

The Role of Augmented Reality in Space Exploration: Usability Requirements for Proposed AR- Assistant

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Abstract

The ability to receive task-relevant information in real-time can be crucial in situations where the user has limited communication with their team, such as an astronaut performing an extra-vehicular activity (EVA) on Mars on the moon. Our team proposed a system design that is rooted in human factors and user-centered design. Our AR system design aims to function as a tool to streamline menial routine tasks that are part of the EVA, be a memory aid to reduce the amount of information that the astronauts must remember, and reduce the overall errors committed during the EVA process. Our design prioritized two main features. The first is the usability of the user interface, including the principles of visibility of system status, match between system and real, and consistency of menu interaction design. Second, our design used Just-in-Time instructions, which provide instructions for completing procedures and the next step to be accomplished for the mission when needed. By creating a design rooted in usability principles, we aimed to reduce the overall cognitive workload of an astronaut during an EVA.

Keywords

augmented reality, space travel, extra-vehicular activity, human factors, usability, interface design



Introduction

Space travel requires constant communication between crew members and on-ground mission control. This is especially true during extra-vehicular activities (EVAs), where astronauts rely on crew members and ground control personnel to minimize risks and successfully complete tasks. Team members currently have access to constant communication during current EVAs; however, lunar and Martian EVAs will result in communication delays, particularly on the Martian missions. As a result, there will be a greater reliance on the EVA astronaut and the tools at their disposal to complete the mission successfully (Belobrajdic et al., 2021). As the future of space exploration expands with programs like NASA's Artemis, the need for innovative solutions to address the challenges of deep space EVAs becomes increasingly important. With the vast distances involved, communication delays between astronauts and mission control are inevitable, necessitating a shift towards more self-reliant strategies for mission success. To tackle this issue, this paper introduces a novel approach involving augmented reality (AR) systems to assist astronauts during EVAs. By integrating human factors (HF) and usability principles, the proposed AR system aims to enhance astronauts' performance, streamline their tasks, and reduce errors committed during these challenging missions. This technology has already proven its efficacy in various fields, from improving manufacturing processes to assisting surgeons and military operations (Eckert et al., 2019; Nee et al., 2012). By leveraging AR technology, astronauts can reduce their reliance on ground control communication and maintain greater autonomy during EVAs. In the following sections, we delve into the concept of augmented reality and its potential benefits in the context of space exploration, while also discussing the critical role of human factors and usability in the design and implementation of such systems.

Augmented Reality

AR provides interactive content to users by providing information as a digital overlay on the real environment (Carmigniani & Furht, 2011). This content can be provided through various modalities, most commonly as a combination of visual and auditory information, with auditory information supporting the visual display (Nizam et al., 2018). AR has been used in various fields to mitigate errors and enhance performance. For example, design and manufacturing fields have used AR to map manufacturing plant layouts and optimize material assembly lines (Nee et al., 2012). Surgeons have been using AR as an assistant to mitigate errors (Eckert et al., 2019). AR has changed military operations through the Tactical Augmented Reality (TAR) system by allowing soldiers to know the exact locations of their allies and foes, thus reducing errors (Haridy, 2017; Livingston et al., 2011). AR would allow astronauts to conduct EVAs with reduced reliance on ground-control communication (McHenry et al., 2020). A well-designed AR system, rooted in human factors and usability principles, can reduce an astronaut's cognitive workload, streamline mental tasks, and reduce errors committed during an EVA.

Human Factors

Human factors is the application of human capabilities and limitations to the design of systems (Lee et al., 2017). Human capabilities can be cognitive abilities, such as working memory capacity (i.e., the number of items held in mind at once/the number of items we can actively remember at once), perceptual processes, such as the ability to see certain colors better in different lighting conditions, or anthropomorphic considerations, such as the distance between one's eyes or the size of one's head (Lee et al., 2017). Including these considerations within a design should yield a usable design. Usability is defined as the ability of the user to use a system to complete a task safely, effectively, and efficiently (Barnum, 2001; International Organization for Standardization, 2018). The goal of usability is to apply human factors principles to the design of systems in order to create a design that a user can operate to complete a task (Barnum, 2001). A well-designed AR assistant for EVAs should incorporate human factors and usability principles. The proposed design incorporates human factors principles relevant to the AR assistant. We describe our process for incorporating each of these principles within an AR assistant and how it was incorporated within the proposed design.

