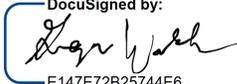


Remote Testing of AR HUDs for Lunar Exploration

by  
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## Abstract

This thesis is an observational case study exploring human navigation using augmented reality (AR) on the moon. This research was conducted remotely using a game-like simulation to test the design of a Heads-Up Display (HUD). This HUD design would later be programmed onto a Magic Leap as part of the University of Baltimore AstroBees' NASA SUITS Challenge entry. The results of this study include recommendations for using voice inputs in space, AR navigation design, and research methods design for remotely testing AR prototypes.

## Acknowledgments

To my wife, Jocelynn, and my boys, Everett and Harrison, who have supported me physically and emotionally for the last 3 years of this degree. Thank you for helping me achieve this goal. I couldn't have done it without your support.

To my parents and siblings who taught me to “shoot for the stars, even if you'll land on the moon” (or something like that, I wasn't a good listener). I think having my designs land on the moon would still be really awesome. Thank you for teaching me to see a hard task through and instilling in me a love of curiosity and learning.

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Thanks for reading.

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## Chapter 1: Introduction

**Overview**

Augmented Reality (AR) is a technology which has been around in various forms since Ivan Sutherland's "Sword of Damocles" in the 1960s (Schmalstieg & Höllerer, 2016), but which has more recently been accessible to more people due to the reduction of computing costs, advancements in computing power, and other advancements in technology. These advancements make AR a quickly growing market aimed at all sorts of various applications such as business efficiency, entertainment, and task completion or assistance.

"Wearable augmented reality enriches reality by displaying virtual components, resulting in the delivery of on-demand information available in physical environments." (Yee, 2020) and creates automatic links between the physical world and virtual information. This is particularly helpful in a navigation setting, where every second counts and could be the difference between life or death in contexts such as driving a car, flying a plane, or piloting a space craft.

AR was first used as a navigation application in 1998 in NASA's X-38 spacecraft, which used a Heads-Up Display (HUD) to overlay map data to enhance visual navigation (Zeal 3dprinting, 2018). It has been implemented in many air- and space-crafts since then, and most recently NASA has been investing research into how astronauts might use AR as part of the 2024 Artemis missions.

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This research adds to NASA's growing body of AR research for astronauts as part of the 2021 NASA SUITS challenge, an initiative which challenges students to create augmented reality interfaces to support future spacesuits. The 2021 NASA SUITS Design Challenge is focused on building an augmented reality system which supports an astronaut's navigation on the Artemis lunar missions. The University of Baltimore students entering the 2021 NASA SUITS challenge consist of undergraduate students in Applied Information Technology (AIT), Simulation and Game Design (SGD), and graduate and post-graduate students in Interaction Design (IDIA and IID) programs.

University of Baltimore's AstroBees created ARGOS – Augmented Reality Guidance and Operations System – to assist astronauts in carrying out their missions. 2021 is the 3<sup>rd</sup> year that groups from University of Baltimore have been participating in these challenges. The 2021 challenge, of which this research is a part, focuses on using augmented reality to navigate the lunar environment.

Test scenarios were completed in a simulated environment due to COVID-19 restrictions. COVID-19 protocols prohibited usability testing in person and restricted our ability to put a Head Mounted Display (HMD) on participants. To test our design, we created a 1<sup>st</sup>-person, simulated environment where users could complete the tasks online and give us feedback via a video call.

This study conducts research through design using observation and exploration. It is rooted in a traditional product design process of discovery, problem definition, solution development, and delivery of a solution. Our proposed solution is backed by academic

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research, built up using experience and usability testing, and validated through user validation testing.

### **Problem Statement**

This study is an observational case study designed to observe how humans perceive and use wearable augmented reality to help them navigate physical space. The focal point of the research documents novice users' perceptions of using augmented reality interfaces to navigate unfamiliar environments. The objectives of this research are to answer:

1. Is augmented reality technology helpful in navigating unfamiliar environments?
2. If it is helpful, what elements must be present in order to be the most helpful?

This thesis explores the impact of augmented reality navigation to human cognition using a simulated moon environment unfamiliar to the participants. The goal is to identify potential opportunities and areas of improvement of applied augmented reality using a standard product design process of interaction design, prototyping, usability testing, research methods, and research analysis.

## Chapter 2: Literature Review

### **Introduction**

With the reduction of computing costs and better computing power, Augmented Reality (AR) is not only a hot topic in the tech and gaming communities, but in many other industries such as business, entertainment, and tourism. The applications for this technology range widely from education to entertainment, to business and social impact. AR is being used to transform industries, educate, save lives, lower business costs, and entertain us.

### **History and Growth of Augmented Reality**

Since the time of Ivan Sutherland's "Sword of Damocles" (Figure 1) in the 1960's (Schmalstieg & Höllerer, 2016), we've learned a lot about how humans perceive computers, how they want to relate to them, and what they expect computers to do for them. We've seen the smartphone, IoT, and wearable markets explode, with little sign of slowing down. The opportunities that cheaper, more reliable, computing power provides are transforming industries and our world.

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**Figure 1**  
*Sword of Damocles*



*Note:* Sword of Damocles, the first head-mounted display built in 1968 by Ivan Sutherland (Schmalstieg & Höllerer, 2016).

We've also witnessed an increasing need to understand how humans relate to computers. Center Centre, a UX Academy, projects that job growth for UX Designers will grow by 22% in the next 10 years (Center Centre, 2018). Large corporations like GE and IBM are growing their product teams by hundreds of designers at a time (Center Centre, 2018). This job growth trend indicates that businesses and other organizations are increasingly recognizing the value of understanding how their product offerings are perceived by their customers (UX Magazine Staff, 2014).

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**Market Sizes**

The global AR and VR market was USD 11.35 Billion in 2017 and is forecasted to reach USD 571.42 Billion by 2025. This is a huge CAGR growth of 63.3% over 7 years (Valuates Reports, 2020).

The Enterprise sector has dominated the AR/VR/MR markets at 84% (Grand View Research, 2019). This is because enterprises have traditionally had both the expertise and resources necessary to fund these projects to benefit their organization. AR is proving beneficial to the Enterprise sector for many reasons including lowering the cost of labor (by making employees more efficient) (Perez, 2020), better workforce training (VRScout, 2019) (Clark, 2019), and enhanced customer experiences (Clark, 2019).

While the Enterprise sector has traditionally dominated the AR/VR/MR market, the IDC reports that commercial sectors will grow to 68.8% by 2023 (Nicastro, 2020). The initial slow growth of AR into the commercial sectors can be attributed to the computing and hardware costs of these types of experiences. AR experiences have traditionally been quite expensive, thus creating a barrier to entry for most people, but new technologies have lowered the barrier to entry and accelerated growth in the commercial sectors.

Large innovations in AR technology, particularly when related to smartphone AR applications, have spurred on much of the growth in the commercial sector. Apple's ARKit (released in 2017) (9To5Mac, 2017) and Google's ARCore (released in 2018) (Google,

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2018) made developing AR experiences much easier, thus reducing the cost of AR experiences and making it easier for developers to get AR experiences into consumer's hands.

### **Defining AR, VR, and MR**

Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR) are all quite similar and carry similar design considerations. However, they are important to distinctly identify because they each create distinctly different experiences for the user. For example, a VR experience creates a completely immersive world, while an AR or MR experience adds digital elements to the real world.

### **Virtual Reality**

Virtual Reality (VR) is an immersive technology that fully immerses the user into a virtual environment, replacing many of their senses; typically sight, sound, and touch (via remote controls). This creates a 3D world apart from the physical world which a user can explore, play in, or complete tasks in. Common applications of VR are in gaming, education, and employee training.

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**Figure 2**

*Walmart uses VR for active shooter training (VRScout, 2019).*

**Augmented Reality**

Augmented Reality (AR) is similar to Virtual Reality, but instead of fully immersing a user into a different experience, it superimposes digital elements onto the real world. This is most commonly seen in car backup cameras, Snapchat filters, or your car GPS voice giving you real-world directions. It is probably most famously been used in Niantic's Pokemon GO (Techcrunch, 2016), a global phenomenon where players travel to physical locations to battle and collect Pokemon.

