Developing an Augmented Reality Lunar Surface Navigation System

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Abstract— **For astronauts, lunar Extravehicular Activity (EVA) operations are extraordinarily challenging to perform. Physically, they must perform demanding tasks while clothed in exhaustingly heavy space suits. Mentally, they must perform complicated tasks without error while exploring unfamiliar and uncharted locations. With the high value of each moment spent on the moon, immense time pressure also increases the mental load placed on these astronauts. The Rhode Island School of Design (RISD) team participated in the 2022 NASA Spacesuit User Interface Technologies for Students (SUITS) Challenge and developed an augmented reality lunar surface navigation system, aiming at reducing the cognitive load for astronauts during their EVA operations. The overall design approach is to unify interfaces, separate planes for interactions, and maximize automation. The navigation system features an intuitive navigational aid, a three-dimensional path guide which is overlaid on the landscape, and a minimized user interface. Hardware components such as a tab-traversal style control are also incorporated to increase usability.**

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1. INTRODUCTION

Lunar Extravehicular Activity (EVA) operations are challenging tasks for the astronauts, both physically and mentally. The National Aeronautics and Space Administration's (NASA's) upcoming Artemis mission goals further compound this challenge. Artemis's target is the lunar south pole, an area with long black shadows set against bright highlights and glare from the sun. As a result, successfully navigating through this environment is a difficult task even without the additional mental load of time pressure and mission objectives. The moon's lack of significant atmosphere also results in a lack of visual distance cues. NASA seeks to increase astronauts' autonomy in these missions too, allowing for more spontaneous exploration and geological science. This in turn adds another layer of mental load for the astronauts. In this new environment, the cuff checklist maps used by Apollo astronauts are no longer enough for quick and successful navigation and completion of mission objectives.

The Rhode Island School of Design (RISD) team has addressed this by developing a prototype interface system for lunar surface navigation using an augmented reality (AR) display. The system specifically minimizes the additional cognitive load placed on the astronaut by navigation and documentation tasks, freeing the astronaut's focus for other mission objectives. This paper details the team's design process and resulting findings.

The system was developed as a part of the NASA Spacesuit User Interface Technologies for Students (SUITS) Challenge. The objective of NASA SUITS is to challenge students to design and develop Augmented Reality displays that assist astronauts in key aspects of the Artemis mission: lunar navigation, geological sampling, and Lunar Search and Rescue (LunaSAR) messaging [1].

2. BACKGROUND

2.1 Astronaut Head-Up Displays

As a part of its Early Career Initiative, NASA developed the Integrated Display and Environmental Awareness System (IDEAS). Building off of the 2015 IDEAS project, NASA has continued development of the Joint Augmented Reality Visual Informatics System (JARVIS) project to design a heads-up display (HUD) and UI that assists astronauts during

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EVA operations on the International Space Station [2][3][4]. The JARVIS team is addressing three primary challenges: Solving the unique optical problems associated with having a near-eye display compatible with the Exploration Extravehicular Mobility Unit (xEMU) helmet configuration, integrating with the informatics systems currently employed in the xEMU design, and demonstrating the utility and value of including the JARVIS system on future missions [2]. Our team's design seeks to expand similar capabilities to lunar EVA environments, and faces similar design and technical challenges. Like JARVIS, our design must strategically display task lists and organize biometrics and telemetry system information in an intuitive manner that does not interfere with astronauts' tasks. Our design also experiments with the integration of MR (Mixed Reality) technology into this environment, using local position tracking to add three-dimensional components registered to the lunar environment in addition to existing two-dimensional HUDs.

2.2 Navigation Data

Given the aforementioned lunar environmental challenges, navigation is one of the most important aspects of lunar exploration. On Earth, GNSS (Global Navigation Satellite Systems) such as the Global Positioning System (GPS) allow for reliable and accurate geo-spatial positioning. On top of that, extensive satellite and aerial photography and mapping allows for navigation using geo-spatial positioning data. The result of this is found in intuitive consumer apps such as Google and Apple Maps. These apps' market success suggest that their design paradigms provide users with fast and intuitive navigation options, and accurate positioning data is vital to their operation.