Purpose of the AR-Assistant

Requirements for the AR assistant were established from existing guidelines provided by NASA SUITS (National Aviation and Space Administration, 2022). This yielded four main tasks. First, the astronaut must complete an egress procedure where all essential functions,

such as oxygen flow, must be transferred to suit power to leave the habitat. This process requires turning switches on and off until all pressure levels reach a specified threshold. This process can be tedious and requires the astronaut to remember both the order and functions of the switches as well as the specified safety thresholds for various suit functions. Second, the astronaut must successfully collect and store geological samples. This requires the astronaut to have a clear field of view and see information on the logged samples. Third, the astronaut must be able to control a ROVER and direct it toward a specified location. The astronaut must also recall a ROVER to their location. Fourth, the astronaut must be able to navigate back to the habitat. This is typically accomplished by adding waypoints along the path the astronaut takes.

The goal of the proposed AR-Assistant was for it to be a tool to aid the Artemis Crew in the execution of their mission while undergoing an EVA, as well as remove the need for ground-control communication. Our AR system design aims to function as a tool to streamline menial, routine tasks that are part of the EVA procedure, to be a memory aid to reduce the amount of information the astronaut must remember, and to reduce overall errors during the EVA procedure. The aim is to reduce the astronaut's workload during EVAs and allow them to provide greater cognitive resources to other tasks that require problem-solving or precision

We address five key human factors and usability considerations in implementing an augmented reality system.

1. **Visual Angle:** Ensure AR elements are easily viewable without straining the user's eyes, allowing them to see the real environment clearly.
2. **Color Visibility:** Ensure all information in AR elements remains visible in various lighting conditions.
3. **Font Readability:** Prioritize easy-to-read fonts for user-friendly information access.
4. **Alert Presentation:** Design alerts for quick user recognition and understanding.
5. **Mental Workload:** Reduce the user's cognitive load by helping them process information efficiently.

Visual Angle

Astronauts conducting an EVA must be able to fully see the physical environment, such as their physical workspace outside of the spacesuit. As such, the majority of an astronaut's field of view must be kept unhindered. This dramatically limits where static AR elements can be placed. These static elements should be easily accessible within the user's field of view at all times without causing eye strain when the user is foveating on the AR elements. The normal line of sight is typically 10-15 degrees below the horizontal plane (Hill & Kroemer, 1986; Lee et al., 2017). As such, this area of the display should remain clear with no AR elements. To determine the location of static AR elements within our design, we referenced the cone of vision (Grandjean & Kroemer, 1997; Prakasa et al., 2019). According to this cone, a user can quickly move their eyes within this area (i.e., the cone of vision) to see elements without needing to move their head. This suggests that eye movements are easiest from +5 degrees above the horizontal plane to -30 degrees below the horizontal plane. Limiting the information density within the cone of vision has been found to enhance visual search performance (Prakasa et al., 2019). As such, information is displayed in groups that are placed far apart.

Vertical versus horizontal peripheral displays

Static AR elements were placed above and below the normal line of sight, rather than to the left or right, to account for VR sickness. Research has shown that delays in the movement of the virtual elements versus the user's movement can cause VR sickness in head-mounted virtual reality displays (Chang et al., 2020; Saredakis et al., 2020). To account for this, elements should be placed on the horizontal plane rather than the vertical plane, meaning that static objects should be placed on the top and bottom of the field of view rather than to the left or right. Further, research on VR sickness in augmented reality has shown that static AR elements lead to less VR sickness than dynamic elements (Kaufeld et al., 2022). Therefore, dynamic elements within the proposed AR system were limited to reduce the likelihood of VR sickness.

The final static elements of our AR design were placed -25 degrees below and 0 degrees above the horizontal plane. Each element measured 2 degrees of visual angle. This allowed the user to see the AR elements without intruding on the working area of the visual field.

