Design of a Hybrid Spacesuit Display for Martian Surface Exploration

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Abstract **—** This paper presents the design, implementation, and evaluation of hybrid heads-up displays (HUDs) for Martian surface exploration. Our HUDs integrate task-specific overlays with adaptive contextual information in a single helmet-mounted interface, enabling real-time decision support to astronauts without obstructing their external field of view. Building upon spacesuit technologies from Apollo, Space Shuttle, and Artemis missions, we developed four HUD prototypes addressing key operational needs: navigation and surface traversal, suit and mission-critical monitoring, emergency response, environmental awareness, and task operation support. The 13 Principles of Display Design guided the development of our HUDs, and usability was evaluated through Likert scale testing. Results demonstrated high usability for surface and task displays (mean > 5.3/7), with user feedback informing iterative refinements. Recommended future work includes VR-based dynamic testing with larger cohorts of participants. Overall, our project demonstrates the feasibility of ergonomic HUD integration for Martian extravehicular activities (EVAs) and provides actionable insights to guide next-generation EVA interface design, enhancing human performance and safety in Martian and deep-space missions.

Keywords — Heads-Up Display (HUD), Helmet-Mounted Display (HMD), Spacesuit Design, Martian Surface Exploration, Human Factors Engineering, Extravehicular Activity (EVA), Extravehicular Mobility Unit (EMU)

I. Introduction

Spacesuits represent a pinnacle of human achievement, encapsulating some of the most iconic moments in space exploration once only imagined in science fiction movies. Initially designed as life-preservation garments—maintaining pressure, regulating temperature, supplying oxygen and water, and shielding against radiation and micrometeoroids—spacesuits have evolved into integrated, task-oriented platforms. Modern suits now support a broad range of extravehicular functions beyond survival, including surface traversal, regolith sampling, equipment servicing, and contingency operations. This evolution reflects a shift from treating the suit as a passive barrier to considering it an active operational node within mission architecture.

To further advance this transition from survival system to operational asset, we propose integrating helmet-mounted HUDs into Martian EVA suits to assist astronauts during surface operations. Head-mounted displays (HMDs) are projection systems embedded into eyewear or helmet assemblies, while HUDs are a subclass that overlays information in the user's field of view without occluding the external scene [1]. For a HUD to function effectively during Martian EVAs, it must present mission-critical information—task instructions, emergency procedures, suit status, environmental hazards, navigation cues, and system alerts—in real time, without diverting the astronaut's attention from the environment.

To identify relevant functional requirements, we conducted a task analysis based on a NASA study cataloging over 400 anticipated Martian surface tasks [2]. From this analysis, we determined that a Martian HUD must support at minimum:

1. Monitoring suit status and mission-critical information
2. Operating and switching situational displays
3. Navigation and surface traversal
4. Monitoring environmental conditions

Building on historical suit display systems and these core task demands, we developed four helmet-integrated HUD concepts (depicted in Section VII) designed to enhance astronaut performance and decision-making during Martian surface exploration.

II. Evolution of Spacesuits

The evolution of spacesuit display systems has been central to human spaceflight, enabling astronauts to monitor health and life-support systems while accessing mission-critical information in hostile environments. These displays evolved from simple mechanical indicators to integrated HUDs, substantially enhancing crew safety and mission performance.

In the early 1960s, spacesuit interfaces were rudimentary: astronauts relied on wrist-mounted gauges to track oxygen, temperature, and battery levels, and communication with mission control relied solely on voice transmission, without visual or digital aids. By the late 1960s, a surge in federal investment accelerated technological development. Apollo-era suits incorporated the chest-mounted Control and Display Unit (CDU), which provided readings for oxygen, carbon dioxide, cooling water, and electrical power, alongside an integrated microphone for communication and a visor-mounted sunshade for glare mitigation. This period established foundational display principles that informed subsequent generations of spacesuit systems.

Since the 2000s, head-mounted display (HMD) technology has advanced significantly, allowing astronauts to access schematics, checklists, and communication interfaces directly within the helmet. Modern systems integrate closely with life-support hardware, enabling more efficient monitoring and control.

In 2020, the Human/Robotic/Vehicle Integration and Performance Lab at the University of California, Davis, in collaboration with NASA Johnson Space Center, designed and evaluated a helmet-mounted display for EVA operations during underwater training in the Neutral Buoyancy Lab (NBL). Two mounting architectures were tested (Figure 1): 1) a swing-arm mount positioned in front of the visor for real-time physiological data, and 2) a surface-mounted peripheral display providing minimal-distraction caution and warning cues. The system employed a voice-based Intelligent Response and Interaction System for hands-free control. Commands followed a structured sequence: the astronaut issued a wake word, which the software transcribed and parsed, or a remote command was sent by the HMD team. Commands were routed via an API to a GovCloud server, with a Raspberry Pi retrieving and interpreting the instruction, processing metabolic data if requested, and signaling the display to change state (e.g., mode selection or on/off) [3]. A schematic of this data flow is shown in Figure 2.

NBL testing of this HMD prototype revealed:

1. Real-time physiological feedback and EVA parameters were both useful and easily readable.
2. Minimal interference occurred between HMD hardware and the spacesuit during EVA activities.
3. Peripheral visual cues were effective only under certain operational scenarios and lighting conditions.
4. Voice control enabled hands-free operation. However, its reliability must be improved before operational use.

