Opportunities and Challenges of Hybrid User Interfaces for Optimization of Mixed Reality Interfaces

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ABSTRACT

Current research highlights the importance of adaptive mixed reality interfaces, as increased adoption leads to increasingly diverse, complex and unconstrained interaction scenarios. An interesting approach for adaptation, is the optimization of interface layout and behaviour. We thereby consider three distinct types of context to which the interface adapts: the user, the activity, and the environment. The latter of these includes a myriad of interactive devices surrounding the user, the capabilities of which we propose to take advantage of by integrating them in a hybrid user interface. Hybrid user interfaces offer many opportunities to address distinct usability issues, such as visibility, reachability, and ergonomics. However, considering additional interactive devices for optimizing mixed reality interfaces introduces a number of additional challenges, such as detecting available and suitable devices and modeling the respective interaction costs. Moreover, using different devices potentially introduces a switching cost e.g., in terms of cognitive load and time. In this paper, we aim to discuss different opportunities and challenges of using hybrid user interfaces for the optimization of mixed reality interfaces and thereby highlight directions for future work.

1 INTRODUCTION

In immersive mixed reality (MR) applications, users frequently interact through graphical user interfaces that are presented in mid-air, also known as 3D user interfaces. These are predominantly perceived through head-mounted displays (HMDs), which present virtual content right in front of the user's eyes, allowing them to explore their surroundings by simply turning their head while leaving the hands available for manipulating their environment. This allows us to create highly convincing and engaging experiences, for example in immersive virtual reality (VR), that have the potential to profoundly impact the user's cognition and behavior. However, a number of challenges hinder wider adoption and effective use of the available technologies. For example, manipulation of 3D user interfaces is known to cause muscle strain [2, 10], the unusual layout of information in 3D space leads to increased cognitive load [17], and the effectiveness of interaction is hampered by limited tracking volumes, low tracking accuracy and lack of (haptic) feedback, which may also reduce the user's confidence [25]. Further, the placement of the 3D user interface may be poorly suited for the activity the user is engaged in and conflict with the physical space it inhabits, leading to safety risks and hampering social interactions.

Adaptive MR user interfaces aim to address these challenges by dynamically optimizing 3D user interfaces, with regards to its content, the presentation thereof, or the interaction with it [4]. For example, such adaptations may affect the placement of information and interactive elements, as well as the employed interaction techniques and feedback. The aim of adaptive user interfaces shall make information accessible when it is needed and enable interactions in a safe and ergonomic manner, while minimizing cognitive load, so that the user can focus on the task at hand and the work environment in which it is completed. Recent developments in augmented reality (AR) technology have already led to first optimization approaches for the positioning of graphical user interface elements (e.g., surface magnetism), which are known as "solvers" [21]. Further, solvers focus mainly on the placement of virtual content (as e.g., [3, 7, 24]) without considering alternative interaction techniques, the level of immersion offered by the technology, or affordances of the environment. More recent publications (e.g., [5] have started considering *multiple objectives* for optimization, though these approaches are still fairly limited. To form the optimization objectives, three central aspects must be considered, which define the *context* of interaction [1]: 1. the *user* who must interact with the user interface, 2. the intention or purpose that is pursued in interaction with the user interface (i.e., the task at hand or *activity*), 3. the *environment* in which the user interface resides and where interaction occurs. For the user (1), we must consider their physical characteristics and abilities (e.g., arm length and movement range to define size of interaction space; the dominant hand may define user interface placement), as well as their knowledge and needs (e.g., level of expertise in a task may affect amount of guidance; important appointments in their personal calendar may trigger reminders), the cognitive load of the user and their personal preferences (e.g., a user may choose to enable a do-not-disturb mode, or may specify preferred locations for particular type of content). The activity (2) requires particular information, may be characterized by a typical workflow, and can pose prerequisites in terms of previous knowledge, available tools and materials, as well as safety requirements. Further, it may involve predefined (intermediate) goals, which may be automatically verifiable by the system.(e.g., a user doing a specific task , this task can be divided into sub-tasks to achieve the overall activity goal). With respect to the environment (3), we must take into account both the user's physical and virtual surroundings, which provide the external context for the interaction. For example, the user's actions may be directed by the spatial layout of virtual content, supported or impeded by physical surfaces (e.g., sitting at a desk the user may not be able to reach for elements at waist-level, whereas superimposing an interface on the desk brings the benefit of interaction confirmation through haptic feedback [9]), or influenced by semantic properties of physical objects or places (e.g., the position of a virtual control dial with respect to a smart speaker or radiator will generate expectations as to whether it adjusts music volume or room temperature). Further, the environment may contain interactive devices that offer particular input and output functionalities (e.g., a computer with attached keyboard affords efficient writing; a touch screen offers a sensing surface to draw on). Recent research has proposed to take advantage of such devices for MR interaction (e.g., [14]), by integrating them into hybrid user interfaces [6]. In a potential interaction scenario, a user might use multiple devices during an activity

