellen Umgebungen auf ebenso natürliche Weise gestaltet werden kann. Lösungen, die eine intuitive, greifbare Interaktion ermöglichen, hätten das Potenzial, das Spektrum der Mixed Reality (MR) fundamental zugänglicher zu machen, insbesondere für Unerfahrene. Die Forschung an Tangible User Interfaces (TUIs) hat dieses Ziel durch das Koppeln virtueller und realer Objekte verfolgt und so hat sich gezeigt, dass greifbare Interaktion für zahlreiche Anwendungsfälle signifikante Vorteile bietet. Spherical Tangible User Interfaces (STUIs) stellen einen Spezialfall von greifbaren Interfaces dar, insbesondere aufgrund ihrer Fähigkeit, beliebige sphärische virtuelle Inhalte vollständig verkörpern zu können. Generell entwickeln sich sphärische Geräte zunehmend von reinen Technologiedemonstratoren zu nutzbaren multimodalen Instrumenten, die auf eine breite Palette von Interaktionstechniken zurückgreifen können.

Diese Dissertation untersucht primär die Anwendung von STUIs in MR-Umgebungen durch einen Vergleich mit State-of-the-Art-Eingabetechniken in vier verschiedenen Kontexten. Dies ermöglicht die Erforschung der Bedeutung der Verkörperung virtueller Objekte, der Benutzerleistung im Allgemeinen und der Fähigkeit von STUIs, die sich lediglich auf ihre Form verlassen, komplexe Interaktionstechniken zu unterstützen.

Zunächst erforschen wir, wie sphärische Geräte immersive Visualisierungen verkörpern können. Eine erste Studie ergründet die Praxistauglichkeit einer einfach konstruierten, getrackten Kugel, die drei Arten von Visualisierungen verkörpert. Wir testen simulierte Multi-Touch-Interaktion auf einer sphärischen Oberfläche und vergleichen zwei Kugelgrößen mit VR-Controllern. Die Ergebnisse bestätigten die Praxistauglichkeit des Prototyps und deuten auf verbesserte Mustererkennung sowie Vorteile für die kleinere Kugel hin.

Zweitens, um die Validität von VR als Prototyping-Technologie zu bekräftigen, demonstrieren wir, wie ein großes, anfassbares sphärisches Display in VR simuliert werden kann. Es zeigt sich, wie VR die Möglichkeiten realer sphärischer Displays substantiell erweitern kann, indem eine simulierte Multi-Touch-Oberfläche um die Fähigkeit der physischen Rotation ergänzt wird. Nach einer ersten Studie, die die generelle Machbarkeit der Simulation eines solchen Displays in VR evaluiert, zeigte eine zweite Studie die Überlegenheit des drehbaren sphärischen Displays.

Drittens präsentiert diese Arbeit ein Konzept für ein sphärisches Eingabegerät für Tangible AR (TAR). Wir zeigen, wie ein solches Werkzeug grundlegende Fähigkeiten zur Objektmanipulation unter Verwendung von zwei verschiedenen Modi bereitstellen kann und vergleichen es mit Eingabetechniken deren Hardwarekomplexität zunehmend steigt. Unsere Ergebnisse zeigen, dass die kugelbasierte Technik, die ohne Knöpfe auskommt, nur von einer Controller-Variante übertroffen wird, die physische Knöpfe und ein Touchpad verwendet und somit nicht auf unterschiedliche Modi angewiesen ist.

Viertens, um das intrinsische Problem der Fortbewegung in VR zu erforschen, untersuchen wir zwei gegensätzliche Ansätze: eine kontinuierliche und eine diskrete Technik. Für die erste präsentieren wir ein sphärisches Eingabegerät zur Fortbewegung, das zwei verschiedene Paradigmen unterstützt, die einen First-Person-Avatar entsprechend bewegen. Es zeigte sich, dass das Paradigma der direkten Positionssteuerung, angewandt auf einen Kugel-Controller, im Vergleich zu regulärer Controller-Interaktion, die zusätzlich auf physische Knöpfe zurückgreifen kann, meist besser abschneidet. Im Bereich der diskreten Fortbewegung evaluieren wir das Konzept einer kugelförmingen Miniaturwelt (Spherical World in Miniature, SWIM), die für die Avatar-Teleportation in einer großen virtuellen Umgebung verwendet werden kann. Die Ergebnisse zeigten eine subjektive Bevorzugung der kugelbasierten Technik im Vergleich zu regulären Controllern und im Durchschnitt eine schnellere Lösung der Aufgaben sowie eine höhere Genauigkeit.

Zum Abschluss der Arbeit diskutieren wir unsere Ergebnisse, Erkenntnisse und die daraus resultierenden Beiträge zu unseren zentralen Forschungsfragen, um daraus Empfehlungen für die Gestaltung von Techniken auf Basis kugelförmiger Eingabegeräte und einen Ausblick auf die mögliche zukünftige Entwicklung sphärischer Eingabegräte im Mixed-Reality-Bereich abzuleiten.

ACKNOWLEDGMENTS

First of all, I would like to thank my doctoral supervisor *Andreas Butz*, who made this work possible and provided invaluable support by encouraging and motivating the exploration of unconventional approaches and new ideas. No less valuable was the support of *Tobias Höllerer*, whom I had the great fortune to meet at an early stage of my doctoral studies and who made a considerable contribution to the success of my thesis. Thanks are also due to my third reviewer, *Dieter Schmalstieg*, who agreed to take on this task at relatively short notice. I would also like to thank *Thomas Krefeld*, *Stephan Lücke* and *Christian Riepl*, who have provided me with a pleasant working environment over the past years and have thus supported this dissertation significantly. Working between two different university institutes and disciplines was not always easy, but at this point, I would like to thank both the whole team at Frauenlobstraße and my project colleagues, whose support was diverse and important.

My deep gratitude goes to my two brothers. *Tobias Englmeier* for having my back in the final phase of this work and *Elias Englmeier* for his calm and unconditional support and especially for the journey of creating virtual worlds together. I would also like to thank my sister, *Miriam Englmeier* for never giving up, as well as *Christiane Bayer* for her revision and uplifting attitude.

I consider myself lucky to have grown up in a creative and open-minded but rational environment. Therefore I address my greatest thanks to my parents *Stefan Englmeier* and *Jutta Englmeier*, who also enabled me to get in touch with computer science at an early age. Finally, I dedicate this work to my grandparents *Ernst Englmeier* and *Elfriede Englmeier* for always encouraging my academic career.

COLLABORATION STATEMENT

In the run-up to the thesis, I would like to clarify that the outlined work builds on the valuable support of various collaborators: peers, students, and collaborating partners. Each paper has emerged from a bachelor or master thesis that I have offered and then supervised in close contact with my own supervisor *Andreas Butz*. Special attention should also be paid to the cooperation with *Tobias Höllerer* from the University of California Santa Barbara and *Julie Williamson* from the University of Glasgow that were of significant help in supporting early publications and later also core projects of this work. I act as the first author for the presented publications as I have mainly written them, developed the guiding idea, and for the most part, have conducted the analysis. For the implementations, I provided programming support as needed and am truly thankful to my students for their patience and endurance, especially in pursuing unusual ideas, unexplored concepts, and new approaches. To sum up, this work would hardly have been possible without the outlined collaborators, and therefore, I will be gladly using the scientific “we” throughout this dissertation. Table A.1 illustrates the contributions of all listed authors.

TABLE OF CONTENTS

1 Introduction and Background 1

1

Introduction and Background

"The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in."

Ivan E. Sutherland - The Ultimate Display [97]

With the scientific and technological progress over the last three decades, the boundaries between the real and virtual world are becoming increasingly blurred. Be it the augmentation of our physical environment in every conceivable situation or the convincing simulation of alternate virtual spaces, the ubiquitous interaction between humans and computers and subsequent blending of both realities is inevitably becoming a part of our daily lives.

Since the first implementation of a head-mounted display (HMD) in 1968 by Sutherland et al. [98], the technology has made enormous progress. However, until recently, the main area of application has been the academic domain. This changed rapidly with the release of commercially available products such as Oculus Rift or HTC Vive. Since then, in particular, VR has seen a rise, predominantly in games[1], but applications in the environment of public installations or immersive data visualization are equally relying on blended realities.

These advancements, especially in computer science, do not correlate with the evolution of human capabilities [21]. Therefore, the development of techniques leveraging natural and learned human skills is becoming increasingly important. To convey interaction with digital content, scientists often rely on metaphors that build on widespread knowledge or are borrowed from facts well established in the real world [71].

One of the most prominent representatives of this principle is the desktop metaphor. In its origin, a two-dimensional graphical user interface (GUI), it mimics the user's desk by, for instance, referencing the functions of a digital system with folders, documents, or a recycle bin. In contrast, a TUI seeks to supply its users with tangible objects that, on the one hand, represent and, on the other hand, can manipulate a system's state. It is worth noting that TUIs do not generally provide advantages over GUI-based systems. However, multiple studies have shown benefits for TUIs in terms of physical interaction, realism, and feedback [111].

The inherent property of a mixed reality environment not having to abide by laws and constraints of physics makes it an especially interesting testbed. The evaluation of interfaces that currently can not be realized outside of a blended reality due to technical limitations, thus opening the possibility to investigate the importance of their physicality, seems promising. This enables us to envision and evaluate user interfaces that may become a reality in the future and contribute to the question of such devices may be more beneficial if we simulate or extend their capabilities in MR.

Even with advances in tracking technology [82, 79] an answer to these questions is not easy. Until now, we can not transfer any object, shape, or surface to the virtual space. Simulating tangible feedback is also not yet developed to the point where it eliminates the need for physical devices. However, current tracking technology allows for the use of a wide range of items fitted with tracking devices or markers. This ability appears especially interesting if the tracking technology does not influence the tracked object's shape or general characteristics. Such a prototype could support many different use cases, for example, by utilizing a universal shape that may not need to be explained to its users.

---

[1] `https://www.roadtovr.com/monthly-connected-headsets-steam-3-million-march-2021/`

An object that meets these requirements is the sphere. It can be efficiently tracked without distorting its outline, we deal with its known symmetric form in a variety of real-world situations, and as a result, it may be able to support several different types of fully embodied interfaces and interaction techniques. Hence, in this dissertation, we are dedicated to studying spherical tangible user interfaces. MR provides a compelling environment to implement, explore, and evaluate such concepts compared to established interaction techniques.

In many different commercial applications and the academic field of human-computer interaction (HCI), we find a variety of interfaces that rely on a tangible spherical shape. Therefore, an analysis of these previous implementations will serve as the basis for formulating the precise research questions that this dissertation seeks to answer. They may ultimately contribute insights to the overarching questions discussed in this introduction.

1.1 Fundamentals and Definitions

In the introduction, we built on an intuitive concept of the real and virtual world. Yet, we must define the spectrum between the two realities and other terms that may also seem self-evident at first glance but require a clear classification.

Concepts of Reality and Virtuality

To gain a deeper understanding of virtuality in contrast to what is generally considered reality, we will start with reviewing a definition of the latter. Reality can be seen as a dichotomy of a natural and an artificial part. One is created by human interference, and the other is not [12]. This philosophic approach shows that we can see reality itself as a blend of two concepts of thought.

In contrast, the term *virtual* usually describes anything that the human mind can imagine, but that does not exist in either of these two parts of reality – a fact that only exists theoretically [95] or in *virtuality*. However, in a contemporary context, the term more commonly refers to entities that are simulated by a computer [72] and do not exist [15] but only are presented [101] in the physical world.

It is important to note that the distinction between reality and virtuality is a contentious topic. The question, for instance, if a simulated reality that can not be distinguished from the real world can still be seen as virtual is not easily answered [46]. Nevertheless, we can often find the crucial factor for such a distinction in the difference between a world that is created and in some form presented and another that just exists [101]. While this general definition of the real and virtual world may not be too far from the intuitive interpretation, terms such as *virtual reality* need a detailed explanation, especially in the scientific sense.

Virtual and Augmented Reality

Virtual Reality (VR): We can divide attempts to define VR into technical and conceptual approaches. Lanier [60] referred to VR as “three-dimensional realities implemented with stereo viewing goggles and reality gloves.” In opposition, Brudea and Coiffet [14] saw it as an interplay of immersion, interaction, and imagination. *Immersion* [78] is often associated with the technical capabilities of a system to communicate a simulated reality convincingly. Simultaneously, the subjective experience is commonly described as a feeling of *presence* [45, 106]. Cruz-Neira’s [19] definition touches on technical and conceptual aspects: “VR refers to immersive, interactive, multi-sensory, viewer-centered, three-dimensional computer-generated environments and the combination of technologies required to build these environments.” A recent and more general definition is given by Dörner et al. [22]: “Due to the natural interaction possibilities, virtual reality is also referred to as a human-machine interface, [...] which, compared to traditional user interfaces, enables a particularly natural or intuitive interaction with the three-dimensional simulated environment.”

These definitions help form a clearer picture of VR and undoubtedly show the importance of interaction and immersion. As natural interaction being a key focus of this work, we prefer the definition by Dörner et al. [22].

Virtual World: Bell [3] defined a *virtual world* as “a synchronous, persistent network of people, represented as avatars, facilitated by networked computers.” An example would be a massive multiplayer online game (MMO), which simulates a world independent of the presence of a particular user [94]. It is obvious that such a definition has evolved with technological progress, as has the colloquial use of the term, which itself is often used (including this work) as a synonym for the concept of virtuality that we discussed above.

Virtual Environment (VE): Opposed to the previous term, a *virtual environment* can be set apart by persistence and a social component [89, 88]. In academia, the term is commonly used to describe the variety of virtual scenes to which a user is exposed during a study and does not necessarily implement the aforementioned properties of a virtual world.

Augmented Reality (AR): Describes a reality superimposed, complemented, or enhanced with virtual content. This ultimately results in a shared space between digital and physical objects [9]. As with VR, we find a difference between technical and conceptual definitions. Milgram et al. [75] presented approaches for both ends of the spectrum. They referred to AR as “augmenting natural feedback to the operator with simulated cues.” in contrast to “a form of virtual reality where the participant’s head-mounted display is transparent, allowing a clear view of the real world.” In a more recent statement, Klopfer and Sheldon [58] saw AR to “provide users technology-mediated immersive experiences in which real and virtual worlds are blended.” As with VR definitions, we will base our interpretation of AR on definitions that include user interaction, such as a recent definition by Dunleavy et al. [25] that states: “users’ interactions and engagement are augmented.” Schmalstieg et al. [86] accordingly attributed greater importance to AR than VR for the “complex manipulation of three-dimensional information.”