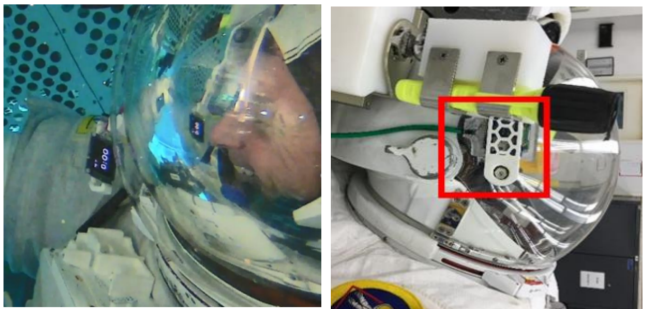


Figure 1. HMD swing arm is mounted on the right side of the astronaut's Extravehicular Mobility Unit (EMU) helmet visor (left). HMD surface mount on EMU visor (right) [3].

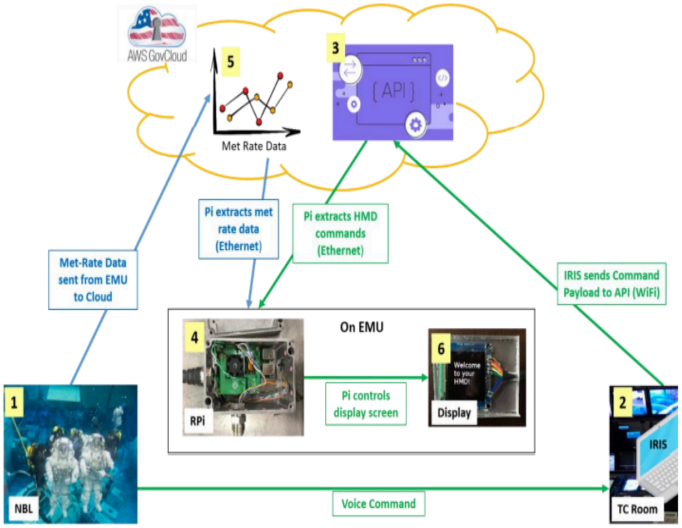


Figure 2. Data flow during the NBL test. The green arrows indicate command pathways used to control the HMD, and blue arrows indicate the data flow for real-time metabolic-rate monitoring [3].

Historically, NASA monitored crew safety during Mercury, Gemini, and Apollo missions using biomedical instrumentation. Astronauts wore electrodes for electrocardiograms, heated thermistors to infer respiration, and, in some cases, rectal probes to measure core temperature [4]. While effective, these methods were intrusive and could impair task performance. For Martian EVA suits, we recommend integrating non-invasive biometric sensing (e.g., heart rate, respiration, thermal status) directly into HUDs. Embedding this data within the display reduces communication latency to habitat systems or mission control and supports more autonomous, timely decision-making during surface operations.

Overall, the success of past human spaceflight missions demonstrates the resilience of spacesuits in extreme environments while preserving astronaut health. Apollo spacesuits established the foundational architecture for extravehicular systems, which was refined in the Space Shuttle EMU that dominated Shuttle-era EVA operations. The current Artemis suit balances life preservation with advanced interface technology for sustained lunar missions. Building on this accumulated heritage, our HUD concepts draw from key elements of past, current, and envisioned helmet display designs. The Apollo suit, the Space Shuttle EMU, and the Artemis suit—examined in the following sections—guided the development of our Martian HUD systems.

III. Apollo Spacesuit Display System

The Control and Display Unit (CDU), shown in Figures 3 and 4, served as the primary interface for monitoring and controlling the Apollo Extravehicular Mobility Unit (EMU). Chest-mounted for continuous accessibility, the CDU provided astronauts with real-time life-support data and essential system controls during lunar surface operations.

The key features and functions of the CDU include:

1. Environmental and life-support monitoring: continuous readouts of oxygen, carbon dioxide levels, coolant-water temperature, and electrical power status–parameters critical to crews' safety.
2. Communication interface: a built-in microphone and push-to-talk mechanism enabling voice communication with the Lunar Module and Mission Control.
3. Operational visibility aids: a deployable sun visor to reduce solar glare during surface tasks.
4. Procedural reference: a transparent, hinged checklist cover allowing astronauts to view mission procedures without manipulating loose pages.
5. Caution and warning indicators: audio and visual cues alerting astronauts to system anomalies or unsafe operating conditions.

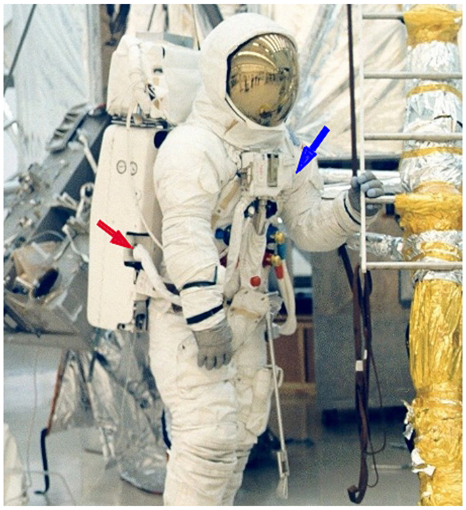


Figure 3. The CDU mounted on an astronaut's A7L spacesuit (blue arrow) and connected to the life support system (red arrow) [5].

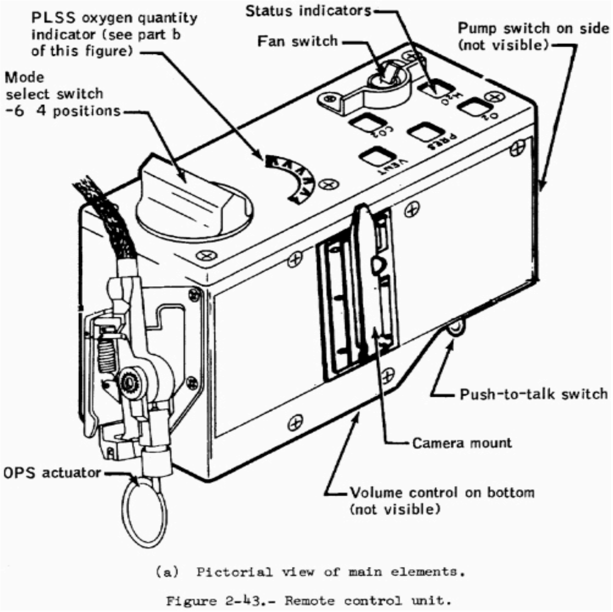


Figure 4. Sketch of the CDU with component breakdown [5].