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that are available in a given environment. Depending on the task at hand, this might include MR HMDs, but also other interactive devices, such as smartphones or tablets that can be combined and utilized simultaneously or in sequence [13]. In considering the particular opportunities for interaction offered by the various available devices, we see unexplored opportunities for the optimization of MR interfaces.

In this paper, we identify a number of opportunities of hybrid user interfaces and discuss how these can aid in solving optimization objectives. Further, we highlight central challenges, aiming to inform future research directions.

2 Background

As MR technologies are maturing and adoption across a wide range of sectors (e.g., entertainment, education, medicine, manufacturing industry) is increasing, there is a dire need for heuristics, guidance tools and recommendations for 3D user interface design. While we have access to decades of research on 2D user interface design, many of these principles and best practices are not directly applicable, due to the shift in interaction paradigm. For example, instead of optimizing the position of a scroll bar on a 2D screen of limited size for interaction with a mouse, we must consider an infinite virtual display space around the user and a variety of possible interaction modalities, such as controllers, mid-air gestures, voice commands, eye gaze, etc.

To tackle the vast problem space, prior work has explored the automatic adaptation of 3D user interfaces for various different objectives, using different technologies, and applying a variety strategies [15, 20]. For example, Tatzgern et al. [24] adapted information density (level of detail) for AR displays, to prevent visual clutter and support the iterative exploration of information, while ensuring that real-world content of interest remains visible. Also focusing on the visualization of information, Fender et al. [7] optimized the visibility of projected content by tracking the user and virtually reconstructing the physical space to identify optimal projection surfaces. Taking the user's activities into account, Lindlbauer et al. [17] adapted user interface elements depending on the user's cognitive load during a task, aiming to avoid overwhelming the user with unneeded information. More recently, Belo et al. [3] proposed a toolkit for optimizing the ergonomics of a 3D user interface for mid-air interaction, by positioning interactive user interface elements within the easily reachable space around the user. This work aimed to address two central challenges for designing comfortable mid-air interactions: First, even though the HCI community has long explored issues such as comfort and fatigue, current metrics [2, 10] focus on evaluating existing mid-air interactions and are difficult to use in the design of *new* interactions. Second, the general guidelines formulated based on existing metrics (e.g., [2, 10, 18]) are hard to apply for MR applications, which are highly dependent on contexts that may change continuously.

In parallel with research on this topic, a variety of commercial toolkits have emerged that support dynamic adaptation of 3D user interfaces according to optimization procedures based on simple rules, often called *solvers* [21]. For example, the MRTK (Mixed Reality Toolkit) supports "surface magnetism"[1], which leads to the apparent attachment of flat user interface elements to flat, physical surfaces (e.g., walls, tables). This registration improves our sense of visual coherence for AR content and can enable the use of haptic props in AR or VR (e.g., tapping virtual buttons on a physical tabletop [9]). Such solvers can also maintain user interface elements within the user's FoV or within arm's reach, as is often supported for the HoloLens2.

As MR technology becomes increasingly mobile (i.e., self-contained computing units with inside-out tracking), enabling users to interact in highly dynamic scenarios, it arguably becomes even more critical and challenging to create user interfaces that can adapt to context changes. However, existing approaches are still few, and limited in that they address only individual objectives and use very simplistic models of the interaction context. In this paper, we wish to contribute towards addressing the latter limitation, by extending the environment context to explicitly include interactive devices in the user's environment, as these offer additional opportunities for interaction. Context aware interactive systems have a long tradition in HCI research [1] and have been abundantly explored in ubiquitous computing or smart home scenarios (e.g., [23]). Sensor-based approaches enable systems to smartly react to changes in the environment, or actions of the user (i.e., context), without requiring explicit input or control. For example, as the user moves through their house, a sound system might play the user's favorite music only in the room they are currently in. Such "magical" system behavior is also highly desirable for MR interaction and, apart from the virtual user interface adapting to the user (e.g., position), it should adapt to incorporate the best available sensors and displays (e.g., smartphones, desktop computers, and keyboards) in the user's physical environment.