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**Figure 3**

*Pokemon GO, an AR game that overlays Pokemon characters and battles over the real-world (GeekWire, 2016).*



AR may use many kinds of devices to achieve this experience. Headsets such as Google Glass, Vusix, or Magic Leap are common headsets in the AR industry, but have not penetrated the consumer market deeply enough to be widespread. More common are AR applications using a smartphone because of the popularity of the smartphone and its ubiquitous use in our lives. It can also be used in camera feeds and Head-Mounted Displays (HMD).

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**Mixed Reality**

Mixed Reality (MR) is really a combination of VR and AR (JustinMind, 2019). It requires the use of a headset but does not completely visually immerse the user. Instead, it allows 3D digital objects to exist and be used in the real world.

**Figure 4**

*VimedixAR by CAE Healthcare lets a group practice radiation treatment on a virtual model (Forrester Research, 2017).*



### **Survey of the AR Landscape**

AR, VR, and MR experiences are being created for many different industries. Only a survey of some of the most common AR applications will be covered here.

#### **Navigation**

AR was first used in navigation as early as 1998 in NASA's X-38 spacecraft, which used a Heads-Up Display (HUD) to overlay map data to enhance visual navigation (Zeal 3dprinting, 2018). Since then, HUDs have been installed into many airplanes (GOMES, 2015) and Navy diving suits (Ungureanu, 2016). NASA is currently investing research into how astronauts might use AR as part of the 2024 Artemis missions.

AR has been used for navigation in commercial and enterprise products. Google Maps, Apple Maps, and other navigation applications for smartphones connect satellite and other data to our current location to help us navigate our world. Enterprises like DHL use AR to direct personal shoppers where to pick the next item for an order (Kyselova, 2020).

#### **Games**

Some of the earliest players in the AR space were in games. AR Quake was released in 2000 (Blippar, 2018) and Blippar released their "Games for Glass" at the 2014 Augmented World Expo (Blippar, 2014). Many other games have followed such as Pokemon GO (GeekWire, 2016), Minecraft Earth (Minecraft, 2020) and Avo (Playdeo,

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2020). Games provide a natural testing ground for AR where we can try new interfaces and interactions with little risk to our wellbeing.

**Figure 5**

*Minecraft Earth. Image taken from minecraft.net (Minecraft, 2020)*



### Education

AR for education plays an important role for advancing AR technology and growth. AR can create a much better learning environment than other traditional methods because it allows us to poke, prod, and explore models (such as in AR Frog or Archeology). It lets us explore an environment with more of our senses and in a way that is entertaining and memorable. Notably, it lets us better teach and explore concepts at a much lower cost (Li & Fessenden, 2016), to more students, while improving task performance (Tang, Owen, Biocca, & Mou, 2003).

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**Figure 6***An AR frog dissection experience by Designmate called Froggipedia.***Productivity**

AR has transformed tasks which may have required a lot of tools or training into simple tasks. Just about anybody with only a smartphone camera can do things like plan landscaping projects with iScape (iScape, 2020), measure distances with Apple's stock Measure app (Apple, 2020), create virtual walkthroughs of spaces with Matterport (Matterport, 2020) or pick paint colors (VRScout, 2018).

**Figure 7***iScape helps users plan outdoor landscaping projects using AR (iScape, 2020)*

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### **Training**

In 1992, Rosenberg introduced “Virtual Fixtures” which gave training to U.S. Airforce pilots for better flying practice (Zeal 3dprinting, 2018). Since then, AR has continued to train people to do their jobs better and more efficiently. It has been used to train doctors for surgery (McFadden, 2020) and guide remote Porsche car technicians (McFadden, 2020).

### **Principles of Design for Augmented Reality**

Augmented Reality requires much of the same design considerations as other digital experiences, but with much more consideration for 3d space. Tyler Wilson (Wilson, 2017) has done great work in identifying AR design principles, outlined here.

### **Environmental Design**

Possibly the most important differentiating consideration between an AR experience and other digital experiences is that of the environmental context. UX Designers are traditionally skilled in designing 2d smartphone or web interfaces. The main thing to consider when designing any kind of AR experience is how a user would expect to interact with your experience within their environment.

Wilson describes that a good way to do this is by imagining looking through a “window” into an enhanced environment. Whatever you experience through that window

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should be considered in your design. The rest of Wilson's considerations should be designed with the user's environment in mind.

**Figure 8**

*Imagine your hardware as a "window" you look through. Image from Portals AR app by Viewport Pty Ltd*

**Interaction Design**

The 2 main Interaction Design considerations are to answer what elements your experience includes and what actions the user can take within your experience.

***Elements***

Elements make up the AR experience and are most likely the reason the experience exists. These could be anything from 3d models for education, instructional media for employee training, or characters in a game

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***Actions***

Actions are how the user can interact with the augmented environment. The actions can range from very basic (i.e. pressing the play button on instructional media) to incredibly complex (i.e. modifying a 3D model).

When considering how to interact with the environment, you should consider what hardware the user will be engaging with and their level of experience with AR. You should also include the ergonomics of the experience. If they're holding a smartphone device, how will they hold it? How will they hold the device and interact with the augmented environment? If they're using a headset, how much do they have to twist their neck to use the experience?

**Cues**

Visual and Audio cues play crucial roles in enhancing an experience and immersing the user into it. Cues inform the user what elements can be interacted with, and how to interact with them.

Cues should guide the user and encourage them to use 3D space. Visual cues should show them that there are elements out of view that they need to turn to see and audio cues can help users notice off-screen objects.

**Color**

Color theory works much the same in AR as in all other mediums, with an emphasis on accessibility and readability. Because the experience doesn't have a flat color background to rest on, you should be very cognizant of the environment

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(i.e. indoors, outdoors, classroom, etc.) that the experience is being used in. Lighting plays a huge role here, and color should be chosen carefully.

Back to our “looking through a window” example, the UI has now been “painted” onto a “window”. What elements need to be transparent? How does the lighting and type choices affect the readability of the UI? Are color choices clear in intention?

### **Weight**

“Lighting can make the difference between immersing your Users and leaving them bored.” (Wilson, 2017). Shadows make objects more substantial and bring them to life. The best position for your light source is at 12 o’clock for the best effect.

### **Be Careful with Innovation**

Putting a high cognitive load on a user in any experience is bad and will likely lead in poor user retention. Even more dangerous though is putting a high cognitive load on a user where they may be in physical danger.

The principle here is to innovate in small doses and only where it makes sense to do so. Use familiar mobile gestures and patterns so that users will feel comfortable exploring your experience.

### **Principles of Human Navigation**

For this project it is also necessary to consider how humans navigate their world. Recent research shows that our brains make complex decisions very quickly and different

areas of the brain perform distinct functions in getting us from place to place. A growing body of research also indicates differences between how men and women navigate.

### **Brain participants in human navigation**

Studies by Thackery Brown et al. (Brown, et al., 2016) discovered that the hippocampus and prefrontal cortex enable humans to plan and navigate routes. These studies also show that the frontopolar cortex helps encode this information into the hippocampus. The parahippocampal cortex, perirhinal cortex, and retrosplenial complex help us “visualize” future spatial contexts. This information, encoded in the hippocampus and other regions is important to helping us create mental navigation models and in rerouting us or making other decisions when unexpected events happen along our navigational path.

### **Gender differences in navigation**

There are some notable differences in how men and women navigate. Evidence suggests that the differences are not significantly different in our ability to navigate, but rather in the strategies that men and women employ to get to their destinations. Studies by Alexander Boone (Springer, 2018) show that men are more likely to reach a destination quicker (in a known environment) through use of shortcuts. In contrast, women were more likely to follow learned routes and wander.

## **Applications in Flight and Space Travel**

AR has been used in space travel since 1998 when NASA used a HUD in the X-38 for flight navigation and instrumentation. Since that time AR has been implemented in

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other space and aircraft to help pilots navigate their flights and give other pertinent information.

While HUDs have been implemented in planes and spacecraft, they have yet to be implemented in an astronaut's suit. For the past 5 years, and with the Artemis missions program underway, NASA has begun investing time and research into exploring how AR might improve human autonomy in space (Engineer, 2020). Teams of students have been selected by NASA the past 5 years to work on different aspects of space travel, such as scientific sampling or navigation, to increase our understanding of how AR would best benefit humans outside of earth.

