Towards Perceiving the Lunar Environment

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Contents

1 – Broad Objective

With the advance of technology and evolution of mission architecture, the role, purpose, and function of the astronaut is changing. Purpose-built (robotic, teleoperated) systems are increasingly reasonable options for simple orbital and planetary tasks and will continue to grow in exploration capability.

When we return to the Moon in, optimistically, ten years, it will be to a different environment than what was broadcast during Apollo; this time we are informed by the lessons of Apollo and many previous and ongoing automated missions. Lunar systems will be optimized for that environment, allowing the astronauts to spend more time performing science experiments and building infrastructure and less time combating poorly designed equipment[1,2,3]. The integration of information technology throughout every lunar system, including astronauts, will greatly expand the amount and quality of data relayed from assets to the outpost and back to Earth.

Astronauts must be able to integrate fully with these lunar assets and orchestrate their collective function. Near-term, astronauts are infinitely more capable than robotic systems, but robots will continue to grow in complexity and capability, eventually exceeding human dexterity (children of Robonaut)[4]. It is significantly less clear if robots will ever match human cognition, though that debate is certainly a ways off. In the face of technological advancement, the astronaut will transition from the sole performer of all construction and experiment tasks to a supervisor of automated assets, directing and prioritizing tasks and lending a hand where needed[3,5,6,7,8]. The astronaut will become a *perceiver* of systems, identifying conflicts and finding creative solutions, while promoting the safest environment possible.

Current astronauts are severely inhibited by their spacesuits and spacesuit development is primarily focused on reducing the physical limitations of the suit, with little attention paid to increasing astronaut perception. Astronauts need to see and understand both the natural and technological aspects of the lunar environment to orchestrate its fullest function. This goal is accomplishable by applying augmented reality (AR) concepts to spacesuits and extravehicular activities (EVAs). AR is, broadly, the real-time addition of information to the user's world that allows them to better understand and perform in their environment. The present effort identified ways that enable the astronaut to perceive and interact with the lunar surface equipment, augmenting and extending their senses to overcome the severe limitations of the suit[9]. Some of the following ideas could be implemented with current technology and little development, though the most useful ideas exceed current spacesuit technology. It is hoped that the simpler ideas can be included in the Constellation Space Suit System (CSSS) and the longer-term ideas established as a target for hardware development.

2 - General Considerations

The hostility of space is well known and significantly complicates the integration of new technologies. At all times the integrity of the suit must be preserved and all systems must 'fail to safe.' The purpose of the spacesuit is firstly to keep the astronaut alive, and secondly to permit them to do useful, extravehicular work.

Near-Term: Constellation Space Suit System (CSSS)

Primary development for the CSSS and its eventual successor (designed within the next ten years) will almost certainly focus on improving the astronaut's physical dexterity with any information technologies being non-essential add-on modules[10,11]. Near-term systems must be small and easy-to-integrate into the spacesuit, without requiring any suit modification. This limits the physical size and power of systems, and is described in documents such as the Man-Systems Integration Standards[12].

AR is a highly multidisciplinary and emerging field; there is no central AR research community. Some researchers have applied AR techniques to spacesuit prototypes, but these appear to be one-off projects and not an on-going development. Specifically, Di Capua developed both helmet- and head- mounted displays and evaluated the latter in a simple fastening exercise[13]. This exercise was augmented by either text instructions or graphical marks drawn onto the exercise fasteners by way of AR fiducials (graphical markers affixed to real objects). Subjects using the graphical augmentation were consistently slower than those using text instructions, but this result is likely a combination of hardware limitations (lag in the AR fiducial registration), the simplicity of the fastening task, and the omission of thorough training with the AR interface. Boucher, et. al. tested a glasses-mounted display and noted "promising" performance, but did not provide any quantitative testing or extended discussion[14].

CSSS engineers at the John H. Glenn Research Center are developing a see-through, helmet-mounted, grayscale monocle with >640x480 resolution[15] that is capable of displaying indicators, graphics, and video[11]. The current design positions the display to the lower right of the line-of-sight, requiring the astronaut to turn their head right and down to use the display.