The combination of MR HMDs with e.g., touch devices has been proposed in a complementary manner [26], thereby compensating the individual shortcomings and exploiting the strengths of each technology e.g., as hybrid user interfaces [6]. Recent research has investigated the usability and user experiences of such environments (e.g., [11, 12, 14]). Building on this, we see hybrid user interfaces as an untapped opportunity for optimizing MR interfaces. This comes with a set of challenges, but also opportunities, that we will discuss in the next sections.

Figure 1: User is wearing an AR HMD while using his smartphone to interact. The environment also has a Desktop PC available with a keyboard for input. The screen behing the user can also be used for visualization and interaction in a hybrid user interface. (Figure genereated by Aobe Express Geneartive AI tool)

3 Hybrid User Interfaces for Adaptive MR

3.1 Opportunities for user interface optimization

Optimization of MR interfaces can address a variety of factors (e.g., reachability, ergonomics, visibility) that impact user experience and usability. We commonly call these *optimization objectives* [5]. In this section, we aim to illustrate the potential of hybrid user interfaces, by discussing three exemplary optimization objectives:

[1] Surface Magnetism: https://docs.microsoft.com/en-us/windows/mixed-reality/design/surface-magnetism

- **Reachability:** An issue with reachability occurs when interactive 3D objects (e.g., user interface elements) are placed in an unreachable position in the user's 3D interaction space [3]. This can be solved by already existing optimization objectives by defining a range of reachable distances within which all user interface elements are positioned. The reachable interaction space can thereby be represented as a half-sphere [3], and reachability can be accommodated for example with cylindrical layouts for user interface elements [5]. However, the issue may be further complicated by the user's physical environment, which restricts their movement. For example, when standing, it is comfortable to reach for UI elements that are located in mid-air in front of us, at approximately waist-level. However, when sitting at a desk, objects at waist level are no longer reachable, as the table-top presents a physical obstacle. This highlights the need for considering the geometry of the user's physical surroundings. Here hybrid user interfaces offer an opportunity to optimize for reachability, by integrating the interactive devices that are available in the user's environment or worn by the user (e.g., smartwatch). For example, the controls for a music player that is visualized as a playlist and extensive song library in the 3D environment, could be mapped onto the user's smartphone, tablet or a smartwatch, if these are more comfortable to reach than mid-air controls. Further potential benefits of these physical interactive devices are that they can be easy to locate (i.e., the smartphone may be in one's pocket and the tablet may be located in its usually place), they support familiar interaction modalities, and can provide multimodal feedback to the user (e.g., vibration, kinaesthetic feedback from touchscreen surface or physical buttons). Mapping user interface elements to a physical device may be a promising alternative to changing the rearranging the UI in the 3D environment, as such changes may negatively impact cognitive load and hamper spatial memory. Further, mid-air interaction is known to cause arm fatigue over time, which brings us to the issue of ergonomics discussed in the following.

- **Ergonomics:** Ergonomics are an important factor to consider in the design of virtual user interfaces, as arm fatigue is a well-known issue in interaction with large vertical screens, also known as the gorilla-arm effect. Similarly, it affects mid-air interaction with 3D user interfaces. Researchers have proposed various approaches to address this issue, ranging from novel interaction techniques [8], to user interface adaptation methods [19] to reduce muscle strain and fatigue. A toolkit was developed to inform the ergonomic design of user interfaces, by computing and visualizing the ergonomic cost for direct manipulation at every position in the user's reachable interaction space, and proposing optimal positions for UI placement. In contrast to reachability, which refers to the space that is within reach of the user's hands, ergonomics concern the user's entire body during interaction. Importantly, optimizing for the ergonomics of one body part may penalize another. For example, for direct manipulation with both hands, the least strenuous object location would be one where the user can maintain their hands in front of their body at waist level, with both arms at their sides and elbows slightly bent [2]. However, if during manipulation the object needs to be constantly looked at, this requires non-ergonomic bending of the neck. Optimizing for the latter in turn would require moving the object up to eye-level, at the cost of increases arm fatigue. The opportunity offered by hybrid user interfaces is to for exampleallow manipulation of virtual content through a physical device in the environment, such as a smartphone or keyboard (see Fig. 1) that is ergonomically better than mid-air interaction, while affording an ergonomic posture of the head and good visibility of virtual content, by employing the HMD to present it in mid-air at eye-level. Hence, the central criteria for optimizing ergonomics, are the interactive and semantic qualities of each particular UI element (e.g., control panel affording direct manipulation vs. information panel that should be looked at). This also relates to the issue of visibility, which we will discuss next.

