Usability And Control Mechanisms of Displays for Planetary Surface Operations

Siddhi D. Bhilare[1], Jake Rohrig[2]
Collins Aerospace, Windsor Locks, CT, 06096

Jesse A. Lane[3], Abhishek D. Rane[4]
Collins Aerospace, Cedar Rapids, IA, 52498

Despite ever-evolving advancements in Human-Computer Interfaces (HCI), spacesuit displays remain limited to a simple 12-character LCD screen for displaying suit status, caution & warning signals accompanied by an EVA cuff checklist strapped on the EMU wrist as a compressed format for providing EVA task and EMU malfunction procedures, and a wrist mirror to aid with EMU controls outside the crewmember's FOV. However, planetary EVAs pose unique operational challenges, demanding HCIs that empower crewmembers to interact seamlessly with their environment while ensuring safety, efficiency, and productivity. Head-up displays (HUDs) offer a means to display critical information while minimizing manual attention shifts and cognitive disruptions during an EVA. Collins Aerospace, with support from SETI Institute and Ntention, performed experiments at the Haughton-Mars Project Research Station (HMPRS) planetary analogue base camp on Devon Island on the northwestern rim area of the Haughton Crater to study the usability of 3 technologically distinguished displays for a geological planetary EVA to perform navigation, sample collection and terrain surveillance operations in-line with the Artemis EVA expectations. An interactive navigation software was developed to support these operations. An Astronaut Smart Glove (ASG) and a Natural Language Interface (NLI) were also developed to study display control methods in tandem with different display interfaces on a high fidelity NextEMU suit mockup. NextEMU is the Next generation spacesuit designed by Collins Aerospace[8]. Test subjects with geology, EMU systems engineering, and aviation pilot experience backgrounds participated in a Human In The Loop (HITL) testing to assess the display, ASG and NLI usability in this remote, high arctic planetary environment. Findings revealed nuanced relationships between display type, display location and display control methods. This paper will discuss the experimental design, product analysis, training, and results of the HITL testing for the development of an ideal display design for planetary surface exploration.

Nomenclature

ANOVA = Analysis of Variance
AR = Augmented Reality
HCI = Human-Computer Interface
LCD = Liquid Crystal Display
EVA = Extra-Vehicular Activity
EMU = Extra-Vehicular Activity Mobility Unit
FOV = Field of View
HUD = Head Up Display
LTV = Lunar Terrain Vehicle
SETI = Search for Extraterrestrial Intelligence
SRD = System Requirements Document

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[1] Insert Job Title, Department Name, and Address/Mail Stop for first author.
[2] Insert Job Title, Department Name, and Address/Mail Stop for second author.
[3] Insert Job Title, Department Name, and Address/Mail Stop for third author.
[4] Insert Job Title, Department Name, and Address/Mail Stop for fourth author (etc).

HMPRS = Haughton-Mars Project Research Station
ASG = Astronaut Smart Glove
NLI = Natural Language Interface
HITL = Human in the Loop
ConOps = Concept of Operations

I. Introduction

PLANETARY EVAs pose unique geological challenges such as rugged terrain with craters, boulders and steep slopes, altered gravity, dust and abrasion, radiation exposure, communication delay and limited mobility. Human-computer interfaces that empower crew members to interact seamlessly with their environment could help tackle some of these geological challenges while ensuring safety, efficiency, and productivity during the EVAs.

Head-up displays offer a means to display critical information while minimizing the need for manual attention shifts and cognitive disruptions during an EVA. Collins Aerospace, with support from SETI Institute, performed an experiment at the Haughton-Mars Project Research Station (HMPRS). This site is located on Devon Island in the High Arctic Canadian desert at the northwestern rim area of the Houghton Crater. Haughton Crater is an impact crater spanning 15 miles in diameter, formed over 23 million years ago by a sizeable meteorite collision[1]. Notably, this crater stands out due to its resemblance to environments found on Mars or the moon – characterized by cold, windy, dusty, rocky, and predominantly arid conditions, largely unexplored. This lunar analog mimicked potential EVA exploration sites, granting access to planetary bedrock, canyons, valleys, gullies and historical liquid water activity. Three technologically distinguished displays were studied to assess usability of for a planetary EVA to perform navigation, sample collection, and terrain surveillance operations, in line with the Artemis EVA expectations.