There are, to the extent of the author's knowledge, no plans to integrate an input device into the spacesuit, leading to the expectation that the display will be sent data over the radio at the verbal request of the astronaut. Greater use of aural indicators is not currently planned in the CSSS development, but they would seem to be a simple method for interfacing to the astronaut. A voice-controlled system is possible (via radio), though this is not being developed or integrated into the CSSS. Of course, there are other methods for displaying information to the astronaut (including tactile, temperature, pressure, etc.), but most of these would require excessive suit modification or increase the complexity of the don-doff process[10]. See pg. 27, Human-Computer Interface Summary, for further discussion.

Long-Term: Lunar Suit Two

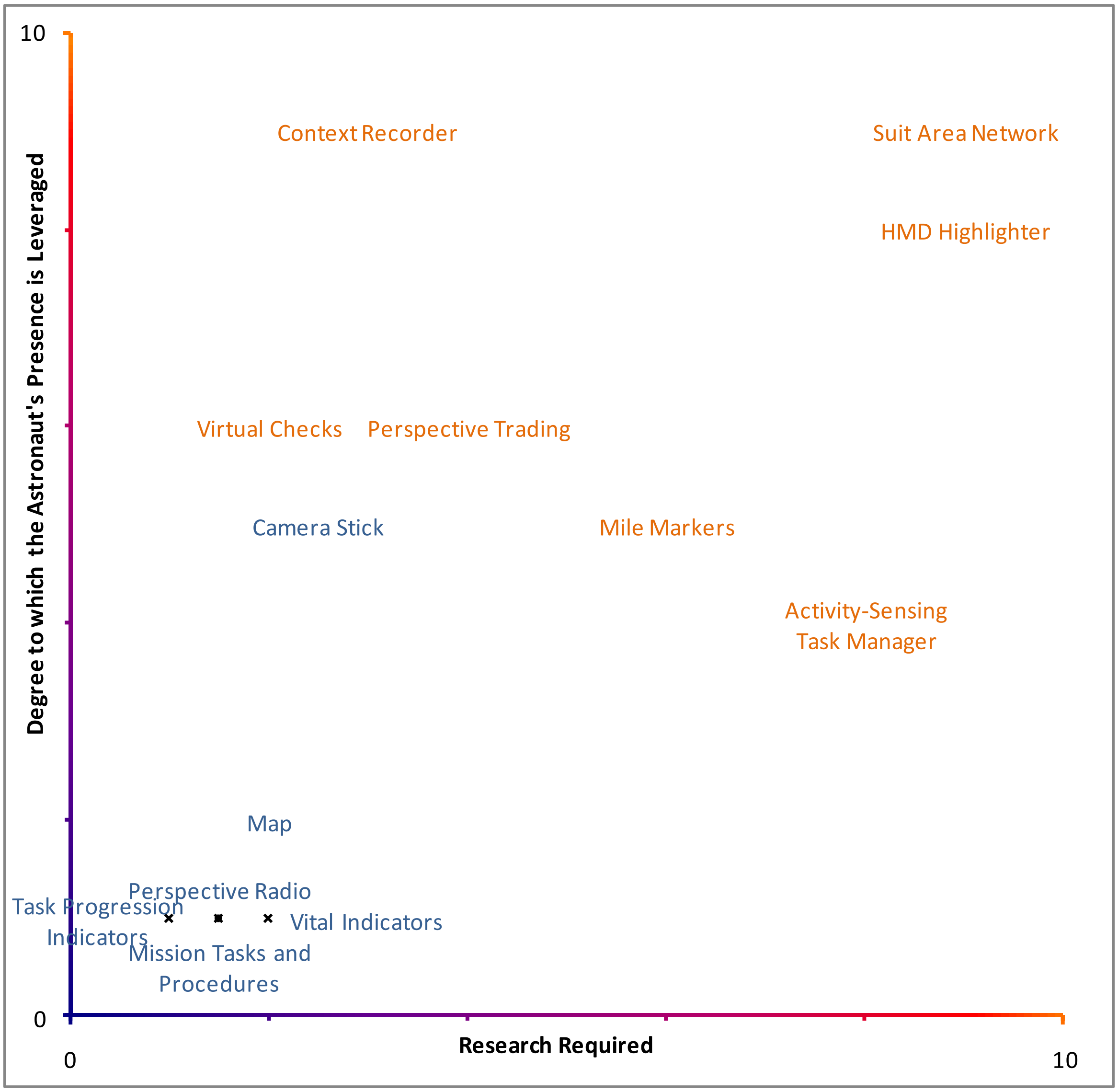
Spacesuits designed after returning to the Moon will surely include mobility and dust management improvements, but a significant focus should be on improving astronaut perception and integration with lunar assets[11,16]. It can be expected that in the intervening years new Human-Computer Interface (HCI) paradigms will be tested, ideally utilizing multiple senses and non-conventional input devices, and that the astronaut will have a significant HCI capability. Since this second lunar suit design is a number of years off (~15), advances in computing technology can be anticipated that will permit greater in-suit processing and enable the display of mixed audio/visual data. Critically, a color, full field-of-view display is expected to be thoroughly integrated with the communication, interface, processing, and other suit and near-astronaut systems.