Although the CDU represented a major advancement in EVA display technology, several limitations constrained its effectiveness. The numeric keypad and minimal button set made interaction non-intuitive by modern human-factors standards and required extensive pre-mission training. Its chest placement, combined with the rigidity of the Apollo A7L suit, at times restricted visibility and manual access, particularly during awkward body orientations. Moreover, the limited computational capability of the period restricted the fidelity, adaptability, and responsiveness of displayed information [5].

These constraints informed the development of subsequent generations of spacesuit interfaces, influencing the more modular, ergonomic, and digitally integrated systems later introduced in the Space Shuttle EMU and Artemis xEMU programs.

IV. Space Shuttle Spacesuit and EMU

The Space Shuttle Extravehicular Mobility Unit (EMU), depicted in Figure 5, represented a major advancement over previous EVA garments, functioning not merely as protective clothing but as a self-contained, single-crew spacecraft. Designed to provide complete life-support functionality for astronauts during EVAs while preserving mobility, the EMU integrated full life-support capabilities, including pressure regulation, thermal control, micrometeoroid protection, oxygen supply, carbon dioxide removal, water cooling, waste management, and robust communication systems (Figure 6) [6]. Its helmet assembly featured a pressure bubble with a neck disconnect ring, a ventilation distribution pad, and multiple visors—including a metallic-gold sun-filtering visor, a clear impact-protective visor, adjustable blinders, optional headlamps, and a TV camera transmitter—enabling reliable EVA operations throughout the Shuttle program [6].

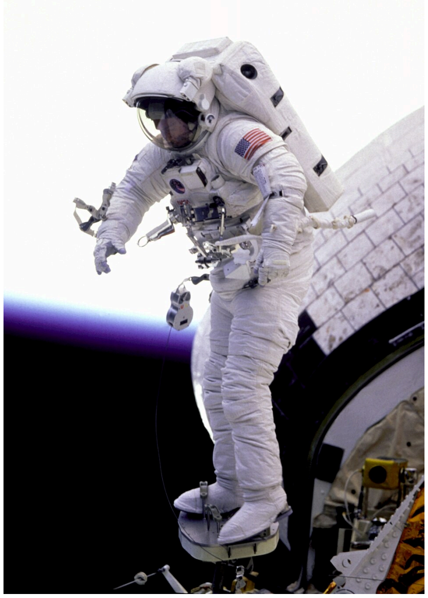


Figure 5. Astronaut performing an EVA while wearing the Space Shuttle spacesuit and attached to the EMU [7].

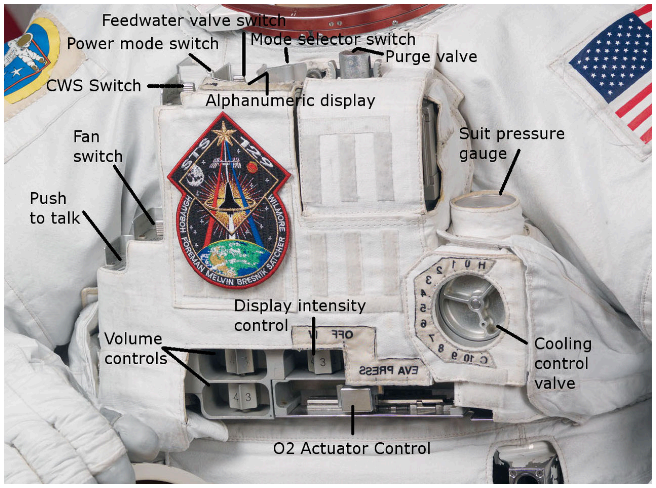


Figure 6. Control Module of a Space Shuttle EMU showing switches, display, and life-support controls [7].

Although state-of-the-art in the 1980s, the EMU imposed several human-factors and display-integration challenges that informed later suit development. Astronauts were required to manage multiple controls and readouts located across the suit and life-support backpack, increasing cognitive load and task-switching demands during complex EVAs. The helmet design also imposed constraints: the fixed bubble limited peripheral visibility, and the visor geometry restricted situational awareness during fine manipulation tasks or operations requiring unusual body orientations. These limitations reflected the technological constraints of the era, driven by the need to balance safety, life-support integration, and manufacturability.

Subsequent generations of EVA suits have sought to reduce these constraints by improving helmet optics, expanding the field of view, and exploring integrated display systems. The HUD concepts developed in this study build upon these lessons by prioritizing ergonomics, intuitive task management, improved user–system communication, and real-time visual support during EVAs. Our designs aim to address longstanding EMU interface limitations by embedding mission-critical and contextual information directly within the astronaut's natural field of view, reducing reliance on distributed controls and enhancing operational effectiveness [6].

V. Artemis Mission Spacesuit

The latest generation of spacesuits is being developed for the Artemis mission (Figure 7) [8]. These suits build on prior mission designs and incorporate state-of-the-art technologies, including an advanced HUD. Because the Artemis suit represents the forefront of current spacesuit engineering, several of its design principles informed the development of our own display system. The primary interface is positioned inside the helmet, directly within the astronaut's field of view (FOV). The information presented updates dynamically in response to task demands.