Blending Realities

Mixed Reality (MR): In 1995 Milgram et. al [75, 74] proposed the reality-virtuality continuum (RV). It covers a bidirectional space spanning from a real to a virtual environment (Figure 1.1). MR, defined within this continuum, constitutes an important part of this thesis and its title. MR presents entities from both realities simultaneously, meaning that at least one object from the real and one from the virtual world is present.

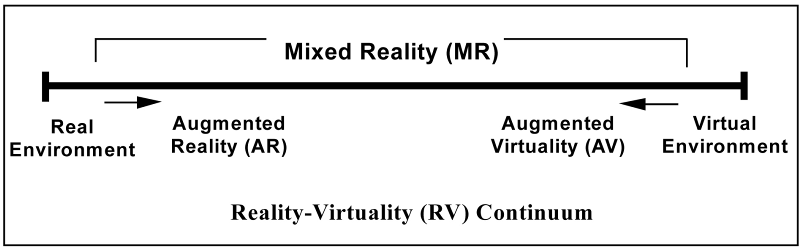


Figure 1.1: Milgram's famous reality-virtuality continuum serves as a basis to defining MR as the conceptual space between real and virtual environments that depend on a majority of real or virtual entities. They can be further split into augmented reality and augmented virtuality [75].

MR is comprised of two main concepts: augmented reality and augmented virtuality (AV). Both conceptual spaces are defined by a majority of the content from either of the two worlds. AR as a composition contains more real than virtual objects, while AV refers to adding real objects to a space that is mainly made up of virtual information. Because all of the publications presented in this thesis either transfer real objects to a virtual environment or augment them with digital information, our experiments exclusively occur in the MR space. Obviously, the interaction with one tangible, real object alone, such as a VR controller, in a VE results in a blend of two realities. In literature, such a space also may be referred to as XR, which serves as an umbrella term for VR, AR, and MR. However, in contrast to AR, an AV setup strongly leaning towards the virtual side is often referred to as VR. We adopt the latter convention for all presented publications.

TUIs and Embodiment

Tangible User Interface (TUI): Ishii and Ullmer [51] defined TUIs in 1997 as interfaces that "augment the real physical world by coupling digital information to everyday physical objects and environments." Fitzmaurice et al. [41, 40] however, made the first distinction between GUIs and TUIs in 1995 while referring to such interfaces as "graspable interfaces" and defining them as "a physical handle to a virtual function where the physical handle serves as a dedicated functional manipulator." While the first definition serves as a solid foundation for the publications [P1 - P7][2] outlined in this thesis, they require a deeper investigation due to their general nature.

---

[2] Abbreviations for publications are assigned in Section 2.

One of the most widely used input devices, the mouse, is a TUI by these two definitions. However, following the assessment of Sharlin et al. [91] this is not the case. The authors proposed three heuristics; TUIs must: provide successful spatial mappings, unify input and output (I/O) space and enable trial-and-error activity. While a mouse can provide excellent spatial mapping [69] neither does it accurately reflect the state of a digital system (since it separates action and perception space), nor does it support trial-and-error activity. This means it would be able to be used out of the context of a pragmatic task enabling the exploration of physical space.

Furthermore, the authors argue that designers should aim at a one-to-one mapping of virtual and real objects for best supporting these heuristics rather than a one-to-many coupling. This proposal certainly makes sense in the context of the defined heuristics, but it also raises the question of what the embodiment of virtual content actually means. In the course of this work, we will therefore refer to the taxonomy by Fishkin et al. [37] that orients TUIs along two axes: embodiment and metaphor.

Embodiment can be split into four levels: *full*, *nearby*, *environmental* and *distant*. For *full* embodiment, the output device is the same as the input device. Therefore a virtual object is fully embodied if a real object fills its complete outline. *Nearby* refers to output occurring in the immediate vicinity of the user input. Such a device is in literature often referred to as a proxy. *Environmental* defines output that only occurs around an arbitrary user's environment. In comparison, *distant* describes an output effect happening in an area neither related to users nor the input device, such as the working principle of a remote control.

Metaphors allow users to connect an interface's functionality to an analog, existing mental model from the real world. An ability tangible interfaces may enable like no other [76]. Subsequently the taxonomy again defines four levels: *none*, *noun or verb*, *noun and verb*, and *full*. Self-explanatory, *none* relates to the complete absence of any metaphor. A *noun* describes an analogy to the physical shape, look, or sound of an object. *Verb* seeks to classify a metaphor by its functionality. Subsequently, *Noun and verb* refers to defining analogous properties and behavior. For instance, if a system deletes a document (noun) dragged (verb) to a wastebasket, it would qualify for this kind of metaphor. Yet, in contrast to the level *full*, the physical and virtual objects still differ. If this is not the case and the TUI literally is the virtual system, it fulfills the last condition and therefore can also be described as “really direct manipulation” [38]. A digital pen can serve as an example. It looks and behaves just like its real-world counterpart.

If we review Fishkin's taxonomy and the heuristics of Sharlin et al., we do not only get a good understanding of the essential properties of TUIs, but it becomes clear that the better a TUI (literally) fulfills these defined guidelines, the greater its potential may be. While this theoretically may lead to intuitive and usable devices, the technical realization of such interfaces is still a huge culprit. This is where VR technology comes into play. It may enable TUIs not always achieving an ideal classification but that could allow us to push beyond the boundaries where interfaces with no or minimal user instrumentation struggle.

1.2 Prototyping STUIs in Mixed Reality

Before introducing our first research question, we will reflect on our choice for spherical devices in light of the classifications outlined in the previous section. The question comes to mind if spherical devices in MR environments qualify for either *full embodiment* and *full metaphor* while meeting the requirements of the three discussed heuristics.

TUIs as a Motivation for STUIs

If we examine the latter, we can answer the question of spatial mapping as long as the spherical device would support six degrees of freedom (6-DOF) interaction [90]. The unification of I/O may seem straightforward, but in a technical sense, the output device is not the tracked object itself but the HMD. Therefore, unified I/O is true if we accept that we simulate this requirement. However, especially in tangible AR (TAR) [11], and in the field of display simulation, such setups have been used to some extent, for example, to investigate latency [62] or novel interfaces in general [57, 53].

Regarding Fishkin's taxonomy, an STUI would likely qualify for full embodiment [39], yet the assignment of the metaphor level is more complicated. Here we can find an interesting phenomenon. If we transfer a simple, embodied object to the VR space, the requirements for a full metaphor appear to be satisfied; a virtual sphere would behave just as in the real world. If we extend its functionality, for instance, by adding more advanced interaction capabilities, the requirements for *noun* and *verb* would still be met. Yet, the virtual object would no longer exactly correspond with the real one. As a result, we diminish the metaphor level by extending interactive functionality. Generally, we use this taxonomy throughout the thesis and will provide an overview of embodiment and metaphor levels for all practical prototypes in the context of their respective studies in Table 3.1.

In general, physical spheres provide the prospect of achieving high levels of tangible quality (regarding both classifications), making them interesting subjects to explore. They may:

- Fully embody any spherical objects in mixed reality.
- Provide intuitive interaction for a variety of existing and novel use cases.
- Convey complex functionality by their natural tendency towards rotation.
- Leverage advantages in ergonomics, visualization, and spatial orientation.

Subsequently, research on STUIs might ultimately inform on the actual usability and possible advantages of spherical tangible interfaces and their potential to support complex interaction that goes beyond but does not alter the natural properties of a sphere.

Transferring Spherical Objects to MR

As mentioned towards the end of Section 1.1, a major hurdle for TUIs is their technical feasibility. As a preliminary step for this work, we had to find a solution for these issues that would ultimately enable the investigation of embodied spherical objects in MR. Hence, we formulated the first research question:

> **RQ1:** *How can commercial hardware be used to efficiently embody virtual spherical objects in MR?*

As primary goals for the hardware implementation, we defined: easy reproducibility, fast and precise object tracking, a completely smooth surface, and as a matter of course, a wireless, room-size tracking experience. After having tried other more costly options [2] we found that the tracking performance [79] of the HTC Vive[3] system was not noticeably influenced if we placed a Vive Tracker[4] behind infrared-transparent material such as acrylic glass. We applied this principle to all prototypes but adjusted them to the requirements of each study.

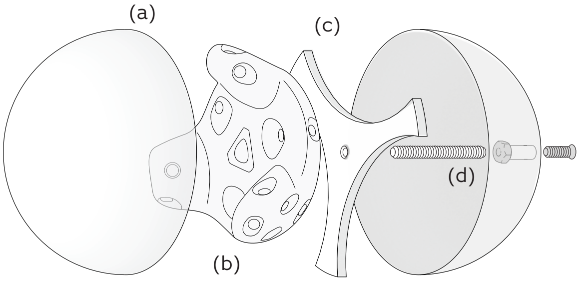


Figure 1.2: This sketch from [P6] illustrates the general working principle of the hardware prototypes we used in all publications. We mounted a Vive Tracker (b) to the center of an acrylic glass sphere using a threaded rod (d) and a stabilization piece (c).

Contribution. Accordingly, [P1] contributes a description and discussion of our devices' basic construction principle (Figure 1.2) and thereby answers RQ1. Besides a detailed illustration of two prototypes (diameter: 25 cm, 40 cm), we discuss their general pros and cons. We elaborate on ergonomic factors, the advantages of an MR setup, and topics such as the visibility of the users' hands and possible feature use cases. For instance, we discovered a slight advantage for the tracker to sit in a centered position. This prevented the tracking device from being shielded by the users' hands, and the center of mass shifted towards the center of the spheres. Simultaneously, as a pleasant side effect, the software implementations did not need to consider a possible offset. In summary, we can attribute the reproducibility to the simplicity of the design but also to the commercial availability of these devices that for a long time only could be found in the professional or academic sector [73].

---

[3] `https://www.vive.com/us/product/`

[4] `https://www.vive.com/us/accessory/vive-tracker/`

1.3 Embodied Spherical Information Visualization

To evaluate our hardware prototypes, we identified three application areas [P2]: the simulation of spherical displays, handheld spherical displays, and the more experimental field of spherical controllers. First, we decided to turn to handheld displays embodying spherical visualizations. We can divide previous work in the field by the technical realization into three groups: inside [4] or outside [7, 6, 35] projected spherical displays and simulated ones [65]. If those displays use a viewer's position to create the illusion of contained three-dimensional content, they are referred to as handheld perspective corrected displays (HPCDs).

While this was not a primary concern for an initial experiment, VR simulated displays could generally provide the advantages of low weight, large operation area, and the ability to show holographic content. The main disadvantage would clearly be strong user instrumentation. Still, the concept of enriching physical items with virtual content is most prominent in AR research [6]. For instance, Schmalstieg et al. [87] implemented a three-dimensional visualization hovering above an augmented tablet in their pioneering project "Studierstube".

As a goal for the first practical exploration, we hoped to gain insights into the possible benefits of fully embodied visualizations on information perception. Additionally, as a secondary objective, we wanted to test an initial implementation of a spherical multi-touch surface that we simulated with tracking gloves. This may allow for a first assessment of the input capabilities of such a device and the general viability of VR simulation, yet the primary focus remained on information perception. Hence, the second research question:

> **RQ2:** *How does the full physical embodiment of spherical visualizations affect information perception?*

Contribution. Our position paper [P2] adds to RQ2 in consolidating our view regarding the importance of fully embodied surfaces in the light of related work [38]. However, our main contribution lies in the user study (N=32) presented in the third publication [P3]. We compared two user groups (Sphere / Controller) and evaluated three embodied visualizations (virtual globe, spherical graph, omnidirectional video). The study was primarily motivated by the potential of TUIs to support the learning process [71, 110, 70]. The ability to naturally interact with embodied visualizations could provide advantages in pattern recognition, spatial orientation, and task performance. Additionally, we aimed at insights on subjective perception and two different display sizes (25 cm, 40 cm) as well as conclusions for VR simulated devices in general.

The results from a selection task only showed an advantage in task completion time for the smaller spherical display that was easier to handle. The most interesting finding was caused by the embodied spherical graph [24]. 56.25% of users that analyzed the visualization with tangible spheres found a hidden pattern, while for the group using VR controllers, only 29.13% of participants were successful.

1.4 Simulating Spherical Displays

Inspired by the practicality of our prototypes and the positive results the previous study [P3] brought to light, we continued with a deeper exploration of the spherical devices' physicality. To investigate multiple aspects of such, display simulation appeared as promising. In the course of this well-tested research principle [50, 43] spherical displays have been simulated in VR to explore perspective corrected displays [33] or possible advantages of AR [65].

Since the implementation of the first spherical displays [67] in the early 2000s, the devices have significantly developed with the advances in display technology. Yet, until now, they mostly serve as eye-catching technology demonstrators that offer minimal interaction. While expensive commercial displays often rely on a multi-touch surface [44, 5] and inside projection, in academia a number of prototypes [99, 36, 13, 109] have been realized that due to outside projection could offer interaction such as physical rotation [17, 55].

The simulation of a large commercial spherical display in VR [P4] would allow us to i) test different interaction techniques influenced by various levels of tangible feedback and ii) gain insights into the capabilities of VR simulated devices in general. Consequently, we formulated the third research question that would be essential to all following work:

> **RQ3:** *How do the physicality of spherical objects and their self-explanatory shape influence user performance and subjective perception?*

Contribution. With [P4], we contribute two studies (N=16, N=32) to RQ3. The first study adds to the general question of the viability of a VR simulated spherical display and the practicality of displays presented inside VR. In summary, results showed a comparable performance for the VR simulated variant in comparison to a Puffersphere display[5]. For an alignment task, the VR condition performed superior. This added further to the motivation for a follow-up study. Subsequently, we compared three different levels of physicality by VR simulation: a purely virtual, a fixed but tangible, and a fully rotatable spherical display. For the latter conditions, we supplied a custom-built prototype. Additionally, the second study contributes a comparison between selection by alignment and tapping, both with either fixed or rotating background. Meaning that for the fixed background, only the task-related elements would rotate along with the sphere, otherwise showing a static grid.

Therefore, the second study would allow conclusions to be drawn about the physicality of the display, the role of real rotation, and the effects of the two selection and visual feedback techniques. As the clearest result, we found that the rotating display was significantly faster, more accurate, and subjectively preferred. We also must add that, interestingly, users achieved better overall results in the alignment task that did not require a simulated multi-touch interface for the rotatable condition.

---

[5] `https://pufferfishdisplays.com/`

1.5 Advanced Interaction Techniques with STUIs

These two findings were crucial to defining the research focus for the next three publications. On the one hand, the spherical device performed superior with a less complex interaction technique (alignment). On the other hand, the physical rotation but not the physicality itself was the determining factor for the found advantages. Therefore we decided to dedicate our following research efforts to the final question:

> **RQ4:** *How can STUIs facilitate complex interaction techniques requiring translation, rotation, and scaling by their shape alone?*

This question, along with RQ3 (since we have tested all of the following concepts in terms of task completion time, accuracy, and subjective ratings), would accompany us over the remainder of our work. To evaluate more complex interaction techniques that would only rely on the shape of a spherical tangible device, we decided to first turn to the field of TAR.