This year's NASA SUITS challenge focuses on human navigation in space (NASA, 2020). This research is part of the NASA SUITS challenge.

## Chapter 3: Methodology

### Overview

The methods used in this research are designed to discover how augmented reality might most effectively help humans navigate unfamiliar terrain and territory. The primary goal of this research is to observe how the user interacts with the digital interface and physical world and determine if user performance is improved with augmented reality assistance. This research focuses specifically on navigation performance.

This study is part of research performed by University of Baltimore students for the NASA SUITS 2021 challenge. The NASA SUITS 2021 project builds on previous years' challenges to challenge students to create augmented reality systems capable of supporting astronauts in spacewalk missions. The 2021 challenge prioritizes using augmented reality to help astronauts navigate the moon.

The research and design strategies used to test University of Baltimore's augmented reality system applied to navigation are explained in this chapter. The methodologies are designed to:

1. Observe how efficiently users are able to navigate unfamiliar territory using an AR HUD with no facilitator interference.
2. Observe how different HUD designs affect navigation efficiency.
3. Learn about users' preferences related to visual design.

## Materials

### ARGOS and Magic Leap 1

The designed HUD is meant for real-world operation on a Magic Leap 1 device running the ARGOS system developed by students at the University of Baltimore as part of the NASA SUITS competition. Due to COVID-19 protocols, in-person testing could not be facilitated and therefore a virtual method to test the design was required.

The purpose of the ARGOS system “is to reduce cognitive load and aid completion of tasks while utilizing hand gestures and voice recognition for users to navigate through the interface” (Yee, 2020). The Magic Leap 1 facilitates these goals by providing a hands-free interface that users can interact with using simple hand gestures and voice.

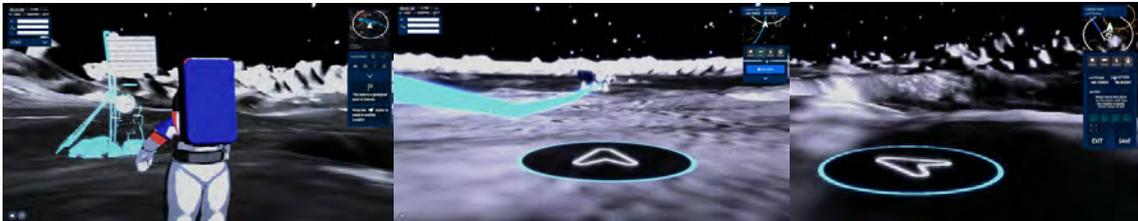
**Figure 9**  
*The Magic Leap 1 device*



### Simulated Environment

The user interface for this study was designed by University of Baltimore students and programmed to a Magic Leap 1 device for the NASA SUITS Challenge. The same design was built by students in the Simulation and Game Design department (Ahsan, et al., 2021) (Hunt Estevez, Jones, Shrestha, & Vincenti, 2021) in a simulated environment for this research to test our HUD design. The simulated environment was built in Unity using C# and hosted on Itch.io, a platform where game developers can get their games tested. Participants were asked to log into Itch.io, share their screen, and play the simulation.

**Figure 10**  
*Simulation of AstroBees' HUD Design*



Note: Figure 10A is from Round 1, while 10B and 10C are from Round 2 of testing.

### Participants

Fourteen adult volunteers from age 18-45 participated in this study. Eight of the participants participated in an initial round of testing. The remaining six participants participated in a second round of testing to validate changes to our design based on feedback from the first round.

Our participants self-reported themselves mostly technology-literate (4.2 out of 5), but less familiar with AR or VR technologies (3.4/5). Our participants were only

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moderately confident (3/5) using Head-Mounted Displays (HMD). When asked about whether they have experience using AR, many participants mentioned using AR or VR to play games (i.e. Pokemon Go), use AR filters, or to use an AR demo (such as at a conference). None of our participants reported using a HMD regularly, but rather used AR on their smartphone (mostly for entertainment purposes).

Table 1 displays relevant demographic characteristics of our participants. The average age of our participants is 28. Our participant pool is 35.71% male and 64.29% female. There are 9 different occupations. This diverse demographic pool gave us a wide range of perspectives and unbiased feedback on our design.

Table 1

*User Demographic Information*

P	Age	Gender	Occupation	TF	ARF	HMD
1A	30	Female	Information Architect	3	2	2
1B	19	Female	Student	4	4	2
1C	18	Female	Student	4	4	2
1D	27	Female	Scientist	4	3	3
1E	33	Male	Assistant Professor	4	4	4
1F	30	Male	Engineer	5	5	5
1G		Female	Student	5	4	5
1H	31	Female	Product Manager	4	2	2
2A	27	Female	Student	5	4	3
2B	27	Male	Student	4	3	2
2C	31	Male	UX Researcher	3	3	4
2D	23	Female	UX Director	5	5	4

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2E	28	Female	PR/Communications	4	3	3
2F	45	Female	UX Researcher	5	3	3
2G	27	Male	Business Analyst	4	2	1

*Notes: P=participant; TF=Tech Friendly; ARF = Familiarity with Augmented Reality; HMD = Confidence using an HMD; TF, ARF, and HMD are rated from a scale of 1-5, 1=least familiar/confident, 5=very familiar.*

### Research Design

This project is an observational case study demonstrating the ability for humans to navigate unknown terrain using augmented reality. It focuses primarily on how humans perceive virtual elements and whether these elements enhance their ability to navigate. This study uses applied foundational design principles, while using new research to enhance our understanding. Additional data and research is created in this study by gathering and synthesizing data collected in usability interviews and tests from a diverse participant pool. Usability tests were used to observe actions and document feedback relative to information architecture, visual design, interaction design, and overall experience. Quantitative feedback was collected using a System Usability Score (SUS) at the end of the study. Qualitative feedback was collected during the interview, analyzed, and broken into themes for further improvement of this system. The learnings from the study is a contribution to research based on augmented reality assistance in navigational tasks.

### **System Usability Score**

The System Usability Score (SUS) was created in 1986 by John Brooke to measure the usability of new computer systems being installed at DEC. It was quickly adapted to many applications and remains a trusted measure of usability. We included it in our research to give us a comparison between variations in our design and measure the usability of our HUD design.

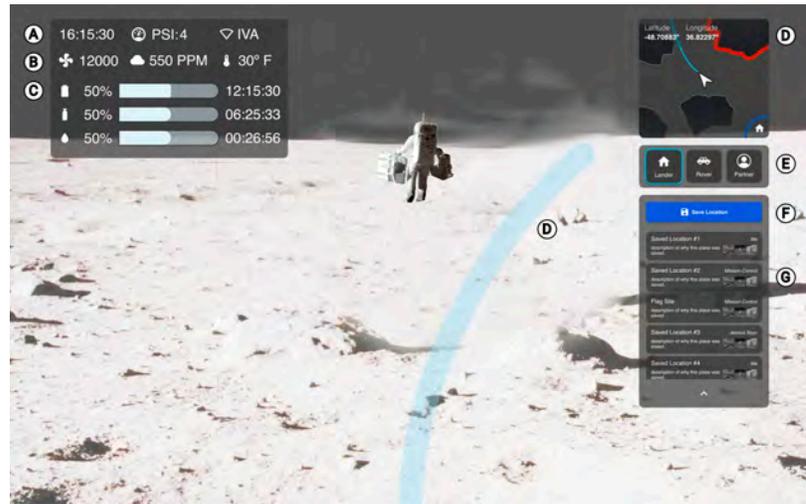
### **Interface Design**

The home screen shows the most important information the astronauts will need to access whenever they are using the interface. This information is displayed on every screen in the HMD interface to maintain platform conventions and ensure consistency. (Nielsen, 1995) As shown in Figure 11, the Home Screen interface consists of connection statuses (A), telemetry data (B) and biometric data (C). Element A displays the connection state between the EVA Operator(s) and MCC or IVA. If the EVA is not connected to the MCC or IVA, then A.R.G.O.S. will enter an offline mode and the system functionality will continue to allow the astronauts to complete their tasks. Elements B and C are positioned in the top left corner of the display for easy viewing access and to not obstruct the astronaut's field of view.