Figure 7. NASA Artemis EVA suit (left) and NASA Artemis lunar module suit (right) [8].

Figure 8 shows a wrist-mounted display from the Artemis prototype, developed at NASA Glenn Research Center in Cleveland. This display provides critical suit metrics—including oxygen reserves, battery state-of-charge, and electrical diagnostic data such as current and voltage across multiple suit subsystems [9].

Primary O2
63 %
04:59
538.6 / 850 psi

Secondary O2
100 %
23:59
3600.0 / 3600 psi

Battery
73 %
07:40
27.6 / 38 amp hr

Water
70 %
06:50
4.9 / 7 lbs

Informatics Carrier Sensors

28V supply voltage	28.00 V
28V supply current	0.50 A
Tool Port supply temp	0 degC
Graphics supply temp	0 degC
5V supply temp	0 degC
FPGA case temp	0 degC
3.3V supply temp	0 degC
Camera supply temp	0 degC
2.5V supply voltage	0.00 V
2.5V supply current	0.00 A
Tool Port supply voltage	0.00 V
Tool Port supply current	0.00 A
12V supply current	0.00 A
3.3V Graphics supply voltage	0.00 V
5V Graphics supply voltage	0.00 V
3.3V supply voltage	0.00 V
3.3V supply current	0.00 A
5V supply voltage	0.00 V
5V supply current	0.00 A
15V Camera supply voltage	0.00 V
15V Camera supply current	0.00 A

Informatics PMAD Sensors

Vehicle voltage	0.00 V
Vehicle current	0.00 A
Battery voltage	0.00 V
Battery current	0.00 A
Suit Bus voltage	0.00 V
Suit Bus current	0.00 A
Glove Heater voltage	0.00 V
Glove Heater current	0.00 A
Suit Light voltage	0.00 V
Suit Light current	0.00 A
Informatics voltage	0.00 V
Informatics current	0.00 A

Metabolic rate 740 BTU/hr

193:15:36:50	UTC Time
02:53:01	EVA Time
Depress4	State
04:59	Time Left
04:59	O2 Left
07:40	BATT Left
06:50	H2O Left
5.94 psi	Suit P
538.6 psi	PO2 P
3600 psi	SO2 P
6.01 psi	FEEDWATER P
59.8 degF	H2O TEMP
26.6 VDC	BATT Voltage
1.03 Amps	BATT Current
26.2 VDC	SCU Voltage
0.99 Amps	SCU Current
5400 mAh	BATT Info Avail
23:59	BATT Info Left
+0.0000 N	Latitude
+0.0000 E	Longitude
0 m ASL	Altitude
0 degrees	Heading

Elapsed Seconds
10381

Figure 8. Screenshot from a NASA Artemis prototype wrist-mounted display [9].

For the helmet, three configurations are under consideration—partially transparent, opaque, and fully transparent—each serving as a platform for integrating the HUD onto the EVA helmet visor (Figures 9, 10, and 11) [10][11][12]. Each configuration offers distinct advantages in visibility, safety, and comfort. A review of the Artemis helmet design emphasized that information layout must be carefully optimized to prevent distraction or information overload. Furthermore, the 13 Principles of Display Design, discussed in Section IX, guided our approach. Key factors included visibility, expected head-movement patterns, minimization of information access time, field of view, and field of regard.

Figure 9. Partially transparent helmet [10].

Figure 10. Opaque helmet [11].

Figure 11. Fully transparent helmet [12]

Taking into account these factors, we selected a fully transparent display for our concept, as it provides essential information while preserving situational awareness and allowing the astronaut to perform mission tasks without visual obstruction.

VI. Functional Requirements for a Martian HUD System

A HUD on a Martian EVA suit integrated into a Martian EVA suit must address the mission-critical demands imposed by Mars' hazardous and unfamiliar surface environment.

1. Situational Awareness: Mars' thin atmosphere and irregular terrain—characterized by boulders, craters, and loose regolith—require continuous environmental monitoring. The HUD should present real-time data on temperature, pressure, radiation exposure, visibility, and dust storm activity to enhance astronaut safety and hazard detection.
2. Navigation and Wayfinding: Surface missions on Mars involve exploration, sampling, and construction tasks that require precise geospatial awareness. The HUD should overlay navigation cues, waypoints, and high-resolution terrain maps to support route planning and efficient surface traverses.
3. Communication Status: Reliable communication with the habitat or orbiting assets is essential during EVA. The HUD should display communication health, channel assignments, and incoming alerts, enabling astronauts to maintain uninterrupted contact with mission control and crew members.
4. Life-Support System Monitoring: Given the reliance on closed-loop life-support systems, the HUD must provide real-time readings of oxygen levels, suit pressure, thermal regulation status, and consumable reserves, enabling timely corrective action if anomalies arise.
5. Health Monitoring: Extended EVA durations and demanding workloads necessitate continuous physiological tracking. The HUD should display vital signs—such as heart rate, respiration rate, and physical exertion indicators—to support health management and early detection of medical concerns.
6. Battery and Power Management: EVA suits depend on finite power reserves for environmental control, communications, and computational systems. The HUD should present detailed power status, projected remaining runtime, and subsystem-level

consumption to support power-aware decision-making.

7. Procedural Guidance and Checklists: To reduce cognitive load and eliminate reliance on physical documentation, the HUD should present context-aware checklists, procedures, and task prompts synchronized with mission workflows.
8. Alerts and Warnings: The system must deliver prioritized visual and auditory alerts for life-support faults, environmental hazards, navigation deviations, and communication outages, ensuring rapid astronaut response during contingency scenarios.
9. Enhanced Productivity: by centralizing mission data, task instructions, and environmental inputs in a single interface, the hud increases operational efficiency and reduces time spent on manual verification and decision-making.