- **Visibility:** This visibility objective is very important, especially in MR environments, where the user interface element may not be adequately visible for multiple reasons: for example, it may be outside the narrow field of view of the HMD, it may be placed too far away in the virtual space and therefore be rendered too small, it may be occluded by other virtual content in a cluttered environment, or, specially with optical see-through HMDs like the HoloLens, it may be poorly visible due to strong background lighting. Researchers have developed many adaptation objectives for visibility. For example the AUIT toolkit [5] allows maintaining specific UI elements in view by specifying the the field of view, inner and outer boundaries, as an optimization objective. A second objective is *look towards*, which adapts the orientation of user interface elements, for example such that they always face towards a certain object (e.g., the user). Another objective is occlusion, which means to avoid to placing virtual content behind other virtual objects in the scene, or environment geometry that may cause cropping or masking in AR. Such objectives can be addressed using hybrid user interfaces, as these can offer more visual space that can be explicitly dedicated to certain content. For example, visualize virtual objects or user interface elements on another device as a smart TV, an interactive screen, a tablet, or a desktop computer, which often offer better resolution and contrast than the HMD. For example, the user in Figure 1 is wearing an AR headset, while having the option to interact with the smartphone in his hand, where some virtual objects can be visualized and manipulated in more detail. The high-resolution wall-display behind him offers further visualization space that can be dedicated to showing particularly detailed information.

3.2 Challenges for integrating additional devices

To exploit the above-mentioned opportunities of hybrid user interfaces for optimizing MR interfaces, a number of new challenges must be addressed. We identified three of these, which we discuss below:

- **Availability of the devices:** Modelling the available interactive devices as part of the environment context, is the first challenge that needs to be addressed. For this we need to know what devices are available, what capabilities they have and what affordances they offer. For example, using a mouse attached to a desktop can me more precise for precise selections in 2D, while a touch screen can be better for direct manipulation tasks. A smart pen with a tablet or a smart screen has better capabilities for sketching than using mid air gestures or a typical mouse. On the other hand, if various smartphones are detected, it may be critical to consider ownership, as these devices are predominantly personal and flexible use by others may not be desired. Beyond understand existing devices and their capabilities, we must also compute the cost of interaction with each interface and the potential overhead cost of switching, which we discuss in the next two sections.

- **Interaction cost calculation:** Cost functions are implemented to compute optimizations that satisfy the specified adaptation objectives. For example, we may compute the ergonomic cost of reaching a particular point in 3D space with our right hand

