Bring-Your-Own Input: Context-Aware Multi-Modal Input for More Accessible Virtual Reality

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ABSTRACT

Virtual reality applications make assumptions about user ability which may be difficult or even impossible to meet by people with limited mobility. However, we can increase the accessibility of these applications by taking advantage of the device combinations and usage contexts that people with mobility limitations already employ. By designing context aware multi-modal interfaces which gracefully adapt not only to the user's input devices, but also to surrounding usage context like body or workspace position, we can meaningfully improve the overall accessibility of spatial computing. My research plan is threefold: first, qualitative research reveals how people with mobility limitations combine input devices to overcome accessibility barriers (published at CHI 2022). Next, we categorize these combinations based on their input dimensions, and develop a study of gracefully degrading input fidelity to understand how device combinations' differing input space affects VR usage. Finally, we examine how the user's surrounding context affects VR input and output, by exploring the design space of context-aware interfaces which adapt to changes in the user's body position, output device (headset or desktop), or workspace proximity. My overall goal is to show how intelligent adaptation to input device combinations and surrounding input context can lead to more accessible spatial interfaces, and to provide actionable recommendations for designers and researchers creating accessible VR experiences.

KEYWORDS

interaction techniques, controlled experiments, accessibility, spatial interfaces

1 INTRODUCTION

The adoption of consumer virtual reality (VR) devices is changing the way that people interact. VR allows people to participate in shared co-located activities regardless of distance, enabling social co-presence, companionship, and mutual experience in a way unachievable by other technologies. However, current VR user interface designs and hardware configurations often make assumptions of user ability [25] that people with limited mobility may find uncomfortable or even impossible to meet in practice. In the era of hybrid work, a reduced or nonexistent ability to use spatial interfaces like VR can hamper productivity, teamwork, and even career progress. Current VR accessibility research focuses on individual input techniques, providing specific solutions for narrowly-defined circumstances. As a result, these techniques and findings are often hard to implement as general accessibility solutions for real-life applications. Developing practical and replicable accessibility solutions for VR demands thoughtful accommodation of a wide range of disabilities over a variety of spatial input situations. Considering this, we take a more multifaceted approach.

My initial research in this space revealed that people with limited mobility commonly combine input devices to overcome accessibility barriers, but these input devices are not typically compatible with VR applications [24]. To address this problem, my research explores the design space of *context-aware multi-modal* interfaces to increase the general accessibility of VR. Context-aware multi-modal input techniques involve deriving six degrees-of-freedom input from combinations of input devices with fewer input dimensions, as well as providing meaningful input and output responses to the user's surrounding input context. I ground my research by describing the challenges, contexts, and remedies encountered by users with mobility limitations, and then use this theoretical baseline to design and evaluate techniques which enable accessible VR input in ways that are faster, more precise, and more expressive.

Through this research, I expect to contribute: (1) an understanding of how users with mobility issues create, configure, and interact with multi-modal interfaces; (2) designs and techniques that use this understanding to allow for device-agnostic input for VR systems; (3) a definition and understanding of how body position, physical movement, and display devices affect VR usage context; and (4) empirically-validated designs and techniques that take advantage of context-aware multi-modal input to create more accessible VR experiences.

2 BACKGROUND AND RELATED WORK

Context-aware multi-modal input builds upon several established categories of work, including those in traditional multi-modality, spatial interface design, and accessible input techniques.

2.1 Understanding Multi-Modality

My work builds upon and characterizes interfaces using categorizations from previous theoretical work in multi-modality. Buxton [4] unified two disparate taxonomies of input into a generic scheme for classifying input devices based on their sensing capabilities, establishing a tableau of continuous input devices alongside potential combinations. Later work [20] decomposes multi-modal input tasks into three subtasks: *user tasks* (what the user has to physically do),

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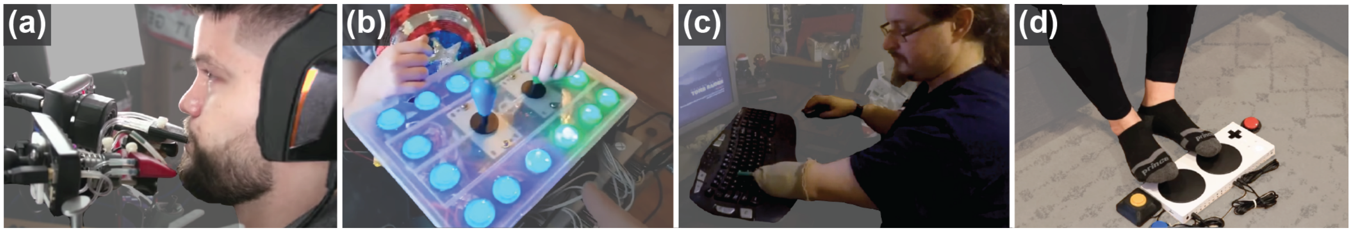

Figure 1: Examples of various accessible multi-modal input devices: (a) multiple QuadSticks; (b) a custom controller connected to the Xbox Adaptive controller; (c) mouse and keyboard used with a typing stick; and (d) switches connected to the Xbox Adaptive Controller. Images © Shot Callers Esports, ELEAGUE, MIZINO: In Over My Head, and ABSHOW, respectively. Originally Figure 1 from Wentzel et al. [24].

system tasks (feedback the system must provide), and *physical design* (the various physical interfaces upon which the user performs the task).