**Figure 11**  
*Interface Design of AstroBees' HUD*

## REMOTE TESTING OF AR HUDS FOR LUNAR EXPLORATION

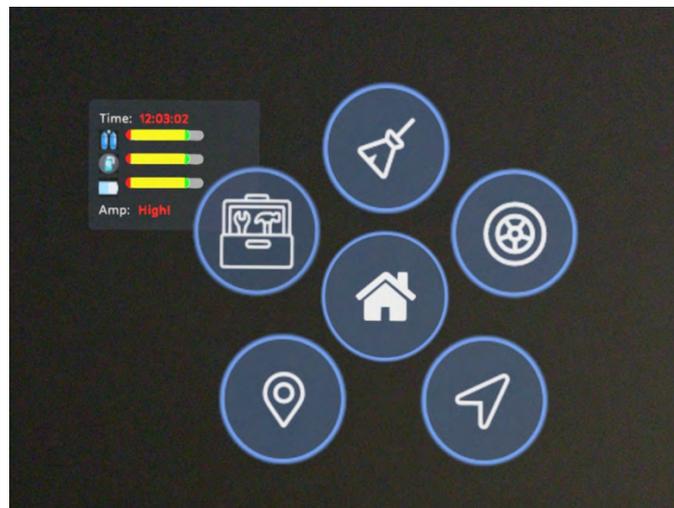
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The Home menu contains various tools to help the astronaut with their work.

These tools include Science Sampling, Rover Repair, and a Tool Library. These can be accessed by holding out a spread hand (Figure 12) and then pointing to the desired tool. Because this research focuses on navigation, only the navigation pieces of the interface will be discussed.

**Figure 12**  
*Home menu figure*



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Our team followed the system requirements provided by the NASA SUITS 2021 challenge for our research. The 2021 criteria include:

1. Design an interface which guides a crewmember between two relative points of interest.
2. Design an interface which guides a crewmember back to the lander and informs them of walk back time.
3. Design an interface which guides a crewmember to areas of geological interest.

**The Mini Map**

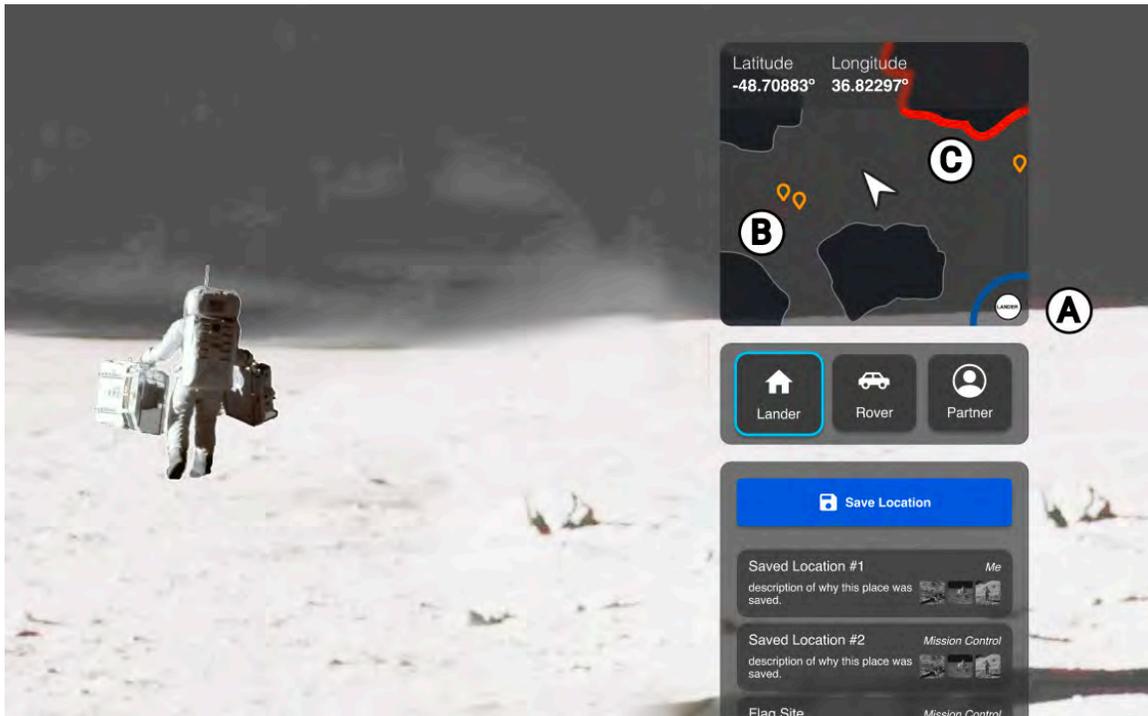
The mini map sits in the top right corner (Figure 11D), at the edge of the astronaut's perception. The map displays the latitude and longitude, which are calculated relative to the lander's position. Positions must be calculated because we currently don't have GPS covering the moon, but we do know where the astronaut is relative to the lander (based on University of Baltimore SUITS Team's ARGOS system).

The current position is fixed to the center of the mini map. This gives the astronaut a full view of the area around them. If the lander gets out of view, it is pinned to the side of the map so the astronaut can always orient themselves to it (Figure 13A).

**Figure 13**  
*Pinned map elements*

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The map also includes pins where locations have been saved (Figure 13B). These can be accessed and navigated to (explained in the following sections) and help the astronaut see what areas have already been explored.

An important feature of the map is its ability to warn the astronauts of hazardous areas. The lighting conditions on the moon, combined with limited mobility of the astronaut's suit make some terrain (i.e. craters) hard to see and hard to navigate. Falling into one could harm the astronaut or lose valuable mission time. The mini map outlines hazardous areas in red when approached to warn the astronaut (Figure 13C).

### Selecting a destination

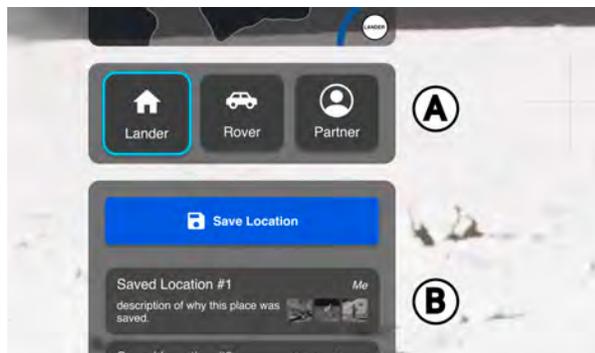
Figure 14 shows the method for selecting a destination. Astronauts can select from 3 always-present destinations (Figure 14A) – such as lander, rover, partner – or can

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select a saved location from the saved locations list (Figure 14B) to navigate to previously saved locations. This was designed to provide an intuitive information architecture, while also providing enough flexibility for astronauts to customize and save locations which may also be relevant to their mission.

**Figure 14**  
*Destination selection*



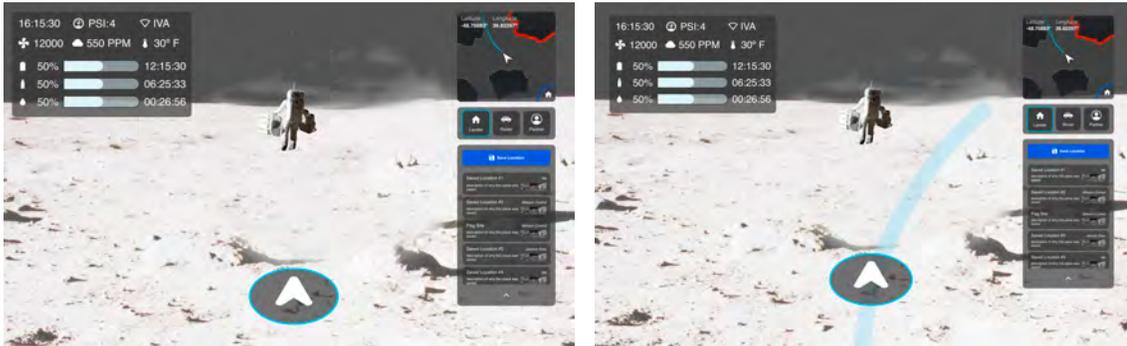
### Terrain-Pathing and Compass

We designed and tested 2 variations of “terrain-pathing”. The first variation used a simple arrow which floated on the ground in front of the simulated astronaut (Figure 15A). It consistently pointed directly to the selected destination. The 2<sup>nd</sup> variation included the same arrow as the 1<sup>st</sup> variation, but added a blue “route line” which drew the most efficient and safest route from the astronaut to the destination (Figure 15B).