Unfortunately, many of the technologies used for this terrestrial navigation have not yet been implemented on the moon. The process that GNSS follows for positioning a user starts with trilateration between four or more medium Earth orbit satellites. These satellites broadcast highly accurate position and time data, which the user's receiver then uses to triangulate its own position. Similar satellites do not currently orbit the moon, so such a system is currently not available on the lunar surface. Even if funding was available for the launch of such a system, lunar gravitational anomalies form a significant technical barrier to placing a similar satellite network into lunar orbit.

There is significant ongoing research into workarounds for this problem. One example is demonstrated by several recent NASA satellites, including the Geostationary Operational Environmental Satellites, Magnetospheric Multiscale Mission Satellite, and NavCube ISS (International Space Station) experiment. These satellites all integrate highly sensitive antennas capable of receiving signals from existing GPS satellites in Earth orbit. They are then able to use those signals to accurately determine their location, even as they orbit far beyond the GPS satellites' own orbits. A NASA team is currently working on improving the antennas and electronics used in those missions to provide lunar positioning services using the existing GPS network with the same technique [8]. The triangulation technique used by GPS is also not exclusive to orbital satellites, and similar positioning systems have been proposed for the lunar surface using surface-mounted radio beacons instead of satellites [10].

Given that there are several technologies in development that solve the problem of lunar positioning, we developed our interface under the assumption that GPS-quality position data is available in a lunar context.

2.3 Emergency Response

With the hostility of any space environment, quickly and safely handling emergencies is critical. We followed the approach of existing EVA emergency systems as a guide. The Simplified Aid for EVA Rescue (SAFER) box is a manual jet pack intended for use if an astronaut's safety tether snaps. It is currently used for all EVA activity on the ISS. An astronaut wearing one of these devices can immediately use it to manually navigate in microgravity and return back to the safety of their spacecraft [7]. The Draper Take Me Home button is a refinement of that SAFER system that is currently in early stages of development. It takes the manual navigation and return aspect of the SAFER system, and automates it. The system provides intuitive return guidance for an astronaut that is injured or disoriented, and automatic return for a completely incapacitated astronaut [6]. While automatic return isn't possible on the lunar surface, our navigation system focuses on the importance of intuitive return guidance in emergency situations.

3. DESIGN METHODOLOGY

To arrive at this design, we approached development of the interface in three phases. We first performed background research and interviews, collecting data on the challenges faced by Apollo astronauts, geologists, and AR system designers. We then produced initial designs, and iterated through several rounds of user testing. Finally, we implemented the design into code on a HoloLens AR headset. The final system on the HoloLens was tested at NASA's Johnson Space Center (JSC) Rockyard in a simulation of lunar south pole conditions.

We started our research by interviewing experts in a variety of fields related to AR system design and lunar exploration. We have condensed the insights gleaned from a select group of these interviews.

We started with insights from astronaut Steve Swanson and publicly available data from each of the Apollo missions to construct a lunar mission timeline, following a hypothetical astronaut through their journey and identifying the challenges they faced. This underscores the limited lunar surface time available in any lunar mission, and the importance of quick and accurate navigation. On Apollo 14, for instance, astronauts fell 30 minutes behind their timeline and were unable to reach the rim of a crater due to navigation issues [11]. Previous missions relied on the astronaut's memory, mission control as a guide, and simplified cuff-mounted maps to get from point A to B. Our interview made it clear that this was inadequate for any autonomous exploration goals.

Our interview with NASA designer Skye Ray gave us good background on the process that mission control follows with astronaut vital and telemetry data. Given that mission control is generally following the exact details of that information, the display of vitals on the astronaut side should focus on unobtrusive and intuitive communication of the astronaut's general vitals state, being sure to avoid overloading the astronaut with overly detailed information.

Our interview with geologist Peter Schultz highlighted the importance of traditional field-notes in terrestrial geological sample collection. With the multimedia technology embedded in the HoloLens, we chose to implement a suite of tools designed around quick notetaking with minimal unnecessary movements by the astronaut. These notes include video recordings, audio recordings, and still photo recordings, all accessible from the system interface. These data may then be exchanged with mission control to facilitate collaboration on geological sampling tasks.