VII. Heads-Up Display Architecture for Martian EVA Operations

Figures 12–16 illustrate our heads-up displays (HUDs). Astronauts can switch between displays using a touchscreen mounted on their spacesuits' arm (Figure 18).

Figure 12 illustrates the Martian surface as observed through the astronaut's visor. A navigation dial in the top-left corner indicates the remaining distance to the Martian ground station. This standard, or "home," view is free of supplemental icons, providing an unobstructed situational perspective. A portion of the arm-mounted touchscreen is shown to demonstrate how the astronaut transitions between the "home" view (highlighted in green) and other display modes. This display directly addresses the task parameter "operating and switching situational displays", allowing astronauts to seamlessly toggle between navigation and task-specific information without compromising situational awareness.

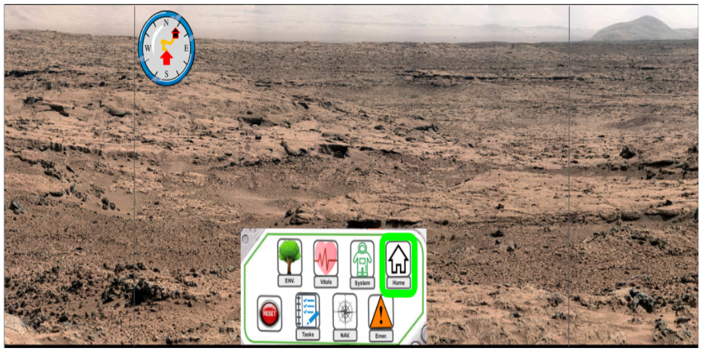


Figure 12. System/Surface display with a navigation dial on an astronaut's spacesuit visor.

Figure 13 depicts the Martian surface from the perspective of an astronaut operating the Mars rover. Key information—including remaining power, estimated traversable distance, weather alerts, and a zoomed-in trajectory—is presented via symbols. A map generated using Java Mission-planning and Analysis for Remote Sensing software is displayed on the touchscreen and depicts the rover's trajectory, enabling astronauts to estimate travel time to their destination. This display addresses the "Navigation and surface traversal" task parameter from our task analysis.

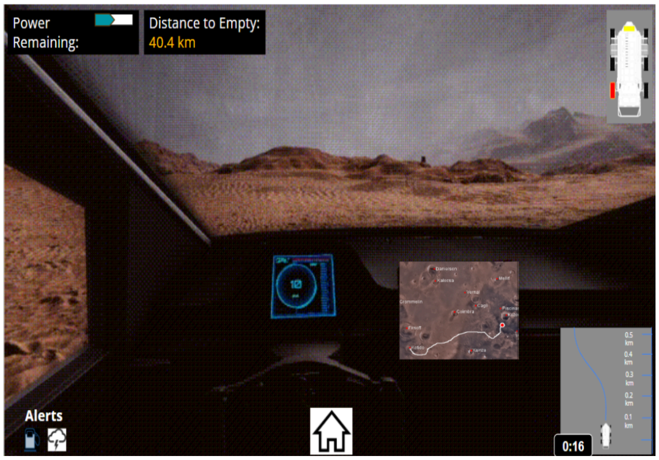


Figure 13. Flight/Driving display showing the rover trajectory map on the touchscreen beside the steering control, along with the forward Martian surface view.

Figure 14 depicts the astronaut's helmet view showing both Suit Status and Surface Status, addressing the task-analysis factors of "monitoring suit status and mission-critical systems" and "monitoring surface conditions." The Suit Status includes oxygen level, suit temperature, remaining power, and available water. Surface Status displays surface temperature, wind speed, current Mars time, and radiation levels. This combination of information addresses the task-analysis parameters “monitoring suit status and mission-critical systems” and “monitoring environmental conditions”, ensuring that astronauts can track both personal safety and situational hazards in real time.

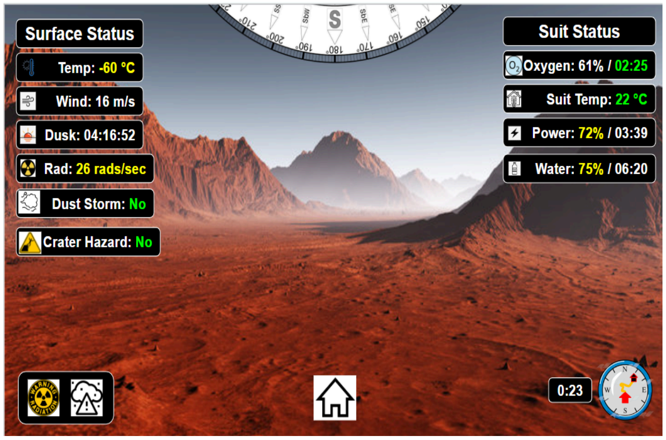


Figure 14. System/Surface display depicting environmental and suit-status information on the Martian terrain..

Figures 15 and 16 show the Task and Emergency displays, respectively. The Task display informs astronauts of upcoming mission tasks, corresponding to the “surface traversal tasks” criterion. In Figure 11, the displayed task instructs drilling a rock with a size A6 drill bit at torque level B and 5 m/s. The display also provides the estimated travel time to the next assignment. The Emergency display alerts the astronaut to hazardous situations, such as an oxygen leak. In this display, a home/hut symbol directs the astronaut to return to base, while the Task display uses a rock symbol to indicate the route to the next task.

Although Mars lacks a magnetic field, the HUD shown in Figures 12, 14, 15, and 16 includes a compass at the top, indicating the geographic North and South poles. This feature provides astronauts with an additional orientation cue while traversing the Martian surface.