**Figure 15**  
*Terrain-Pathing*

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Note: Round 1 (Left) only included the compass arrow, while Round 2 (Right) used both the compass and the terrain-pathing.

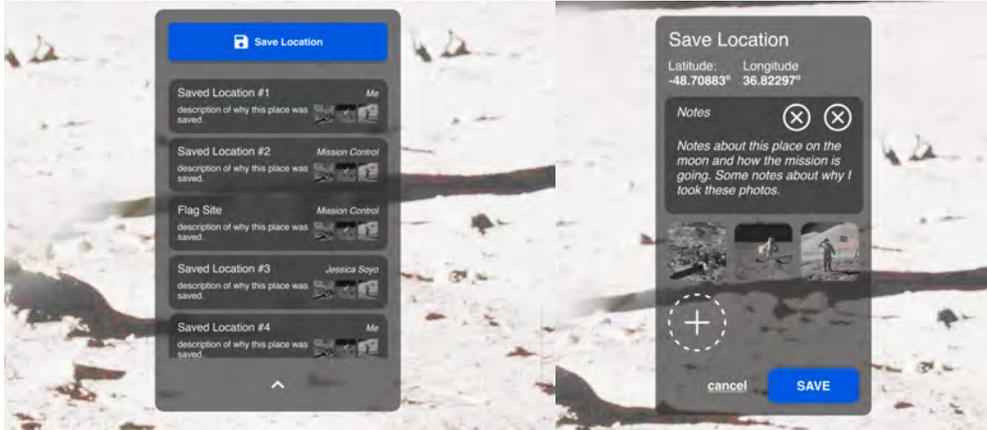
### Save a Location

Users can save their current location by activating the blue “Save Location” button (Figure 16). Activating this button opens the panel in Figure 16B and immediately saves the latitude and longitude. The user can then use voice-to-text to enter notes about the saved location and take pictures. Pressing the “Save” button saves location and adds it to the top of the “Saved Locations” list in Figure 16A.

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**Figure 16**  
*Saved Locations List (A) and Save Location Panel (B)*

**Protocol****Usability Testing Structure**

This project was heavily influenced by the NASA SUITS mission. The testing protocol is our own, but is based on three scenarios determined by the NASA SUITS challenge. All three scenarios are related to navigational tasks for astronauts on the moon for the upcoming 2024 Artemis moon missions.

## REMOTE TESTING OF AR HUDS FOR LUNAR EXPLORATION

Table 2

*NASA Goals and how we tested our solution*

NASA Goal	Testing Method
1 Get from point A to point B	Participants asked to use the interface to set a destination and travel to it.
2 Get back to the lander	Participants asked to use the interface to set the navigation to the lander and travel to it.
3 Find geological points of interest	Participants asked to pick an interesting landmark (crater, mountain, etc.) and save the location for later exploration.

To validate our interface design, participants were asked to play a simulation while on a Zoom video call with a facilitator. This simulation helped us understand how humans understood and interacted with the interface. This experiment had to take place in a simulated environment per CDC and IRB guidelines due to the COVID-19 pandemic.

Testing was divided into two phases. Each phase used the same testing procedure and methods, but were separated by 2 weeks to allow time to analyze the results of the first round and improve the design based on observations from the first round. Both phases shared the same research goal.

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Table 3

*Testing Phases*

Phase	Participants	Purpose
1	8	Initial test of design
2	6	Validate improvements

**Procedure**

Participants were asked to access a link and share their share while on a Zoom video call. The sessions lasted approximately 45 minutes and were divided into four sections: introduction to the simulation, task scenarios, exit interview, and system scoring. Two moderators joined each test to moderate the test, help troubleshoot issues, and take notes.

Once participants got the simulation running, they were given a few moments to move around the simulation to make sure they understood how to look and move around. Participants were then asked to complete 3 tasks:

1. Navigate to the rover.
2. Navigate back to the lander.
3. Save your current location as a site for further exploration.

Following the completion of these tasks, participants were asked a series of questions to learn more about their experience and perspectives on the tasks. It also highlighted the participant's comprehension of the interface. These questions included:

1. Which task felt most difficult? Why?

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2. If you could change a feature, what would it be?
3. Were there any features missing?
4. How would you prefer to interact with this system (remembering that it is a HMD)?
5. Did you find this system helpful in completing your tasks?
6. Complete the following statement: If I could only \_\_\_\_\_ this system would make my job much easier. (function)
7. Complete the following statement: If it just had \_\_\_\_\_ this system would be much easier to use. (feature)
8. Complete the following statement: If they could add \_\_\_\_\_, this system would be much better.
9. Complete the following statement: My experience would be so much better if I could \_\_\_\_\_.
10. If you were playing this simulation as a game (not imagining wearing an HMD), do you have any suggestions for the simulation game play?

Following this questionnaire, participants were asked to complete a standard SUS questionnaire, using a Likert Scale, by verbally responding to the moderator reading the questions. The session was then completed.

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### Chapter 4: Results

#### Overview

We collected two primary metrics on each round of our testing to help us determine the usefulness and efficacy of our HUD design. Participants were timed and given a binary “pass” or “fail” scoring. Participants also completed a SUS survey. These metrics were used alongside observational notes and qualitative survey data to build our interpretations, implications, and recommendations described in the next chapter.

#### Usability Test Evaluation

##### Success Metrics

Successful outcomes were determined by timing participants on each task. A task that required the help of the moderator was deemed a failure. The task was deemed successful as long as a participant could complete the task without help from the moderator.

Participants were timed on two tasks, “Navigate to the Rover” and “Save your current location”. These tasks required a button interaction with the interface, making them natural indicators of success if used properly. For each of these tasks the participant was asked to use the interface to complete the task and timed to see how long it took them to correctly complete the task. Times were recorded in seconds in a spreadsheet. Timing data was not collected if a participant could not complete the task within a reasonable amount of time or required help from the moderator.

**Measured Results**

This study measured completion time, success rate, participant interview responses, and System Usability Score's (SUS). Collecting these metrics on each round of testing informed later design improvements by identifying areas of success and failure. SUS scores were somewhat helpful in determining whether our design was working, though less than we had hoped because it was frequently hard for the participant to answer the question imagining that they were wearing a HUD, not just playing a videogame. This made these results somewhat skewed, as discussed in the next chapter.

***Task 1 (Navigation) Results***

Table 4 displays time and percentage of success for our navigation tasks for both rounds of testing. This task asked the participant to navigate from the lander (home base) to the rover by using the interface to set a destination and navigate to it. In Round 1 it took participants an average of 63.75 seconds (standard deviation 23.8) to set the destination, and only 50% of participants were successful. Round 2 was much more successful (66.7%) and participants were more efficient, only taking 7.75 seconds (standard deviation 4.79 seconds).

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Table 4

*Task 1 Results: Navigation*

Participant	Time (seconds)	Success
1A	51	Yes
1B		No
1C		No
1D	97	Yes
1E		No
1F		No
1G	64	Yes
1H	43	Yes
2A	4	Yes
2B		No
2C		No
2D	14	Yes
2E	4	Yes
2F	9	Yes
Round 1 Averages	63.75	50%
Round 2 Averages	7.75	66.7%

*Note:* 1A = Round 1 Participant A, 2A = Round 2 Participant A

Table 5 shows time and success results from our second task. Task 2 asked participants to find an interesting landmark (such as a crater, mountain, etc.) and save their location for further exploration. This task was considered successful if participants

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could find and use the save location button without help from the moderator. Timing results were fairly similar between these rounds with Round 1 participants averaging at 13.2 seconds (standard deviation 9.4) and Round 2 participants averaging at 13.8 seconds (standard deviation 9.7). Success rate was somewhat better on Round 2 at 83.3% compared to 75% in Round 1.