Color

EVAs are typically conducted in harsh environments with challenging lighting conditions, dark backgrounds, and harsh light glares. As such, the colors of the AR display must be visible in both dark and light glare conditions. For this design, three colors were needed: the main color for all elements, the waypoint marker color, and the hazard marker color. Military standards state that the green color (14260) should be used for night vision goggles and other night displays (Department of Defense, 2012); however, iterative testing during the development of our AR system showed that this color did not perform well in glare conditions. As such, we elected to use the blue color established by Microsoft as the standard for the HoloLens II (Microsoft, 2019).

The same color was selected for both alarms and hazards, as both required the user to pay attention to the item. The red color (11105) defined in the Army standards for warnings was used (Department of the Army, 2013). As many NASA astronauts have military backgrounds (U.S. Air Force Academy, 2023), this color fits our anticipated user's existing mental model of warnings.

Font size and color

The font size used within the AR display must be large enough to be easily read and small enough to fit on preexisting static elements. Generally, in normal reading conditions, such as reading text from a book, font size must be greater than 0.2 degrees, the critical print size (Lee et al., 2017; Legge & Bigelow, 2011). Fonts smaller than the critical print size have been shown to reduce reading speed significantly (Akutsu et al., 1991; Legge et al., 1985, 2007). In abnormal reading conditions, such as in-vehicle displays, font size must be larger to accommodate environmental disturbances, such as the vibration of the vehicle (Campbell et al., 2007; Degani, 1992; Legge & Bigelow, 2011). Research on the font used within virtual reality should be as high as 0.8 degrees, though trained users can still accurately read virtual text that is closer to the critical print size (Gådin, 2021). As such, the font size within the proposed AR system is 0.5 degrees, larger than the critical print size but smaller than the suggested 0.8 degrees to ensure it fits within the static AR elements.

The font color needed to have enough contrast to be easily legible across the different colors of the AR display. Typically, a contrast of 30% is recommended for physical reading displays, known as the Michelson contrast (FAA Human Factors and Engineering Group., 2007; Lee et al., 2017). The Michelson contrast provides the ratio of the difference in luminance for the light and dark areas. For consistency, the same colored font, white, was used throughout the display. For the static AR elements, this led to a Michelson contrast ratio of 14:1. For alerts, this led to a contrast ratio of 9:1. In both cases, the contrast sensitivity fell within the recommended contrast sensitivity.

Alerts

Alerts must present information that is considered important or time-sensitive, per FAA guidelines. Not all alerts are critical. Therefore, alerts can be separated into three categories from least to most important: advisories, cautions, and warnings (Yeh et al., 2013). Advisories are the least important of the three alerts and present the user with helpful information about the system's current state. Cautions alert to a change in the system. Though this system change is not yet critical, the user may need to take action to prevent a critical issue from occurring. Warnings alert the user to a critical situation in the system that requires the user's immediate attention. If possible, alerts should be designed to present advisories and cautions before critical warnings. An advisory should provide the user with useful information without distracting the user from the task at hand. A caution should capture the user's attention without causing distress or jeopardizing the current task. Finally, a warning should capture the user's

attention and communicate the urgency of the situation. Typically, a warning alert will include an auditory cue and a visual cue (Yeh et al., 2013). Though warnings are essential and must be seen by the user, they must not be too cumbersome to impede the user's ability to perform a task, including solving the issue.

Our design included cautions and warnings in the bottom left-hand corner of the display on the bottom strip of the static AR elements. When a suit parameter (i.e., pressure or oxygen level) reaches a predetermined "caution" threshold, text describing the issue flashes on the alert section of the screen in the lower left-hand corner of the user's field of view. It will remain visible as long as the parameter is within the caution interval. Warnings will be displayed with text describing the issues when a suit parameter reaches the predetermined "warning" threshold. When a warning is activated, the bottom strip of the static display will turn red. The red is 11105, matching the color for warnings established in the military standard MIL-STD-1472F (Department of Defense, 2012). Further, an auditory alarm will sound when the warning is first triggered. The auditory alarm, combined with the change in color of the visual display, ensured that the user would be aware of the warning. Though warnings capture the user's attention, they do not impede their working field of view.