Object Manipulation in TAR

Generally speaking, TAR applications profit from a relationship between the real and virtual world [68]. Subsequently, Billinghurst et al. [10] defined two properties: users interact with virtual objects by manipulating a real-world equivalent, and each virtual representation is coupled to only one physical counterpart. However, we can find an increasing number of approaches that rely on proxies [16, 47, 23]. Such items can be coupled with a variety of virtual objects while embodying them to various degrees.

An important ability to interact with virtual objects is manipulation, most commonly rotation, translation, and scaling (RTS). For such a task, TAR applications often supply physical devices [48, 85]. This approach benefits from objects that indicate their functionality by their shape [54, 42, 108]. However, the question remains how users can select a virtual object by connecting it to a physical one. The virtual hand [80] and virtual pointing [64] techniques describe the general principle of picking up an object within the range of the input device or selecting an item out of reach. In our concept, we rely on the first paradigm since this may fit the natural character of a tangible proxy.

As we aim to investigate a sphere's ability to support object manipulation by only utilizing its shape, we have to supply a dwell-time-based solution for performing the actual selection [93]. Consequently, we are missing one degree of freedom to allow for simultaneous RTS (7-DOF). Therefore, we implemented a mode-based approach that allows switching between rotation/translation and scaling [102]. For scaling, we decided to make use of the sphere's tendency towards rotation over a distance-based approach [92]. We tested our implementation (diameter: 12 cm) against three controller conditions, one of which allowed for simultaneous 7-DOF interaction.

Contribution. In total, we contribute three studies [P5 - P7] to RQ4 that at the same time add to RQ3. This paragraph will discuss the contribution derived from the fifth publication's [P5] study (N=30). The study evaluated our implementation of a spherical proxy compared to three VR controller conditions with increasing hardware complexity both in mid-air and on a table. As outlined, our prototype could not support 7-DOF interaction and therefore had to rely on a menu to switch between rotation/translation and scaling. As by the definition of RQ3, this constraint is necessary since we want to explore interaction solely benefiting from the spherical shape. Subsequently, two conditions only must differ in shape while interaction is identical. To gain further insights, we compared two additional controller conditions that once incorporated a button to switch between interaction modes and ultimately allowed for simultaneous 7-DOF interaction.

As the most notable result, we found the spherical device to be faster than all controller conditions except for the one mentioned last. A similar picture showed for overall task performance and subjective ratings. An analysis of what interaction types caused the advantages for the spherical controllers revealed that most users achieved the lower task times by the scaling interaction that we based on rotation around a central axis.

Discrete and Continuous VR Locomotion

Next, we decide to explore VR locomotion as yet another topic that would allow us to conclude a sphere's potential to support complex interaction. VR locomotion concepts rely on techniques that often make use of multiple degrees of freedom. Overall it is a challenging topic since the virtual space mostly largely exceeds the physical space. Therefore, elaborated methods that allow users to navigate a large VE at ease are needed. In general, we can divide the field into two opposing paradigms: continuous and discrete techniques [1]. As the names suggest, the first aims at reproducing a fluent locomotion experience (e.g., walking) while the latter allows users to change their position often without any intermediate action instantly (e.g., teleportation). While both techniques have their advantages, we see the potential of a spherical device to contribute a solution to each field.

For continuous locomotion, we build our approach on classical control theory [52] and gesture-based methods [104], since a sphere (diameter: 12 cm) rotated in hands would elicit a hand-gesture [56] associated with locomotion that allows users to mimic a ball rolling on the ground. For discrete locomotion, we explored a world-in-miniature (WIM) implementation. A WIM supplies users with a miniature version of a VE that can be used for navigation and object manipulation. The original concept was implemented by Pausch and Stoakley [96] in 1995 and since then has been extended [105] and successfully applied to locomotion in modern VR settings [8]. As a result, we saw potential in a tangible spherical WIM (SWIM) that would unify the advantages of TUIs and discrete VR locomotion by projecting a planar WIM to the surface of tangible spheres (diameters: 12 cm, 25 cm).

Contribution. Based on the use cases of discrete and continuous VR locomotion, we contribute, as mentioned, two studies [P6, P7] to answering RQ3 and RQ4. In [P6], we implemented a spherical device, rotated in hands that would constitute a hybrid solution between a controller and a gesture-based approach. Additionally, it could realize a zero-order system [52] that, due to the direct translation of input to movement, appeared as particularly promising. Still, we decided to test two paradigms: the zero-order system and a first-order system that would transfer the sphere's directional tilt to a corresponding velocity and direction. The results from our study (N=20) showed clear advantages for the zero-order system that could eventually outperform the first-order variant and two controller-based methods, mainly in task completion time and accuracy. However, subjective ratings were in favor of the VR controllers. These findings affirmed the viability of a spherical VR controller only relying on its shape for first-person locomotion.

In contrast to [P5], the SWIM implementation allowed for simultaneous 7-DOF interaction solely based on the tangible device. Apart from answering RQ3 with a comparison to VR controllers in objective and subjective ratings, our study (N=20) naturally contributes to answering RQ4. To be able to navigate a large terrain, a WIM needs to support scrolling and zooming. We aimed at conveying these interaction techniques by only utilizing the spherical shape. For instance, if users rotated the device, it would scroll a planar WIM projected onto a sphere. Only appearing as rotation users would, in reality, perform a more complex type of interaction (scrolling). Since our implementation would require simulated holographic content protruding from the sphere's surface, it can only be realized in MR environments that can use the visual space surrounding the device. The results from the study we conducted in the course of [P7] were unambiguous. The SWIM technique could outperform a VR controller technique in all ratings.

1.6 Summary and Overview of the Thesis

As the goal of this thesis, we pursue the exploration of the potential and practicality of spherical tangible interfaces in MR. Following the preliminary technical exploration, we defined three main research objectives (RQ2-RQ4): first, we examine the impact of embodied spherical visualizations on user perception. Second, we wanted to gain knowledge on the overall task performance of handheld spherical devices in display simulation and, more prominently, in tasks requiring complex interaction such as object manipulation and locomotion. Third, we studied possible advantages stemming from the spherical shape alone by deliberately limiting interaction to this constraint.

Chapter 2 introduces the publications this thesis is based on in greater detail and places them in the context of the general research objective.

Chapter 3 discusses the results of this thesis regarding the research questions and then provides an outlook on respective future work.

2

Publications

After the introduction of the leading research questions and relevant fundamentals, we will now, in greater detail, focus on the publications that form this dissertation. We introduce each section briefly before we present a preview and summary of the contained papers. Table 2.1 gives a complete overview of all publications, their addressed research questions, research methods, and primary contribution. It is worth noting that the papers are presented roughly in order of their publication, as the primary research questions (RQ2, RQ3, RQ4) have evolved throughout the studies. However, a strict separation of the research questions is not meaningful, as most publications touch on multiple questions. Hence, the assignment to the questions refers to the main contribution of the papers as outlined in the previous chapter.

The original publications and a table explaining the contributions of all listed authors (Table A.1) are available in the Appendix A.

	RQ	Title of Paper and Publication Venue	Research Method	Primary contribution
[P1]	RQ1	“Sphere in Hand: Exploring Tangible Interaction with Immersive Spherical Visualizations” in *IEEE VR ’19*	Observation, hardware evaluation	Development and description of a low-cost hardware prototype for tracking spherical objects in MR.
[P2]	RQ2	“Spherical Objects as an Opportunity to Investigate Physical Embodiment in Mixed Reality Environments” in *MUC ’19*	Position paper	Outlining use cases and research opportunities for fully embodied spherical objects mainly from an academic perspective.
[P3]	RQ2	“Feel the Globe: Enhancing the Perception of Immersive Spherical Visualizations with Tangible Proxies” in *IEEE VR ’19*	Controlled experiment (N=32)	Practical evaluation of spherical prototypes in the context of tangible information visualization and multi-touch selection.
[P4]	RQ3	“TangibleSphere – Interaction Techniques for Physical and Virtual Spherical Displays” in *NordiCHI ’20*	Controlled experiments (N=16), (N=32)	Description and evaluation of the simulation of a large tangible spherical display in VR in regard to three levels of physical feedback.
[P5]	RQ3, RQ4	“A Tangible Spherical Proxy for Object Manipulation in Augmented Reality” in *IEEE VR ’20*	Controlled experiment (N=30)	Development and analysis of a buttonless, sphere-based object manipulation technique and comparison to three controller-based methods with varying hardware complexity.
[P6]	RQ3, RQ4	“Rock or Roll – Locomotion Techniques with a Handheld Spherical Device in Virtual Reality” in *ISMAR ’20*	Controlled experiment (N=20)	Development and analysis of two buttonless, sphere-based continuous first-person locomotion paradigms and subsequent comparison to two controller-based techniques.
[P7]	RQ3, RQ4	“Spherical World in Miniature: Exploring the Tiny Planets Metaphor for Discrete Locomotion in Virtual Reality” in *IEEE VR ’21*	Controlled experiment (N=20)	Development and analysis of a buttonless, sphere-based discrete locomotion technique for avatar teleportation and comparison to a controller-based technique.

Table 2.1: Overview of publications the thesis is based on, abbreviated as [P1 - P7] with corresponding research methods and primary contributions.

2.1 Prototyping STUIs in Mixed Reality

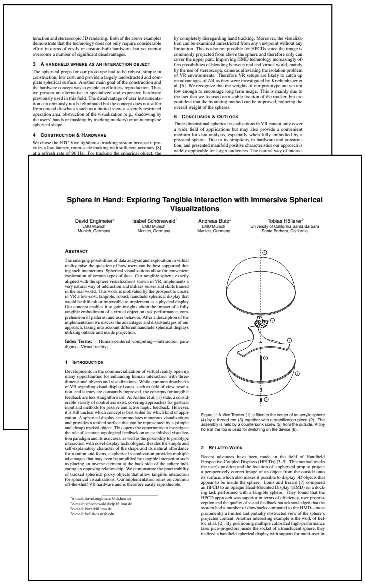
The first paper [P1], lays the technical foundation for the following publications. We describe the used hardware and construction of the technical prototype that we in its principle used in all projects of this thesis. However, since the implementation for each paper had to be adjusted or slightly tweaked, all papers contain their own description of the exact prototype construction in regard to the context of the respective area of application (see Appendix A).

After having studied the performance and complexity of various hardware solutions we found that a simple tracking device mounted to the center of an acrylic glass sphere would not only provide fast and responsive tracking but could also support a large area of operation while keeping implementation and hardware costs comparatively low.

> **RQ1:** *How can commercial hardware be used to efficiently embody virtual spherical objects in MR?*

[P1] Sphere in Hand: Exploring Tangible Interaction with Immersive Spherical Visualizations

Summary. This publication describes and illustrates how a spherical object can be tracked at a low cost in VR by using commercially available hardware. We then discuss the emerging possibilities of data analysis and exploration in VR that raise the question of how users can be best supported during such interactions. Spherical visualizations allow for convenient exploration of certain types of data. Our spherical prototype, exactly aligned with virtual content presented in VR, implements a very natural way of interaction and utilizes senses and skills trained in the real world. At its core, this work is motivated by the prospect to create in VR a low-cost, tangible, robust, handheld spherical display that would be difficult or impossible to implement as a physical display. We realize this concept by placing a tracking device in the center of two differently sized acrylic glass spheres (25 cm, 40 cm). We emphasize that we hardly encountered any tracking errors caused either by obstruction or light refraction. After a description of the implementation, we discuss the advantages and disadvantages of our approach, taking into account different handheld spherical displays utilizing outside and inside projection.



teraction and stereoscopic 3D rendering. Both of the above examples demonstrate that the technology does not only require considerable effort in terms of costly or custom-built hardware, but yet cannot overcome a number of significant disadvantages.

3 A HANDHELD SPHERE AS AN INTERACTION OBJECT

The spherical props for our prototype had to be robust, simple in construction, low cost, and provide a largely unobstructed and complete spherical surface. Another main goal of the construction and the hardware concept was to enable an effortless reproduction. Thus, we present an alternative to specialized and expensive hardware previously used in this field. The disadvantage of user instrumentation can obviously not be eliminated but the concept does not suffer from crucial drawbacks such as a limited view, a severely restricted operation area, obstruction of the visualization (e.g., shadowing by the users' hands or masking by tracking markers) or an incomplete spherical shape.

4 CONSTRUCTION & HARDWARE

We chose the HTC Vive lighthouse tracking system because it provides a low-latency, room-scale tracking with sufficient accuracy [8] at a refresh rate of 90 Hz. For tracking the spherical object, the

by completely disregarding hand tracking. Moreover, the visualization can be examined unrestricted from any viewpoint without any limitation. This is also not possible for HPCDs since the image is commonly projected from above the sphere and therefore only can cover the upper part. Improving HMD technology increasingly offers possibilities of blending between real and virtual world, mainly by the use of stereoscopic cameras alleviating the isolation problem of VR environments. Therefore VR setups are likely to catch up on advantages of AR as they were investigated by Krichenbauer et al. [6]. We recognize that the weights of our prototype are yet not low enough to encourage long term usage. This is mainly due to the fact that we focused on a stable fixation of the tracker, but are confident that the mounting method can be improved, reducing the overall weight of the spheres.

6 CONCLUSION & OUTLOOK

Three-dimensional spherical visualizations in VR cannot only cover a wide field of applications but may also provide a convenient medium for data analysis, especially when fully embodied by a physical sphere. Due to its simplicity in hardware and construction, and presented manifold positive characteristics our approach is widely applicable for larger audiences. The natural way of interac-

---

Sphere in Hand: Exploring Tangible Interaction with Immersive Spherical Visualizations

David Englmeier[*] LMU Munich Munich, Germany
Isabel Schönewald[†] LMU Munich Munich, Germany
Andreas Butz[‡] LMU Munich Munich, Germany
Tobias Höllerer[§] University of California Santa Barbara Santa Barbara, California

ABSTRACT

The emerging possibilities of data analysis and exploration in virtual reality raise the question of how users can be best supported during such interactions. Spherical visualizations allow for convenient exploration of certain types of data. Our tangible sphere, exactly aligned with the sphere visualizations shown in VR, implements a very natural way of interaction and utilizes senses and skills trained in the real world. This work is motivated by the prospect to create in VR a low-cost, tangible, robust, handheld spherical display that would be difficult or impossible to implement as a physical display. Our concept enables it to gain insights about the impact of a fully tangible embodiment of a virtual object on task performance, comprehension of patterns, and user behavior. After a description of the implementation we discuss the advantages and disadvantages of our approach, taking into account different handheld spherical displays utilizing outside and inside projection.