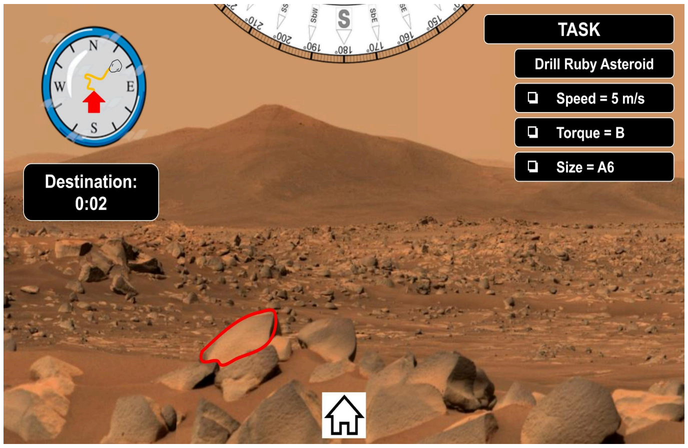


Figure 15. Task display while a task is in progress.

Figure 16. Emergency display depicting an oxygen leak in the spacesuit.

VIII. HUD Interaction Methods

The primary method for interacting with the HUD is voice control, inspired by the Space Shuttle EVA NBL helmet-mounted display. Astronauts can operate the display by issuing verbal commands, similar to digital assistants such as Siri. Voice input offers a key advantage in EVA: it is hands-free, allowing astronauts to perform tasks without diverting their hands from mission-critical operations. However, speech recognition can be prone to errors, particularly in high-stress situations when speech patterns, tone, or speed may vary. While voice-recognition technology continues to improve, backup interaction methods are essential for robust operation in the Martian environment.

The first backup method is a virtual touchscreen (Figure 17), adapted from contemporary virtual-reality

(VR) devices such as the Meta Quest 3 [13]. This system detects finger gestures—tapping to click and holding and moving fingers to drag—allowing astronauts to switch displays, adjust information density, and interact with HUD elements with precision comparable to a computer mouse. Sensors integrated into the astronaut's gloves track these gestures. Although this interface has a modest learning curve, it enables accurate and ergonomic control of the HUD without the need for bulky physical controls, which would be impractical in a Martian EVA.

Figure 17: AI-generated image of an astronaut using a virtual touchscreen interface to plan a navigation route on the Martian surface.

The second backup is a wrist-mounted touchscreen, inspired by the Artemis spacesuit prototype (Figure 18) [14]. This resistive, pressure-sensitive display functions even while wearing gloves, allowing astronauts to navigate menus, switch HUD modes, and adjust displayed information. It provides a familiar, tactile interface that complements voice and gesture input, ensuring operational redundancy under all mission conditions. However, the wrist-mounted display introduces a few drawbacks: it is vulnerable to impact and abrasion during extravehicular activity, it increases sleeve bulk that can snag on structures, and it introduces an additional powered subsystem whose failure or software glitches could distract the astronaut during critical operations.

Figure 18. AI-generated image of a wrist-mounted touchscreen for surface navigation, task management, and emergency alerts.

IX. The 13 Principles of Display Design

In designing the HUD interfaces, we explicitly incorporated the 13 Principles of Display Design [15]. Legibility was ensured through high-contrast white text on a dark background, facilitating readability under variable lighting conditions. Color coding was applied conservatively and consistently: green for nominal conditions (e.g., suit temperature), yellow for cautionary or sub-nominal states, and red for critical faults (e.g., oxygen leakage). To prevent sensory overload and maintain perceptual clarity, we limited the number of colors and fonts, ensuring fewer than seven distinct visual categories.

To avoid top-down expectation errors, information was not presented in hierarchical lists; instead, layouts highlighted task-relevant groupings and logical flow. Discriminability was reinforced through distinct symbols for different parameters. For example, the Task Display features a rock icon paired with a directional dial to represent the route to the next sampling location, while the Emergency Display uses a hut symbol to indicate the need to return immediately to the habitat. Pictorial realism was incorporated using terrain imagery and intuitive icons (e.g., an oxygen cylinder labeled "O_2" and a dust-storm symbol modeled on standard meteorological graphics). Proximity compatibility was achieved by (1) grouping suit-status and surface-status data into separate clusters and (2) positioning the full-scale and zoomed-in maps adjacently in the Driving Display, enabling rapid cross-referencing of navigational information.

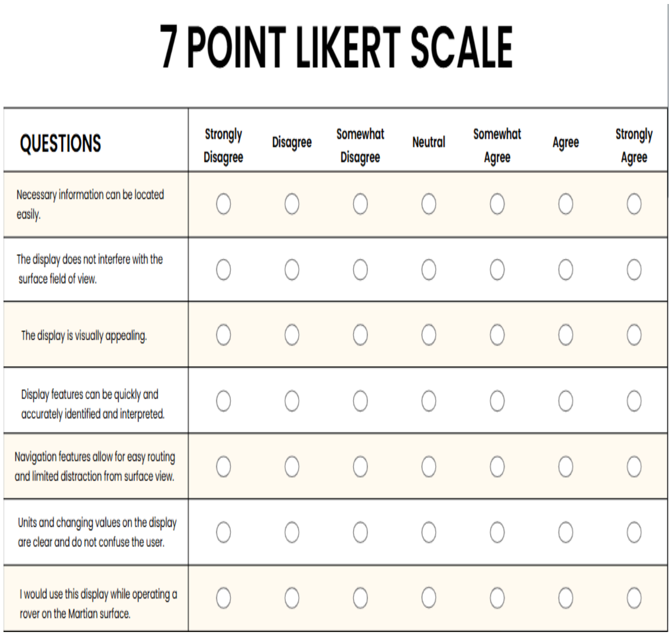
To implement the principle of the moving part, we included a flat-bottomed linear speedometer rather than a circular one, ensuring that increases in speed correspond to intuitive clockwise movement rather than continuous rotation. This principle was also applied to the top-mounted compass and dynamic map, both of which update based on the astronaut's orientation, reinforcing spatial congruence between display motion and physical motion.