Working Memory and Mental Workload

The cognitive demands of an EVA can be very high, taking up a lot of valuable cognitive resources. An important requirement for all EVA AR-Assistant designs is to reduce the cognitive resources needed to perform menial tasks in order to reduce the overall mental workload of the EVA. The complexity of any task can determine its mental workload, the attentional demands, and the working memory requirements (Lee et al., 2017). The difficulty will be high when conducting an EVA task due to the foreign environment. An AR-Assistant design should, therefore, reduce working memory demands to reduce overall mental workload. Usability principles have been applied within our design to accomplish this goal. Instructions, such as in the egress procedure, are displayed one step at a time when completing tasks. This ensures the user recognizes the next step rather than recalling all the instructions from memory. This minimizes the user's memory load by providing written instructions on the current step (Budiu, 2014; Tulving, 1968). Further, by presenting all alarms in the same area of the visual field, the user can develop a mental model and come to expect that all alerts will be displayed there. This consistency reduces mental workload by creating an expectancy of the location of all alerts (Bellenkes et al., 1997). Similarly, menus can be accessed on the left or right, corresponding to the location of the static AR elements. Task-related menu options can be found on the left-hand side, corresponding to the task information displayed on the left side of the AR elements. Static AR elements (location and suit information) are displayed on the right-hand side. The right-hand menu allows users to add navigation elements to the environment and access all suit vitals. This creates an expectancy for where items should be located and reinforces the user's mental model.

Final Design

The final design was created using the game development software Unity version 2021.3.31f1. The mixed reality toolkit from Microsoft was imported to Unity and used to create the augmented reality environment. The finished design was presented to users in a Microsoft HoloLens II augmented reality headset.

Egress Procedure

The specific goal for this component was to design an Umbilical Interface Assembly (UIA) Egress Procedure that can successfully transition astronauts from habitat to suit power safely, effectively, and efficiently. To accomplish the goal mentioned above, the design strived to reduce potential mistakes and errors made by astronauts during an egress procedure. Specifically, the design aimed to mitigate the following errors identified in the "NASA Office of Safety and Mission Assurance Human Factors Handbook" (Dillinger & Kiriokos, 2019): (1) Error due to misperception (AP001), (2) Controls and Switches are Inadequate (PT004), (3) Complacency (PP104), and (4) Misinterpreted/Misread Instrument (PP405).

When the astronaut first started the UIA Egress Procedure, a textbox was presented on the left-hand side of the switchboard with the instructions for completing the current step of the

egress procedure. If an astronaut selected the wrong control on the control panel, the AR-Assistant would display a message stating that the wrong control was selected and state which control should be used. When all steps were completed, a message was presented to the user stating that the Egress Procedure was complete and that all parameters had been switched to suit power.

All aspects of the design were intended to reduce human errors. Error reduction was achieved by reducing the astronaut's working memory and mental workload. By presenting steps one at a time, controls can be recognized rather than recalled.

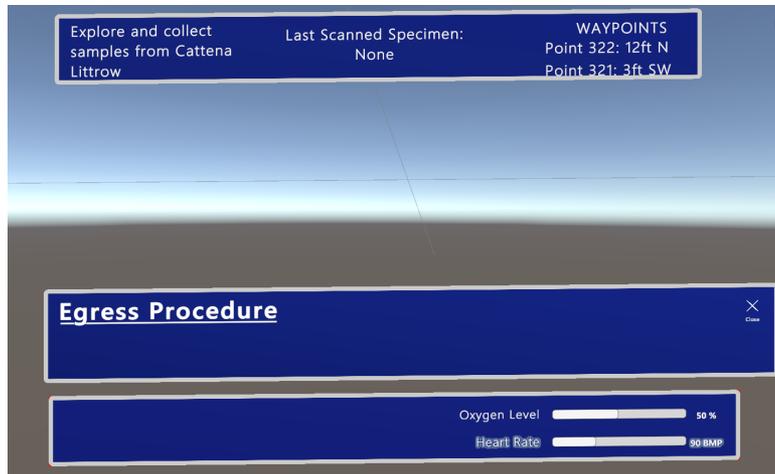


Figure 1. HUD Display and Egress Procedure of the AR-Assistant.

