MRAT+Passthrough: Using Passthrough in VR to Prototype Mixed Reality User Studies

Christian Gutierrez
University of Michigan
School of Information
Ann Arbor, Michigan, USA
cfgutier@umich.edu

ABSTRACT

Mixed Reality (MR) is more widely available than ever, resulting in a recent surge of user-centered research and a need for tools that streamline the design, development, and analysis of MR user studies. This is especially true for accessibility focused research, where developing preliminary prototypes can increase safety outcomes when working with vulnerable populations. We present MRAT+Passthrough, a toolkit designed for virtual reality (VR) systems to simulate various MR experiences for the purpose of prototyping MR user studies. Researchers can select between immersive VR environments or enable Passthrough mode, which replaces the virtual background with live footage of the participant's current physical surroundings, effectively producing an augmented reality (AR) view onto the real world. Additionally, researchers can select between two device simulations, a headworn or handheld AR device. To test our toolkit, we replicated a subset of features from a previous study, which utilized MR to assist visually impaired users in wayfinding tasks. To evaluate the usability and utility of our toolkit, we organized a workshop to present it to a panel of subject matter experts. Their feedback will help inform future iterations of this rapid prototyping system to ultimately develop robust software tools for MR accessibility research.

Figure 1: In this simulation of a smartphone-based AR system, the user is using a phone to wayfind inside a virtual room.

ACM CLASSIFICATION KEYWORDS

• Human-centered computing → Human computer interaction (HCI); Accessibility technologies; Mixed / augmented reality.

AUTHOR KEYWORDS

Virtual Reality; Augmented Reality; Mixed Reality; Oculus Passthrough; Unity; low vision; prototyping; accessibility;

1. INTRODUCTION

MR refers to technologies that "mix" multisensory elements of both reality and virtuality, as in the case of augmented reality and augmented virtuality (AV) [5]. MR has recently become a widely discussed emerging technology, creating a widespread conversation about what it fundamentally is [11] and how it can improve our lives. This technology has matured to a point where it is useful beyond its novelty aspect, and can serve a real purpose to help its users accomplish meaningful tasks. Although MR user experience (UX) and interaction (UI) have been steadily researched topics for decades [1, 4], MR technology's significant technical leaps in recent years have resulted in an explosion in popularity as a research topic. In particular, there is an ever-growing interest in including MR technology in accessibility research due to its potential to meaningfully assist people with disabilities [3, 7, 13].

Given these potential benefits, we implemented a software toolkit used for prototyping and piloting MR user studies, with a particular focus on AR capabilities for the first version of our tool. Our toolkit is developed for the Oculus Quest, a VR head mounted display (HMD) that has been recently updated to enable MR features through use of the Passthrough application programming interface (API). Passthrough allows developers to access live video feed captured by the HMD's array of external cameras and stream the video onto virtual surfaces within the application. By bringing real time visuals of the user's surroundings into the experience, Oculus Quest headsets can effectively function as limited MR devices, allowing us to incorporate basic AR features. Additionally, because the MR experiences are actually VR applications under the hood, we were able to simulate different form factors, such as headworn AR and handheld AR devices. For the headworn AR simulation, we replicated prominent features of the Microsoft HoloLens AR headset. For the handheld AR simulation, the user is provided a virtual smartphone that can display AR graphic overlays on its screen. Furthermore, our toolkit allowed users to toggle between a Passthrough environment and a virtual environment, giving more flexibility for researchers to customize the experience. Our toolkit's four MR modes are enabled through the various combinations of device and environment simulations.

To test our toolkit, we replicated a subset of features from an AR tool developed in an existing research study focused on guiding visually impaired users during navigation tasks. We prototyped the AR tool presented in this prior research study to validate if MRAT+Passthrough could replicate the main features of an accessibility focused AR application. After testing a minimum-viable prototype of our toolkit, we hosted a workshop presentation, where we met with a group of accessibility researchers who possess expertise working with visually impaired populations. We presented the current state of our system and gathered feedback for future iterations of the toolkit. Based on the insight gathered in our workshop, we believe that the main contributions of this work are leveraging the novel Oculus Passthrough API to: (1) Develop a toolkit for researchers to prototype and pilot MR user studies using existing VR technology; (2) New possibilities in the design and development of general MR applications for headworn and handheld devices; (3) Provide a novel software solution to safely prototype MR assistive technology for people with visual impairments.