After speaking with cartographer Jonathan Levy, we designed color grading and iconography to support our topographical map display. Color grading helps astronauts easily distinguish landmarks and points of interest. Iconography draws the astronaut's eye in an unobtrusive way. Both of these aid the accuracy of navigation by making the navigation system itself more intuitive.

4. INTERFACE DESIGN

4.1 Overall System Design

Unifying Interfaces - The team's initial user-tested design included multiple 3D panels that floated in front of the user. These initial tests found user confusion when there are multiple panels to keep track of in the AR environment. The team discovered that by minimizing the number of separate free-floating interfaces in the environment, workflow efficiency on the HoloLens increased. The team followed this by integrating all actionable interfaces into one single unified floating panel within the AR environment for all subsequent rounds of design and testing. Interfaces for different functions are then unified by the quick switch menu shown on the left side of Figure 1, which the user uses to switch the single panel between different functions: navigation, vitals and controls display, search and rescue messaging, and geological sampling tools.

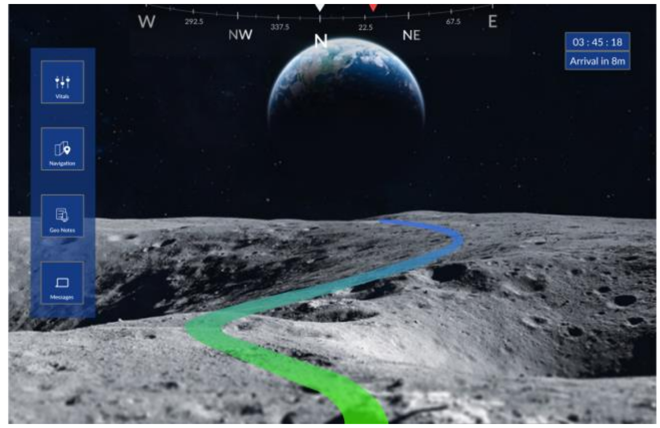

Figure 1. Minimized Menu

Separate Planes of Interactions - Research from Microsoft [9] has also found that user attention should be limited to one plane of distance at a time. For example, when users are focusing on task selection on a menu directly in front of them, they are less likely to notice changes in the background environment. The team adjusted the initial design by creating separate use cases for each plane of interaction within the HoloLens. Actionable tasks are displayed on a unified interface at arm's length from the user. This interface's distance to the user also shifts based on how often the user will need to interact with the current menu. Permanent visual guides such as time and compass are attached to the HUD in front of the user, and temporary and interactable visual guides such as the navigational directions are placed in the environment away from the user's immediate surroundings. Features are also split into three categories of interactions according to their frequency of use and use case: The mission clock is the most frequently used feature and is thus placed on the HUD, where it is always visible. The navigational compass is used less often, but when the user is navigating it is constantly needed. Thus, the compass is also in the HUD, but only shown when a user selects a destination and is currently being guided towards that destination by the navigation system.

Automation – When in a spacesuit, movements are limited. Astronauts must spend significant effort on the arm and hand gesture movements required to operate an AR interface that is placed in the physical space in front of them. As such, it is vital for the technology to require as little physical interaction from the user as possible. The team minimized the amount of different triggers required for an action to start, and for a user flow to continue. User research and testing was done to find the user actions that happen most often, and those actions were automated to require fewer triggers wherever possible. Take the initial version of the design as an example: When users needed to navigate to a specific beacon location, they selected the map to show possible options, selected the location, and then tapped to start navigation. After that, they had to tap the map to open the map again to see where their destination was. We minimized the interactions required by this flow by showing all allowed location selections immediately once the map is opened, and then had the map automatically open to the navigation screen as soon as the user started the navigation process. This turned a user flow involving four triggers into one that only required two, reducing the number of costly movements required.