In practice, several works in HCI examine multi-modality through the combination of pre-existing input devices. Within assistive technology, previous work includes speech plus head tracking [21], gaze plus both keyboard [2] and face tracking [19], and head plus joystick [8]. Outside of assistive technology, previous work combines input devices like those within cars [15], speech and pen [6], or speech and gestures [9].

2.2 Multi-Modality in VR

Previous work has provided broad examples of multi-modal input categorizations and cross-device input [3, 11], and we narrow our scope to those specifically for spatial input environments like virtual or augmented reality. For example, DualCAD [12] explores integrating both desktop and smartphone user interfaces for AR design applications, and previous work explored handheld tablet devices as input devices in both VR [22] and AR [1]. BISHARE [28] provides an overview of the benefits of bidirectional interactions between AR head-mounted displays and smartphones.

2.3 Accessibility and VR

In addition to various exploratory works eliciting design problems [14] and opportunities to make VR more accessible [13], previous work explores input and output techniques that can be used and combined to improve the accessibility of mixed reality computing. Previous work has examined walking in VR with an instrumented cane controller [26], as well as developer tools to make VR more accessible for blind and low-vision users [27]. Previous developer tools have also enabled more accessible input options for people in wheelchairs or for people with reduced arm mobility [5, 23].

2.4 Summary

Previous work in accessible VR design provides methods for adapting new hardware to VR environments, or adapting software and existing hardware to individual users' capabilities. However, these solutions are typically individual adaptations for narrowly-defined input circumstances, and lack the level of device-agnostic input accessibility that more widely-adopted platforms like desktop or mobile computing can provide. The adoption of VR (and mixed reality in general) requires thoughtful design for the wide variety of input scenarios encountered by people with mobility limitations. Instead of creating individual input techniques and device adaptations, my work aims for broader real-life applicability by providing general, system-level adaptations to the input devices that users already employ. My work builds upon previous techniques, but inhabits the larger design space of multi-modal input to provide results more applicable to real-life scenarios.

3 UNDERSTANDING MULTI-MODAL INPUT COMBINATIONS

As a first step toward creating context-aware multi-modal VR interfaces, I explored the range of multi-modal input already deployed in the computing setups of people with mobility limitations. Previous work establishes baseline conceptual models of multi-device input including the cognitive science behind multi-modal interaction [4, 10], as well as initial conceptual explorations into how multi-modality can apply to accessibility more generally [7]. Building upon these results, my work with Microsoft Research [24] explored how people with limited mobility combine input devices to overcome accessibility barriers (Figure 1). Using surveys, semi-structured interviews, and a systematic review of social media, we found that these barriers are typically caused by deficiencies in either body-to-device compatibility or device-to-application compatibility (Figure 2). Users remedy these deficiencies using a wide variety of devices in personalized combinations, highlighting that there is no one-size-fits-all solution for accessible input. As a result, scalable solutions for accessible VR must focus on intelligent adaptation instead of individualized solutions. Previous work in multi-device input for accessibility typically involves emulating conventional mouse-and-keyboard input by combining separate input devices, including speech and head tracking [21] or gaze and keyboard [2]. I can use these findings as inspiration for developing input mappings that achieve meaningful, expressive 3D input using the specialized and often custom designed devices that users with mobility limitations already have.

4 DEVICE-AGNOSTIC INPUT TECHNIQUES

A significant barrier to VR is the implicit requirement of hands or hand controllers as a primary source of input, which can be inaccessible or even impossible to use by people with reduced mobility [14]. Likewise, users often find virtual reality to be difficult to use because their preferred input devices and combinations are not compatible with the spatial input requirements of typical applications [24]. These insights reveal an opportunity to develop spatial