Alt-text: Two horizontal bars represent the static elements of the HUD. The right side of the top bar shows the current task being performed. The middle of the top bar represents additional information needed for the current task. The left side of the top bar shows the closest waypoints dropped by the user. The right side of the bottom bar shows the oxygen level and heart rate of the user. A middle bar displays the current step of the egress procedure.

Navigation

This extra-vehicular activity (EVA) procedure component aimed to create a design that allowed the astronaut to navigate their environment to complete tasks. The astronaut could drop waypoints in their environment to successfully navigate the lunar or Martian surface. The design included two types of waypoints: direction-based and obstacle avoidance waypoints. Direction-based waypoints were used to mark the astronaut's path from the airlock. These waypoints allowed the astronaut to create a breadcrumb trail that they could use to navigate successfully to and from the airlock. The astronaut could use obstacle waypoints to indicate areas or objects that must be avoided while completing tasks on the lunar surface. Each waypoint allowed the astronaut to navigate their environment safely, effectively, and efficiently.

Waypoints could be accessed through a small hand menu activated through two-step activation. The hand menu was triggered when the user gazes at their right hand. Their right hand must be flat with their palm facing up. Requiring the astronaut to gaze at their hand palm-up as a second step prevented accidental activation of the menu, particularly when the astronaut was using their hand to gesture or manipulate other objects in their environment. Once the menu was activated, the astronaut used their left pointer finger to tap the button corresponding to the waypoint they wanted to place in the environment. Once selected, a waypoint would appear and could be moved into the environment by moving the left pointer finger.

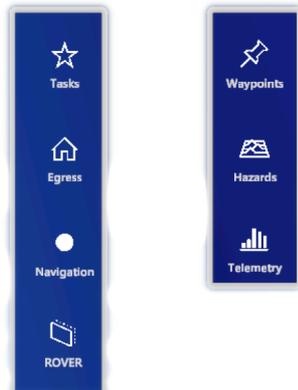


Figure 2. Left and Right Hand Menus of the AR-Assistant.

Alt-text: The left hand-menu has four vertically stacked buttons on a blue background: tasks, egress, navigation, ROVER. The right hand-menu has three vertically stacked buttons on a blue background: waypoints, hazards, telemetry.

Navigation HUD Design

Our design attempted to minimize clutter in the center of the visual field and has task-relevant information in the peripherals so that the astronaut could attend to it when necessary. Alerts directed the astronaut's attention to the relevant information when their attention was required.

The display's top left corner showed just-in-time (JIT) step-by-step instructions for completing the current mission. The upper right corner of the display showed the two nearest located waypoints, as well as their distance and heading. This helped the astronaut judge when they should drop a new direction-based waypoint. Once the mission was complete, it also helped the astronaut locate the waypoints when navigating back to the airlock. The lower left corner of the display showed alerts. The alert information was displayed in this location when an alert was activated. The lower right corner displayed information about the astronaut's suit vitals.

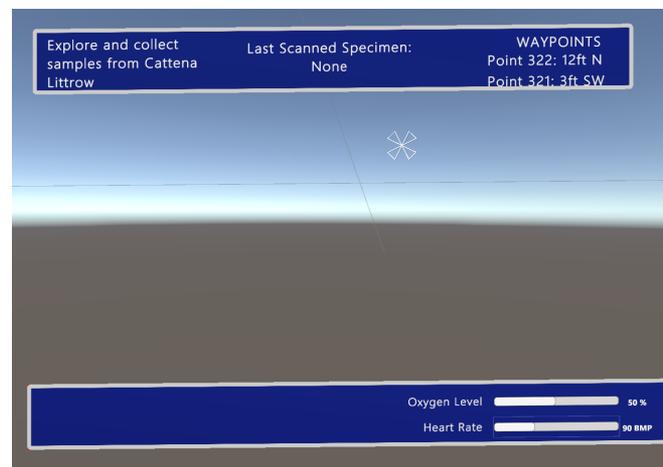


Figure 3. Static Elements of the HUD for the AR-Assistant.

Alt-text: Two horizontal bars represent the static elements of the HUD. The right side of the top bar shows the current task being performed. The middle of the top bar represents additional information needed for the current task. The left side of the top bar shows the closest waypoints

dropped by the user. The right side of the bottom bar shows the oxygen level and heart rate of the user.