Combining Features – Another way to minimize physical efforts by the astronaut is to combine multiple features into one when possible. This not only reduces physical actions needed by an astronaut to achieve a goal, but also reduces mental and attention load for the astronaut when interacting with the technology. One example of such practice is the merging of the mini-map with the existing compass and environmental guidance tool.

Multiple Avenues of Interaction – To further mitigate the physical workload of precisely tapping in space using inflated gloves to interact with the interface, the team connected physical buttons to the system. That way, the astronaut could easily feel around for these physical chest-mounted buttons to control the interface, even if they could not easily see or reach the AR buttons floating in front of them. The design of these interactions was inspired by the efficient mode of tabbing navigation that is used on desktop computers, where the enter, shift, and tab keys may be used to navigate entire complicated user interfaces. The team wired and mounted a set of three buttons to the harness holding the headlights. With those buttons, astronauts are able to fully navigate the interface using just an up button, down button, and select button. An additional feature was also added here to further reduce distraction to the user when desired: By pressing and holding the select button, the astronaut can show and hide all but the most essential interface features.

Clear Field of View – The last crucial finding from the team's user research with past astronauts and geologists was that while on a mission or in the field, any interfaces that open directly in front of the user would obscure their view and interfere with current tasks. The design team therefore had to find a solution that would allow interfaces to open in a noticeable area while still maintaining a clear field of view straight ahead of the user. The team tested solutions including registering the interface to the user's hand, using larger menu buttons floating higher in the environment so that they would only block the sky, and building a HUD layer minimized frame for the left side of the view area. Ultimately, the team found that, in the AR environment, the entire interface still feels whole to the user even after it has been carefully placed partially past the edge of the headset's field of view. In any real environment, people often see objects that are partially obscured. It feels natural for them to shift their head a little bit to see the rest of that obscured object. By initially opening our interfaces partially past the edge of the headset's field of view, we capitalized on that instinct. If the user wanted to see the UI, they would turn their head towards it and the entire interface would then be in their view. As a result of this finding, the team tuned the UI so that it tends to stick to the edge of the headset's view area, only taking up space in the center of the user's field of view if the user actively turned towards the UI to interact with it.

4.2 Navigation

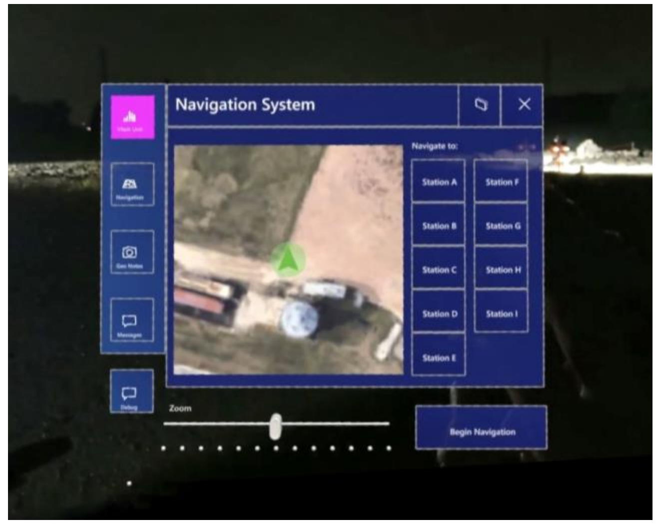

Figure 2. Map while not in Active Navigation Mode

Map - Navigation is a core objective of the team's AR interface design. The astronaut has the option to open a two-dimensional site map from the menu bar. The software provides a floating window with a top-down map view of the area around the astronaut. This map provides a detailed overview of the surrounding terrain, should the astronaut need it. When the astronaut selects a destination, the interface then physically places a line on the ground within their vision, avoiding any obstacles that are known from maps of the area. This gives the astronaut intuitive guidance towards their destination.