Figures of Merit

Many factors determine the net usefulness of the following ideas, but two broad measures will aid comparison: whether the idea makes current tasks more efficient or allows new capabilities that leverage the astronaut's presence[4,11,16], and the magnitude of research required for flight. To rate the degree to which the astronaut's lunar presence is leveraged, current tasks are given 1s while the most useful, new capabilities are given 10s. The research rating ranges from 1-10, with a 1 approximately equating to TRL-6, requiring advanced testing in space for full flight-readiness, and a 10 for requiring fundamental research. These two measures collect many other considerations and provide a first-pass, qualitative comparison.

3 – Idea Plot

This graphic briefly summarizes the research cost and benefits of the following ideas:



Concepts applicable to the CSSS are in blue, and Lunar Suit 2 in orange.

4 – Ideas for CSSS:

The following ideas are developed considering the limitations of current technology and those systems that are being developed for the CSSS. Specifically, a helmet-mounted, monochrome display positioned to the lower right of the horizontal line of sight is expected, as well as the ability to push data to the suit via radio communication for display. These ideas would be benefitted if the astronaut had a local interface to the helmet mounted display (HMD), but if this is not present the astronaut will need to request display updates over the radio, whereupon a crewmember will send new data to the HMD[10].

Vital Indicators

The central idea is to take the current Display and Control Module (DCM) displays and present the same data on the HMD in a more readable and easily seen format[15]. Whereas the current DCM consists of a twelve character, alphanumeric LCD display[17], the HMD, as planned, can use simple symbols and numbers to provide vital data due to its superior resolution. As expendables deplete, the indicators can grow in size and eventually crowd out other task-related items on the display so that the astronaut must take action[18]. The astronaut should be able to choose the indicator behavior in the most severe condition[18,19,20].

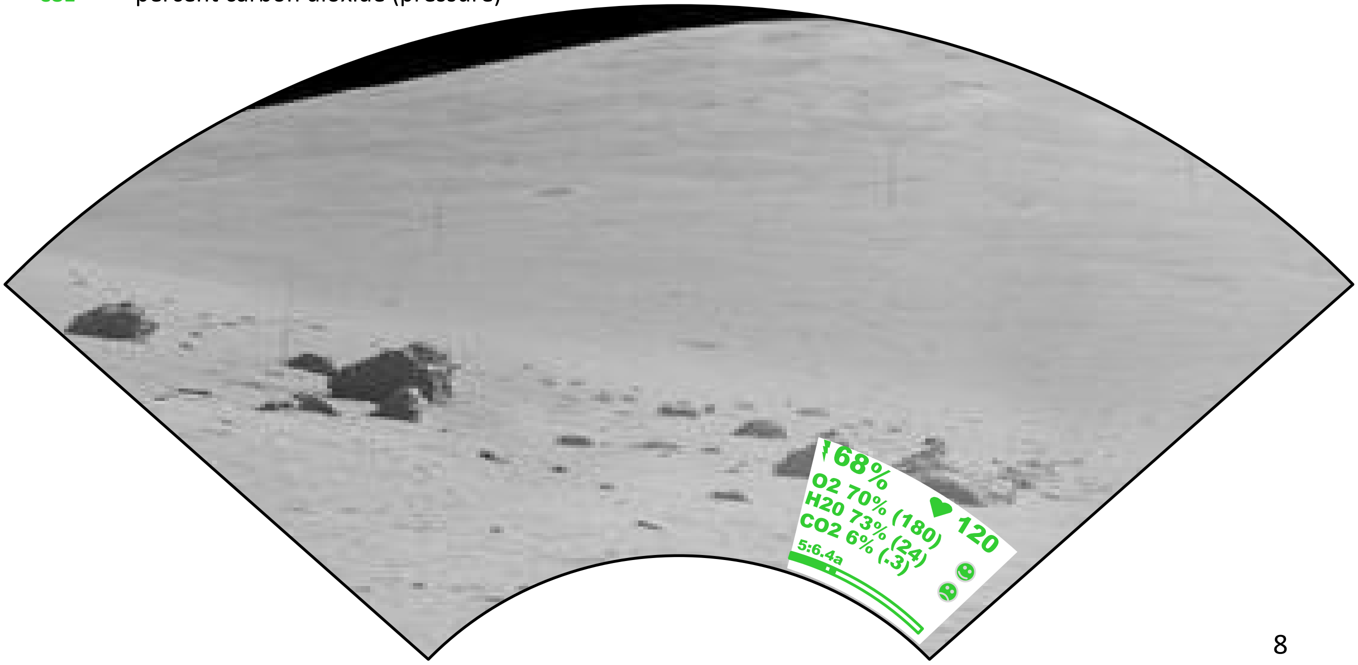
For the majority of the spacewalk vital indicator status is not needed, but should be available on a call-up basis[18,21]. The DCM selector switch could be used to call-up this information or the display could cycle through indicators if display space is at a premium. In the near-term a HMD-based system will not replace a dedicated DCM-like device, but the eventual goal is to replace the system status display and electronics to free up more of the astronaut's hand box[10].