Index Terms: Human-centered computing—Interaction paradigms—Virtual reality;

1 INTRODUCTION

Developments in the commercialization of virtual reality open up many opportunities for enhancing human interaction with three-dimensional objects and visualizations. While common drawbacks of VR regarding visual display issues, such as field of view, resolution, and latency are constantly improved, the concepts for tangible feedback are less straightforward. As Anthes et al. [1] state, a considerable variety of controllers exist, covering approaches for gestural input and methods for passive and active haptic feedback. However, it is still unclear which concept is best suited for which kind of application. A spherical display accommodates numerous visualizations and provides a unified surface that can be represented by a (simple and cheap) tracked object. This opens the opportunity to investigate the role of accurate topological feedback on an established visualization paradigm and its use cases, as well as the possibility to prototype interaction with novel display technologies. Besides the simple and self-explanatory character of the shape and its natural affordance for rotation and focus, a spherical visualization provides multiple advantages that may even be amplified by tangible interaction such as placing an inverse element at the back side of the sphere indicating an opposing relationship. We demonstrate the practicability of tracked spherical proxy objects that allow tangible interaction for spherical visualizations. Our implementation relies on common off-the-shelf VR hardware and is therefore easily reproducible.

Figure 1: A Vive Tracker (1) is fitted to the center of an acrylic sphere (4) by a thread rod (3) together with a stabilization piece (2). The assembly is held by a countersunk screw (5) from the outside. A tiny hole at the top is used for switching on the device (6).

2 RELATED WORK

Recent advances have been made in the field of Handheld Perspective-Coupled Displays (HPCDs) [3–5]. This method tracks the user's position and the location of a spherical prop to project a perspectively correct image of an object from the outside onto its surface, which also makes it possible to display 3D objects that appear to be inside the sphere. Louis and Berard [7] compared an HPCD to an opaque Head-Mounted Display (HMD) on a docking task performed with a tangible sphere. They found that the HPCD approach was superior in terms of efficiency, user proprioception and the quality of visual feedback but acknowledged that the system had a number of drawbacks compared to the HMD—most prominently a limited and partially obstructed view of the sphere's projected content. Another interesting example is the work of Belloc et al. [2]. By positioning multiple calibrated high-performance laser pico-projectors inside the socket of a translucent sphere, they realized a handheld spherical display with support for multi-user in-

[*] e-mail: david.englmeier@ifi.lmu.de
[†] e-mail: schoenewald@cip.ifi.lmu.de
[‡] e-mail: butz@ifi.lmu.de
[§] e-mail: holl@cs.ucsb.edu

Englmeier, D., Schönewald, I., Butz, A., and Höllerer, T. (2019b). Sphere in Hand: Exploring Tangible Interaction with Immersive Spherical Visualizations. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. doi:10.1109/VR.2019.8797887

2.2 Embodied Spherical Information Visualization

Following the first tests and the implementation of our hardware concept [P1], we (i) defined use cases [P2] to explore the concept and (ii) conducted a first user study [P3] where we applied spheres with two different diameters (25 cm, 40 cm). While we identified several use cases, we decided to target tangible information visualization [49] for the first study.

In the position paper [P2], we first consolidated our view regarding the importance of embodied interaction. Then, we identified three main areas of application that would set the course for the following projects: the simulation of spherical displays, handheld spherical displays, and spherical controllers. While the latter also serve as tangible displays, the main difference to handheld spherical displays is rooted in focus on more complex interaction in contrast to perception and the presentation of information. We also emphasized our prototype's capability to fully embody tracked objects since our approach does not modify the (spherical) surface of the tracked object in any way. Consequently, these kinds of implementations enable a completely topologically accurate embodiment of virtual spherical objects, as described in the summary below.

[P2] Spherical Objects as an Opportunity to Investigate Physical Embodiment in Mixed Reality Environments

Summary. In this position paper, we introduce our approach of using current VR and AR technology to explore fully tangible spherical user interfaces. We present three prototypes utilizing this technique. We briefly outline possible challenges, advantages, and fields of application for the presented concepts. Accordingly, we discuss why VR is an interesting tool to investigate interaction with TUIs that are currently not feasible in real world applications such as tangible holographic interfaces or lightweight handheld non-planar displays. This allows for studying various levels of tangible feedback on established use cases such as spherical visualizations. Subsequently, a tangible sphere, due to its natural shape enables an investigation of interaction techniques transferred from the real to the virtual world. Building on these prospects we represent the position that such objects could play a leading role not only in research but in future VR and AR applications and research projects that rely on or seek to explore natural interaction based on realistic physical feedback.

Spherical Objects as an Opportunity to Investigate Physical Embodiment in Mixed Reality Environments

David Englmeier
David.Englmeier@ifi.lmu.de
LMU Munich
Munich, Germany

ABSTRACT

In this work, we introduce our approach of using current VR and AR technology to explore fully tangible spherical user interfaces. We present three prototypes utilizing this technique. We briefly outline possible challenges, advantages, and fields of application for the presented concepts

1 INTRODUCTION

As described in the vision [5] of Ishii and Ullmer physical objects play a key role in bridging the gap between real and physical world. Current VR technology allows for precise tracking of controllers and Head Mounted Displays (HMDs) but lacks the possibility to efficiently transfer custom objects

Physical Embodiment by Spherical Objects in VR

MuC'19 Workshops, Hamburg, Deutschland

controller method the handheld spheres needed significantly less introduction time for users due to well-known shape. Qualitative results in form of a questionnaire also spoke in favor of the spheres concerning user preference and self proprioception even if the users were not able to see their hand but just the controllers.

Spherical Controllers for VR

While the previous prototypes mainly were focused on detecting the effect of the spherical shape regarding perception and task performance (selection and rotation) we also work on more unconventional applications for the spherical tracked objects in VR while considering the core concepts of natural interaction and high learnability. Thus, we are developing a locomotion concept for navigation in virtual environments that is based on rotating a spherical handheld controller that is also capable of showing visual content such as a miniature variant of the environment. This prototype offers the prospect to gain insights on the impact of the shape and the constant tangible feedback provided by continuous rotation and its influence on risks such as cybersickness. We expect to gain part of these results by issuing a comparison to movement concepts utilizing standard VR controllers.

While the concept in a first version is solely focused on movement further extensions could regard selection and other types of interaction concepts such as tilting or even tossing the controller. In comparison to a classic trackball, the idea offers a full spherical shape, the capability to display content and the utilization of full six-degree-of-freedom

Figure 1: Our prototypes allow for the exploration of novel display technology such as this holographic visualization utilizing the space around the fully tangible object.

interaction. Positive results could point in the direction of application in the fields of public HMD usage where high learning times and long introduction for rather basic types of interaction (movement) are to be avoided.

6 CONCLUSION AND OUTLOOK

The outlined projects acknowledge the general assumption that full tangible embodiment provides an advantage above simulated or absent haptic feedback. The possibility of VR and AR to realize displays that are not possible in reality while still generating an accurate tangible sensation from a similarly shaped object opens interesting opportunities for future research.

Our current results show that tangible spherical objects have advantages in a number of use cases. However, the full potential of this method could lie within conjunction with more commonly used interaction techniques. For example, a sphere could play an important role in a toolkit of tangible objects in which it could take over the tasks of rotation and alignment while other shapes are more suited to other kinds of interaction. Apart from that, an application in research for gradually modulating various levels of real and simulated tangible feedback is interesting in its own right.

If we consider our environment to become more and more digitized in the future the attribution of virtual content to real-world objects is inescapable. Therefore, we see our research as a foundation that may expand to more complex shapes while building on the knowledge gained from basic objects just like a sphere.

REFERENCES

[1] O. R. Belloc, M. R. Nagamura, D. Fonseca, A. Rodrigues, D. A. R. Souza, C. S. Kurashima, M. M. Almeida, E. Z. Borba, R. D. Lopes, and M. K. Zuffo. 2017. OrbeVR: a handheld convex spherical virtual reality display. In *ACM SIGGRAPH 2017 Emerging Technologies*. ACM, 19.
[2] Francois Berard and Thibault Louis. 2017. The object inside: Assessing 3d examination with a spherical handheld perspective-corrected display. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 4396–4404.
[3] David Englmeier, Isabel Schönewald, Andreas Butz, and Tobias Höllerer. 2019. Sphere in Hand: Exploring Tangible Interaction with Immersive Spherical Visualizations. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE.
[4] Kenneth P Fishkin. 2004. A taxonomy for and analysis of tangible interfaces. *Personal and Ubiquitous Computing* 8, 5 (2004), 347–358.
[5] Hiroshi Ishii and Brygg Ullmer. 1997. Tangible bits: towards seamless interfaces between people, bits and atoms. In *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems*. ACM, 234–241.
[6] Stefanie Kettner, Christopher Madden, and Remo Ziegler. 2004. Direct rotational interaction with a spherical projection. In *Creativity & Cognition Symposium on Interaction: Systems, Practice and Theory*.
[7] Colin Ware and Jeff Rose. 1999. Rotating virtual objects with real handles. *ACM Transactions on Computer-Human Interaction (TOCHI)* 6, 2 (1999), 162–180.

Englmeier, D. (2019). Spherical Objects as an Opportunity to Investigate Physical Embodiment in Mixed Reality Environments. In *Mensch und Computer 2019 - Workshopband*, Bonn. Gesellschaft für Informatik e.V., doi:10.18420/muc2019-ws-454

It becomes clear that the outlined property to fully embody spherically shaped objects could constitute a major advantage in contrast to tracked items whose shape and center of mass could be distorted by tracking devices. Accordingly, we decided to investigate this potential further. First, we wanted to obtain insights on the effects of this kind of physical embodiment on the perception of three-dimensional information. Second, we wanted to test a first implementation that provides an input technique for a handheld spherical device. However, we set the main focus of the experiment on investigating a possible positive effect of topologically embodied spherical visualizations in contrast to visualizations coupled with a standard VR controller [P3].

> **RQ2:** *How does the full physical embodiment of spherical visualizations affect information perception?*

[P3] Feel the Globe: Enhancing the Perception of Immersive Spherical Visualizations with Tangible Proxies

Summary. In the course of this paper, we explore the opportunities that recent developments in the commercialization of virtual reality have created for enhancing human interaction with three-dimensional objects and visualizations. Spherical visualizations allow for convenient exploration of certain types of data. Our tangible sphere, exactly aligned with the sphere visualizations shown in VR, implements a very natural way of interaction and utilizes senses and skills trained in the real world. In a lab study, we investigate the effects of the perception of actually holding a virtual spherical visualization in hands. As use cases, we focus on surface visualizations that benefit from or require a rounded shape. We compared the usage of two differently sized acrylic glass spheres to a related interaction technique that utilizes VR controllers as proxies. On the one hand, our work is motivated by the ability to create a tangible, lightweight, handheld spherical display in VR that can hardly be realized in reality. On the other hand, gaining insights about the impact of a fully tangible embodiment of a virtual object on task performance, comprehension of patterns, and user behavior is important in its own right. After a description of the implementation we discuss the advantages and disadvantages of our approach, taking into account different handheld spherical displays utilizing outside and inside projection.

Englmeier, D., Schönewald, I., Butz, A., and Höllerer, T. (2019a). Feel the Globe: Enhancing the Perception of Immersive Spherical Visualizations with Tangible Proxies. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. doi:10.1109/VR.2019.8797869

2.3 Simulating Spherical Displays

As outlined in Section 1.4 the positive results from the previous study [P3] led to the concept of a large VR simulated spherical display (60 cm in diameter) that would allow for a deeper investigation of possible benefits of the spherical shape on measurable performance and user ratings. The reason why we conducted two studies for [P4] is rooted in the fact that only very little previous work on VR simulated spherical displays [65, 33], exists, especially in combination with a multi-touch surface [5]. Therefore, the second study followed the positive results from the first that showed the general viability of a VR simulated STUI.

> **RQ3:** *How do the physicality of spherical objects and their self-explanatory shape influence user performance and subjective perception?*

[P4] TangibleSphere – Interaction Techniques for Physical and Virtual Spherical Displays

Summary. Tangible interaction is generally assumed to provide benefits compared to other interaction styles due to its physicality. We demonstrate how this physicality can be brought to VR by means of TangibleSphere – a tracked, low-cost physical object that can (a) be rotated freely and (b) is overlaid with a virtual display. We present two studies, investigating performance in terms of efficiency and usability: the first study (N=16) compares TangibleSphere to a physical spherical display regarding accuracy and task completion time. We found comparable results for both types of displays. The second study (N=32) investigates the influence of physical rotation in more depth. We compare a pure VR condition to TangibleSphere in two conditions: one that allows actual physical rotation of the object and one that does not. Our findings show that physical rotation significantly improves accuracy and task completion time. These insights are valuable for researchers designing interaction techniques and interactive visualizations for spherical displays and for VR researchers aiming to incorporate physical touch into the experiences they design.

TangibleSphere – Interaction Techniques for Physical and Virtual Spherical Displays NordiCHI '20, October 25–29, 2020, Tallinn, Estonia

Figure 3: The tangible sphere was assembled in four steps (1-4 from left to right). First, we built a frame to join the two halves (a). Second, we created a stand (b) that allows the sphere to be held in a fixed position or to rotate it. We included a threaded rod (c) to firmly hold the VR tracker. Finally, we added a counterweight to the top part in order to balance the sphere during rotation (d).

TangibleSphere – Interaction Techniques for Physical and Virtual Spherical Displays

David Englmeier
LMU Munich
Munich, Germany
david.englmeier@ifi.lmu.de

Joseph O'Hagan
University of Glasgow
Glasgow, United Kingdom
j.ohagan.1@research.gla.ac.uk

Mengyi Zhang
LMU Munich
Munich, Germany
mengyi.zhang@campus.lmu.de

Florian Alt
Bundeswehr University
Munich, Germany
florian.alt@unibw.de

Andreas Butz
LMU Munich
Munich, Germany
butz@ifi.lmu.de

Tobias Höllerer
University of California Santa Barbara
Santa Barbara, California
holl@cs.ucsb.edu

Julie Williamson
University of Glasgow
Glasgow, United Kingdom
julie.williamson@glasgow.ac.uk

Figure 1: We present *TangibleSphere* – a setup that allows physical, interactive displays (in our case a spherical display with a diameter of 60 cm) to be simulated inexpensively in VR. We preserve the advantages of such displays' physical counterparts by enabling tangible interaction, such as free rotation in all directions. Comparing *TangibleSphere* to a purely virtual display, we found that allowing true physical rotation significantly improves accuracy and reduces task completion time.