II. Methodology

A simulated planetary EVA course was designed for 3 test subjects at the HMPRS base camp on Devon Island, (Arctic) Canada. The test subjects were selected from geology, aviation and spacesuit engineering experience fields. Each test subject performed 3 EVAs, with each EVA testing the use of a different type of informatics display: conformal augmented reality (AR) glasses worn within the spacesuit helmet, a waveguide display[5] mounted outside the spacesuit helmet, and a tethered display mounted on the forearm of the suit as shown in Figures 1, 2, and 3. The conformal AR glasses within helmet and waveguide display outside the helmet both use waveguide optical combiner technology. Waveguides are heavily used in augmented reality applications because they enable users to simultaneously view the real world along with digital information relayed on the display[2] as shown in Figure 4. The wrist-mounted display used was a simple LCD display.

The average duration of each EVA was 30 minutes and 9 such EVAs were performed. The chronological order of selecting the display type under test for each EVA was randomized to avoid user bias. Each EVA was perfomed by a single test subject with one safety and one medical supervisor following the crewmember throughout the EVA course. The test subjects also had communication available with a simulated Mission Control to relay mission objectives, risks and safety parameters for an effective EVA.

Two types of control mechanisms were developed to manipulate the information shown on the displays. The first was a Natural Language Interface (NLI) that enabled the user to control the displays with their voice, both for informational queries and drive commands. The NLI allowed for a hands-free operation of key navigation functions. The second control mechanism was a Astronaut Smart Glove (ASG), that allowed the wearer to control content on the displays with hand gestures. For example, maps, like that shown in Figure 5, could be intuitively pivoted in three dimensions by making a fist and rotating the hand wearing the ASG. Additional system information is presented in Section III.

Figure 1: Test subject navigating a route back to base on an EVA assisted by HUD – Waveguide display
(outside helmet)

Figure 2: Tethered display mounted on an EVA glove

Figure 3: Test subject collecting rock samples on an EVA assisted by HUD - Conformal AR Glasses (within helmet)

Figure 4: Rendering of in field view through waveguide displays

Prior to the experiment, test subjects underwent 45 minutes of training to familiarize themselves with the operation of the displays and control systems (NLI and ASG) and the tasks involved in the simulated lunar EVA. Training sessions included instruction, hands-on practice with the display and control systems, and simulated EVA scenarios. Task completion times improved rapidly with practice and error rates were severely diminished; test subjects attributed this to their familiarity in using existing user intefaces such as drone controllers, video game controllers and also systems as banal as computer screens controlled using a mouse. Test subjects were shown maps and simulations about the EVA traverse prior to their simulated EVAs, but their first EVAs were the first time they actually experienced walking on this traverse. This was intentional to maintain fidelity with a planetary EVA scenario.

Test subjects were evaluated on their proficiency in using the display interfaces and their ability to perform EVA tasks accurately and efficiently. During the experiment, test subjects donned spacesuit prototypes equipped with one of three display systems, one display tested per simulated EVA. The experiment simulated a lunar EVA for which test subjects were required to:

i. Scope the perimeter using the provided navigation display.

ii. Determine the path of least resistance.
iii. Plan a walking traverse to a selected sample collection worksite.
iv. Navigate to the sample collection site.
v. Collect panoramic pictures of the sample collection site.
vi. Collect rock and soil samples at the sample collection site using simulated EVA tools such as a hammer, a chisel, a sample grabber and sample collection bags, all mounted on a tool belt.
vii. Navigate back to base.

The EVA walking traverses were limited to 1km radially from the HMPRS base camp and the allowable gradients were limited to less than 20 degrees in order to represent allowable slope traverses planned anticipated around Shacklton crater on the moon. The limitations set on distance and slope were also set to maintain sufficient emergency response time, ensure reliable communication, and maintain healthy test subject fatigue levels.

III. System Description

To support the experimental objectives, a prototype spacesuit informatics system was designed and implemented. This system offers capabilities that align with some, but not all, of NASA's requirements for the Artemis program. Table 1 depicts the informatics system requirements for Artemis, as conveyed through the Exploration Extravehicular Activity Services (xEVAS) Systems Requirement Document (SRD)[3], and compares them against the capabilities that were designed and implemented for this test.