2. RELATED WORK

Our toolkit is meant to contribute to a large body of research aimed at developing MR experiences for people with low vision for the goal of increased user autonomy and quality of life [14, 15, 16, 18, 19]. In order to test our own toolkit, we replicated and expanded upon a research scenario described in Yuhang Zhao's paper, *The Effectiveness of Visual and Audio Wayfinding Guidance on Smartglasses for People with Low Vision* [17]. In this research work, Zhao's team developed an MR guidance system for the Microsoft HoloLens. While wearing the headset in an indoor environment, the guidance system provided audio and visual cues to help the participants accomplish navigation tasks. The system denoted the navigation path with a 3D digital trail that traversed within the environment to guide participants towards the destination marker. There were also several other navigation artifacts along the path, such as turn arrows and distance markers. It was found that for participants with some reliable vision, the combination of visual artifacts with audio cues was effective in wayfinding guidance over audio navigation alone.

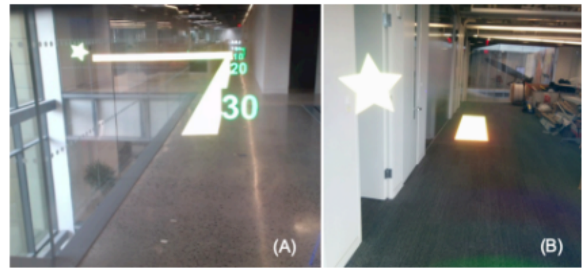

Figure 2: Graphic AR overlays of (A) guiding path with navigation artifacts and (B) destination marker presented to participants during wayfinding tasks

The exploration of MRAT+Passthrough as a tool for prototyping MR user studies has a goal of ultimately being incorporated into an existing MR research toolkit. The Mixed Reality Analytics Toolkit (MRAT), is described in the paper *MRAT: The Mixed Reality Analytics Toolkit* [8], by Michael Nebeling et al. In this work, Nebeling's team developed MRAT as a cross-platform toolkit for rapid data collection and data filtering for enabling the visualization of AR and VR user sessions. MRAT is available as a plugin for Unity and allows for the instrumentation of existing MR apps. It allows researchers to define tasks and metrics from their user studies for data collection and analysis. Additionally, the toolkit provides in-situ visualizations that can be viewed in MR or using a digital tablet. These features allow for the replaying of various data from user studies in both real and simulated environments. Incorporating our four MR modes into MRAT will extend its capabilities by allowing it to simulate different MR device form factors as well as advanced and experimental features (e.g. wider FOV), all within the context of both Passthrough and virtual environments. It would also enable MRAT to leverage Passthrough to transition between AR, AV, and VR modes, providing more streamlined user studies. Additionally, it would allow MRAT to support accessibility studies by providing a flexible and customizable framework for prototyping simulated MR experiences that offset physical risks and cater to specific user impairments and needs.

Figure 3: Mixed Reality in-situ data visualization of a user study as collected by MRAT

Developing tools and applications for exploring the Reality-Virtuality continuum has been a topic of interest for years [5, 6, 10]. One recent interesting effort is introduced by Gruenefeld et al. in their paper *VRception: Rapid Prototyping of Cross-Reality Systems in Virtual Reality* [2]. The authors of this work designed VRception as a tool that allows for rapid prototyping of the various levels in the reality-virtuality continuum, all simulated within immersive virtual experiences. By simulating all reality levels within one virtual reality experience, this toolkit is able to smoothly synchronize all realities and add, subtract, and/or merge elements from the real and virtual worlds as their transition across the continuum. MRAT+Passthrough takes this concept further by granting the user access to their real surroundings via Passthrough, rather than immersing them in a digital 3D LIDAR scan of their physical environment. This not only provides a much higher level of fidelity for prototyping the continuum, but has the potential to produce better safety outcomes and more natural user interactions.

(a) Simulated Reality. (b) Simulated AR.