***Task 2 (Save Location) Results***

Table 5

*Task 2 Results: Save Location*

Participant	Time (seconds)	Success
1A		No
1B		No
1C	31	Yes
1D	6	Yes
1E	13	Yes
1F	12	Yes
1G	5	Yes
1H	12	Yes
2A	2	Yes
2B		No
2C	13	Yes
2D	8	Yes
2E	27	Yes
2F	19	Yes

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Round 1 Averages	13.2	75%
Round 2 Averages	13.8	83.3%

*Note:* 1A = Round 1 Participant A, 2A = Round 2 Participant A

### ***System Usability Score***

Table 6 shows results from our SUS questionnaire. We decided to use it for this study to give us insight into how participants perceived our system and interpreted it as a HUD. This was somewhat helpful, but also largely misinterpreted by participants. A vast majority of participants interpreted the SUS questions using the lens of the simulation instead of “wearing a HUD”. While our SUS score was not conclusive, we have decided to include it here for discussion.

Table 6

#### *SUS Score*

Participant	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
1A										
1B										
1C	5	2	4	2	4	1	4	2	3	3
1D	5	1	4	1	3.5	2	4	2	4	1
1E	5	1	4	4	3	2	4	2	3	1
1F										
1G	4	2	4	1	5	3	2	2	5	1
1H	4	2	4	3	3	2	5	3	4	2
2A	4	3	3	4	5	2	5	2	3	2
2B	5	2	5	1	3	2	4	1	4	1

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2C	3	1	4	4	3	1	4	1	3	1
2D	1	3	1	5	3	1	4	5	1	4
2E	5	5	3	5	5	1	1	4	2	5
2F	3	2	4	1	3	2	3	2	4	1
Round 1 SUS	47.34									
Round 2 SUS	61.25									

*Note:* 1A = Round 1 Participant A, 2A = Round 2 Participant A

### Key Observational Results

The following are themes that emerged from our discussions with test participants regarding their perspectives and understanding of the simulation interface. Themes were extracted by watching recordings of each test, taking further notes on key observations, and then grouping them on a Miro board by themes. These observations were not conclusive or measurable, but nevertheless give insight into how our participants perceived navigating unfamiliar terrain and using a HUD to enhance their experience.

#### *Mini-map, Compass, and Terrain Pathing*

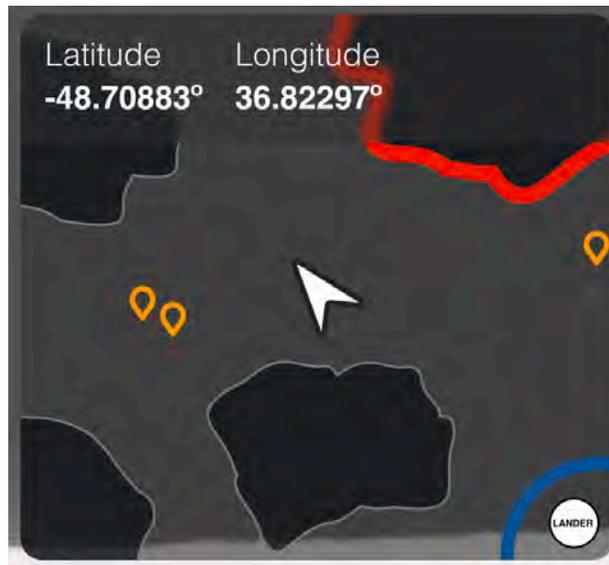
Our mini-map component (Figure 18) wasn't able to be implemented and tested this year due to a hardware challenge. Our team had some data from last year's tests which indicated positive results from having a mini-map, but this year's different testing protocol (testing it remotely) resulted in difficulty getting the mini-map to load because of incompatible browser and operating system support from Unity exports. Despite this challenge, a theme that did emerge in our testing was the participant's need for a greater

## REMOTE TESTING OF AR HUDS FOR LUNAR EXPLORATION

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perspective while navigating unfamiliar terrain. Many participants suggested using a mini-map, such as in videogames.

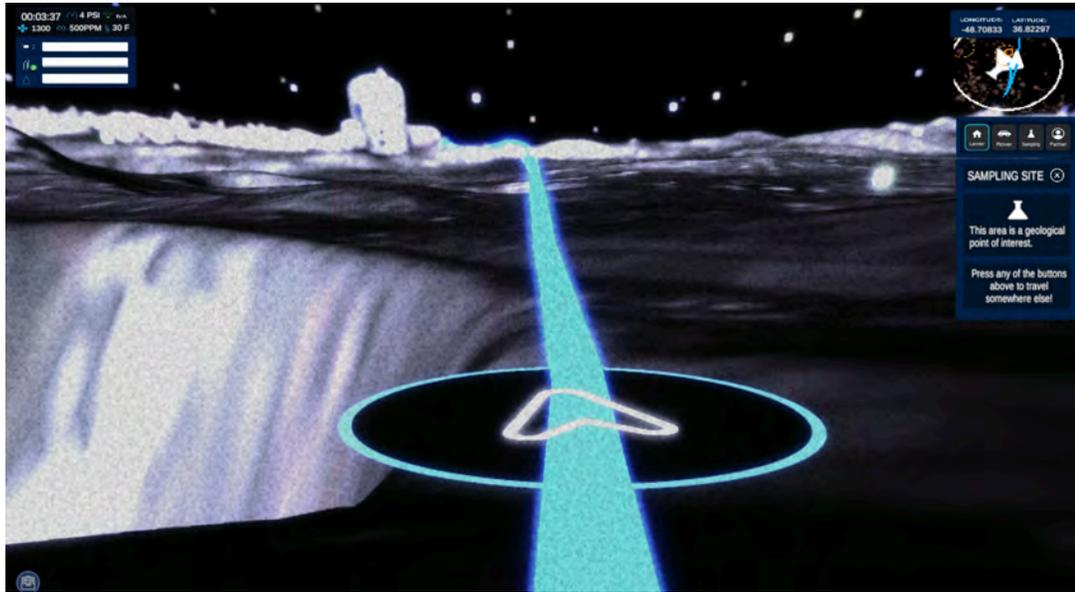
**Figure 17**  
*Mini-map design*



Our first round of testing showed us that in addition to a mini-map, we should implement a navigation element which exists in “world-space” (virtual elements that exist in physical space) to help participants navigate the terrain (Figure 19). Most participants found this helpful, but not for the reason we initially expected. We had originally intended the pathing to provide a general direction, while an arrow or compass gave an exact heading. Our test results provided a different perspective. Participants wanted to use the terrain pathing to avoid hazardous areas and to show the most efficient path to the destination. They used the compass to keep them moving toward the destination, but it helped them feel free to explore without getting lost.

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**Figure 18***Terrain Pathing and compass simulation****Saving Location & Notetaking***

Saving a location was nearly unanimously understood by our participants, especially on our second round of testing. However, there was a lot of debate on the best way to take notes and collect other information about the site to help the participant, or others, identify and find the location again. This topic was hotly debated, and did not result in any conclusive evidence.

One area where most participants agreed was that, while voice may be the obvious choice of input while wearing an astronaut suit, it may be the most difficult to implement correctly. When asked how they would prefer to interact with the system (i.e. using gestures, voice, etc.), most participants chose gestures or some kind of keyboard because of lack of trust in digital assistants (i.e. Siri, Google Assistant, Alexa). Many

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participants explained that their digital assistants often either did not understand the instruction, or did not do the right action when asked.

*Input Methods*

Participants almost universally agreed that voice has its issues and would be difficult to implement correctly due to transcription issues or performing the wrong task, but participants had a harder time coming up with better alternatives that would be efficient for the astronaut. Voice is difficult and nuanced, but if implemented correctly, could be the most efficient way to operate an interface in an environment where hand movement is limited.

Participants did lend some interesting ideas to combat this problem. Some of these include only allowing for certain interactions to be usable by voice, such as when it doesn't matter the exact syntax for a voice command (such as when leaving a note). Others suggested using voice to select options or tags that are visible on the interface to keep the syntax simple and always available visibly so the astronaut can more easily remember the correct voice syntax. Participants noted that the best option would, of course, be a voice assistant with a robust language recognition system capable of correctly interpreting commands no matter the user's word choice, speech patterns, or accents.