Table 1: xEVAS SRD required capabilities demonstrated and tested in the analog informatics system

xEVAS SRD Requirement #	**Requirement Description**	**Sub-Requirement**	**Sub-Requirement Description**	**Analog System**
RQMT-065	The xEVA System shall provide an EVA information system and graphical display with the following key information to the suited crew member:	A	Consumable monitoring and display	YES
		B	Procedure viewer	YES
		C	Display of photo imagery and graphics	YES
		D	Timeline viewer	
		E	Data storage	YES
		F	Display for send/receive of text messaging	
		G	Camera viewfinder	
		H	Recording of crew audio/video/still image field notes	
		I	Map display, which includes EVA crewmember position and supports real-time navigation	YES
		J	Communication of relevant biomedical information	YES

A description of the prototype's key elements, input modalities, conveyed information, and interactions that demonstrate compliance to the claims in Table 1 are further described below.

A. Key Prototype Element

1. *Astronaut Smart Glove*

The astronaut smart glove (ASG) is an input device described in greater detail in the following subsection.

2. *Suit Computer*

To reduce development time, an embedded computer wasn't chosen. There was a limited choice of commercially available 3D rendering engines that could be used to drive a user interface from an embedded/single board computer. A standard x86_64 based laptop with a discrete GPU could take advantage of the vast quantity of readily available tools, allowing engineers to focus on developing the content to display and not the rendering pipeline.

3. *Navigation Sensors*

The primary aim of this excursion was to test the user interface. Lunar positioning and orientation technology testing was out of scope for this experiment. As such, GPS was chosen as the position system for this suit due to its ubiquitous availability and ease of integration with suit electronics and off the shelf hardware. A commercially available embedded GPS receiver along with an external antenna provided sub 2-meter position accuracy which was considered sufficient for navigation purposes. To provide additional orientation information to the suit user, a tilt compensated digital compass was also added to the microcontroller. Tilt compensation was needed to allow the user more flexibility in movement and to compensate for the non-parallel nature of the Earth's magnetic field lines near a magnetic pole. Both the GPS and digital compass were connected to a small microcontroller which was then connected to the primary suit computer via a serial link.

4. *Suit/Internet Connectivity*

Due to technical challenges and data availability restrictions, we were unable to use an offline map layer during testing. Map data could be cached on the suit. This required periodic check-ins to the map data provider's servers to ensure the data didn't expire. Given the remote test location, infrastructure was extremely underdeveloped. Satellite internet was the only option. Given the high bandwidth needs of map layer streaming, SpaceX's Starlink was used. The user during the pre-EVA process at basecamp would move the map and look at all the mission objectives. The suit computer was connected to the internet and could load map layers and/or extend the expiration time of precached layers.

5. *Display(s)*

As mentioned in Section II, Methodology, three types of displays were evaluated for use of visually conveying information as part of the larger spacesuit informatics system. The three types of displays that were evaluated were conformal AR glasses, a monocular waveguide display, and a tethered display mounted on the forearm of the suit. Again, these displays and their respective configurations are shown in Figures 1, 2, and 3. Waveguides were selected as the technology of choice for the head-up display options because of their ability to columnate the light exiting the waveguide. Columnated light allows for greater eye relief in displays because it minimizes the need for precise alignment between the viewer's eye and the display surface. Additionally, columnated light allows images to appear focused at infinity by directing light rays in parallel, simulating the effect of how the eye receives light reflected from distant objects, which reduces the need for the viewer's eyes to accommodate or focus on the actual physical distance between the display surface and they eye; this makes waveguides great for near-eye and mid-distance displays. The conformal AR glasses within helmet and waveguide display outside the helmet both use waveguide optical combiner technology[6]. The wrist-mounted display used was a simple LCD display.

B. Input Modalities

1. *NLI*

Users can interact with all informatics system capabilities via a natural language interface (NLI). To minimize false command activations and provide a unified conceptual reference for system interaction, a hot phrase, "hod-os", initiates NLI interactions. "Hodos", a Greek term meaning "road" or "pathway", aptly describes a system designed to assist with navigation.