Figure 4: VRception toolkit simulating (A) reality and (b) augmented reality during multi-user session

3. DESIGN PROCESS

To test our toolkit's utility as a prototyping tool, we prototyped and replicated the wayfinding guidance system described in Yuhang Zhao's work. As a minimum viable product, we focused on the visual guidance features, replicating the AR graphic overlays of their system, including the guiding path, navigation artifacts, and destination marker. While the original AR system was deployed on the Microsoft HoloLens smartglasses, we implemented our prototype for the Oculus Quest using Passthrough to simulate the AR experience. We developed an initial prototype of the guidance system in virtual reality, using a 3D model of an indoor environment as a stand-in for the real world. Once our exploration phase was complete, we replaced the virtual environment of our prototype with a Passthrough video feed to simulate higher fidelity AR. By bringing in the real world to our prototype, the end-user is situated in their real environment and able to be aware of any obstacles or sudden changes in their surroundings, resulting in a safer experience. The benefits of using Passthrough to prototype AR experiences is not only limited to safety reasons, but also has the potential to reduce participant onboarding friction, inspire more natural interactions, and produce an AR prototype of a much higher fidelity.

Figure 5: Prototyping a wayfinding guidance system using VR to simulate a real-world environment

Figure 6: Replicating a wayfinding guidance system using Passthrough to simulate AR

User Interface. Our toolkit makes use of the Microsoft Mixed Reality Toolkit (MRTK), a software plugin for Unity which includes a wide library of various modular user interface (UI) components that developers can incorporate into their applications. MRTK was originally launched as a toolkit aimed at accelerating cross-platform app development for headworn AR devices, but has recently been made available for VR systems like the Quest. Additionally, making use of MRTK UI components will help to streamline the process of porting our toolkit to advanced AR HMD's such as the Microsoft HoloLens in future evaluations of our software system.

The MRTK-based UI we designed for our system consists of a flat panel with two large buttons, each of which can be toggled between two states. The first button is titled "Environment" and toggles between the Passthrough mode and the virtual environment mode. The second button, titled "Device", toggles between the headworn AR device simulation and the AR-capable phone simulation. The UI panel can be placed in any location within the 3D space and remains static until it is grabbed and moved by the user's hand. The panel can also be "pinned", attaching it to the user's avatar. The four MR modes are achieved by selecting a combination of these two main buttons. AR Mode 1, *Headworn AR with Passthrough Environment*, is activated when the AR Mode is set to "Headworn" and the Environment button to "Passthrough". Similarly, AR Mode 2, *Headworn AR with Virtual Environment*, is selected by setting the AR Mode set to "Headworn" and the Environment button to "Virtual". The user can then switch to AR Mode 3, *Handheld AR with Passthrough Environment*, by toggling the AR Mode to "Handheld" and the Environment button to "Passthrough". Lastly, AR Mode 4, *Handheld AR with Virtual Environment*, can be engaged by setting the AR Mode to "Handheld" and the

Environment button to "Virtual". To interact with the UI panel buttons, the user can choose to either physically reach out and press on the buttons or use their hand's laser pointer to select the button by aligning the reticle to the button and pinching their index and thumbs together.

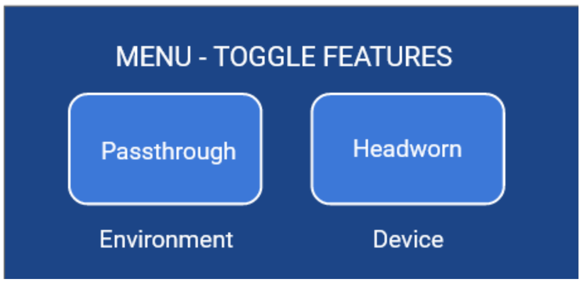

Figure 7: Mockup of UI, illustrating MR Mode 1

4. MRAT+Passthrough

We designed MRAT+Passthrough, a software toolkit consisting of a set of distinct MR modes that together allow researchers to prototype and pilot MR user studies. Our system runs on the Oculus Quest 2 hardware, the most popular VR headset on the current market and was built with Unity, a leading cross-platform development platform. The four MR modes are intended to simulate two common types of devices with AR capabilities–head mounted displays and mobile smartphones. Further, researchers have the option to situate participants in either a virtual or Passthrough environment. They can select a live video feed of the user's physical environment accessed by the headset's external cameras. Alternatively, they can choose a virtual environment and place participants within a completely virtual setting, providing greater customization for elements such as the environment and objects in the scene.