Subject to computing resources in the DCM, it would be useful to display resource consumption trends and project those consumption patterns through the end of the spacewalk[20]. Additional displays are possible though they require more advanced and integrated systems; they will be covered in Vital Indicators for Lunar Suit 2, pg. 14.

Replicating the status of suit systems requires very little additional capability beyond creating the display (suit data are currently transmitted to mission control and could be echoed back to the suit display). This is one of the stated objectives for the CSSS effort, meriting a research rating of 2 and a novelty of 1[15].

Sample Conception (seen from astronaut's perspective):

⚡	charge remaining
♥	metabolic rate
O2	percent oxygen remaining (pressure)
H2O	percent cooling water remaining (pressure)
CO2	percent carbon dioxide (pressure)
☻	fellow spacewalker status indicator
5:6.4a	current task number, total EVA progression indicator with the break representing that the EVA is ahead of schedule (below)



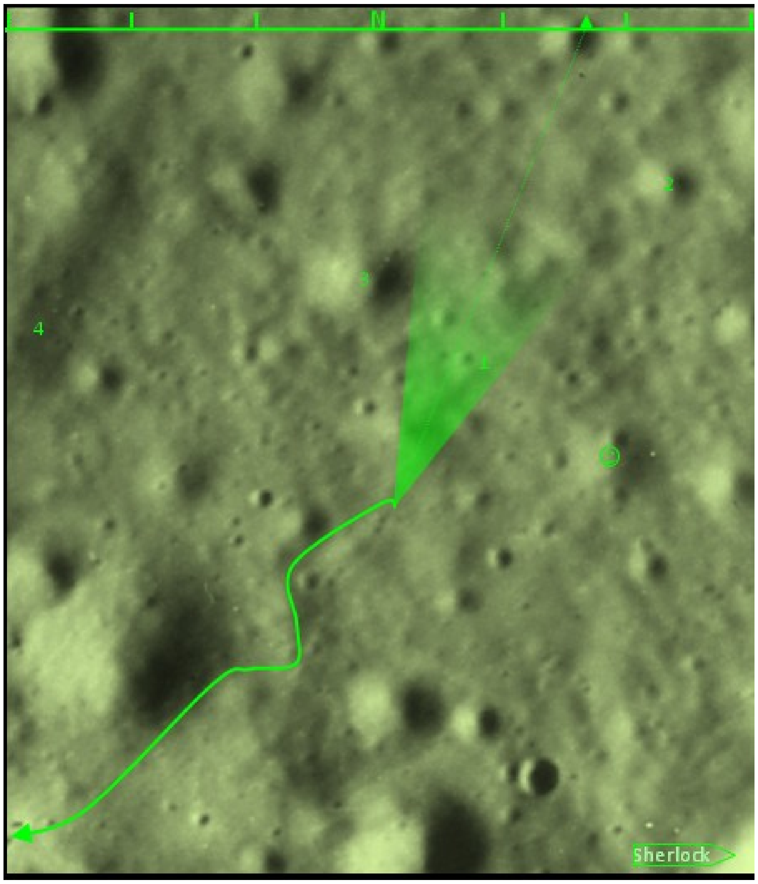
Map

The Moon is devoid of natural, familiar objects and landmarks which humans normally use to navigate. Without these familiar references astronauts will have difficulty accurately measuring their progress and may get confused or lost on extended sojourns. It is therefore assumed that the astronaut will have some position-finding system, either relying on strategically-placed beacons or orbiting assets, with which the HMD can integrate[15]. The preferred presentation is a 2D map which rotates according to the astronaut's current orientation and displays the route to the next task (similar to reference [22]). The map should be able to be zoomed and panned under the control of the astronaut (though it could also be remotely operated for the astronaut).