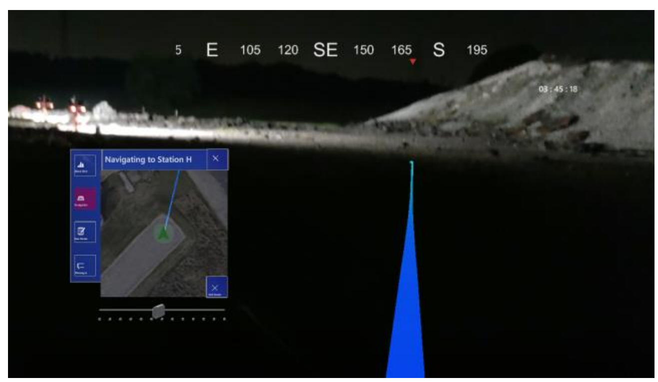

Figure 3. Active Navigation Mode

Three-Dimensional Navigation Path Guide - Navigating new terrain is difficult. We strove to reduce the amount of information on the display while navigating as much as possible, to reduce cognitive load. Our navigation system's primary focus is a mid-ground line that guides the user to the desired location. The line is able to guide the user around large dangerous areas such as craters and boulders, but it is otherwise as intuitive as possible: Since it is placed directly into the environment with the path for the user to follow, they do not need to reference a separate map or navigation instructions, just follow a line. To the end of reducing mental load, the path is colored in a blue-to-green gradient along its length, which provides an instinctive visual cue to the astronaut of their navigation progress without adding visual clutter.

Compass - A compass at the top of the user's vision serves two purposes: First, it indicates the astronaut's direction at all times during navigation. This lets the astronaut easily speak to fellow astronauts and mission control about the relative location of objects around them, using intuitive phrases like "The crater to my North" to quickly convey a lot of information. The second is to indicate the direction of the destination of current navigation, further highlighting the current destination in the astronaut's view.

Supporting Features - In addition to the access to the site map, the minimized navigation bar also integrates other critical mission functions. This includes communication systems, geological sampling tools, and the astronaut's vital information displays. From the minimized bar, the astronaut has the option to access each of the following screens:

1. Vitals Display. Similar to the Display and Control Unit (DCU) on the spacesuit, this screen displays the status of the spacesuit and the vitals of the astronaut. The display went through several rounds of redesigns to compress information and allow comprehensive data to be displayed clearly on a single screen, using intuitive colors and iconography to provide an overview of the astronaut's vitals at a glance.

2. Geological Sampling. Our geological sampling tools are implemented using the HoloLens camera hardware. Our software is able to take videos, photos and audio notes of a geological sample through the HoloLens camera and microphone, and store the notes in the HoloLens. Additionally, it features a cheat sheet with instructions on the use of the geological sampling tools, as well as a finder view which supports replaying those notes in the field or after the end of the mission.

3. LunaSAR Communication. The Lunar Search and Rescue (LunaSAR) is another feature of the software, closely connected to the navigation system. Upon receiving a LunaSAR message from a fellow crew member, the system will automatically redirect the navigational path, and start navigating to the endangered crew member. In LunaSAR mode, the user can communicate with the endangered crew member in the messaging window through short, preformatted messages (OK, Negative, On My Way). During the on-site testing, these are all simulated through the telemetry stream which passes the LunaSAR messages and the location to the client server of our software.

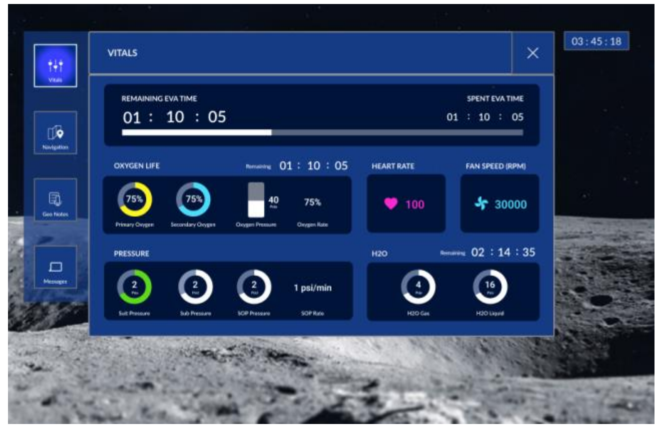

Figure 4. Vitals Display

5. System Software & Hardware

We implemented the entire system on HoloLens using the Unity MRTK framework. All of the system software is freely available in the NASA SUITS 2022 GitHub repository.