Leveraging Passthrough Technology. Our system is built on top of several cutting-edge MR technologies that extend the abilities of modern VR systems. Recent software updates from leading MR headset manufactures such as Oculus, Pico and Varjo are allowing developers to access the video feed captured by the HMD's external cameras and live stream it within an MR experience, a novel technology which is commonly referred to as Passthrough. Our toolkit leverages the Oculus Passthrough API, a collection of features for the Oculus Quest 1 and 2 that enable developers to access real-time video footage captured by the device's external forward-facing cameras. This grayscale video feed was previously only available to the device's operating system for managing tasks such as inside-out tracking in six degrees of freedom and more recently with user hand tracking, all but eliminating the need for physical controllers. Updates to the Unity Oculus Integration SDK have made this video data available to Unity developers in the form of a Passthrough Layer component that can be applied to a GameObject, effectively acting as a dynamic texture. This can be leveraged to replace any surfaces with the Passthrough video feed, including the entire background environment, exposing the user to their physical surroundings. Alternatively, it can also be projected onto a smaller surface to create an achromatic window to the outside world. It is this novel technology that affords us the capabilities to develop our toolkit and its associated MR modes. Below is an in-depth description of all four modes.

AR Mode 1: Headworn AR with Passthrough Environment. The first mode simulates the experience of the participant using an AR headworn device, such as the Microsoft HoloLens. The headset's FOV is presented as a stationary digital frame in the center of the participant's gaze. Only content rendered within the FOV frame is to be considered AR content. The participant is meant to feel situated within their real physical environment, as they can see the Passthrough video feed being rendered into the entire background environment. This mode could be useful for situations where researchers deem that the participant's real environment is the appropriate scenario to conduct experiments in. For example, this mode could be used to prototype an application where the participant is in an outdoor environment, like a crosswalk path, where they are receiving voice and audio assistance crossing one side of the street to the other. Furthermore, we designed this mode to provide the option to customize the capabilities of the simulated AR headset. An example of this is by enlarging the dimensions of the FOV or simulating communication between the HMD and an external tablet device, effectively prototyping advanced AR features which might not be currently available.

Figure 8: AR Mode 1

AR Mode 2: Headworn AR with Virtual Environment. The second mode is similarly intended to simulate the experience of wearing a head-worn AR device. Once again, a static FOV frame is presented in the participant's screen space to denote the boundaries of where the AR graphic overlay will be rendered. In this mode, however, the participant is situated within a synthetic virtual environment, potentially serving as a substitute for a similar real world setting. Because the entire environment is virtual, researchers are given much more control over the setting to place the participant. This mode is appropriate for situations where researchers prefer that the participant be situated in an environment alternative to their own, such as a simulated medical building or a grocery store, which could also represent a physical location to be used for testing at a later stage. Further, this mode can also be used for training purposes inside of a lab setting where a real environment might present safety hazards. Additionally, the virtual environment presents opportunities for better tracking of implicit interactions such as scanning of the environment, head movements, and the path traversed by the participant.