2. *ASG*

The display, primarily for the purposes of map interaction, can be manipulated using the ASG. The ASG provides a way to physically interact with the informatics system as an alternaitive to traditional switches, dials, or buttons. The ASG uses sensors integral to the glove to perceive gestures of the wearer and transmit this to the informatics system controller, which in this case is a suit computer described in a later section. Notably, a benefit that the ASG provides compared to traditional input mechanisms is flexibility in programming. Endless combinations of gestures can be programmed and used to provide input to the informatics system. Some control gestures are exemplified later in this paper.

C. Conveyed Information

1. Biometrics and consumables

The system displays a concise set of real and simulated biometrics and consumable information through the display as label/value pairs. This includes a simulated heart rate, the actual remaining battery level percentage, and the actual CPU temperature as shown in Figure 5. These displays are informational only, offering no interaction mechanism.

2. Procedures

Users can view a pre-loaded set of procedures on the display. Selecting between procedures is as simple as voicing a "next procedure" or "previous procedure" command. Similarly, progressing through a procedure's steps is managed with "next step" or "previous step" commands, allowing for seamless navigation through the tasks.

Figure 5: Birds eye view rendering of the HMPRS Base camp along with navigation, consumables and biometric data displayed

Procedures are not controlled using the ASG. EVA experience has shown that a large number of procedures would be performed that require using the hands; since the hands would usually be already occupied with the current task, controlling the procedures using the ASG was not attempted in this study.

3. Maps

The system presents a high-fidelity, 3-dimensional map that users can show or hide using verbal commands. Interaction with the map involves manipulating the virtual "camera" that offers a view of the map, aligning with real-world coordinates for latitude, longitude, and altitude. To assist in navigation, the system provides indicators for the user's location, orientation, and a compass, facilitating the alignment of the camera with the user's desired coordinates. Users control the camera through verbal NLI commands specifying both absolute (e.g., "altitude", "heading", "pitch", "roll") and relative positions (e.g., "fly to base", "look at waypoint one", "bird's eye view"). Alternatively, interaction with the map is possible through the ASG, enabling gestures for camera movement—flattening the hand for translation and forming a fist for rotation—intuitively linking hand motions to virtual actions.

We experimented during prototyping with allowing the amount the thumb was bent vs. extended to control the speed of the translations and rotations but found that it added too many degrees of freedom to the interaction to allow smooth control and was left out of the version used in the experiments.

D. Interactions & Uses

1. Navigation

The informatics system enhances navigation with preloaded routes comprised of waypoints, which users can show or hide with "show route" and "hide route" commands. These waypoints are visually connected along the map's topography, allowing for a clear visual representation of the route. Highlighting individual waypoints or the entire route is simplified through commands like "light on waypoint one," enabling users to focus on specific navigation points. The system also supports a marking function, allowing users to mark their current location or the location of their vehicle on the map as shown in Figure 6. This feature is crucial for navigation back to a marked point or vehicle, demonstrating the system's adaptability to the user's spatial orientation needs. Targeting of navigation objects, such as waypoints, points of interest (POIs), or vehicle markers, is seamlessly integrated, with targeted objects prominently displayed and directional indicators guiding the user towards these objectives.

2. Common Interactions

User interface elements are individually managed through specific "show" and "hide" commands, facilitating user

LAT 75.4323 HEAD 325.19
LON -89.8586 PITCH 0
ALT 214.17 ROLL 0

LAT 75.4326 HEAD 109.71
LON -89.8614 PITCH 77.77
ALT 219 ROLL 360

Figure 6: Vehicle marked rendering as displayed on the HUDs

control over the display of information. Commands like “show all” and “hide all” provide quick options for users to clear or populate their visual field, enhancing the user experience by allowing for tailored information visibility.

3. *Brightness*

To adapt to different environmental lighting based on the glare from direct sunlight or terrain reflected sunlight, users can adjust the brightness of the screen to view digital information displayed on the HUD and the real-world terrain simultaneously. This helps the user to more comfortably navigate in different directions without straining their eyes.

4. *Feature display control*

This capability allows the user to selectively show or hide any of the display parameters on the HUD based on the relevance to the task at hand, thereby optimizing the FOV and improving task efficiency. This way, once the user has reached the location of interest, they can hide the map to have a more transparent real-world view. They can then start displaying mission procedures to aid with the EVA activity needed, such as sample collection.