This dynamic map display is common to many first-person-shooter video games and should include markers for worksites and objects needed in the mission, as well as the path to the closest safe haven, should something go wrong during the EVA[11]. During survey missions, previously visited areas could be denoted on the map to ensure uniform sampling. It is anticipated that astronauts will name objects of interest as opposed to exact, global coordinates, as seen in the Apollo, Phoenix, MER, and Pathfinder missions[5,23]. The map should be able to integrate this data, updating as new objects are encountered and named (it may also suggest a new name based on the surrounding names should the astronaut's fairytale recollection falter).

Displaying location information is another basic goal of the CSSS, but as conceived here it will require research to combine the positional information, task information, and map database, a 2. This conception does improve the astronaut's mental map of their surroundings, also a 2.

Sample conception, as would be seen in the CSSS HMD:



1-4	denote locations for EVA tasks
☺	locates a fellow spacewalker; smiley face indicates they are on-task
▼	gradient wedge shows the current field of view and
▲	indicates the heading
ϟ	shows the quickest and safest route to safety
Sherloc	shows a named feature for named referencing

Mission Tasks & Procedures

Every effort will be made to ensure that EVAs occur in well-characterized environments with definite procedures and goals. However, as we transition from short orbital assembly missions to daily EVA treks on multi-month missions, astronauts will not be able to infinitely rehearse and perfect every task [2,9,11,18]. To improve EVA efficiency and precision, today's printed cuff checklist needs to be replaced with a dynamic mission task display[15,18]. This module will display mixed data (text, images, and video) to help the astronaut through every task, providing varying levels of assistance (terse acronyms < descriptions < images < video of simulated procedure) to ensure proper task completion[1]. The astronaut should be able to request more or less assistance through either a suit-HMD interface or over the radio to an EVA monitor who can push new data to the task list[6].

When problems arise, the task list should be updated with fault-finding and -resolution information to guide the astronaut through the decision tree towards the best solution. The astronaut should also be able to call up an overview of the contingency so that he/she can verify that the prescribed tasks are appropriate for the observed failure and will likely solve the problem.

It should be trivially easy for the astronaut to move to the next task, either locally by a quick facial or vocal action or remotely by the action of a crewmember monitoring the EVA. Depending on suit resources, the primary task tree may be local, but additional data will likely need to be pulled from a rover, habitat, or Earth repository.

This concept is pretty simple and only helps the astronaut perform current procedures more quickly, meriting a novelty of 1. Some research will be needed to determine the best way to present mixed data to the astronaut, though hyperlinked web pages are a good model, a 1.5 research rating.

Task Progression Indicators

Closely related to the Mission Tasks & Procedures is the concept of Task Progression Indicators. These are depicted as happy or sad faces in the monochrome monocle display, representing if fellow spacewalkers or related assets are proceeding according to plan or have encountered some difficulty. Much of the chatter during a spacewalk is simple status-keeping; here, the indicator remains ‘happy’ when tasks are completed in their allotted time (derived from training times) but changes into a frown (with a diagonal bar for improved visibility) if the allotted time has been significantly exceeded. This allows the beleaguered astronaut to focus on the task without having to answer questions as to his or her status while communicating that information to fellow spacewalkers and mission managers. Since spacewalks will rarely require more than three spacewalkers[18], the placement of the symbols in the display would correspond to which spacewalker is represented.

This indicator will likely take inputs from each astronaut’s task list to determine which the appropriate indicator and add that information to updates to the Map and Vital Indicators displays; leading to research and novelty ratings of 1.

Perspective Radio

A recurring theme in the literature and first-hand interviews is the diminished ability of astronauts to keep track of their location and the relative positions of fellow astronauts, their vehicle, other assets, and the habitat[6]. One simple improvement to keep the astronaut's mental map up-to-date is to combine position data with the communication system, so that communications sound like they come from the speaker's position. One can envision EVA astronauts and the habitat sounding in-plane while messages from Earth or orbiting assets appear omnidirectional.