ROVER Control

The operator used the Remotely Operated Vehicle in Extended Reality (ROVER) to perform a task. To control the ROVER, the user generated an object (i.e., traffic cone) within the AR environment and placed it at the desired location. Using a button press, the user directed the ROVER to the virtual cone. Another button press recalled the ROVER to the user's location.

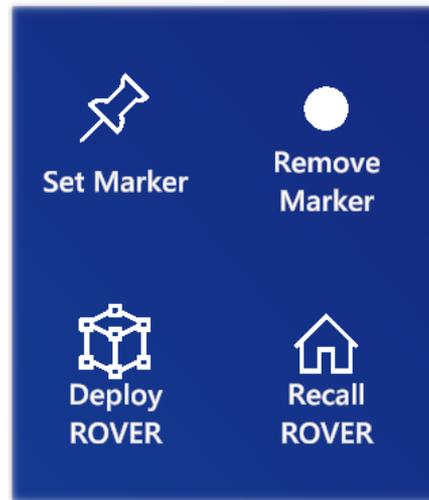


Figure 4. ROVER Controls Menu of the AR-Assistant.

Alt-text: Blue table with four buttons: Set Marker, Remove Marker, Deploy ROVER, and Recall ROVER

Geological Scanning

One of the goals for the operator was to evaluate a rock using a spectrometer. The data was presented in the headset once the operator scanned the rock using the provided spectrometer. The operator saw the likely rock type scanned based on the information obtained from the spectrometer. This information was presented in the top center of the visual field so as not to impede the user's field of view. This way, the user could easily see what specimen they had scanned and ensure that the scan worked properly.

Alerts

The overarching objective of this design was to reduce the number of errors made by the user. Therefore, the design must ensure that the user is aware of any issues that may occur while in suit power. Alerts are the typical way of ensuring that the user is aware of any issues requiring attention; however, alerts have limitations that minimize their effectiveness. Alerts must be designed to not startle the user to the point that they are not immediately responsive. Furthermore, alerts must be relatively sensitive not to provide many false alarms but should also catch any irregularities in the system. Alerts are therefore split into three distinct categories: (1) warnings-most critical; requires immediate attention, (2) cautions-important but do not require immediate attention, and (3) advisories-informational only; do not require attention (Lee et al., 2017). The alerts in the proposed design follow Human Factors (HF) Principles outlined in Lee et al. (2017) and the Federal Aviation Association Guidelines (2010).

All alerts have a caution phase and a warning phase in order to reduce the number of false alarms. Cautions were displayed when an issue was identified, while warnings were displayed when the issue turned critical. Per FAA regulations, warnings were presented in red along with an auditory signal. All alerts were displayed until the issue was resolved. Alerts were used to monitor the suit conditions, such as oxygen levels, and actions that could be

detrimental if executed. For example, an alert would sound if the user tried to open the airlock without all the controls having been transitioned to suit power.

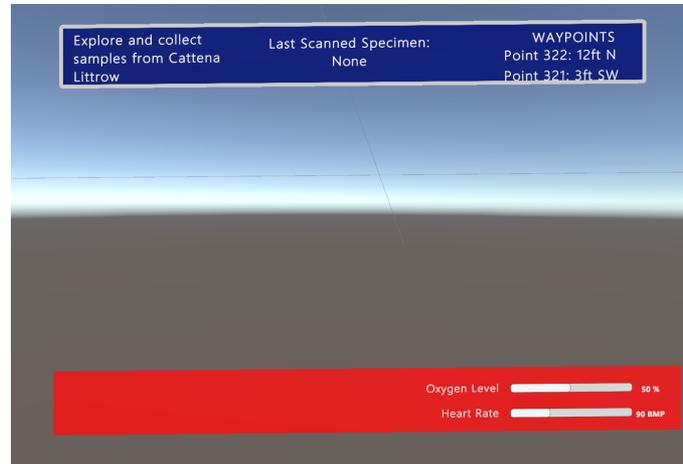


Figure 5. HUD Display with Alert within the AR-Assistant.

Alt-text: Two horizontal bars (top and bottom) represent the main HUD display. The bottom bar is red to indicate a warning to the user.