IV. Data Collection and Analysis

Data collection during the experiment included quantitative metrics such as task completion time, navigation accuracy, and user satisfaction ratings collected on a Cooper-Harper scale[4]. Qualitative feedback was also gathered through debriefing sessions and post-experiment surveys to assess user experiences and preferences. Based on the experience with planetary EVA ConOps and past career experiences, some test subjects were given a higher weightage than others to ascertain more confidence in the data analysis methods. A weighted average was performed on the collected data and summarized as shown in tables 2, 3, and 4.

The objectives of this experiment were:

A. To understand the usability of waveguide displays as compared to the LCD display. To assess this parameter, a navigation capabilities question was asked such as:
   - On a scale from 1 to 5, how easy was it for you to navigate to the target location using the [insert display name: waveguide/conformal glasses/tethered] display and using the combination of ASG and NLI;

   where:
   5 = I could not locate target or navigate to the target
   4 = I could locate the target, but, could not navigate there
   3 = I located the target, navigated there, but, I found it difficult
   2 = I navigated to the target with reasonable ease but the system can be improved
   1 = I had no difficulty navigating to the target

Quantitative data summary:

Table 2: Mean Table for Navigation capabilities

3x3 factors		Independent variable 1: Display type			
		Conformal glasses	Waveguide	Wrist mounted display	Average
Independent Variable 2: Actuation mechanism	ASG	2.67	4.67	3.67	3.67
	NLI	2.33	3.67	3.33	3.11
	Both ASG and NLI	1.33	3.67	3.67	2.89
	Average	2.11	4.00	3.56	

A two way ANOVA was performed to analyze the effect of display type and actuation mechanism on Navigation capabilities.

The null hypotheses were as follows:

- H01: Display type will have no significant effect on navigation capabilities
  Analysis results: F(2,4)=15.8042, p-value = 0.01262 indicates that the chance of type I error (rejecting a correct null hypothesis) is small (1.26%) and sample difference between the averages of some displays is big enough to be statistically significant. Hence, we rejected the null hypothesis.
  Conclusion: *Display type will have significant effect on navigation capabilities*.
- H02: Actuation mechanism will have no significant effect on navigation capabilities
  Analysis results: F(2,4)=2.6095, p-value = 0.1883 indicates that the chance of type 1 error (rejecting a correct null hypothesis) is too high (18.83%) and sample difference between the averages of the different control mechanisms is not big enough to be statistically significant. Hence, we cannot reject the null hypothesis.
  Conclusion: *Actuation mechanism will have no significant effect on navigation capabilities*.

B. To understand an appropriate display mounting location on the spacesuits during EVA operations. To assess this parameter, a Field Of View capabilities question was asked such as:

- On a scale from 1 to 5, how easy was it for you to view the EVA ops area and perform tasks with the display as positioned by the experiment conductor?
  5 = The display blocked a good part of my field of view and compromised my ability to perform tasks other than just viewing the display itself
  4 = The display blocked some part of my field of view but i was able to accomodate (by moving my head/upper torso) to view the EVA ops area and perform some tasks
  3 = The display blocked some part of my field of view but i was able to accomodate (by moving my head/upper torso) to view the EVA ops area and perform all tasks
  2 = The display blocked some part of my field of view and I was able to successfully view the EVA ops area and perform all tasks
  1 = The display did not block my field of view and I was able to successfully view the EVA ops area and perform all tasks

Quantitative data summary:

Table 3: Mean table for Field of View capabilities

Parameter	Conformal glasses	Waveguide	Wrist mounted display
FOV Capability	3.78	4.56	1.85

See section V for results summary and section VI for discussion.

C. To understand the usability of a Natural Language Interface as compared to a physical interface, Astronaut Smart Glove, during EVA operations.