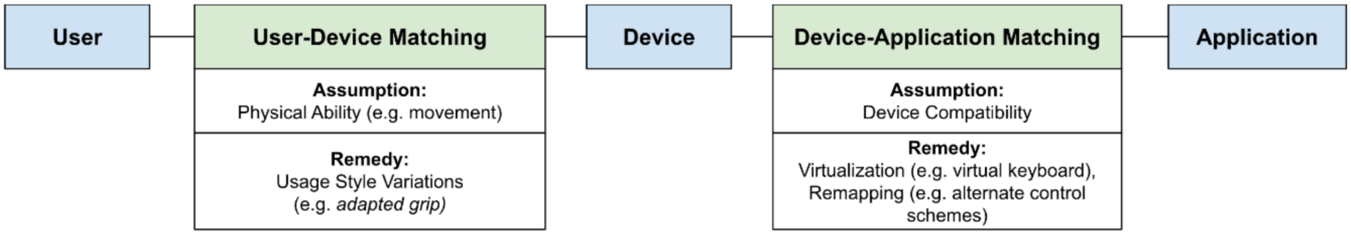

Figure 2: The two-stage matching process between the three components of interaction with a system. Each step in the matching process has an associated assumption, as well as commonly-deployed remedies to failures in meeting this assumption. Accessibility issues reported by participants came from mismatches either between the user and device, or device and application. Originally Figure 6 from Wentzel et al. [24].

interfaces that intelligently respond to the devices that users with mobility limitations prefer, adapting the *application* to the *devices* rather than vice versa. Developing this "bring-your-own" input concept, allowing users to have meaningful spatial input regardless of the devices used, can make it easier for designers to create accessible spatial interfaces as well as make VR more accessible for end users.

Users with mobility limitations often combine input devices to overcome accessibility barriers [24]. However, the wide variety of devices used makes developing a system that adapts only to devices themselves sub-optimal. Instead, we focus on developing input systems that adapt to devices' general input dimensionality, as a way to abstract and generalize our findings to any combination of input devices. Intelligently adapting a system's input accommodations to the fidelity of the input devices provided requires understanding the affordances and effects that each level of input fidelity can have on overall task performance, as well as the holistic effect of varying input combinations. As such, to achieve the overall goal of a "bring-your-own" design concept for VR, this project examines the research question: **how should a system adapt its input processing to accommodate the wide variety of accessible input combinations?**

This research builds upon the two-stage input matching process (Figure 2) described in my initial paper [24]. If we assume the user uses the input devices to which their abilities are most accustomed (i.e., the devices they already prefer), we can assume sufficient *user-device matching*. The heart of this research lies in exploring the space of *device-application matching*, in which the input signals from the devices are mapped in a way that faithfully matches the user's intended action. The overall goal of this research is to provide novel, effective, and replicable techniques for improving a system's device-application matching, and subsequently its overall compatibility with a user's preferred accessible input configurations. This research goal involves the exploration of several questions. The approach, methods, and rationale for each question are described below.

First: how do we most effectively map a 2D input signal to accommodate 3D input operations? People with mobility limitations are often limited to the use of 2D input devices such as mice or trackpads as their primary input device, regardless of the requirements of the task at hand. 3D input scenarios such as VR require a higher level of input fidelity than what 2D devices typically provide. One solution for this problem is to "collapse" 3D input into a space that can be interacted with via a 2D input device. Previous work involves projecting a 3D axis into a 2D plane, or intelligently "snapping" between the three input axes [16]. I will implement various input mappings from a single 2D input device into a 3D input space, and evaluate their accuracy, usability, and accessibility with a user study and semi-structured interviews. This study can serve as a theoretical baseline for mapping a single lower-fidelity input device to a higher-fidelity input scenario.

Next, how should a system with a required input dimensionality adapt to combinations of lower-dimensionality devices? Consider a 3D object manipulation task in a VR application. Whereas in typical hand-controller control schemes the user has the full range of 6 degree-of-freedom controller input as well as buttons, a user employing a combination of a trackpad plus a button switch requires additional accommodation. Here, we could combine the 1-dimensional discrete input of a button switch with the 2-dimensional continuous input of a trackpad to allow the user to explicitly switch a cursor's movement plane from a horizontal to vertical axis. This mode switch enables movement in all three axes, recreating 3D input using a "2+1-dimensional" input scheme. However, what is the effect of this input degradation, from 3-dimensional to 2+1-dimensional input? Using input combinations comprised of devices from full six degree-of-freedom input to a single button switch, I plan to explore the space of "gracefully degrading" input fidelity by developing a user study evaluating the impact of stepwise changes in input dimensionality on performance in common VR tasks.

Finally, how can we enable meaningful VR locomotion for users with a single low-fidelity device? Using locomotion techniques to traverse a 3D scene is one of the fundamental input goals in VR. Without the ability to manipulate a VR controller, users typically have to rely on joystick-based movement which can cause motion sickness. As a remedy, we can draw inspiration from a smartphone accessibility technique that uses a single button switch. A cursor scans left and right across the VR scene, and the user can press a button switch to teleport to the location of the cursor. This technique can be extended to include further axes of movement, as well as rotation. I plan to create a user study to evaluate this switch-based input scheme with users with reduced mobility as well as against other VR locomotion techniques, in terms of performance and perceived usability.