To facilitate interaction between design and software teams, we developed a custom branch of the MRTK importer for Figma. This lets us pull design elements directly from the design team's Figma boards into the AR space. This importer is capable of accurately reproducing panels made up of images, buttons, sliders, and other common interface elements. This produced the majority of the visible interface. Interactions were then manually programmed by the team, and elements with custom interactions like the map and compass were also programmed separately in Unity.

One of the significant challenges that the team initially faced was the HoloLens' lack of any GNSS/GPS absolute positioning capability. The HoloLens is fitted with an array of cameras and LiDAR sensors. When the HoloLens is used indoors, it can determine its absolute position in space by correlating what it sees on those sensors with a pre-scanned map of the room. This works well indoors, but obviously does not work in a novel non-pre-scanned environment like the lunar surface.

In spite of this, those sensors can still provide an excellent source of relative positioning when coupled with the IMUs built into the HoloLens. This is relative positioning, so it still can't tell us where we are on the moon, but if another source intermittently provides our absolute position on the lunar surface, then these sensors can accurately update that position as the astronaut moves around.

Getting absolute position data into the HoloLens is a challenge of its own. The lack of wired interfaces on the HoloLens makes attaching standard GPS hardware impossible. To solve this, the team developed a custom battery-powered low-latency Bluetooth Low-Energy (BLE) connected device based on the Espressif ESP32 microcontroller. A high-end GPS receiver was then integrated into this device. This custom embedded system connects with the HoloLens over BLE and provides a tailormade protocol that lets our software running on the HoloLens access high-accuracy, high update rate location data from the GPS with minimal latency.

From there, data fusion algorithms were implemented that combine the user's absolute GPS position with the HoloLens' local position tracking, producing a high-accuracy 3D world-space user position. The team has some experience with these algorithms, and expected this to be a significant development challenge. However, both the absolute and relative positioning data were of such high quality that acceptable results were achieved with a simple algorithm composed of a set of EMA filters and simple heuristics. Since the relative positioning data is based on camera, LiDAR, and IMU data together, it does not drift when dead-reckoning is performed in the same way that pure IMU data does. Similarly, the GPS has a continuous uninterrupted view of the sky, so a high-quality absolute fix was maintained at all times.

This absolute position source lets the team overlay world-space information, like the 3D navigation line, directly onto the real-world environment. Publicly-available elevation map data of the NASA JSC rockyard test site was then used in combination with Unity's built-in NavMesh path-finding capability to inform the navigation solution. The end result is a line which in the astronaut's eyes appears to sit on the ground. This line curves around steep and bumpy areas, letting the astronaut intuitively follow the line to their destination.

Battery life is another area where the team's previous experience ensured success. The ESP32 microcontroller was chosen in part because it is already designed for lightweight low-power applications. With some minimal firmware work to use low-power modes, a small 1100mAh battery can run the entire system for at least 20 hours, easily keeping everything running for the course of an EVA mission.

Since the team had already implemented a separate hardware device, the hardware buttons were an easy addition to the BLE protocol and device hardware. The resulting BLE-connected device and battery sits behind these chest-mounted controls, with the GPS antenna mounted separately on the user's shoulder to provide an unobstructed view of the sky.

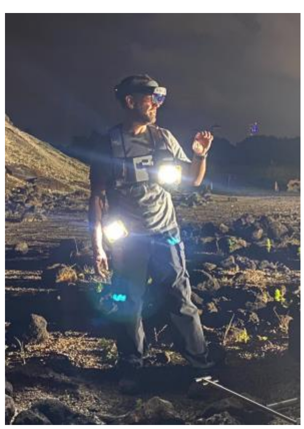

Figure 5. Hardware Testing / Figure 6. Chest Mounted Control

6. User Testing

6.1 Testing Environment

The test was conducted at NASA's JSC Rockyard in a simulation of lunar south pole conditions. To mimic the lunar landscape, the rocky plot contained undulating terrain and predetermined sample sites. Tests were conducted at night with beam lights and harsh lighting conditions similar to those found on the lunar south pole. During the testing, the suit's vital data, messaging, and LunaSAR location data was delivered through a telemetry stream server. Our system incorporated a client server to receive the data and act accordingly.