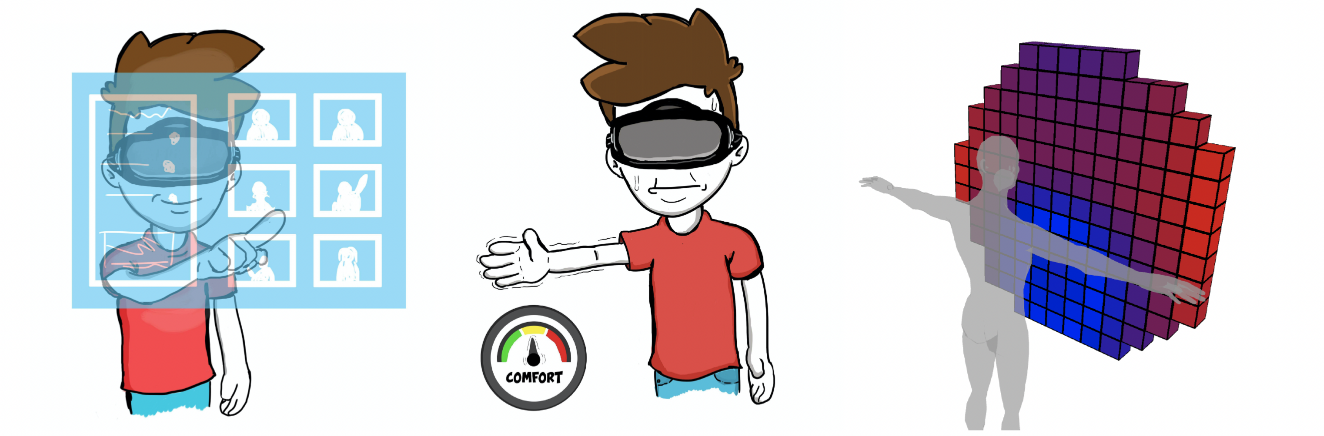

Figure 2: XRgonomics toolkit aims to facilitate the design of ergonomic 3D user interfaces, common in MR applications (left). The toolkit uses a user's physiological model to compute the ergonomic cost of interaction at each reachable position in the interaction space (center). Visualization of the interaction space and ergonomic cost is visualized in form of colored voxels Color mapping for the ergonomic cost, from blue (most comfortable) to red (least comfortable) [3].

based on some model [3], be it a detailed computational model of muscle activation [2], or a simple rule-based system [18]. By quantifying potential user actions in this way, we can determine optimal options, e.g., for UI placement. While this appears straightforward for satisfying individual objectives, realistic interaction scenarios would require the consideration of multiple objectives simultaneously [5]. This requires additional models for cost calculation (e.g., quantifying the degree of visual clutter, amount of cognitive load, or visibility) and strategies for resolving conflicts between contradicting objectives, for example through assigning weights. Considering devices in the environment adds another level of complexity, as we must not only model the user's body (for direct manipulation of virtual content) and their physical environment geometry, but also the each of interactive devices and the input mapping functions they support, to compute respective interaction costs. However, it is difficult to develop holistic cost functions due to the large number of possible interaction devices. For example, using a tablet to interact with user interface elements can be ergonomically better, or perhaps more accurate, than manipulating these user interface elements with mid-air gestures. Moreover, using a tablet can be different than using a smartphone that is smaller in size, which has for example been shown to affect perceived workload and spatial memory [14]. Clearly, the optimal choice is highly dependent on the context (user, environment, activity) and, while hybrid user interfaces offer more flexibility and potential for optimization, they also increase the complexity of computing interaction costs. In addition to the cost of interaction, we must also consider the cost of switching between devices, which we discuss last.

- **Cost of switching between devices:** As the availability of devices can change from one environment to another, or even over time, it may be difficult to establish standards. Adding or removing devices may imply a change in input modality, feedback, and interface location, which can affect the discoverability of interfaces for the user, as well as the general learnability of using MR systems. Further, using more than one device can cause visual attention shifts which cause overhead [26]. For example, switching from a MR HMD to a tablet can be exhausting for the user. The resulting cost of switching between devices, interfaces and modalities needs to be modeled and taken in consideration when calculating optimum interactions [22]. For example, we can analyze cognitive load through eye gaze and physiological data [4, 16], to establish models that allow us to predict and quantify cognitive load. The resulting switching cost can then be applied as a penalty to the overall interaction cost, allowing us to choose optimal interactions through optimization.

4 Conclusion

In this paper, we propose the use of hybrid user interfaces for optimizing MR interactions. Hybrid user interfaces can be considered as part of the environment context, where we must identify their availability and suitability for a particular task, and then compute the cost of interaction. With these challenges addressed, we can then determine the optimal placement and behavior of UI elements and the used interaction modality. Hybrid user interfaces thereby offer unique opportunities to address common optimization objectives, as for example improved reachability (e.g., a mobile device is hand-held and therefore in easy reach, compared to a mid-air UI), ergonomics (e.g., a touchscreen allows a user to rest their fingers, compared to mid-air interaction), and visibility (a desktop monitor offers higher resolution and contrast, for a better reading experience compared to an HMD). With this paper we aim to inspire designers and creators of MR interfaces to consider the interaction opportunities provided by devices in the users' environment, and facilitate hybrid user interfaces to improve interaction.

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