- To assess this parameter, an error correction capabilities question was asked such as:

  On a scale from 1 to 5, how easy was it for you to correct and recover from any errors you made during the navigation phase while using the waveguide display, where:
  5 = I could not recover from any errors made during navigation
  4 = I could recover but only with help from the experiment conductor
  3 = I recovered from the errors myself, but, it was difficult
  2 = I recovered with reasonable ease but the system can be improved
  1 = I had no difficulty recovering from any errors

Quantitative data summary:

Table 4: Mean Table for error correction capabilities

3x3 factors		Independent variable 1: Display type			
		Conformal glasses	Waveguide	Wrist mounted display	Average
Independent Variable 2: Actuation mechanism	ASG	5.44	4.44	5.67	5.19
	NLI	1.78	3.00	3.44	2.74
	Both ASG and NLI	4.00	4.00	5.67	4.56
	Average	3.74	3.81	4.93	

A two way ANOVA was performed to analyze the effect of display type and actuation mechanism on error correction capabilities.

The null hypotheses were as follows:

- H01: Display type will have no significant effect on error correction capabilities
  Analysis results: F(2,4)=3.4441, p-value = 0.135 indicates that the chance of type I error (rejecting a correct null hypothesis) is too high (13.5%) and sample difference between the averages of some displays is not big enough to be statistically significant. Hence, we cannot reject the null hypothesis.
  Conclusion: *Display type will no have significant effect on error correction capabilities*.
- H02: Actuation mechanism will have no significant effect on error correction capabilities
  Analysis results: F(2,4)=12.5437, p-value = 0.01891 indicates that the chance of type 1 error (rejecting a correct null hypothesis) is small (1.89%) and sample difference between the averages of

the different control mechanisms is big enough to be statistically significant. Hence, we can reject the null hypothesis.
Conclusion: *Actuation mechanism will have significant effect on error correction capabilities*.

V. Results

A. Navigation capabilities

Although quantitative data suggested that actuation mechanism may not affect navigation capabilities, qualitative user feedback concluded that for navigation and terrain visualization type of activities, conformal glasses controlled by a combination of both ASG and NLI control methods was the most convenient option. As shown in Figure 3, the test set up required the conformal glasses to be donned on the user's face like sunglasses inside the helmet. With proper fit, the waveguide technology assisted with alleviating strain off the eyes of the test subject. Hence, even though the display itself was close to the user's eyes, the displayed information is perceived more embedded with real-world objects at a distance. Among the 3 displays tested, the conformal glasses offered the widest surface area for information display. This display is also almost transparent, as shown in Figure 4, thereby providing a seamless integration of visual information without obstructing the user's field of view.

However, persistent fit issues arose due to the constrained environment of the helmet. Once misaligned, there is no good way to readjust the conformal glasses within the helmet during an EVA, thereby exacerbating fit discrepancies and hindering optimal waveguide alignment. This impacted user experience and performance negatively. In altered gravity environments, face mounted avionics sensitive to misalignment are not ideal and further investigation into developing the waveguide prototype to better adapt to the within-helmet use case is warranted.

Although the outside-the-helmet waveguide display alleviated such hardware fit challenges, they required the test subjects to adapt to the asymmetrical display placement.

The wrist-mounted tethered display provided convenient access to information but necessitated additional hand movements, affecting task efficiency. The tethered display came across as the best option to mitigate the risk of FOV obstructions. However, with proper fit, the almost transparent waveguide displays did not obstruct the FOV to a degree of non-adaptability. These waveguide displays worn by the test subject can be seen in Figures 1 and 3. A view though the waveguide displays can be seen in Figure 4, where the mission information is overlayed on real world terrain in the EVA field.

B. Field Of View Capabilities

For placement of the external helmet mounted waveguide display, crew members had their own preferences on the most convinient location on the helmet. For example, some crew members liked the top right or top left position on the helmet, whereas some preferred the sideways and downward angle. Although all of these locations would require the user to turn their head/neck to peep into the waveguide display, they seemed to prefer it since this kept the display out of their normal line of sight when not required, allowing them to focus on the task at hand. A minor FOV obstruction was caused by this display, demanding the test subjects to make allowances for this obstruction by moving their neck or body to view hindered sights. However, with technological advancements, this FOV hindrance can be minimized/eliminated completely. Given the close proximity to the eye of the user, the waveguide type displays (both conformal glasses and the singular waveguides) did not cause any strain on the eyes owing to their comfortable immersive display technology.

Although the wrist-mounted display was deemed best for FOV capabilities, it was observed to be a potential deterrent in several geological ConOps which involved using tools for sample collection, logging and driving a vehicle. The crew members would essentially have to stop what they are doing, to check the display on their wrists and then continue where they left off.