ABSTRACT

Tangible interaction is generally assumed to provide benefits compared to other interaction styles due to its physicality. We demonstrate how this physicality can be brought to VR by means of *TangibleSphere* – a tracked, low-cost physical object that can (a) be rotated freely and (b) is overlaid with a virtual display. We present two studies, investigating performance in terms of efficiency and usability: the first study (N=16) compares *TangibleSphere* to a physical spherical display regarding accuracy and task completion time. We found comparable results for both types of displays. The second study (N=32) investigates the influence of physical rotation in more depth. We compare a pure VR condition to *TangibleSphere* in two conditions: one that allows actual physical rotation of the object and one that does not. Our findings show that physical rotation significantly improves accuracy and task completion time. These insights are valuable for researchers designing interaction techniques and interactive visualizations for spherical displays and for VR researchers aiming to incorporate physical touch into the experiences they design.

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from permissions@acm.org.
NordiCHI '20, October 25–29, 2020, Tallinn, Estonia
© 2020 Association for Computing Machinery.
ACM ISBN 978-1-4503-7579-5/20/10…$15.00
https://doi.org/10.1145/3419249.3420101

CCS CONCEPTS

- **Human-centered computing → Virtual reality.**

Englmeier, D., O'Hagan, J., Zhang, M., Alt, F., Butz, A., Höllerer, T., and Williamson, J. (2020). TangibleSphere – Interaction Techniques for Physical and Virtual Spherical Displays. In *Proceedings of the 11th Nordic Conference on Human-Computer Interaction: Shaping Experiences, Shaping Society*, NordiCHI '20, New York, NY, USA. Association for Computing Machinery, doi:10.1145/3419249.3420101

2.4 Advanced Interaction Techniques with STUIs

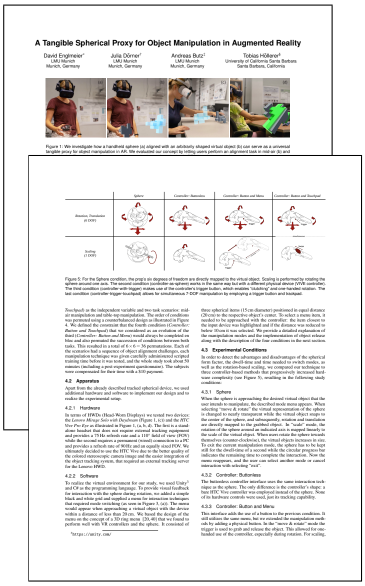
As one of the most interesting findings from the previous two studies [P4], we identified that user performance was best for the physical rotating display for the alignment task. In this combination, the STUI did not need to provide a multi-touch surface. In summary the less complex hardware performed superior in combination with a physical device that let users feel its rotation. Therefore, we decided to dedicate future studies also to exploring this phenomenon along mandatory contributions to RQ3.

> **RQ4:** *How can STUIs facilitate complex interaction techniques requiring translation, rotation, and scaling by their shape alone?*

2.4.1 A Spherical Interface for Object Manipulation

According to the aforementioned properties of TAR (Section 1.5), we decided to test an STUI for object manipulation in AR. Opposed to previous papers, we coupled the STUI with arbitrarily shaped objects that did not necessarily embody the sphere's outline.

[P5] A Tangible Spherical Proxy for Object Manipulation in Augmented Reality



A Tangible Spherical Proxy for Object Manipulation in Augmented Reality

David Englmeier* LMU Munich Munich, Germany
Julia Dörner† LMU Munich Munich, Germany
Andreas Butz‡ LMU Munich Munich, Germany
Tobias Höllerer§ University of California Santa Barbara Santa Barbara, California

Figure 1: We investigate how a handheld sphere (a) aligned with an arbitrarily shaped virtual object (b) can serve as a universal tangible proxy for object manipulation in AR. We evaluated our concept by letting users perform an alignment task in mid-air (b) and

Summary. In this paper, we explore how a familiarly shaped object (a sphere) can serve as a physical proxy to manipulate virtual objects in AR environments. Using the example of a tangible, handheld sphere, we demonstrate how irregularly shaped virtual objects can be selected, transformed, and released. After a brief description of the implementation of the tangible proxy, we present a buttonless interaction technique suited to the characteristics of the sphere. Users can select from two different interaction modes that allow for translation and rotation and for scaling the picked up object. In a user study (N=30), we compare our approach with three different controller-based methods that increasingly rely on physical buttons. As a use case, we focused on an alignment task that had to be completed in mid-air as well as on a flat surface. Results show that our concept has advantages over two of the controller-based methods regarding task completion time and user ratings. Our findings inform research on integrating tangible interaction into AR experiences.

Englmeier, D., Dörner, J., Butz, A., and Höllerer, T. (2020a). A Tangible Spherical Proxy for Object Manipulation in Augmented Reality. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. doi:10.1109/VR46266.2020.00041

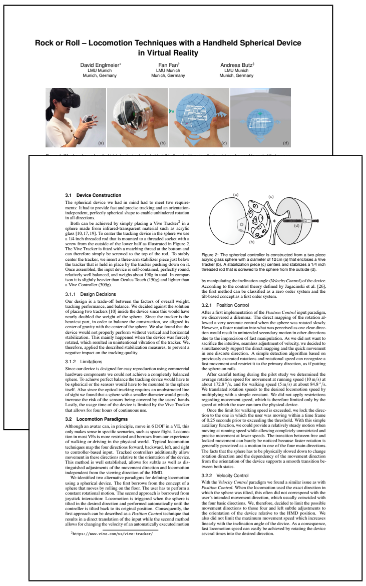
2.4.2 Spherical Interfaces for VR Locomotion

For the final use cases, we have chosen the problem of VR locomotion. As discussed, we contribute one study to each sub-domain (continuous/discrete). While first-person locomotion is a challenging topic in VR, we dedicated our approach to finding a viable method for an STUI that would provide a convincing metaphor. Consequently, we only used two rotation axes for locomotion and the transitional DOFs for positioning the sphere in the virtual space. We decided against using the up-axis for rotating the user's camera mainly because continuous locomotion in VR is prone to cybersickness [103, 34, 18]. This phenomenon describes an unpleasant feeling caused by a perceived disparity of virtual and real motion [61, 20]. It can be occur when virtual and real movement do not match but also by the virtual camera rotating, for instance, by additional controller input.

Accordingly, locomotion techniques often struggle on the one hand with limited physical space and on the other hand with cybersickness. While scholars have addressed both issues in multiple ways, a controller technique can mitigate these problems to some degree. Our main motivation from the user perspective lies in the self-explanatory character that an STUI could provide in this field. If the sphere is rotated in one direction and the user's avatar moves accordingly, this may provide an accessible technique that may appeal in particular to novice VR users.

[P6] Rock or Roll – Locomotion Techniques with a Handheld Spherical Device in Virtual Reality

Summary. In this work, we investigate the use of a handheld spherical object as a controller for locomotion in VR. Rotating the object controls avatar movement in two different ways: As a zero order controller, it is continuously rotated to the target position as if rolling a ball on the floor. As a first order controller, it is tilted like a joystick to determine the direction and speed of movement. We describe how our prototype was built from low-cost commercially available hardware and discuss our design decisions. Then we evaluate both locomotion techniques in a user study (N=20) and compare them to established methods using handheld VR controllers. Our prototype matched and in some cases outperformed these methods regarding task time and accuracy. All results were obtained without any usage instructions, indicating easy learnability. Some of our insights may transfer to interaction with other naturally shaped objects in VR experiences.



Rock or Roll – Locomotion Techniques with a Handheld Spherical Device in Virtual Reality

David Englmeier
LMU Munich
Munich, Germany

Fan Fan
LMU Munich
Munich, Germany

Andreas Butz
LMU Munich
Munich, Germany

Englmeier, D., Fan, F., and Butz, A. (2020b). Rock or Roll – Locomotion Techniques with a Handheld Spherical Device in Virtual Reality. In *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. doi:10.1109/ISMAR50242.2020.00089

The seventh publication [P7] tackles the problem of discrete VR locomotion and implements a system for avatar teleportation. Building on previous insights, we see the potential of a spherical device embodying a topologically matching miniature world. By simple rotation and translation of the device, we aim at naturally conveying more complex types of interaction to users that otherwise would, as in the compared controller-based methods, needed to be learned, e.g., by studying a button layout. This idea is particularly related to the scrolling interaction that at first sight appears as a naturally rotating spherical object when in reality, a viewport is scrolled along a planar WIM wrapped around a sphere.

In contrast to [P5], this implementation may allow for simultaneously 7-DOF interaction mainly due to the fact that the SWIM can always be coupled with the tangible device since it does not need to be placed at a specific position in the VE. As a result, we may be able to support scrolling and scaling with an STUI that can only provide its own shape. Overall, this would create the impression of a tangible interactive tiny planet that may present a compelling tool for VR locomotion.

[P7] Spherical World in Miniature: Exploring the Tiny Planets Metaphor for Discrete Locomotion in Virtual Reality

Summary. In the last presented paper, we explore the concept of a Spherical World in Miniature (SWIM) for discrete locomotion in Virtual Reality (VR). A SWIM wraps a planar WIM around a physically embodied sphere and thereby implements the metaphor of a tangible tiny planet that can be rotated and moved, enabling scrolling, scaling, and avatar teleportation. The scaling factor is set according to the sphere's distance from the HMD, while rotation moves the current viewing window. Teleportation is triggered with a dwell time when looking at the sphere and keeping it still. In a lab study (N=20), we compare our SWIM implementation to a planar WIM with an established VR controller technique using physical buttons. We test both concepts in a navigation task and also investigate the effects of two different screen sizes. Our results show that the SWIM, despite its less direct geometrical transformation, performed superior in most evaluations. It outperformed the planar WIM not only in terms of task completion time and accuracy but also in subjective ratings.

Spherical World in Miniature: Exploring the Tiny Planets Metaphor for Discrete Locomotion in Virtual Reality

David Englmeier* LMU Munich Munich, Germany
Wanja Sajko† LMU Munich Munich, Germany
Andreas Butz‡ LMU Munich Munich, Germany

Englmeier, D., Sajko, W., and Butz, A. (2021). Spherical World in Miniature: Exploring the Tiny Planets Metaphor for Discrete Locomotion in Virtual Reality. In *2021 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. doi:10.1109/VR50410.2021.00057

3

Discussion and Future Work

This thesis aims to explore STUIs to provide easily understood but yet effective input devices that leverage the advantages of tangible interfaces. First, we presented the technical concept that at low cost allows for constructing such devices and then demonstrated a total of five implementations [P3 - P7]. In the course of these, we explored the applicability of STUIs each in four different contexts: embodied visualization, display simulation, and more complex interaction techniques required for object manipulation and avatar locomotion.

For all application areas, we found various results that contribute to spherical devices as usable and self-explaining tools that could ultimately provide greater access to the MR space. In this concluding chapter, these findings are reflected upon in detail, and implications and future possibilities are discussed in light of the research questions outlined previously.

3.1 Protoyping STUIs in Mixed Reality

To answer RQ1, we can state that as for now, our approach of placing a Vive tracker inside an acrylic glass sphere constitutes a cost-effective and overall very performant solution to transfer spherical devices to MR. If we recall Fishkin's taxonomy [37] and the heuristics of Sharlin et al. [91] our devices qualify as TUIs (as long as we accept the fact of HMD output) and also for embodiment and metaphor levels that may help in explaining some of our results. Therefore, as a reflection on prototyping STUIs, we classify our implementations according to the above taxonomy (Table 3.1) as this may not be as straightforward as the fulfillment of the heuristics.

	Embodiment	**Metaphor**	**Description**
[P3]	*full*	*full /* *noun & verb*	Visually fully embodied, but the globe visualization offered extended functionality (selection).
[P4]	*full*	*noun /* *noun & verb*	Visually fully embodied, but only the rotating display builds an analogy to the behavior of a sphere.
[P5]	*nearby*	*noun & verb*	Embodiment of arbitrary objects that still behave largely analogous to the real world.
[P6]	*full*	*noun & verb*	Visually fully embodied, yet extended functionality (movement by rotation).
[P7]	*full / nearby*	*noun & verb*	Visually fully embodied only when zoomed out and extended functionality to manipulate a WIM.

Table 3.1: Embodiment and metaphor levels according to Fishkin [37] for papers [P3 - P7].

As outlined in Section 1.2 a simple spherical object such as a globe transferred to VR that acts just like its real counterpart would qualify for both *full* levels. However, if we extend the virtual representation both in functional and visual ways, we likely diminish both levels. If we again look at the example of a globe that we presented in [P3] and extend its functionality by adding a touch-sensitive surface, the requirement for *verb* would be no longer met since the real object does typically not support this kind of interaction.

One could argue that such a virtual sphere acts as a simulation of a theoretically existing display, and thus, the criteria for *full* metaphor are satisfied. However, this would presuppose users to recognize the display as such. While it may be an interesting thought to see a display as a metaphor itself and thereby convey functionality (for example, by building on visual concepts users might have of a certain kind of display), we discard the idea. We argue that the extension of functionality (visual and interactive) most likely results in a reduction of embodiment and metaphor levels since users would associate a virtual sphere more likely with its presented content than recognize it as a display. While this might change in the future, all of our demonstrated TUIs support a sphere's natural properties, for example, rotation. Therefore, regarding metaphor, a part of the *verb* level is met. Hence, we classify this case to diminish the *full* level to *verb and noun*. In the following discussion of the results, we include a short explanation of the taxonomic classification for each paper.

3.2 Embodied Spherical Information Visualization

As discussed, the reason that the outlined prototype of [P3] does not completely qualify for the *full* metaphor level is rooted in the possibility to select targets on the virtual globe. The other visualizations, however, exclusively provided 6-DOF interaction hence qualifying for full embodiment and metaphor. We tested the spherical prototypes in one exploratory and two analytical tasks and found advantages for the physically embodied visualizations for the spherical graph (RQ2). Users more often recognized a hidden pattern when analyzing the graph while generally rating the STUIs higher in perceived learnability and overall subjective feedback. To solve the exploratory task, users had to select a succession of countries on a globe. For the sphere conditions, we implemented a simulated multi-touch surface based on tracking gloves. Simultaneously, controller selection worked by pointing a ray at the desired spot before pulling a trigger. For this task, we neither found advantages for the sphere-based technique nor the controller.

The results regarding the spherical graph showed clear advantages for the tangible virtual spheres, leading to the question of what properties of the spherical device these might have been caused. The data from the exploratory task hinted that a simulated multi-touch surface is a viable approach, but other methods that may, in a greater sense, adept to the properties of a sphere appear as worth exploring. While we found a slight preference and faster task completion times for the smaller sphere, users would provide unconventional strategies for operating with the larger one. Some users placed the spheres on the floor and rotated them. Others sat down and placed the STUIs on their lap, subsequently exploring the physical space. This trial-and-error activity clearly demonstrates how a tangible object in VR can fulfill the eponymous heuristic. It is also interesting to note that users did not conduct any comparable actions with the VR controllers.