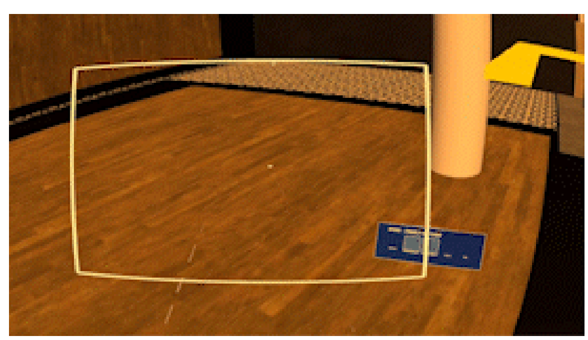

Figure 9: AR Mode 2

AR Mode 3: Handheld AR with Passthrough Environment. The third mode simulates the participant utilizing a handheld AR-capable smartphone. The participant is presented with a virtual mobile phone that is placed within their avatar's hand meant to represent a physical phone. The participant can hold and freely move the device similarly to how they might handle a smartphone in real life. In this mode, the graphic augmentations are only rendered on the phone's screen, and not anywhere else in the environment, similar to how a physical smartphone would behave. In this mode, the background is replaced with the Passthrough feed, allowing the participant to see into the real world in real time. We designed this mode for situations where researchers intend for participants to see and even engage with their physical environment. Further, it affords researchers the ability to quickly experiment with the handheld AR device's settings as well as track analytics in various scenarios. For example, if the researchers want to analyze data related to tracking and spatial mapping from the user's perspective rather than the device's, the use of a simulated smartphone would prove more beneficial than a real hand-held device. This mode enables a range of scenarios where tracking and sensing capabilities that are not available on a smartphone could be simulated in VR, such as user gaze tracking relative to the simulated handheld device, in circumstances when advanced and experimental AR content needs to be rendered on the virtual handheld device, or when interactions beyond the smartphone's capabilities or cross-device interactions between the headset and handheld are the focus of the study [12].

Figure 10: AR Mode 3

AR Mode 4: Handheld AR with Virtual Environment. This fourth mode is also meant to simulate a participant using a smartphone to view graphic augmentations rendered in their environment. When this mode is activated, a virtual smartphone is placed in the participant's avatar's hand to be handled like a real phone. The participant is situated within a virtual environment, providing the researchers with complete control over where to place the participant as well as what content is displayed in the chosen setting. Additionally, the graphic overlays are only rendered on the device's screen and not on the participant's virtual environment, simulating the experience of using an AR device in real life. We designed this mode for situations where the researchers wish to customize details of the participant's environment. These scenarios might include aspects such as changing lighting conditions in a room and the addition of virtual obstacles that represent no real physical danger, which can be important when piloting accessibility tools with low-vision users. For example, the experimenters might design a virtual environment that simulates the participant's home. In this simulation, the participant might be tasked with looking for specific personal items inside their home. The virtual nature of the environment will allow for the customization of settings such as where in the home the personal items are placed or the environmental lighting based on what time of day it is. In other more general scenarios, this mode could allow for environment customization involving which objects appear in the scene, the spawning of obstacles, and the speed at which objects move.

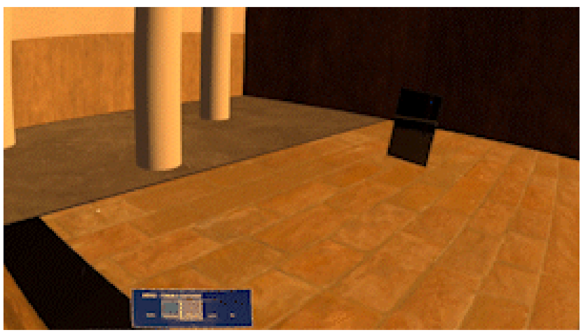

Figure 11: AR Mode 4

5. IMPLEMENTATION

Our toolkit made use of several novel resources for developing MR applications using VR that were made only recently available, as of the time of this writing. We implemented our toolkit on the Oculus Quest 2 VR system using Unity 2020.x as the development engine. We initially used the Oculus Integration SDK version 31.2 to access the experimental version of the Passthrough API, eventually migrating to the general release version of the API, found in SDK version 35.0. We also made use of the MRTK UI development toolkit for the future benefit of streamlined cross-platform tech transfer from the Quest to a HoloLens.