C. Error Correction Capabilities

Some users preferred the NLI method to navigate through the map, using the method of commanding the map compass to a specific needed direction, example "pitch 90" or "roll 270" whereas, some users preferred the continuous map control feature provided by the ASG using a hand gesture such as 'grab and rotate in the needed direction'. For specialized view commands such as ''birds eye view'', ''locate base'' or "Hide Map", hands-free operation of the NLI was deemed the more convinient control option as compared to the ASG. Other key helpful features of the map were being able to see the location markers for the crew member, base camp, work site and vehicle as this takes away the cognitive load associated with orientation and route planning.

Overall, an NLI type of control mechanism was deemed adequate for HUD information control, however, for use cases other than navigation tasks, such as controlling augmenting EVA robotic devices such as robotic arms, rovers, drills, drones or helicopters, an ASG like control device could be a better option.

Comparing the feedback received for ASG and NLI, the following conclusions were derived:

1. *Direct Manipulation*

With an ASG, users had direct control over the system parameters, allowing gradual and precise selection of and interaction with the elements on display. For HUDs and EVA tasks beyond display controls, such as controlling drones, rovers, robotic arms and other unmanned EVA supporting equipment, an ASG could be a convenient means of control.

2. *Hands-Free Operation*

The NLI aids in multitasking , allowing the users to control displays without the need to physically interact with the device. For navigation tasks during Lunar Terrain Vehicle (LTV) driving operations, captains log or panoramic picture captures, looking at mission procedures and other mission supporting instructions, NLI could be a convenient means of control.

3. *Learning Curve*

While NLI can be convenient, it has a steeper learning curve based on the time needed to familiarize the user with specific NLI vocabulary and speech control.

VI. Discussion

The choice of display system depends on the specific requirements of the mission and user preferences. While each display system offers unique advantages and challenges, further technological refinement and display control optimizations are necessary to ensure optimal performance in planetary EVA missions.

Operational performance of body fitting control devices such as the ASG highly depends on the fit of the devise over the user's physical profile. Especially for a glove, due to variability in palm and finger length, width and thickness, different users had different difficulty levels in harnessing the ASG's full potential.

The conformal glasses HUD, although securely strapped, provided significant challenges in terms of fit and general comfort. During sample collection and general traverse maneuvers, the glasses would shift on the user's face, thereby changing the comfort calibrated focal point needed by the user's eyes. There is no convenient way of re-adjusting the conformal glasses over one's face, when in a spacesuit on an EVA traverse. A within helmet HUD such as this also makes the available helmet space more cumbersome for the user. However, looking past the hardware challenges, this display was still deemed as the most convinient as it provided a true immersive EVA experience without the need to pause EVA activities to look at the display. This display provides seamless transition between EVA activities such as navigating while walking/driving, switch from map to procedures display for sample collection ConOps and hide display altogether to focus on tasks needing the maximum FOV. More research here can help overcome the hardware and fit challenges.

VII. Future Scope

Analogous field trials, like the experience offered by the Haughton Mars Project, provide research teams, like ours, the opportunity to analyze elements of our spacesuit informatics system in an authentic environment. Instead of being limited to conceptual trade studies, our team was able to gain valuable insights into the limitations and interactions with each configuration of the system we tested. Spacesuit informatics systems involve intricate interactions between hardware, software, and human operators. Analogous field studies provide an opportunity to observe these interactions firsthand, capturing nuances that might be missed in controlled laboratory settings or virtual simulations. This year's field campaign was valuable in helping us answer key questions about system usability, user experience, and unexpected challenges that arise during real-world use.

The lessons learned through this study took Collins Aerospace another step torward legitimizing an informatics system for integration into exploration spacesuits, but there is more work to be done to develop a system that can be used for flight operations; the systems and technologies investigated so far have been developed using Earth-based, commercial components. Using these commercial components have been valuable for studies and investigating the art-of-the-possible, but the unique environment in which spacesuits operate, the challenges imposed by the spacesuit itself, and additional human factors will impose design limits on the final form of the informatics system.

Some of these key factors are shown in Figure 7, and their relative difficulty of being overcome to achieve a flight informatics system. The relative scoring portrayed in Figure 7 was established during an engineering assessment of

the required effort to develop a spacesuit informatics system based on military and commercial head-up display systems that Collins Aerospace already provides to other industries and customers. Scoring was subjective and ranked by subject matter experts.