While no EVA research projects are currently looking into this, it should be a relatively simple fusion of stereo technology with position data. Field testing is surely required to quantify any improvement to the astronaut's mental map, but the potential is apparent. It is especially important to consider how information is presented in order to minimize the amount of content that is presented visually. It is possible that some functions of the map display can be supplanted by this perspective radio, with the visual map being used only when exact location information is needed[9].

This prospect is simple and untested, leading to a research rating of 1.5 and 1 for novelty.

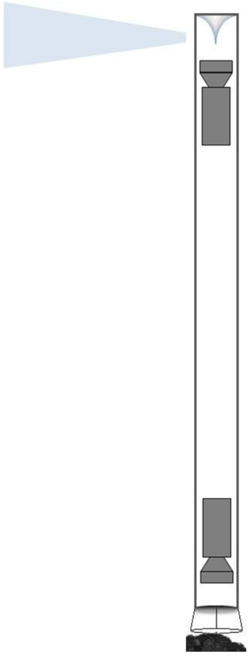
Camera Staff

One of the primary motivations for lunar exploration is to determine how the solar system formed, a task at which planetary geology contributes enormously. Field geology involves the study of both the dispersion and composition of various types of rocks, and one of the field geologist's most useful tools is a handheld magnifier[21]. Since the suit significantly prevents astronauts from picking up and inspecting rocks, a staff-like magnifier is proposed, containing a macro camera whose feed is wirelessly transmitted to the HMD[7,10]. While the astronaut's display will be monochrome in the near future, the staff should be able to capture high resolution, full color images or video, annotating them with time and location information for each acquisition[24]. The astronaut should also be able to record voice notes and link them to each acquisition 'package.' Recording several images (or video) may mitigate small movements of the staff during imaging. A simple wire cage could ensure proper focus distance while a ring of LEDs illuminate the sample. Sampling several sites would allow large-scale geological features to be discovered with a more thorough analysis of each image occurring at the habitat and Earth.

Opposite the macro imager would be a 360° field of view (FOV) camera to record the terrain surrounding the rock under investigation. This should provide some sense of local geological patterns, showing, for example, that this rock is one of small band of similarly sized and colored rocks deposited on a crater wall[21]. This would bridge the gap between orbital reconnaissance photos (with meter resolution) and close-up images of the rock (with micrometer resolution).

Like the macro imager, this element would also provide a video feed to the astronaut's display, saving higher resolution, color panoramas internally. The staff will be around a meter in length for ease in handling and should be stowed on the astronaut's Portable Life Support System or the rover. If stored upright, the FOV camera could continuously stream the astronaut's surroundings to the habitat as they transit to work sites; it would also allow astronauts to see their surroundings and avoid any inadvertent contact.

As envisioned for CSSS, the Camera Staff would be developed independently of the suit with coordination required only for the display of video and images and annotation of acquisitions by over the radio. This imaging system will require a moderate amount of research to ensure operation in the lunar environment, but should integrate relatively easily with the CSSS display system, a 2.5. This idea will benefit the astronaut by allowing them to see and record the environment, but it will be a significant benefit to Earth-based mission managers and science teams by allowing them to more fully comprehend the lunar environment and, thus, better direct the EVA. This idea moderately leverages the astronaut's presence, a 5.



5 – Ideas for Lunar Suit 2

This suit will build upon the Constellation spacesuit by incorporating lessons learned from the first return-to-the-Moon missions. The CSSS will get us to the Moon, building the outpost, and performing simple science. Once established on the Moon, a suit designed for both astronaut survival and productivity will be essential to conducting advanced assembly and science missions. These EVAs will be more frequent, spontaneous, and longer lasting than initial CSSS missions. They will often have a degree of task uncertainty and success will hinge on the astronaut correctly perceiving the situation and choosing an appropriate action; information access and collaboration with the habitat will be essential[11,25]. Seamless integration with and command of lunar systems is envisioned[18]. The following ideas explore what is possible when the astronaut has a substantial human-computer interface (HCI) and a full field-of-view (FOV) display; technologies potentially providing this HCI are discussed in Human-Computer Interface Technology Summary, beginning on page 27.