Access cost was minimized by placing rarely used tools at the periphery of the FOV, while critical information remained central and unobstructive to the visor's outward visibility. High-salience visual alerts—such as a flashing oxygen-depletion icon on the Emergency Display—were positioned in the lower visual field to ensure rapid detection. Audio alerts supplement key warnings, guaranteeing immediate crew response under high workload conditions.

We also incorporated predictive aiding, allowing the HUD to estimate travel time to a destination or habitat and compare it to remaining oxygen reserves. Consistency in symbol size, typographic style, and spatial layout was maintained to preserve a maximized, uncluttered FOV. Collectively, these measures ensure that the HUD minimizes memory demands and provides astronauts with immediately actionable information aligned with established human-factors principles.

X. HUD Evaluation Methods and Results

We evaluated and refined the HUD designs using a two-stage testing strategy consisting of an initial static assessment followed by a proposed dynamic experiment. The static evaluation employed a 7-point Likert-scale questionnaire to gather user feedback on each display. Four distinct surveys were administered—one each for the Driving, Surface, Task, and Emergency displays. As shown in Figure 19, the first four questions were consistent across all surveys, while the fifth and sixth questions were tailored to display-specific functions. A final question assessed overall preference by asking whether participants would choose to use the display for its intended operational purpose.



7 POINT LIKERT SCALE

QUESTIONS	Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
Necessary information can be located easily.	○	○	○	○	○	○	○
The display does not interfere with the surface field of view.	○	○	○	○	○	○	○
The display is visually appealing.	○	○	○	○	○	○	○
Display features can be quickly and accurately identified and interpreted.	○	○	○	○	○	○	○
Navigation features allow for easy routing and limited distraction from surface view.	○	○	○	○	○	○	○
Units and changing values on the display are clear and do not confuse the user.	○	○	○	○	○	○	○
I would use this display while operating a rover on the Martian surface.	○	○	○	○	○	○	○

Figure 19. The 7-Point Likert Scale for the Driving Display.

Ten participants completed the surveys, and both quantitative and qualitative feedback were analyzed. Quantitatively, the Surface and Task displays received higher ratings than the Driving and Emergency displays. Mean scores for each display, with a neutral response defined as 4, are reported in Table 1. Participants noted that certain navigation elements in the Driving display were visually distracting and that its overall layout was less appealing. In the Emergency display, some users reported that the heavy use of red increased perceived stress. Figure 20 presents average question-level responses across all four displays.

Table 1: Likert Scale averages for each display

	Flight	System	Task	Emergency
Mean	5.36	5.86	5.9	5.73
Standard Dev	1.65	1.22	1.13	1.25

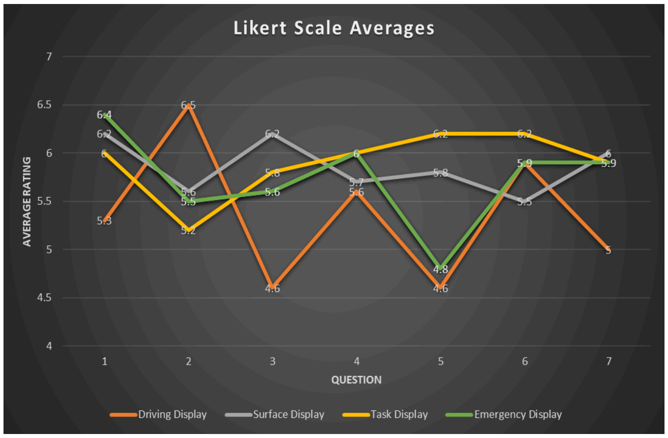


Figure 20. Likert Scale averages for each question and display.

Qualitative feedback yielded several actionable insights. Users found the triangular marker in the Driving display's fuel gauge ambiguous and recommended improved font clarity and contrast for the wrist-mounted controller to enhance legibility. Multiple participants requested wider HUD coverage to achieve a fuller field of view. One participant explicitly commented that red coloration in the Emergency display heightened stress levels.

This feedback informed a revised design iteration, illustrated in Figure 21 (original above, revised below). The updated displays incorporate an improved organizational structure, enhanced proximity compatibility to reduce information access cost, additional on-screen cues to decrease memory demands, and expanded visual coverage to distribute critical information more effectively across the field of view. Collectively, user feedback directly contributed to measurable improvements in legibility, situational awareness, and functional clarity.

Figure 21. System/Surface displays: original version (top) and revised version (bottom).

XI. Discussion and Future Work

Building on the insights gained from our initial static evaluation, we propose a comprehensive dynamic study designed to assess HUD performance under conditions approximating Martian extravehicular activities (EVAs). Given that the HUD is intended to support extraterrestrial navigation and task execution, high-fidelity simulation represents the most appropriate methodology. The proposed experiment would engage more than 50 participants—ideally including individuals with prior EVA or analog-mission experience—immersed in a virtual-reality "Mars exploration" environment incorporating the HUD designs. Participants would complete scripted operational tasks using VR headsets and controllers, while key performance metrics, such as task completion time and error rate, are systematically recorded.