As a consequence, we can record a clear benefit for the VR simulated STUI, while comparable effects have been found for physical visualizations [49]. However, a future experiment could tackle the problem to what degree shape or embodiment have caused this advantage in perception. Another productive extension may be a further combination of previous work regarding spherical visualizations. For instance, Vega et al. [100] showed that virtual globes presenting statistical data [83] could communicate complex scientific concepts to a wider audience due to linking phenomena to a recognizable system (globe). A surrounding visualization based on previous research on immersive spherical visualizations [59, 107] may also be a rich research topic. Lastly, a comparison to systems requiring less [65] or no user instrumentation may be promising, yet the technical progress of movable displays with non-planar shapes [63] currently appears as the main hurdle.

3.3 Simulating Spherical Displays

For the fourth publication [P4], we conducted two studies, and the taxonomic classification is also twofold. In the visual sense, all tested prototypes fully embodied matching spherical content. The difference in classification for the metaphor is a result of the fixed conditions in contrast to the rotating ones not being able to provide this very property naturally associated with a sphere.

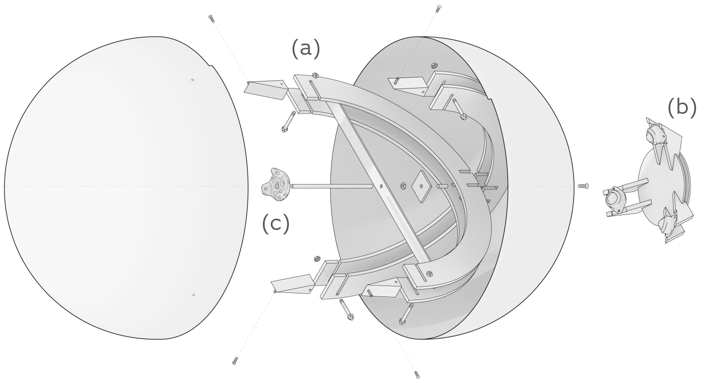


Figure 3.1: This illustration from [P4] describes the construction of our rotatable VR simulated display prototype. As with the other implementations, a Vive tracker (c) is mounted to the center of an acrylic glass sphere that, due to its diameter (60 cm), required a stabilization scaffold (a) and sat on a socked equipped with interchangeable ball-bearings (b).

We formulated RQ3 based on the motivation derived from the positive results for the spherical embodied visualizations. We answer this question by means of the second study. The first experiment's goal was to test for the general validity of a VR simulated spherical multi-touch display. While the positive effects for user performance and accuracy clearly substantiate the second study, the first study makes a clear point for VR as a useful prototyping tool. Following this principle, we constructed a prototype that resembled the outline and extended the capabilities (by physical rotation) of a real spherical display (Figure 3.1).

From the results of our second study comparing three levels of tangible feedback (no tangible feedback, simulated rotation on a static display, physical rotation) we can derive that despite users having to rotate a large device (diameter of 60 cm) they achieved significantly lower task completion times and higher accuracy than with both variants that only simulated rotation. These findings make a strong case for VR as a tool to simulate (tangible) displays in general and again emphasize the importance of physical feedback that allows users to sense weight, inertia, momentum, and rotation. In addition, we compared two selection techniques. One required users to simply tap on a target and another for which users had to align a fixed interface element with the desired target. Then, the selection was triggered with a dwell-time of one second. When supplied with the rotatable display, users were significantly faster but also more precise, while the alignment technique that did not require a multi-touch surface achieved the best results.

These unambiguous results lead to the conclusion that this selection technique, in combination with a movable spherical device, constitutes a viable approach that interestingly needs less complex hardware (no multi-touch surface) than the tapping technique. A comparison between the tangible and non-tangible conditions, both simulating rotation, showed no significant differences. This finding emphasizes our assumption that the advantages of the rotatable display are mainly rooted in the experienced and actively executed rotation of the device and not just its physical presence and felt passive haptic feedback. Therefore, the results from [P4] contribute to answering RQ3 by clearly exposing a positive impact on task completion time, accuracy, and subjective perception when the spherical device can be touched and physically rotated.

From an academic perspective, these conclusions substantiate VR as a prototyping tool [81, 57] allowing us to experience TUIs that can yet only exist in MR. Regarding spherical devices, the selection-by-alignment technique appears promising for further exploration since it can be facilitated by a sphere's properties alone. We also have to leave a further investigation of a multi-touch surface combined with physical interaction to future research. However, concluding from both studies, a VR simulation may facilitate such a project.

3.4 Advanced Interaction Techniques with STUIs

As mentioned, we formulated RQ3 based on these previous results and related work discussed in Section 1.5. This question of how STUIs can leverage a sphere's shape alone without implementing additional input options presents an overarching and important guideline that significantly influenced the design and use cases for publications [P5 - P7].

A Spherical Interface for Object Manipulation

A quick recapitulation: Tangible AR applications often rely on input devices that establish functionality by their shape. For example, a controller shaped like a shovel or a scoop [54, 42] indicates that it can be used to pick up a virtual object. However, our approach of picking up arbitrary objects with a sphere and manipulating them in RTS only constitutes *nearby* embodiment. Yet, we see the metaphor level of *noun and verb* still being met due to spatial 6-DOF interaction and the spherical shape clearly indicating rotation. The *full* level can not be reached because of the extended ability allowing for object scaling.

As a critical property of our technique, we have to emphasize that we implemented object manipulation based on two separate modes that had to be selected from a menu. We made this decision because we needed to enable object-scaling at the current object position and therefore only had a maximum of six degrees of freedom at our disposal per interaction mode (while simultaneous RTS would have required at least seven degrees of freedom). Following the constraint of only using the sphere we based the pick-up and menu interaction as before on the selection-by-alignment technique with a dwell-time of one second. We compared our approach to three controller techniques that would i) provide similar functionally at a different shape, ii) integrated a button to switch between modes and iii) enable full 7-DOF interaction utilizing buttons and a touchpad. While a comparison to the first condition would allow for conclusions regarding the shape alone, the second and third conditions would again generate insights on the benefits of more complex hardware.

The spherical device was faster than two controller conditions but was outperformed by the controller condition that supported simultaneous 7-DOF interaction and made use of buttons and a touchpad. The same picture showed for subjective user ratings. These results undoubtedly make a strong point for the spherical shape as a manipulation interface in AR but also for simultaneous RTS. An analysis of what interaction types caused the advantages for the spherical controllers revealed that most users achieved lower task times by the scaling interaction that we based on rotation around a central axis.

In summary, we again found solid evidence for a positive influence of the spherical shape on user performance and subjective ratings (RQ3) even with a more distant level of embodiment. Therefore, our approach solely based on a tangible sphere constitutes a viable solution for object manipulation in AR (RQ4). We can further confirm the usability of the selection-by-alignment technique that we used to select menu items and pick up objects. However, the switching between modes caused a significant disadvantage in task completion times that the surprisingly well-performing scaling-by-rotation strategy could not mitigate.

Consequently, the most crucial additional feature for our proxy solution [16, 23] would be an extension that would unify both interaction modes. This could be achieved either by implementing another interaction level such as buttons or touch sensitivity or by finding a viable gesture-based technique [84]. A multi-touch surface would generally enable the support of additional interaction techniques such as the selection of objects at a distance as recently explored by Louis et al. [66] in an AR setup.

Spherical Interfaces for VR Locomotion

While VR locomotion presents a challenging topic itself (Sections 1.5 and 2.4.2) for us, it provided an interesting opportunity to test novel spherical devices and to gain insights mainly regarding the research questions RQ3 and RQ4.

Implications from Continuous VR Locomotion

In the course of [P6], we tested an STUI supporting two different paradigms. For the zero-order system, it is continuously rotated towards a target, while for the first-order system, the angular tilt would set a constantly executed velocity. Both paradigms enabled movement in four directions, which we mapped to pitch and roll angles, while the yaw angle regarding locomotion remained unused. We transferred all six degrees of freedom to a matching visualization but only utilized two for actual first-person locomotion. Consequently, the visual representation (a spherical grid that, in analogy to a snowglobe, contained a WIM as a navigation aid) qualifies for *full* embodiment. Likewise, the functionality of movement prevents a similar level for the metaphor classification. While we again see a clear resemblance to the real-world properties of a rotating sphere, we can set this level to *noun and verb*.

Despite the lower scores that both sphere-based paradigms received in terms of subjective ratings, we found significant advantages for the zero-order system (in comparison to the first-order system and two matching controller conditions). Still, the subjective ratings were clearly in favor of a position-control technique that made use of the VR controller's directional touchpad. However, users were more precise and faster when using the STUI in combination with the zero-order paradigm. Additionally, we emphasize the easy learnability of this paradigm. Users were able to execute avatar movement without any given instructions. As with other approaches, for instance, requiring the constant execution of a gesture [56] study participants subjectively disliked the constant activity while some also reported a greater feeling of involvement.

Overall, these findings answer RQ3 in showing the potential of an STUI to embody an efficient first-order system. As for answering RQ4, we again find evidence that an STUI can support complex interaction by its shape if applying the right paradigm, in our case, the direct translation of rotation to movement. Future research could provide further insights on a possible use case for the yaw angle, while additions, for example, allowing to switch between a zero- and a first-order system a multi-touch surface could reduce physical demand or provide more refined interaction with the VE.

Implications from Discrete VR Locomotion

The taxonomic classification for our SWIM technique may be less straightforward than for the others. At first, in terms of embodiment, the virtual content is only fully embodied as long as possible elevations (e.g., mountains, buildings) are not, due to the current zoom-level, protruding visibly from the surface. Second, for the metaphor, a SWIM may appear as a handheld globe or tiny planet but does not exactly behave like one. At the same time, we use this effect to convey interaction techniques. The scrolling functionality only looks like a rotating sphere, but in fact, the miniature world is scrolled, which may eventually require many full rotations to get back to a starting point compared to just one with a simple globe. As shown in [P3], such would qualify for full embodiment. The SWIM, however, provides a strong resemblance to a sphere but extends its capabilities by scrolling and scaling.

In total, the SWIM technique built on a sum of advantages that we found for STUIs: it makes use of a strong metaphor that allows the sensation of rotation, thereby communicates more complex interaction, and utilizes the selection-by-alignment technique for teleportation. We mapped the scrolling interaction linearly to the yaw and pitch angles of the handheld sphere. Since only these two degrees of freedom are needed for scrolling the viewport, the roll angle remained unused. However, we found that for natural behavior, it is important to map the rotation of the plane in which we placed the planar WIM to this angle. This means that if the sphere is rolled, we rotate the WIM around a pivot point defined by the intersection of the user's camera vector and the WIM plane. The general working principle is shown in Figure 3.2.

After analyzing the results from [P7], a clear picture showed: the SWIM concept clearly outperformed a controller method inspired by the classical WIM implementation. The controller method was based on two separate VR controllers, one for holding the map and one for pointing and teleportation. Particularly noteworthy herewith is the fact that users did not rate the spherical distortion as negative. On the contrary: some even found the distortion helpful for spatial orientation. Therefore, we can conclude that for a spherical miniature world, a tangible spherical device is capable of communicating complex interaction such as scrolling and zooming to users (RQ4) while providing advantages in terms of task completion time, accuracy, and subjective ratings (RQ3) and maintaining a simple and easily understood interaction metaphor.

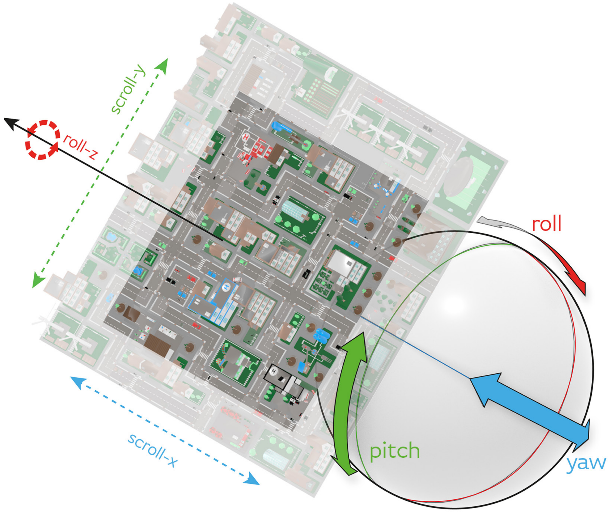


Figure 3.2: This sketch from [P7] illustrates the working principle of the SWIM technique. Pitch and yaw angles scroll the viewport while the roll angle rotates the WIM in place. After projecting the planar WIM to the sphere, it convincingly represents a handheld planet.

As flawless as discrete locomotion with the SWIM technique performed, an extension in the direction of a multi-touch surface appears as meaningful to additionally support object manipulation. Future work could also provide further insights into the advantages of the spherical shape by comparing it to a tangible planar WIM [77, 105] utilizing similar interaction. We also want to emphasize the usability of the applied selection-by-alignment technique that we again could demonstrate. Lastly, an application and evaluation in the environment of an actual geographic application seems exciting and could further substantiate the concept based on a spherical shape conveying complex interacting by a catchy metaphor.

3.5 Closing Remarks

> *"Everything in nature takes its form from the sphere, the cone and the cylinder."*
>
> *Paul Cezanne*

This thesis has presented a first exploration of the capabilities of STUIs completely simulated in MR. Following the initial finding of the spherical devices' positive effect on information perception, we investigated STUIs by simulating spherical displays as well as studying their capability to support object manipulation and two paradigms for VR locomotion. Our results have shown that STUIs can often support these demanding use cases by only relying on their shape while eventually outperforming established and more complex controller techniques.

The crucial finding from our fourth publication that not the physical shape of a sphere may constitute an interactive benefit but its property to communicate a self-inflicted feeling of mass, inertia, and momentum to the user's fingertips has significantly shaped the course of this dissertation. This result adds to the assumption that STUIs can afford the possible property of TUIs to experience a given input directly at fingertips and palms by means of rotation like hardly any other device. Due to VR simulation, we have shown that they also leverage the advantages of low weight and display simulation in general. By the demonstrated high levels for embodiment and metaphor and insights such as the convincing performance of the selection-by-alignment technique, this dissertation may inspire further research efforts to contribute to the overarching goals of enriching interaction in a subsequently more accessible user experience.