Vital Indicators

As before, vital suit parameters will be displayed at the astronaut's request or if nearing resource depletion. With a full-FOV, color display the symbolic indicators can change color with resource level, with actual values shown on request. The indicators could be continuously displayed at the far periphery of the suit, such that an intentioned effort is required to see them and to avoid cognitive tunneling[22,26], and incrementally moved towards the center of the FOV with resource severity. Additionally, tactile stimuli could provide a non-visual indicator that attention is required.

Sudden events should be indicated with an aural alarm which is clearly distinguishable from standard EVA operation sounds. Greater computing power is presumed, allowing alarms to be customized for each event and delivered by computerized voice. The astronaut will be told exactly what is wrong and reminded of the appropriate fault resolution steps.

While this conception is more advanced than the CSSS Vital Indicators, the essential idea is the same and a separate rating is not required.

Dynamic Map

In addition to being larger and in color, the map display will convey more information about the astronaut's surroundings than the CSSS map mentioned previously. It is again envisioned to be a two dimensional lunar surface projection with selectable levels of annotation, including geological sites, equipment locations, robotic assets, and the primary route to safety. Selecting an annotation should call up additional information about its purpose, current status, any services it can provide the astronaut, and related items. For controllable assets, this option should be apparent. The astronaut should be able to add/edit annotations and choose map orientation, either rotating the map to match the astronaut's perspective or having a static map projection with a rotating astronaut indicator to matches the current orientation. On request, topographic, resource concentration, and other data should be presented in a fully pan- and zoom-able way.

These improvements rely on a substantial human interface, and all computing, information consultation, and asset control functions are expected to be performed in-suit and independently of habitat and rover support. A limited amount of task-specific information will be stored locally in case communication is lost with rover or habitat databases.

Lunar Suit 2 allows for many improvements to the Dynamic Map display, but the basic idea is the same and a separate rating is not necessary.

Mile Markers

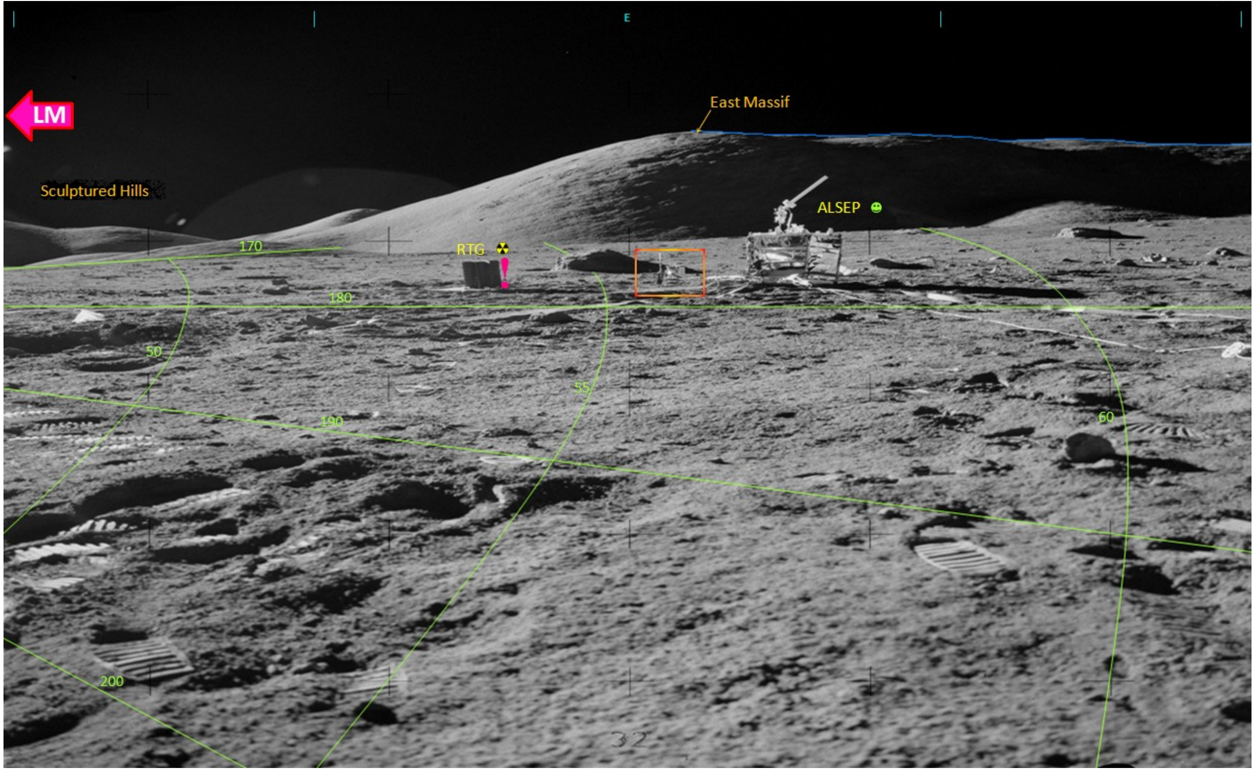
As mentioned before, the Apollo astronauts had difficulty estimating their progress across the lunar surface due to the absence of familiar landmarks. While it may be possible for astronauts to become accustomed to lunar sizes, shapes, and distance scales, it is relatively simple, in the context of the other capabilities expected for Lunar Suit 2, to create 'mile markers' in the helmet display. Specifically envisioned are regular lines or symbols appearing on the lunar surface at regular intervals to indicate distance traveled and current orientation, referenced to the rover or habitat. It is hypothesized, though not tested in the literature, that this sort of a regular indicator will help the astronaut keep their mental map up-to-date and require fewer attention-shifting checks of the Dynamic Map[11,13].