5 CONTEXT-AWARE WORKSTATION TRANSITIONS

Understanding context-aware multi-modal interfaces involves understanding not only the explicit input signals provided by the user's input devices, but also the implicit aspects of the user's surrounding context. Gathering context clues about the user's usage state, like position in the room, or body posture, can allow the system to more intelligently adapt how it parses user input and how it presents output. Just as responsive web design enables usable and organized layouts for websites regardless of screen size, context-aware VR design enables meaningful input and output regardless of input context. As a final step toward understanding the design space of context-aware multi-modal interfaces, we examine the research question: **how does a change in the user's input scenario affect 3D task fidelity, and how can interfaces accommodate these changes most effectively?**

As an example, VR and 2D desktop interfaces are each best suited for different tasks. In the event that a user's workflow demands the use of both VR and desktop interfaces, this creates a gap between the user's desired and actual input fidelity. In addition to a variety of hardware accessibility issues related to entering or exiting VR [14], switching between desktop and VR interfaces adds unnecessary friction to the user's workflow. Existing techniques try to remedy this through explicit VR-to-desktop mapping, such as simple ray-casting techniques to interact with desktop interfaces from VR. However, sub-optimal body movement range, input devices, or physical space (e.g. using VR seated, at a desk) create further situational impairments that apply to users with and without body mobility limitations. Intelligently responding to the user's input situation to solve these situational impairments is a challenging interaction problem, the solution to which can provide HCI insights both within and outside of accessibility.

To explore the effect of overall input context and how a system can best adapt to its changes, I am developing a system [18] that intelligently adapts its input and output to every unique combination of body position (standing or seated), proximity to a desk (near or far), and interface (headset or desktop). Early design and pilot work revealed that users often "peek" between these modalities, quickly and temporarily changing their usage context to adapt to their desired step in their workflow. My system adapts its input recognition and output format to fit the user's current context. As a next step, I will evaluate this system in a user study, evaluating the effect of "peeking" between modalities on overall cross-modality performance. Using a task that requires users to change between modalities to simulate a cross-modality workflow, I will evaluate this system with regard to its speed and perceived usability.

6 RESULTS AND CONTRIBUTIONS

To date, my dissertation-specific work has produced one paper [24] and one patent [18]. The paper, published at CHI 2022, provides important background regarding how people with mobility limitations combine input devices to overcome accessibility barriers (Section 3), and provides the key background knowledge necessary for the further work in developing interfaces which gracefully respond to changes in user context or device changes. The patent exists as an early artifact created by the work described in Section 5. Future work on this topic will significantly expand the scope of this work including a user study of graceful interface adaptations to user state changes.

7 OPEN QUESTIONS

At this stage in my PhD, I welcome any available feedback regarding my proposal, as well as answers to the following standing questions.

First, how best do I narrow the scope of my study in Section 4? Evaluating context-aware multi-modal input, as with any multi-modal input, requires thoughtful scoping to make studies feasible to implement, feasible to run, and useful in their findings. However, the accessibility component of my research, and my previous findings that accessible multi-modal input takes a wide, hard-to-predict variety of forms [24], means that my user study factors have the risk of a combinatorial explosion. Refining the domain of my investigation to be the most useful and informative will be a valuable avenue of feedback.

Second, how can I design a study task for my work in Section 5 in order to provide useful and practical results about context-aware cross-modality input? The "peeking" concept provides an interesting avenue for exploration, especially in tasks that require the participant to gather information that can only be found in specific modalities, but designing a user study task remains an ongoing area of thought.

8 DISSERTATION STATUS AND LONG-TERM GOALS

The University of Waterloo's PhD program is in three parts [17]. First is the *PhD Comprehensive Examination I*, which requires PhD students to complete courses in a breadth of topics in computer science. I have already completed this section of the program. Next is the *Comprehensive Examination II*, which involves selecting an examination committee and chairs, then submit (and orally present) a thesis proposal for questioning and validation. I expect to be completing my Comprehensive Examination II by the end of April 2023. Finally, I must present my research at least three publicly announced research seminars.

I have not attended a previous doctoral symposium. I am in my third year of study and have taken a total of 12 months of leave for industry internships. I would place my dissertation at around one-third complete. The first exploration into accessible multi-modal input combinations in Section 3 has been published at CHI 2022 [24]. I will use this work to complete the later sections of my dissertation, as described in the above sections. Publication is typical for dissertation papers, but not necessary for University of Waterloo degree requirements. I expect to complete all degree requirements by the end of April 2024.

Long-term, I will seek industry research positions in companies whose aim is to improve virtual and augmented reality as a category of computing. Working alongside industry partners, my goal is to use my skill set in designing, implementing, and evaluating spatial interfaces to improve the accessibility and usability of mixed reality interfaces and applications.

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