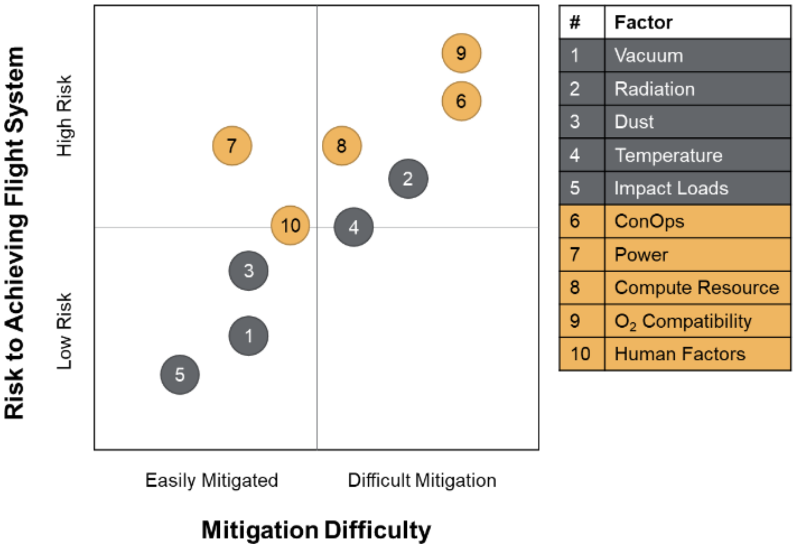

Figure 7: A graphical depiction of the risks and mitigation difficulties to achieve a flight-capable spacesuit informatics system.

The navigation system described in this experiment was only one of the use cases for a HUD in planetary EVAs. However, HUDs can serve to support a multitude of ConOps for different missions concepts. A display larger than the 30 degree field-of-view waveguide display would be ideal to assist with multiple use cases such as controlling robotic devices like rovers, drones, drills, etc. Increasing the field-of-view however either requires decreasing the distance from the eye to the display, or making the waveguide display surface larger.

Near-eye displays have placement limitations in spacesuit helmets, posing eye or face impact hazards, while larger displays lessen this risk, but require additional power. The shortcomings of the small waveguides tested and the wrist-mounted display could be overcome by custom waveguide and microprojector design, allowing for a greater field of view and could eliminate the need to halt ongoing EVA activities to check the display. It is also possible to envision use cases where a combination of display interfaces might be desirable. This will need to be studied in the future.

In particular near-future work will be done to increase the fidelity of the informatics system

processor(s). For instance, a concerted effort needs to be undertaken to migrate the informatics system that runs on a commercial laptop, to that of a spacesuit-viable processor. Relatedly, sub-factors that influence the selection of the processing system will be radiation susceptibility and power consumption. The desired abilities of the informatics system also contribute to the risk of a power-hungry system processor, ultimately and undesirably reducing the duration of a spacewalk. Balancing desired informatics system capabilities with the limitations of spacesuit-viable processors is an important next step. Additionally, designing the display system to be compatible with a pure-oxygen environment (assuming the display system resides within the atmospheric conditions of the spacesuit) poses challenges. Generally speaking, larger, more-capable displays consume more power than smaller less-capable displays. Increasing the electrical power to the display system is not only detrimental to the overall power consumption of the informatic system, but it also increases the risk of flammability inside the spacesuit. Balancing display form factor, and directly display capability, with power consumption is also a crucial next step in the development of the informatics system.

Undeterred, Collins looks to overcome these challenges with our continued research and development of spacesuit informatics systems and associated technologies.

VIII. Conclusion

The experiment demonstrates the feasibility of utilizing various display systems in spacesuit prototypes for enhancing navigation and task efficiency in preparation for lunar EVAs. Implementing a helmet mounted display into spacesuits represents a transformative leap in EVA interface technology. Providing mission critical and emergency information integrated with the helmet would streamline work flow and reduce cognitive load on the user. This augmented reality approach not only enhances situational awareness but also enables interactive features, empowering the user to adapt swiftly to mission challenges. Continued research and development in this field are crucial for enabling successful human exploration of the Moon and beyond.

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