As a natural property of the MR space, our findings may transfer to other virtual spaces, and thus the discussed techniques could be applied in different contexts. As we have shown with the SWIM technique, this context could be a reiteration of a classical interaction technique that may eventually profit from a tangible spherical shape or challenging fields such as VR locomotion in general. The simplicity and cost-effectiveness of the demonstrated prototypes strongly facilitate such a future exploration. Our results have uncovered profound evidence for VR as a prototyping tool for novel displays and input devices and as a space for experiencing capabilities that can yet not be realized outside MR. These findings clear the path to manifold future studies. Be it the implementation of a multi-touch surface in conjunction with an STUI, the exploration of simulated holographic content, or the subsequent extension of the evaluated use cases; this work may form the basis for many opportunities to deepen our understanding of elemental geometric shapes acting as tangible interfaces in MR.

STUIs are not only transitioning from technology demonstrators such as spherical displays to versatile input devices [66] but, as demonstrated, undoubtedly have the potential of constituting viable input devices that may, in the right context, provide the best possible solution for interaction. Even if the vision of Sutherland [97] and Ishii [51] of displays forming matter creating completely tangible bits might come true someday, users will most likely still benefit from a simple and yet natural interaction metaphor such as a tangible sphere.

LIST OF FIGURES

LIST OF TABLES

BIBLIOGRAPHY

[1] Al Zayer, M., MacNeilage, P., and Folmer, E. (2018). Virtual locomotion: a survey. *IEEE transactions on visualization and computer graphics*, 26(6):2315–2334.

[2] Ameler, T., Blohme, K., Brandt, L., Brüngel, R., Hensel, A., Huber, L., Kuper, F., Swoboda, J., Warnecke, M., Warzecha, M., et al. (2019). A comparative evaluation of steamvr tracking and the optitrack system for medical device tracking. In *2019 41st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, pages 1465–1470. IEEE.

[3] Bell, M. W. (2008). Toward a definition of virtual worlds. *Journal For Virtual Worlds Research*, 1(1).

[4] Belloc, O., Nagamura, M., Fonseca, D., Rodrigues, A., Souza, D., Kurashima, C. S., Almeida, M., Borba, E. Z., Lopes, R., and Zuffo, M. K. (2017). OrbeVR: a handheld convex spherical virtual reality display. In *ACM SIGGRAPH 2017 Emerging Technologies*, page 19. ACM.

[5] Benko, H., Wilson, A. D., and Balakrishnan, R. (2008). Sphere: multi-touch interactions on a spherical display. In *Proceedings of the 21st annual ACM symposium on User interface software and technology*, pages 77–86. ACM.

[6] Berard, F. and Louis, T. (2017). The object inside: Assessing 3d examination with a spherical handheld perspective-corrected display. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pages 4396–4404. ACM.

[7] Berard, F. and Louis, T. (2018). A Low-Latency, High-Precision Handheld Perspective Corrected Display. In *Adjunct Proceedings of the IEEE International Symposium for Mixed and Augmented Reality 2018*.

[8] Berger, L. and Wolf, K. (2018). WIM: fast locomotion in virtual reality with spatial orientation gain & without motion sickness. In *Proceedings of the 17th International Conference on Mobile and Ubiquitous Multimedia*, pages 19–24.

[9] Billinghurst, M., Clark, A., and Lee, G. (2015). A survey of augmented reality.

[10] Billinghurst, M., Grasset, R., and Looser, J. (2005). Designing augmented reality interfaces. *ACM Siggraph Computer Graphics*, 39(1):17–22.

[11] Billinghurst, M., Kato, H., Poupyrev, I., et al. (2008). Tangible augmented reality. *Acm siggraph asia*, 7(2):1–10.

[12] Birnbacher, D. (2006). *Natürlichkeit*. Walter de Gruyter.

[13] Bolton, J., Kim, K., and Vertegaal, R. (2011). SnowGlobe: A Spherical Fish-Tank VR Display. In *CHI '11 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '11, page 1159–1164, New York, NY, USA. Association for Computing Machinery, doi:10.1145/1979742.1979719.

[14] Burdea, G. C. and Coiffet, P. (2003). *Virtual reality technology*. John Wiley & Sons.

[15] Cambridge-Dictionary (2021). Virtual. Retrieved 8 Apr. 2021 from `https://dictionary.cambridge.org/de/worterbuch/englisch/virtual`.

[16] Cheng, L.-P., Ofek, E., Holz, C., Benko, H., and Wilson, A. D. (2017). Sparse haptic proxy: Touch feedback in virtual environments using a general passive prop. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pages 3718–3728.

[17] Companje, R., Van Dijk, N., Hogenbirk, H., and Mast, D. (2006). Globe4D: time-traveling with an interactive four-dimensional globe. In *Proceedings of the 14th ACM international conference on Multimedia*, pages 959–960. ACM.

[18] Coomer, N., Bullard, S., Clinton, W., and Williams-Sanders, B. (2018). Evaluating the effects of four VR locomotion methods: joystick, arm-cycling, point-tugging, and teleporting. In *Proceedings of the 15th ACM Symposium on Applied Perception*, page 7. ACM.

[19] Cruz-Neira, C., Sandin, D. J., DeFanti, T. A., Kenyon, R. V., and Hart, J. C. (1992). The CAVE: audio visual experience automatic virtual environment. *Communications of the ACM*, 35(6):64–73.

[20] Davis, S., Nesbitt, K., and Nalivaiko, E. (2014). A systematic review of cybersickness. In *Proceedings of the 2014 Conference on Interactive Entertainment*, pages 1–9. ACM.

[21] Denning, P. J. and Lewis, T. G. (2016). Exponential laws of computing growth. *Communications of the ACM*, 60(1):54–65.

[22] Dörner, R., Broll, W., Grimm, P., and Jung, B. (2013). Virtual und Augmented Reality. *Grundlagen und Methoden der Virtuellen und Augmentierten Realität. Berlin und Heidelberg: Springer*.

[23] Drogemuller, A., Walsh, J., Smith, R. T., Adcock, M., and Thomas, B. H. (2021). Turning everyday objects into passive tangible controllers. In *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction*, pages 1–4.

[24] Du, F., Cao, N., Lin, Y.-R., Xu, P., and Tong, H. (2017). iSphere: Focus+ Context Sphere Visualization for Interactive Large Graph Exploration. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pages 2916–2927. ACM.

[25] Dunleavy, M., Dede, C., and Mitchell, R. (2009). Affordances and limitations of immersive participatory augmented reality simulations for teaching and learning. *Journal of science Education and Technology*, 18(1):7–22.

[26] Englmeier, D. (2019). Spherical Objects as an Opportunity to Investigate Physical Embodiment in Mixed Reality Environments. In *Mensch und Computer 2019 - Workshopband*, Bonn. Gesellschaft für Informatik e.V., doi:10.18420/muc2019-ws-454.

[27] Englmeier, D., Dörner, J., Butz, A., and Höllerer, T. (2020a). A Tangible Spherical Proxy for Object Manipulation in Augmented Reality. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. doi:10.1109/VR46266.2020.00041.

[28] Englmeier, D., Fan, F., and Butz, A. (2020b). Rock or Roll – Locomotion Techniques with a Handheld Spherical Device in Virtual Reality. In *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. doi:10.1109/ISMAR50242.2020.00089.

[29] Englmeier, D., O'Hagan, J., Zhang, M., Alt, F., Butz, A., Höllerer, T., and Williamson, J. (2020). TangibleSphere – Interaction Techniques for Physical and Virtual Spherical Displays. In *Proceedings of the 11th Nordic Conference on Human-Computer Interaction: Shaping Experiences, Shaping Society*, NordiCHI '20, New York, NY, USA. Association for Computing Machinery, doi:10.1145/3419249.3420101.

[30] Englmeier, D., Sajko, W., and Butz, A. (2021). Spherical World in Miniature: Exploring the Tiny Planets Metaphor for Discrete Locomotion in Virtual Reality. In *2021 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. doi:10.1109/VR50410.2021.00057.

[31] Englmeier, D., Schönewald, I., Butz, A., and Höllerer, T. (2019a). Feel the Globe: Enhancing the Perception of Immersive Spherical Visualizations with Tangible Proxies. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. doi:10.1109/VR.2019.8797869.

[32] Englmeier, D., Schönewald, I., Butz, A., and Höllerer, T. (2019b). Sphere in Hand: Exploring Tangible Interaction with Immersive Spherical Visualizations. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. doi:10.1109/VR.2019.8797887.

[33] Fafard, D., Stavness, I., Dechant, M., Mandryk, R., Zhou, Q., and Fels, S. (2019). FTVR in VR: Evaluation of 3D Perception With a Simulated Volumetric Fish-Tank Virtual Reality Display. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI '19, page 1–12, New York, NY, USA. Association for Computing Machinery, doi:10.1145/3290605.3300763.

[34] Fernandes, A. S. and Feiner, S. K. (2016). Combating VR sickness through subtle dynamic field-of-view modification. In *2016 IEEE Symposium on 3D User Interfaces (3DUI)*, pages 201–210. IEEE.

[35] Ferreira, F., Cabral, M., Belloc, O., Miller, G., Kurashima, C., de Deus Lopes, R., Stavness, I., Anacleto, J., Zuffo, M., and Fels, S. (2014a). Spheree: a 3D perspective-corrected interactive spherical scalable display. In *ACM SIGGRAPH 2014 Posters*, page 86. ACM.

[36] Ferreira, F., Cabral, M., Belloc, O., Miller, G., Kurashima, C., de Deus Lopes, R., Stavness, I., Anacleto, J., Zuffo, M., and Fels, S. (2014b). Spheree: A 3D Perspective-Corrected Interactive Spherical Scalable Display. In *ACM SIGGRAPH 2014 Posters*, SIGGRAPH '14, New York, NY, USA. Association for Computing Machinery, doi:10.1145/2614217.2630585.

[37] Fishkin, K. P. (2004). A taxonomy for and analysis of tangible interfaces. *Personal and Ubiquitous computing*, 8(5):347–358.

[38] Fishkin, K. P., Gujar, A., Harrison, B. L., Moran, T. P., and Want, R. (2000). Embodied user interfaces for really direct manipulation. *Communications of the ACM*, 43(9):74–80.

[39] Fishkin, K. P., Moran, T. P., and Harrison, B. L. (1998). Embodied user interfaces: Towards invisible user interfaces. In *IFIP International Conference on Engineering for Human-Computer Interaction*, pages 1–18. Springer.

[40] Fitzmaurice, G. W. et al. (1997). *Graspable user interfaces.* Citeseer.

[41] Fitzmaurice, G. W., Ishii, H., and Buxton, W. A. (1995). Bricks: laying the foundations for graspable user interfaces. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 442–449.

[42] Fjeld, M. and Voegtli, B. M. (2002). Augmented chemistry: An interactive educational workbench. In *Proceedings. International Symposium on Mixed and Augmented Reality*, pages 259–321. IEEE.

[43] Gabbard, J. L., Swan, J. E., and Hix, D. (2006). The Effects of Text Drawing Styles, Background Textures, and Natural Lighting on Text Legibility in Outdoor Augmented Reality. *Presence: Teleoperators and Virtual Environments*, 15(1):16–32, doi:10.1162/pres.2006.15.1.16.

[44] Grossman, T., Wigdor, D., and Balakrishnan, R. (2004). Multi-Finger Gestural Interaction with 3d Volumetric Displays. In *Proceedings of the 17th Annual ACM Symposium on User Interface Software and Technology*, UIST '04, page 61–70, New York, NY, USA. Association for Computing Machinery, doi:10.1145/1029632.1029644.

[45] Heeter, C. (1992). Being there: The subjective experience of presence. *Presence: Teleoperators & Virtual Environments*, 1(2):262–271.

[46] Heim, M. (1994). *The metaphysics of virtual reality.* Oxford University Press.

[47] Hettiarachchi, A. and Wigdor, D. (2016). Annexing reality: Enabling opportunistic use of everyday objects as tangible proxies in augmented reality. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pages 1957–1967.

[48] Hinckley, K., Pausch, R., Goble, J. C., and Kassell, N. F. (1994). Passive Real-world Interface Props for Neurosurgical Visualization. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '94, pages 452–458, New York, NY, USA. ACM, doi:10.1145/191666.191821.

[49] Hogan, T., Hornecker, E., Stusak, S., Jansen, Y., Alexander, J., Moere, A. V., Hinrichs, U., and Nolan, K. (2016). Tangible Data, explorations in data physicalization. In *Proceedings of the TEI'16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*, pages 753–756.

[50] III, J. J. A., III, L. P., Shelton, K., Kramer, L. J., Williams, S. P., Bailey, R. E., and Norman, R. M. (2007). Design and testing of an unlimited field-of-regard synthetic vision head-worn display for commercial aircraft surface operations. In Verly, J. G. and Guell, J. J., editors, *Enhanced and Synthetic Vision 2007*, volume 6559, pages 136 – 154, Bellingham, WA, USA. International Society for Optics and Photonics, SPIE, doi:10.1117/12.719695.

[51] Ishii, H. and Ullmer, B. (1997). Tangible bits: towards seamless interfaces between people, bits and atoms. In *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems*, pages 234–241.

[52] Jagacinski, R. J. and Flach, J. M. (2003). *Control theory for humans: Quantitative approaches to modeling performance*. CRC Press.

[53] Jose, R., Lee, G. A., and Billinghurst, M. (2016). A comparative study of simulated augmented reality displays for vehicle navigation. In *Proceedings of the 28th Australian conference on computer-human interaction*, pages 40–48.

[54] Kato, H., Billinghurst, M., Poupyrev, I., Imamoto, K., and Tachibana, K. (2000). Virtual object manipulation on a table-top AR environment. In *Proceedings IEEE and ACM International Symposium on Augmented Reality (ISAR 2000)*, pages 111–119. Ieee.

[55] Kettner, S., Madden, C., and Ziegler, R. (2004). Direct rotational interaction with a spherical projection. In *Creativity & Cognition Symposium on Interaction: Systems, Practice and Theory*, Sydney, Australia. Creativity & Cognition Studios Press.

[56] Kim, J.-S., Gračanin, D., Matković, K., and Quek, F. (2008). Finger walking in place (FWIP): A traveling technique in virtual environments. In *International Symposium on Smart Graphics*, pages 58–69. Springer.

[57] Kim, S. and Dey, A. K. (2009). Simulated augmented reality windshield display as a cognitive mapping aid for elder driver navigation. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 133–142.

[58] Klopfer, E. and Sheldon, J. (2010). Augmenting your own reality: Student authoring of science-based augmented reality games. *New directions for youth development*, 2010(128):85–94.

[59] Kwon, O.-H., Muelder, C., Lee, K., and Ma, K.-L. (2016). A study of layout, rendering, and interaction methods for immersive graph visualization. *IEEE transactions on visualization and computer graphics*, 22(7):1802–1815.

[60] Lanier, J. (1992). Virtual reality: The promise of the future. *Interactive Learning International*, 8(4):275–79.