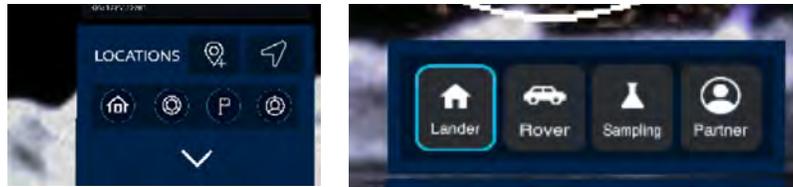
Participants also gave some ideas on alternative input methods that could be useful. Some of these included using eye-tracking on a virtual keyboard or using some kind of forearm input (such as Buzz Lightyear) which could either be a physical

keyboard, but this would be difficult with large gloves. If the forearm input was used to navigate the HUD instead of having a keyboard it could potentially navigate a virtual keyboard more accurately.

### *Icons and Labels*

During our first round of testing our buttons only used icons to communicate meaning to the user (Figure 20). Some of our icons clearly communicated the button's intent, while others failed. Some buttons were clear to some users and not to others. In round 2 of testing we added labels to the buttons. Users preferred this method and were much more successful with this approach.

**Figure 19**  
*Buttons Testing Round 1 vs. Round 2*



## Chapter 5: Discussion

This chapter discusses our findings and their implications in further detail, along with our recommendations for further study. We identified several themes that showed up during the course of our testing from which we drew our interpretations. Our implications and recommendations are based on these interpretations.

### **Interpretations**

#### **Remote testing of HUDs**

This research took place during the COVID-19 pandemic, which required that we use a remote approach for human testing. This made testing mixed reality applications extremely difficult because the mixed reality device, such as the Magic Leap, is a critical part of a successful mixed reality experience. Because we tested our HUD design in a simulation and not on an actual device, it was somewhat difficult to interpret whether our design would have the same level of success on the device as in our simulation.

HUDs are similar enough to video game and simulation interfaces that, under the circumstances, that we could use a simulation to test our HUD design remotely. This kept our research going, but also added another virtual layer on top of our project because we were essentially asking our participants to “imagine” they were wearing a mixed reality device while playing a simulation while on a Zoom call.

Participants struggled to consistently give feedback as if they were wearing the device, and often gave feedback more on game mechanics. It was also difficult for them to keep the primary use case – how would an astronaut use AR on the moon – in mind and changed the scenario to “playing the simulation” in either VR or on a computer. SUS

survey data, along with observational notes taken during the survey, indicate that participants were either unsure of their response to the question, or clearly answered it with a different use case in mind, such as “playing a videogame”. For example, when answering whether they “found the system unnecessarily complex” several participants commented that the mouse controls were a bit cumbersome.

### **Inputs and Human Cognition**

Our results showed that while participants largely agreed that voice commands could be the most ideal way to interact with a HUD (especially in a spacesuit), they almost unanimously did not trust voice enough to be the only input method. Voice assistants are much more pervasive today than in the past, but our participants don’t trust them to carry out every task flawlessly, and they wouldn’t trust their lives to a digital assistant while in space.

Another problem our participants had with voice assistants is that of being unsure of what the voice assistant was even capable of. Every voice assistant has different capabilities and vocabulary. Each voice assistant requires a lot of research and testing before the user begins to trust it to execute a task without help.

### **Navigation and Human Cognition**

Our design included a mini-map to help users get a greater perspective on their environment and help them navigate difficult terrain efficiently. Unfortunately this part of the design did not make it into the simulation because of technical issues that we were unable to resolve in time for testing. The results of this setback were actually very

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positive. Not only did participants specifically request the missing mini-map, but they clearly articulated why that was important to them, even with the terrain pathing and compass.

Terrain pathing was important to participants because it gave them something to visually hold on to, and a constant target to move with in an unfamiliar and visually harsh environment. Our simulation simulated moon lighting conditions with dark shadows and bright reflections, making it difficult to distinguish craters and mountains from the rest of the terrain. The terrain pathing helped safely navigate participants through these harsh areas. Occasionally the terrain pathing miscalculated and guided the participant into a hidden crater and the participant found themselves stuck. Several participants requested that the pathing go around the crater and even turn orange when it is next to craters to help them avoid hazards. This validated our unimplemented mini-map design which included these elements.

From our first round of testing we learned that participants wanted both the terrain-pathing and the compass on the screen at the same time. To them, the terrain pathing provided security and assurance, but the compass helped them visualize their final destination and gave them the freedom to explore the moon without fear of getting lost. Our second round of testing validated this result with other participants.

## **Implications**

### **Humans and Trusting a Machine**

We still have a long way to go before we trust a machine to make decisions in our behalf. The prospects of AI, machine learning, and voice assistants are intriguing and promising, but unfortunately they often don't hold up under pressure of the simplest everyday tasks. Much more research and development is needed in order to remove biases, bugs, and improve results.

There's also a lot more training involved in using voice assistants, despite the promise of using natural language processing. While a voice assistant may be able to derive intended meaning from a request, our research suggests that users don't even know what they would like to ask an assistant to do for them in a space environment. Digital assistants could be a great way to help astronauts complete tasks quickly in an environment where they have less use of their hands, but it would require a firm understanding of what the digital assistant is capable of, and various ways to request that help.

Adding a digital assistant to an astronaut's support team could be really helpful, but would require careful consideration of what it is allowed to help with, and where it falls in the line of command between the astronaut and Mission Control. There are many issues to consider while creating a successful digital assistant for space exploration. Does it take orders from the astronaut and Mission Control, or just the astronaut? Who has

visibility into its actions and who is responsible if it does something wrong? How would the astronaut or Mission Control perform an action if the voice assistant is unavailable?

### **Required Navigation Elements**

Participants require three elements to successfully navigate unfamiliar terrain. The first is a need for a greater perspective of the area their navigating. This perspective provides a general knowledge and feeling about the area. This perspective provides contextual clues which help them interpret directions more easily in the moment.

The second element is a handhold. The handhold provides visual reassurance that the path is safe, efficient, and moving them toward their destination in the best way possible.

The third element is a compass. The compass gives the user immediate direction to the destination and helps them to stay on target. It is similar to the handhold in that they both provide direction, but different in one key area. The handhold appeals to the human need to feel safe, while the compass allows them to feel free to explore without fear of becoming completely lost.

## **Recommendations**

### **Mini-Map Sizing and Elements**

The mini-map should be large enough that the astronaut can distinguish between elements, but not so large that it obstructs their view. A good starting place to test for

## REMOTE TESTING OF AR HUDS FOR LUNAR EXPLORATION

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optimal size would be to start with 48px icons, then scale other environmental markers around those. Another alternative would be to have a smaller mini-map that can be temporarily enlarged by the astronaut to get a greater perspective, but then the map shrinks back into its corner when the astronaut is only in need of a less detailed view.

The compass was an important navigational element, but our implementation obstructed the participant's view somewhat and was visually confusing in relation to the terrain-pathing despite our results indicating that participants preferred both the terrain pathing and compass. Our hypothesis is that the compass just needs to be implemented in a different way. A couple of suggestions:

1. Remove the compass from world space and add it to the mini-map. This is the most natural place for the compass, as this is a signature element of most digital maps.
2. Add a destination marker to the mini-map which is always visible. The astronaut can point their location arrow toward the destination and move toward it. This is essentially the same action that our compass enabled, but this option would also show the user and their heading.
3. Make it smaller and less obtrusive, but still noticeable, in world space or HUD space.

### **Terrain Pathing**

Terrain pathing is an important element in our design because it provides a visual handhold for the participant in an unfamiliar environment. It instantly grounds them in their surroundings and gives a clear indication of where they should go. It also helps them safely navigate difficult terrain in poor lighting conditions.

This pathing works in conjunction with the mini-map to provide environmental context, clues, and security. Its main purpose is to allow the user to perceive digital and visual information at the same time, generating feelings of security and confidence. This is one of the most important benefits of Augmented Reality.

### **Inputs for an AR Experience in Space**

#### *Voice*

Voice may be the most natural input method given the constraints of space exploration. Unfortunately, voice may also be the most difficult to get right because it requires a deep understanding and consideration for the nuances of human speech. We highly recommend voice as the most natural input method, but caution that it should be developed and tested rigorously to eliminate risk and errors. In the scenario of space travel, it is highly unlikely that Siri, Alexa, or Google would be the voice assistant of choice because the user could say anything and result in recognition issues. Our recommendation would be to create an owned voice assistant which can be built and tested for specific scenarios.