The four MR modes were achieved with a combination of accessing the Passthrough capabilities, key changes to the simulated device's user interface, and selectively rendering groups of objects to the active cameras. To generate *Mode 1: Headworn AR with Passthrough Environment*, the scene's virtual background was entirely replaced with a Passthrough layer. Some of the key specifications to achieve this are to add an *OVR Passthrough Layer* component to the *OVR Camera Rig* and setting the *Projection Surface* to *Reconstructed*, the *Placement* to *Overlay*, and the *Background* to *Black*. To create the headworn UI, a rectangular frame was attached as a child of the OVR Camera Rig, denoting the boundaries of the FOV. In *Mode 2: Headworn AR with Virtual Environment*, the main difference from Mode 1 is to use a standard virtual environment instead of the Passthrough layer. To generate *Mode 3: Handheld AR with Passthrough Environment*, we followed the same method to replace the virtual environment with a Passthrough layer. To simulate using a smartphone to experience AR, we attached a separate camera onto a primitive Cube that served as the participant's phone. The camera, much like in a real phone, rendered its footage onto the phone screen via a Render Texture. To exclusively render the AR overlays onto the phone screen, any *GameObject* representing an AR hologram was assigned to the same custom *Layer Mask*. That layer was then added to the phone camera's *Culling Mask* attribute and omitted from the main camera in order to only display the holograms on the phone. To create *Mode 4: Handheld AR with Virtual*

Environment, we once again transitioned to a virtual environment by deactivating the Passthrough component.

6. EVALUATION

To evaluate the effectiveness and utility of our software toolkit, we organized a one-hour workshop to introduce our work, to present how we believed our toolkit could be useful in a research setting, and to receive feedback for the current and future versions of our system. We invited a three person panel of accessibility researchers who possess expertise working with visually impiared populations as well as with AR. One audience member was a professor within a Department of Blindness and Low Vision Studies. Another panelist was a professor in Biomedical Engineering. The third guest was a graduate student in Electrical Engineering and Computer Science (EECS).

Our workshop was segmented into three blocks, each consisting of a presentation followed by a question and answer segment. In the first block, *Experimental Design*, we introduced the project, the motivation behind our work, and an overview of the toolkit. This was followed by a series of experimental design questions pertaining to our attendees' past research experiences working with visually impaired participants and AR technology. The second block, *Toolkit Design*, focused on our proposed solution, diving deeper into our software toolkit's abilities and user interface. This block concluded with a series of questions relating to the usefulness of our system, including feedback on what features seemed the most helpful as well as speculation regarding what obstacles our participants might encounter. The third and final block, *Future Research*, consisted of a disclosure of the current limitation of our software system and some workarounds that we recommend research teams to adopt. The final set of questions focused on future research, with an emphasis on incorporating additional features and improving the user experience for the research team.

7. RESULTS

During the various stages of our workshop, we received feedback on the usability and utility of our current system, as well as recommendations of what to consider incorporating into our future work. Below we go through the key questions we posed to the researchers, and summarize their answers, organized by their respective blocks.

Block 1. During our *Experimental Design* block, we asked the following questions:

Question 1: Is our research focus on navigation assistance adequate?
Key Insights: (1) Our focus should not only be on getting a user from a starting point to a destination, but also on finding items within a room, as this is a very common task among the visually imapired, producing many challenges. (2) Course correction must be addressessed. If the individual fails to follow the prescribed navigation due to any reason, the system must mitigate those issues and provide cues to guide them back to the correct path.

Question 2: What data are important to collect during the experiment?
Key Insights: (1) The participant's natural walking speed should be measured and compared to their speed during the experiment, to rule out a possible confounding factor. (2) It is important to get both the objective and subjective measure of the participant's mental energy expenditure during the navigation task. After the experiment, ask the participant to rate how much they had to explicitly think about the tasks while following the instructions, from a scale of 1 (easy) to 9 (very difficult). Compare this subjective measure against the objective measure of the participant's walking speed during the task. (3) A qualitative analysis of the types of mistakes made by the participant should be conducted to determine more accurate findings.

Question 3: What are the requirements for a user session to be successful?
Key Insights: (1) The participant should locate the destination within a reasonable time frame, determined beforehand (2) It is important to have a time limit for each navigation task, since reaching the destination after an excessively long time does not equate to a successful task. (3) The participant's time to completion should be compared against the average completion time for a person with normal vision.

Block 2. During our *Toolkit Design* block, we asked the following questions:

Question 1: Which AR Mode(s) seem the most and least useful?
Key Insights: (1) It is best not to require a participant to hold a phone while completing a navigation task. The participant will likely already be holding a walking cane with one hand, and will need to open doors with their remaining hand. Being expected to hold a phone and have no unoccupied hands will present many challenges. (2) It is important to allow participants to actually walk and travel a physical distance since this mirrors how they would behave in the real world to a much higher degree compared to strictly standing or seated MR experiences. (3) For training purposes, or when supervision is not available, it is acceptable to place the participant in a stationary MR experience (those involving alternate locomotion techniques such as teleportation).