[61] LaViola Jr, J. J. (2000). A discussion of cybersickness in virtual environments. *ACM Sigchi Bulletin*, 32(1):47–56.

[62] Lee, C., Bonebrake, S., Bowman, D. A., and Höllerer, T. (2010). The role of latency in the validity of AR simulation. In *2010 IEEE Virtual Reality Conference (VR)*, pages 11–18. IEEE.

[63] Li, Z., Miyafuji, S., Wu, E., Kuzuoka, H., Yamashita, N., and Koike, H. (2019). OmniGlobe: An Interactive I/O System For Symmetric 360-Degree Video Communication. In *Proceedings of the 2019 on Designing Interactive Systems Conference*, pages 1427–1438.

[64] Liang, J. and Green, M. (1994). JDCAD: A highly interactive 3D modeling system. *Computers & graphics*, 18(4):499–506.

[65] Louis, T. and Berard, F. (2017). Superiority of a Handheld Perspective-Coupled Display in Isomorphic Docking Performances. In *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces*, pages 72–81. ACM.

[66] Louis, T., Troccaz, J., Rochet-Capellan, A., and Bérard, F. (2020). GyroSuite: General-Purpose Interactions for Handheld Perspective Corrected Displays. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*, UIST '20, page 1248–1260, New York, NY, USA. Association for Computing Machinery, doi:10.1145/3379337.3415893.

[67] Machida, T. (2002). GEO-COSMOS: world's first spherical display. In *ACM SIGGRAPH 2002 conference abstracts and applications*, pages 189–189.

[68] MacIntyre, B. (2002). Authoring 3d mixed reality experiences: Managing the relationship between the physical and virtual worlds. *At ACM SIGGRAPH and Eurographics Campfire: Production Process of 3D Computer Graphics Applications-Structures, Roles and Tools, Snowbird, UT*, pages 1–5.

[69] MacKenzie, I. S. and Buxton, W. (1992). Extending Fitts' law to two-dimensional tasks. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 219–226.

[70] Markova, M. S., Wilson, S., and Stumpf, S. (2012). Tangible user interfaces for learning. *International Journal of Technology Enhanced Learning*, 4(3-4):139–155.

[71] Marshall, P. (2007). Do tangible interfaces enhance learning? In *Proceedings of the 1st international conference on Tangible and embedded interaction*, pages 163–170.

[72] Merriam-Webster (2021). Virtual. Retrieved 8 Apr. 2021 from `https://www.merriam-webster.com/dictionary/virtual`.

[73] Meyer, K., Applewhite, H. L., and Biocca, F. A. (1992). A survey of position trackers. *Presence: Teleoperators & Virtual Environments*, 1(2):173–200.

[74] Milgram, P., Drascic, D., Grodski, J. J., Restogi, A., Zhai, S., and Zhou, C. (1995a). Merging real and virtual worlds. In *Proceedings of IMAGINA*, volume 95, pages 218–230.

[75] Milgram, P., Takemura, H., Utsumi, A., and Kishino, F. (1995b). Augmented reality: A class of displays on the reality-virtuality continuum. In *Telemanipulator and telepresence technologies*, volume 2351, pages 282–292. International Society for Optics and Photonics.

[76] Mithen, S. (1997). The prehistory of the mind. *Cambridge Archaeological Journal*, 7:269–269.

[77] Pausch, R., Burnette, T., Brockway, D., and Weiblen, M. E. (1995). Navigation and locomotion in virtual worlds via flight into hand-held miniatures. In *Proceedings of the 22nd annual conference on Computer graphics and interactive techniques*, pages 399–400.

[78] Pausch, R., Proffitt, D., and Williams, G. (1997). Quantifying immersion in virtual reality. In *Proceedings of the 24th annual conference on Computer graphics and interactive techniques*, pages 13–18.

[79] Peer, A., Ullich, P., and Ponto, K. (2018). Vive tracking alignment and correction made easy. In *2018 IEEE conference on virtual reality and 3D user interfaces (VR)*, pages 653–654. IEEE.

[80] Poupyrev, I., Ichikawa, T., Weghorst, S., and Billinghurst, M. (1998). Egocentric object manipulation in virtual environments: empirical evaluation of interaction techniques. In *Computer graphics forum*, volume 17, pages 41–52. Wiley Online Library.

[81] Ragan, E., Wilkes, C., Bowman, D. A., and Hollerer, T. (2009). Simulation of augmented reality systems in purely virtual environments. In *2009 IEEE Virtual Reality Conference*, pages 287–288. IEEE.

[82] Rolland, J. P., Davis, L., Baillot, Y., et al. (2001). A survey of tracking technology for virtual environments. *Fundamentals of wearable computers and augmented reality*, 1(1):67–112.

[83] Satriadi, K. A., Ens, B., Czauderna, T., Cordeil, M., and Jenny, B. (2021). Quantitative Data Visualisation on Virtual Globes.

[84] Schlömer, T., Poppinga, B., Henze, N., and Boll, S. (2008). Gesture recognition with a Wii controller. In *Proceedings of the 2nd international conference on Tangible and embedded interaction*, pages 11–14.

[85] Schmalstieg, D., Encarnação, L. M., and Szalavári, Z. (1999). Using transparent props for interaction with the virtual table. In *Proceedings of the 1999 symposium on Interactive 3D graphics*, pages 147–153. ACM.

[86] Schmalstieg, D., Fuhrmann, A., Hesina, G., Szalavári, Z., Encarnaçao, L. M., Gervautz, M., and Purgathofer, W. (2002). The studierstube augmented reality project. *Presence: Teleoperators & Virtual Environments*, 11(1):33–54.

[87] Schmalstieg, D., Fuhrmann, A., Szalavari, Z., and Gervautz, M. (1996). Studierstube-an environment for collaboration in augmented reality. In *CVE'96 Workshop Proceedings*, volume 19.

[88] Schroeder, R. (2006). Being there together and the future of connected presence. *Presence: Teleoperators and Virtual Environments*, 15(4):438–454.

[89] Schroeder, R. (2008). Defining virtual worlds and virtual environments. *Journal For Virtual Worlds Research*, 1(1).

[90] Shaer, O. and Hornecker, E. (2010). *Tangible user interfaces: past, present, and future directions*. Now Publishers Inc.

[91] Sharlin, E., Watson, B., Kitamura, Y., Kishino, F., and Itoh, Y. (2004). On tangible user interfaces, humans and spatiality. *Personal and Ubiquitous Computing*, 8(5):338–346.

[92] Song, P., Goh, W. B., Hutama, W., Fu, C.-W., and Liu, X. (2012). A handle bar metaphor for virtual object manipulation with mid-air interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 1297–1306. ACM.

[93] Steed, A. (2006). Towards a general model for selection in virtual environments. In *3D User Interfaces (3DUI'06)*, pages 103–110. IEEE.

[94] Steinkuehler, C. A. and Williams, D. (2006). Where everybody knows your (screen) name: Online games as "third places". *Journal of computer-mediated communication*, 11(4):885–909.

[95] Stevenson, A. (2010). *Oxford dictionary of English*. Oxford University Press, USA.

[96] Stoakley, R., Conway, M. J., and Pausch, R. (1995). Virtual reality on a WIM: interactive worlds in miniature. In *CHI*, volume 95, pages 265–272.

[97] Sutherland, I. (1965). The ultimate display.

[98] Sutherland, I. E. (1968). A head-mounted three dimensional display. In *Proceedings of the December 9-11, 1968, fall joint computer conference, part I*, pages 757–764.

[99] Ushida, K., Harashima, H., and Ishikawa, J. (2003). i-ball 2: An Interaction Platform with a Crystal-Ball-Like Display for Multiple Users. In *ICAT*.

[100] Vega, K., Wernert, E., Beard, P., Gniady, C., Reagan, D., Boyles, M., and Eller, C. (2014). Visualization on spherical displays: Challenges and opportunities. *Proceedings of the IEEE VIS Arts Program (VISAP)*, pages 108–116.

[101] Wang, W. (2020). Difference between the Real World and Virtual World. In *Multidisciplinary Digital Publishing Institute Proceedings*, volume 47, page 35.

[102] Ware, C. and Osborne, S. (1990). Exploration and virtual camera control in virtual three dimensional environments. *ACM SIGGRAPH computer graphics*, 24(2):175–183.

[103] Whitton, M. C., Cohn, J. V., Feasel, J., Zimmons, P., Razzaque, S., Poulton, S. J., McLeod, B., and Brooks, F. P. (2005). Comparing VE locomotion interfaces. In *IEEE Proceedings. VR 2005. Virtual Reality, 2005.*, pages 123–130. IEEE.

[104] Wilson, P. T., Kalescky, W., MacLaughlin, A., and Williams, B. (2016). VR locomotion: walking> walking in place> arm swinging. In *Proceedings of the 15th ACM SIGGRAPH Conference on Virtual-Reality Continuum and Its Applications in Industry-Volume 1*, pages 243–249. ACM.

[105] Wingrave, C. A., Haciahmetoglu, Y., and Bowman, D. A. (2006). Overcoming world in miniature limitations by a scaled and scrolling WIM. In *3D User Interfaces (3DUI'06)*, pages 11–16. IEEE.

[106] Witmer, B. G. and Singer, M. J. (1998). Measuring Presence in Virtual Environments: A Presence Questionnaire. *Presence: Teleoperators and Virtual Environments*, 7(3):225–240, doi:10.1162/105474698565686.

[107] Yang, Y., Dwyer, T., Jenny, B., Marriott, K., Cordeil, M., and Chen, H. (2018). Origin-Destination Flow Maps in Immersive Environments. *IEEE transactions on visualization and computer graphics*.

[108] Zhou, F., Duh, H. B.-L., and Billinghurst, M. (2008). Trends in augmented reality tracking, interaction and display: A review of ten years of ISMAR. In *Proceedings of the 7th IEEE/ACM international symposium on mixed and augmented reality*, pages 193–202. IEEE Computer Society.

[109] Zhou, Q., Miller, G., Wu, K., Correa, D., and Fels, S. (2017). Automatic calibration of a multiple-projector spherical fish tank vr display. In *Applications of Computer Vision (WACV), 2017 IEEE Winter Conference on*, pages 1072–1081, New York, NY, USA. IEEE, IEEE.

[110] Zhou, Y. and Wang, M. (2015). Tangible user interfaces in learning and education. *International Encyclopedia of the Social & Behavioral Sciences*, (20-25).

[111] Zuckerman, O. and Gal-Oz, A. (2013). To TUI or not to TUI: Evaluating performance and preference in tangible vs. graphical user interfaces. *International Journal of Human-Computer Studies*, 71(7-8):803–820.

Appendices

A

Original Publications

Table A.1 describes my own and others' contributions to all included publications. Afterward, links to original papers are given in the order in which they are presented in this thesis [P1 - P7]. For any future reference, please refer to these published versions.

	My Contribution	**Contributions of others**
[P1]	I developed the design and built the hardware prototypes and was the leading author of the resulting publication.	Isabel Schönewald contributed to the construction; Andreas Butz and Tobias Höllerer supervised the project and edited the final version of the paper.
[P2]	I conducted the literature survey, developed the outlined position, and authored the publication.	No contribution of others.
[P3]	I developed the original research idea and supervised the implementation and the study. I authored the resulting publication.	Isabel Schönewald implemented and conducted the study; Andreas Butz and Tobias Höllerer supervised the project and edited the final version of the paper.
[P4]	I developed the original research idea, built the hardware prototype, analyzed the results, and supervised the second study. I was the leading author of the publication.	Mengyi Zhang conducted and implemented the second study, while Joseph O'Hagan conducted and implemented the first study. Julie Williamson and Tobias Höllerer supervised the project and contributed to writing the publication, while Florian Alt and Andreas Butz edited the final version of the paper.
[P5]	I developed the original research idea and supervised the implementation of the prototype and study as well as the analysis of results. I authored the resulting publication.	Julia Dörner created the prototype and conducted the study. Tobias Höllerer and Andreas Butz supervised the project and edited the final version of the paper.
[P6]	I developed the original research idea; I supervised the implementation and study and analyzed the resulting data. I authored the resulting publication.	Fan Fan implemented and conducted the study. Andreas Butz supervised the project and edited the final version of the paper.
[P7]	I developed the original research idea; I supervised the implementation and study and analyzed the resulting data. I authored the resulting publication.	Wanja Sajko implemented and conducted the study. Andreas Butz supervised the project and edited the final version of the paper.

Table A.1: Publications included in this thesis with clarification of respective contributions.

[P1] Englmeier, D., Schönewald, I., Butz, A., and Höllerer, T. (2019b). Sphere in Hand: Exploring Tangible Interaction with Immersive Spherical Visualizations. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. doi:10.1109/VR.2019.8797887

[P2] Englmeier, D. (2019). Spherical Objects as an Opportunity to Investigate Physical Embodiment in Mixed Reality Environments. In *Mensch und Computer 2019 - Workshopband*, Bonn. Gesellschaft für Informatik e.V., doi:10.18420/muc2019-ws-454

[P3] Englmeier, D., Schönewald, I., Butz, A., and Höllerer, T. (2019a). Feel the Globe: Enhancing the Perception of Immersive Spherical Visualizations with Tangible Proxies. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. doi:10.1109/VR.2019.8797869

[P4] Englmeier, D., O'Hagan, J., Zhang, M., Alt, F., Butz, A., Höllerer, T., and Williamson, J. (2020). TangibleSphere – Interaction Techniques for Physical and Virtual Spherical Displays. In *Proceedings of the 11th Nordic Conference on Human-Computer Interaction: Shaping Experiences, Shaping Society*, NordiCHI '20, New York, NY, USA. Association for Computing Machinery, doi:10.1145/3419249.3420101

[P5] Englmeier, D., Dörner, J., Butz, A., and Höllerer, T. (2020a). A Tangible Spherical Proxy for Object Manipulation in Augmented Reality. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. doi:10.1109/VR46266.2020.00041

[P6] Englmeier, D., Fan, F., and Butz, A. (2020b). Rock or Roll – Locomotion Techniques with a Handheld Spherical Device in Virtual Reality. In *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. doi:10.1109/ISMAR50242.2020.00089

[P7] Englmeier, D., Sajko, W., and Butz, A. (2021). Spherical World in Miniature: Exploring the Tiny Planets Metaphor for Discrete Locomotion in Virtual Reality. In *2021 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. doi:10.1109/VR50410.2021.00057

Eidesstattliche Versicherung

(Siehe Promotionsordnung vom 12.07.11, § 8, Abs. 2 Pkt. 5)

Hiermit erkläre ich an Eidesstatt, dass die Dissertation von mir selbstständig und ohne unerlaubte Beihilfe angefertigt wurde.

München, den 04. Mai 2021

David Englmeier