Voice Commands

Users of the AR system were likely to have equipment that restrict their mobility, such as a spacesuit. As such, an alternate mode of interaction was added as a redundancy. Voice commands can have issues such as involuntary activation, difficulty recognizing speech input, and difficulty discovering input commands. As such, voice commands used within our AR system were secondary to the touch input commands. All voice commands started with “system,” followed by the input command to account for involuntary activation. For increased discoverability, all voice commands used the same vocabulary as the hand menu commands. To account for difficulty recognizing speech input, voice commands were limited to simple phrases and were secondary to touch input commands. The user can still operate the system even if they cannot operate the voice commands. Figure 6 presents the voice command hierarchy.

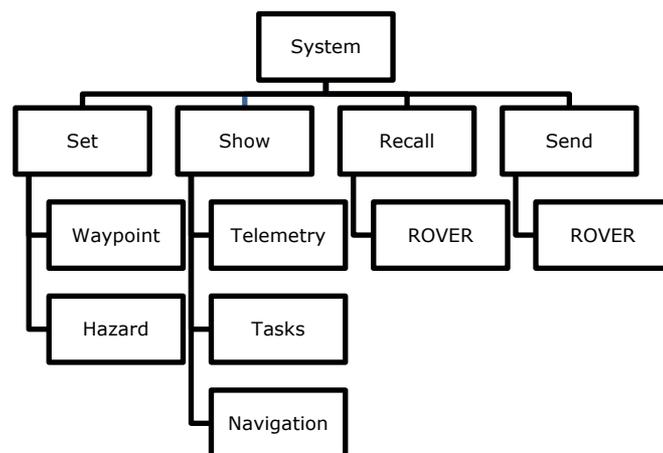


Figure 6. Voice Command Hierarchy for the AR-Assistant

Alt-text: A hierarchy with three levels. Level 1: system. Level 2: set, show, recall, send. Level 3: set-Waypoint, hazard. Level 3: show-telemetry, task, navigation. Level 3: recall-ROVER. Level 3: send-ROVER.

Testing Methodology

A cognitive walkthrough was conducted on the original design to determine areas in the design where the user may become confused. The results highlighted issues with the group of menu items. New menus were designed so that all items were within one degree of separation from the main button. Further, the cognitive walkthrough identified gaps in the design, such as how the location of the waypoints should be displayed. Finally, the cognitive walkthrough led to changes in how the user switches from one task to another. The final design clarified what tasks have and still need to be completed.

The final design was tested at NASA's Johnson Space Center's Planetary Analog Test Site by an experienced user familiar with both NASA's mission and mixed reality. The Planetary Analog Test Site is a multi-acre area that simulates lunar and Martian landscapes. For increased accuracy of the simulated environment, testing was conducted at night. The tester received a short demonstration of the AR system's capabilities before completing the four tasks established by NASA SUITS requirements. The tester successfully completed all tasks. An unstructured interview was conducted after testing. Suggestions for improvement included creating an automatic direction guidance system and an automatic hazard detection system. Overall, the tester thought that the UI and the AR system were intuitive and helpful for the completion of tasks.

Conclusion

The proposed AR system provides users with a self-contained assistant for deep-space EVAs, thus reducing the impact of the communication lag characteristics of deep-space missions. By focusing on Human Factors and Usability principles throughout the design, the AR system is user-friendly, allowing the experienced tester to successfully navigate through four tasks performed during standard EVAs. Future works should test the usability of an automatic hazard detection system to determine if it can help users successfully avoid obstacles. Developers can create user-friendly designs by leveraging existing Human Factors and Usability research.

Tips for Usability Practitioners

- When including hand gestures within an augmented reality interface, include an alternate interaction method; hand gestures are difficult to register in dark environments and with a spacesuit.
- When designing an augmented reality interface, make sure the elements are easily seen by the user but do not block the user's field of view. The interface should be a tool, not the main view.
- When designing alerts for an augmented reality interface, make sure the alerts are clearly seen by the user *without* blocking the user's field of view. The user should not lose visual of the task they are completing.

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Image caption: photo of author



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Image caption: photo of author

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Image caption: photo of author