To evaluate robustness under realistic variability, successive trials would introduce controlled perturbations, including environmental changes (e.g., dust opacity, lighting, terrain type), display variations, and simulated control or tool failures. Human-performance factors would be systematically manipulated by adjusting visual, auditory, and somesthetic parameters, including color contrast, luminance, alert volume, and suit-related tactile feedback. Each participant would perform a given task only once to mitigate learning effects and minimize bias.

This experiment aims to determine key usability characteristics and quantify statistical relationships between display conditions and human-performance outcomes. To complement objective performance metrics, participants would complete a Bedford Workload Analysis (Figure 22) to assess perceived cognitive load and a Modified Cooper–Harper Scale (Figure 23) to evaluate operational acceptability. Together, these measures will determine whether HUD designs effectively supports astronaut task execution without imposing excessive cognitive or physical burden, providing actionable insights for development of next-generation Martian EVA interfaces.

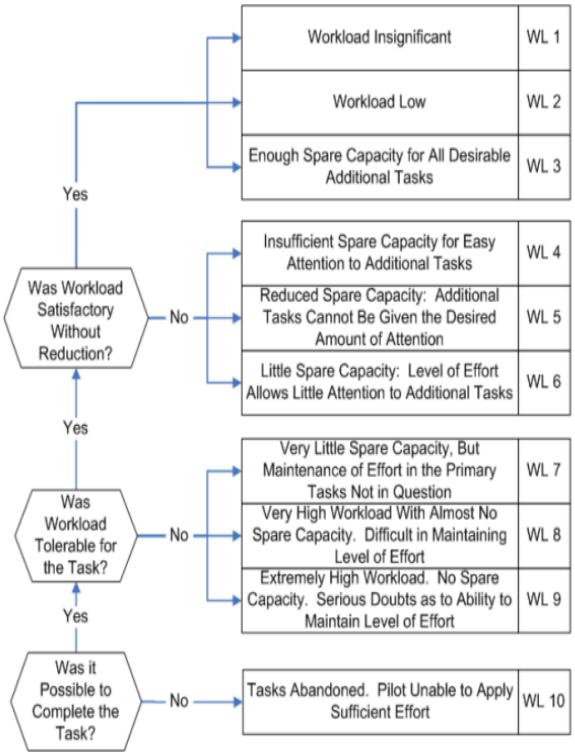


Figure 22. Bedford Workload Analysis Scale [16].

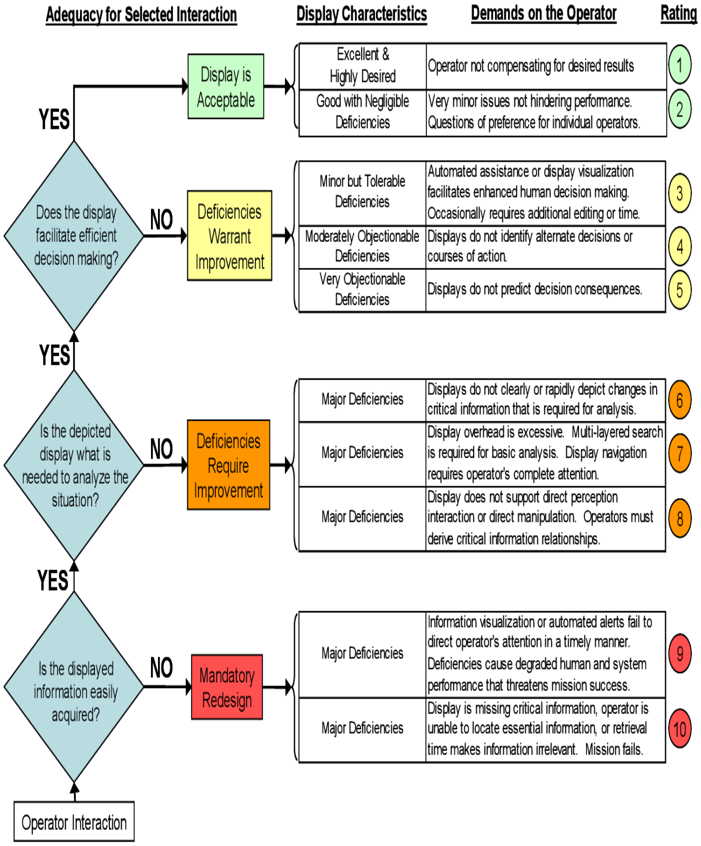


Figure 23. Modified Cooper-Harper Scale elucidating the effectiveness of our display system [17].

XII. Conclusions and Future Work

Throughout the history of human spaceflight, spacesuit display systems have been integral to mission success. Evolving from basic life-preservation interfaces in the early 1960s to multifunctional guidance systems within a decade, helmet-mounted displays have continually expanded operational capability. As mission objectives grow more ambitious and exploration extends to increasingly hazardous environments, next-generation display technologies must adapt accordingly.

In this project, we developed and evaluated four helmet-mounted HUD concepts for Martian EVA operations: Driving, Surface, Task, and Emergency displays. Drawing inspiration from legacy systems used in the Apollo, Space Shuttle, and Artemis programs, these designs address key functional requirements including navigation, environmental monitoring, life-support status, task execution, and emergency response. Initial usability testing (n = 10) produced favorable mean ratings (5.36–5.9 on a

7-point Likert scale) and yielded actionable feedback that informed design improvements. Most notably, it helped enhance fuel-gauge clarity, expand the effective field of view, and adjust color schemes to reduce stress in emergency scenarios.

To strengthen reliability and ecological validity, future work should implement these displays within a high-fidelity VR simulation environment and incorporate comprehensive human-factors evaluations, such as the NASA Task Load Index. Overall, by adhering to the 13 Principles of Display Design within a human-centered design framework, we developed operationally robust HUD concepts that have the potential to support astronaut performance and mission success during Martian surface EVAs.

XIII. References

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