Question 2: Do you foresee any obstacles that participants might encounter?
Key Insights: (1) Participants might experience motion sickness during the navigation task. A possible way to mitigate this is by issuing sparse intermittent visual and voice commands. (2) It is important to keep in mind that there are different forms of visual impairments and various ways in how they can manifest. The UI and user experience should be tailored generally to the different forms of impairments and specifically to the participant's unique needs. (3) Participants might feel comfortable wearing bulky MR equipment in a lab setting, but they might be hesitant to wear the hardware outdoors. In order to expect wide tech adoption among this population, the technology should look like common standard-looking accessories.

Block 3. During our *Future Research* block, we asked the following questions:

Question 1: How useful do you think the toolkit can be given its current limitations?
Key Insights: (1) The system should run on hardware that is reasonably lightweight and able to be carried by the participant, allowing them to be fully autonomous during the navigation task. (2) A second person should not be following the participant around during the navigation task, this will cause too much interference and affect the performance of the participant.

Question 2: Are there other important features you can think of?
Key Insights: (1) The user interface should allow users to modify application settings such as the contrast and color of the image as well as the thickness of the path lines, in order to optimize the toolkit experience to individual needs and impairments. (2) Instead of displaying the navigation artifacts (e.g. path, distance indicators, destination marker) with a single color, add a checkerboard pattern to them in order to make them more visible to a wider audience. (3) Include multimodal guidance in the form of both visual and auditory feedback to make the toolkit more effective. These guidance features should be customizable to fit the needs of the user.

Question 3: How can we improve our system for you as experimenters and researchers?
Key Insights: (1) It is important to record a first-person perspective with an external camera (e.g. head or chest mounted GoPro) for the research team to evaluate and compare footate against the recording of the in-device MR experience. (2) A good assessment can be achieved with about a couple dozen participants. Acquiring high quality data from a small pool can yield very valuable results and insights that can expand to a larger population.

8. DISCUSSION

Overall, our workshop audience members responded with enthusiasm and optimism towards the potential of our toolkit in user studies. Additionally, they provided valuable feedback that will inform future versions of our system. For example, one important topic that was raised is the difference between objective and subjective measurements, where the former is done by the participants and the latter is performed by the researchers. Another possible improvement dealt with our toolkit's user interface. It was advised that our system allow for customization of the MR experience and UI to fit their particular impairments. Additionally, one significant criticism of our handheld AR simulation was that participants should not be expected to be holding a phone while they are completing a wayfinding task due to potential dangers. Other recommendations covered the topics of course correction features, multimodal feedback, the ideal form factor of the headset to maximize adoption outside the lab, and the importance of allowing participants to physically walk around the room while utilizing the system.

9. FUTURE WORK

Currently, our toolkit consists of two toggle buttons which produce our system's four MR modes. These modes were sufficient to prototype a user study focused on wayfinding, where the participant is not expected to actively interact with the UI during the experience. However, to make our toolkit more effective at prototyping a wider range of user studies and more complex scenarios, several additional features need to be implemented. Beyond our own limitations and the scope of our user study, there are a number of different scenarios our toolkit could be leveraged by developers. Based on feedback gathered from our expert panel during the workshop presentation, we outline actionable recommendations and features to be implemented in future iterations of our toolkit.

Firstly, for the research team to be able to conduct meaningful analysis on their user studies, several analytics-focused features must be implemented. A point that arose multiple times during our workshop is that it is important for the experimenters to be able to observe what the participant actually sees during the AR/VR experience as well as any video footage captured via external cameras (e.g. GoPro camera). Due to the limitations imposed by Facebook's security policies not allowing for Passthrough video content to be directly recorded by the Oculus Quest, we have relied on third party software that requires the headset to be physically tethered to a laptop computer which is then strapped to the user's body. A future version of this toolkit should provide a way for the Passthrough video to be recorded in the headset itself, allowing researchers to analyze the video footage in real time as the participant is experiencing it. Something future researchers could also explore is the potential of streaming to an external screen via Oculus's new AirLink feature, which is still in experimental mode. Further, our toolkit would benefit from a "Research Mode", that allows researchers additional access to data captured from sensors and the Passthrough feed itself. For example, a researcher could be interested in analyzing a number of raw data obtained by the MR hardware, such as data from the user eye tracking camera, the headset's inertial measurement unit (IMU), computer vision data from the video feed, and environmental data captured from the user's surroundings. Additionally, a Research Mode is highly relevant to issues of privacy and security. With participant consent, this mode could be activated in order to allow researchers to ethically collect data that might otherwise be considered unethical or illegal to collect.