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Other considerations for voice include:

- Limiting the number of actions that an astronaut can use voice for.
- Ensuring that both the astronaut and mission control know what the digital assistant is doing at all times and that all actions taken by a digital assistant are communicated clearly and logged.
- Produce extensive training for the astronaut to understand how to use the digital assistant and become aware of its abilities, limitations, and risks.

***Other Inputs***

Other input methods may be helpful either separately or in tandem with a digital assistant. For example, an astronaut may use a gesture to save a location, and then use a voice assistant may be used to take freeform notes on that location. Astronauts could also use a forearm-mounted input to select a destination, then receive voice guidance while traveling to the destination. These and other input methods working in tandem may help to reduce risk of failure from a single input, increase task efficiency, and accommodate personal preference.

**Design for Harsh Environments**

It can be tempting to try and make all elements on a screen stand out, to make things colorful or add playful elements. This kind of design works well in some environments, contexts, or applications, but is inappropriate for space travel for several reasons.

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First, the lighting in space makes AR accessibility difficult. For example, on the lunar surface the sun is either casting long shadows in front of you (Down Sun) or blinding you right in the face (Up Sun). In Down Sun conditions these shadows make it hard to discern safe paths through the terrain. Up Sun conditions also make it difficult because the sun angle is  $8^\circ$  directly in front of you. These lighting conditions also make it hard to design a HUD with proper contrast on design elements because lighting conditions change so drastically depending on the direction you're facing and time of day.

**Figure 20***Up Sun and Down Sun Lunar Views*

Second, a lot is at stake on space missions, so astronauts should be focused on only the most important thing at any given time. Everything else is a distraction that could jeopardize the mission or their life. Adding a lot of colors, animations, or too much information could distract from the task at hand. Even small amounts of color can be quite distracting due to the physically and emotionally intense situation of being in space. This intense situation heightens an astronaut's awareness, so all distractions should be

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kept at a minimum and colors muted. While the Iron Man HUD (Whedon, 2012) is cinematically awesome, the actual usefulness is questionable.

**Figure 21**

*Iron Man's HUD from The Avengers ©Marvel*



## Chapter 6: Limitations & Conclusion

### **Limitations**

This study is an exploration of recent growing technology where hardware, software, and design are all still in development. Further, this study took place during the 2020 COVID-19 pandemic, complicating this research even more due to compliance with CDC guidelines.

#### **Remote HUD Testing**

Our largest limitation to our research was the requirement to do this research remotely due to the COVID-19 pandemic. We learned that designing, prototyping, and testing a HUD design is difficult to do remotely because HUD design relies so much on actually experiencing the digital overlaid on the physical. Doing this remotely removes that experience, as well as adds other complications like whether you need additional hardware because your team cannot share AR devices remotely. Remote HUD design challenges your testing protocols, and may easily limit the ways that you can feasibly prototype and test anything.

Fortunately for our team, we had the skills necessary to build a simulated environment to test our design in, which we could then translate into the Magic Leap device. Without that simulation, we may have been heavily constrained to using our families or roommates to test with low-fidelity prototypes. This simulated environment was a great benefit to our research, but brought it's own challenges, discussed in the following sections.

### **Simulation Hardware Difficulties**

The simulation was built by 2 engineers using C# in Unity. In previous years, participants tested the simulation on the same machine it was built on. This required a lot less QA and bug fixing due to different hardware capabilities.

Unfortunately this wasn't the case this year, as we were asking participants to test on their own machine, and we had no say whether they were going to use an Apple computer, a Windows computer, or something else. We had a little bit of influence over what browser they were using, which helped the simulation run a little better. The simulation was built on a Windows laptop and uploaded to a game-testing website called itch.io. Participants would log into itch.io (preferably in a Firefox browser) and run the simulation while sharing their screen on a Zoom call.

Most features of our HUD design performed well and were available for the participant to try. However, the mini-map would never load. Our engineers worked hard to try and fix this bug, but couldn't figure out what was causing it to not load no matter what operating system or browser the participant was using.

Naturally this was a setback to our research because we felt the mini-map was an important piece of the space navigation puzzle. Our users validated that it is an important piece through their comments, but weren't able to validate our implementation.

### **Conclusion**

This study adds to a growing body of research on Augmented Reality and the practical application of mixed reality technology. It explores various benefits of this technology, particularly in harsh environments, and highlights the many nuances that must be considered when designing and building AR experiences for these environments. It also suggests methods for prototyping and testing these experiences remotely and makes several recommendations for designing intuitive and useful experiences for humans.

This study was focused on space exploration, but its implications reach farther than that. AR is changing how industries operate and how they engage with their partners and customers. As it is applied in different industries and problem-spaces, it will continue to be important that corporations, agencies, and others implementing this technology understand how it's benefiting their organization and how to design and build so that those benefits actually come to fruition. If the AR experience is not intuitive to people using it, your organization may not actually benefit from building an AR experience.

These results are particularly useful for understanding how to design AR experiences in environments with poor lighting conditions, hazardous areas, or where the operator's body is not exposed to the environment. Some environments to consider are deep sea diving, cave diving, search and rescue scenarios, and public safety scenarios. These scenarios require careful, non-distracting, design because life is on the line. In these scenarios it's especially important to make sure the interface only presents the most

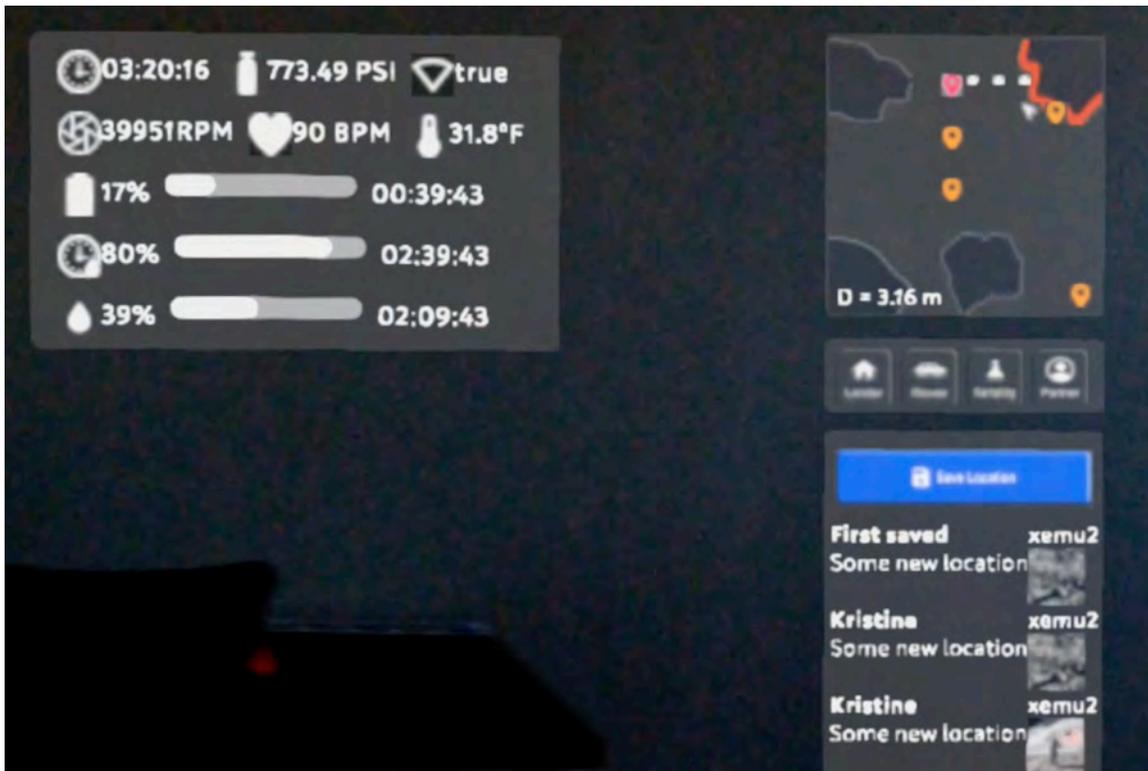
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important information at the correct time and that it will help the operator accomplish their goal better.

Augmented Reality has the potential to improve human exploration and creativity. Designed correctly, AR tools can unlock our own capabilities as humans to perceive, diagnose, repair, improve, and help us go where we may never have gone before.

**Figure 22**  
*AstroBees' Magic Leap 1 Prototype*



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