6.2 Usability Test

As a part of the test, we were asked to collect geological samples at designated areas around the site, as well as respond to a LunaSAR message. After each field test, our on-field researcher debriefed with us to understand potential problem areas, pain points, and successes and help us prioritize our action items. Some main questions were: How intuitive was the interface for the user? How often do they use the interface, and what elements do they use the most? What is the user satisfaction? What are their pain points and frustrations?

6.3 Feedback

Some findings from the tests include: Providing more instructional guidelines during geological sampling for the astronauts to follow, providing more feedback for when an action has taken place, and designing for more emergency scenarios that could occur during a lunar mission.

6.4 Conclusion

Users found the design intuitive and straightforward. The finished product has a fast learning curve and a clear structure. As soon as the display was opened up in the HoloLens, participants were able to intuitively pick up the mental model of the app layout and instinctively interact with the design. Participants noted that they liked the collapsible layout and that they found the side menu format to be intuitive. Elements most utilized in the side menu were the navigation feature and geological sampling tab. Participants complimented the AR wayfinding visual path on the ground. The gradient path was helpful for participants to mentally measure the distance to their destination. With the video recording and cheat sheet features in the geological sampling tab, participants enjoyed step-by-step hands-free documentation and voice recordings. Participants noted that all biometrics were readable, with the colors and clarity of the vitals screen standing out.

7. Future Work

There are a lot of opportunities to improve the design based on feedback from NASA staff members during on-site testing. This includes having a less intrusive vitals interface, and including an additional small indicator of the suit status. For the navigation system, voice control features can be a next step to further increase the number of available interaction modalities and enable the astronaut to multitask.

Due to the limited time, our team was not able to explore as many AR interaction modes as we would have liked. Actions such as pinning an element on a user's body part were left untouched. Moving forward, multiple modes of AR interaction will be explored. One user feedback that points at areas for improvement was that there weren't enough visual indicators for progress. For example, during navigation, there could be some precise distance indicators and summaries during wayfinding.

Lastly, more scenarios need to be considered for a fully comprehensive space mission interface design. There are many unresearched scenarios, such as displays for when a key consumable is in low supply, or when an astronaut needs to assist another in an emergency.

8. Conclusion

Through these user tests, our interface demonstrates how AR will aid astronauts' ability to tackle the monumental challenge of lunar South pole exploration. By focusing on astronauts' needs, our design decisions such as unifying interfaces, separating planes of interactions, increasing automation, and incorporating a three-dimensional navigation guide reduced astronauts' mental load while performing navigation tasks. Astronauts could then solely focus their attention on successfully completing mission objectives.

Acknowledgements

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BIOGRAPHY

Kienan Trace Ahner-McHaffie *received a B.S. in Computer Science at Case Western Reserve University, and is currently pursuing an M.S. in Computer Science at Case Western. He is an experienced software engineer who has led multiple development teams. He previously served as the president of the Case Western Math Club, and is now the founder and president of the embedded software firm Byte & Word.*

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Bowen Zhou *received a B.S. in Fine Arts with the double major of industrial design and sculpture from Rhode Island School of Design in 2022. She is a contemporary artist and experience designer based in San Francisco. Her experience design works are based on the philosophy of crafting a human-centered strategy before all else. Other than her consulting work, she has led the user experience design team of the Brown Space Engineering Ground Software team, and led a design strategy team for WangYing Real Estates's government-funded financial district development project.*

Outside of experience design works, within the design realm, she has been researching urban analytical models and scenario-based planning to propose human-centered speculative energy infrastructures and emerging technologies. Her recent works surrounding the topic of emerging systems include future city mobility plans and soft adaptive robotic architectures for Hyundai, as well as a proof of concept for spatial audio communication platform.