Other analysis features that should be incorporated into our toolkit to extend its utility include the three main processes supported by the original MRAT tool. One such feature includes *Interaction Tracking*, which is concerned with the tracking of interactions such as the user and app status, gestures and voice commands, tasks and modes, as well as object and tasks markers. Other MRAT features our toolkit would benefit from all within *Task Definition*, and include a detailed specification of tasks, as well as the defining of heuristics and metrics. The third MRAT process that would help extend our tool's analytics capabilities is the *Session Inspection* category, which includes features such as an app dashboard to visualize data and metrics, as well as in-situ visualizations projected while the app is running. One final aspect of MRAT that can be adopted to make our tool more accessible is to offer our toolkit as a Unity plugin that developers can import into their scene and customize to their specific needs. Enabling researchers to analyze the data captured by our system is crucial to achieving the toolkit's ultimate goal of supporting the design, implementation, and analysis of user studies.

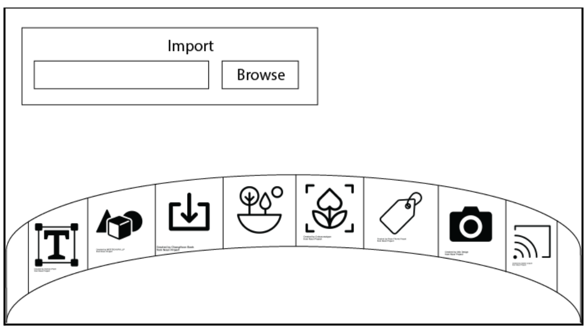

Figure 12: Mockup design of a more feature-rich UI

There are a number of additional advanced capabilities that were originally discussed during the design stages of our toolkit, but were out of scope for the system evaluation during our workshop. One such feature is the ability for experimenters to import 3D models into the application. This could be in the form of importing models from a local directory within the headset's hardware, or from an online repository, such as Turbo Squid or Sketchfab. A related feature is the capability to select and place primitive 3D shapes within the environment, along with any associated tools such as scaling, rotation, and translation. Another useful tool would be the option to capture a screenshot of the external physical setting as well as the virtual in-app environment. An additional feature that was initially discussed is the capability to annotate the 3D environment by means of typing text to add notes in world-space, sketching and jotting down handwritten notes via a mechanism similar to Google Tiltbrush, as well as a system to tag and classify items in the environment. The addition of these features would not only extend the capabilities of our toolkit for the purpose of designing user studies focused on visual impairments, but it would also become a very strong instrument to prototype and pilot a number of different user studies that leverage MR technology.

10. CONCLUSION

In this paper, we introduced and evaluated MRTK+Passthrough, a software toolkit for the Oculus Quest VR system that allows researchers to rapid prototype and pilot user studies that involve MR experiences. Our toolkit consists of a set of four distinct MR modes, used to simulate the experience of headworn AR and handheld AR systems, with the additional capability to render either a virtual environment or a Passthrough video stream. To test the usability and effectiveness of our toolkit, we replicated an existing AR research scenario, in which the original authors developed an MR toolkit to assist people with vision impairments during navigation tasks. To evaluate our efforts, we hosted a workshop presentation to a panel of researchers with experience working with both AR technology and visually impaired populations, where we presented our toolkit and gathered feedback and insights from our experts. Based on their recommendations, we plan on updating our toolkit and testing it with participants. Further validation is expected by porting a more feature-rich version of our software to the Microsoft HoloLens AR system. Our preliminary work serves as the foundation for future lab experiments using this toolkit.

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