While the two-dimensional, top-down view envisioned in Dynamic Map has many uses, the selective inclusion of information in the astronaut's perspective view will reduce the need to divert attention to the map display[22]. In combination with the positioning system, object and terrain recognition will allow the suit to recall relevant status information on the astronaut's surroundings and naturally present that information to the astronaut[6]. As the following example shows, the astronaut will see the physical object and its operational status at the same instant, through a common set of indicators and information display conventions.

This concept will require a moderate amount of research, 6, and significantly improves the astronaut's perception of their local environment, 5.

Sample conception; actual display would cover the astronaut's entire FOV:

⬅	path to safety, the Lunar Module (LM) in this case	□	next task item
┼	'mile markers' in radial coordinates; origin is the LM	ALSEP	object name, can be selected for more info.
East Massif	recognized terrain	!☢	danger (Radioisotope Thermal Generator)
~	terrain contour hidden from view	☺	system is functioning



Activity-Sensing Task Manager

By this point in the return to the Moon, EVAs will likely not be planned or practiced on the Earth, but developed while the astronaut is on the Moon[24]. The astronauts will have extensively practiced small procedures common to multiple missions prior to launch and will need only be told which procedures are required for each task[2].

There will also be an increasing amount of hardware on the Moon which must be monitored and serviced, but whose exact configuration may not be known. As the astronauts roam the surface, their task manager should query nearby devices and the habitat database to check if any work needs to be done while the astronaut is near, subject to the astronaut's current mission[7,11].

These concerns require a flexible task manger that can be automatically or manually modified during the EVA[11]. This system will be similar to an astronaut's secretary, keeping them on-task, making simple, rule-based decisions for task scheduling, and providing requested, relevant, or recently updated information during the procedure. Clancey analyzed the Apollo transcripts and realized that the Capsule Communicator (CapCom) "…was virtually a third person on the moon…advising nearly every step in deploying equipment, navigating, scheduling, regulating life support, logging data, and interpreting observations"[9]. Significantly automating the CapCom information interface will yield economic savings in lunar ground support requirements[21] and be required for Mars missions, due to the communication delay.

Lunar Suit 2 systems will be highly integrated so that the task manager may add, for example, a spacesuit status check or five-minute break to the mission-specific tasks. Equally, the dynamic map would be updated, so that each task's location is shown along with the quickest way to move between the tasks.

Though a human-computer interface is presumed for Lunar Suit 2, the task list could be updated autonomously by the suit computer and passively by fellow astronauts or habitat crew, without requiring directed effort by the astronaut. As compared to the CSSS version, the advanced lunar suit considered here may include sensors in the arms, hands, and legs that determine what the astronaut is currently working on by way of stored activity profiles[27]. When the activity profile stops, the task list would automatically advance to the next item. These profiles would be recorded during Earth training but would likely need to be modified to account for the lack of gravity, pressurized suit environment, and relative exterior vacuum. These issues need to be investigated and characterized, but the addition of activity sensing to the task list may allow the astronauts to work naturally, spending more time on the task and less on keeping mission management systems up-to-date.

As before, all of these functions must be highly customizable and controllable by the astronaut such that their focus remains on the mission, not on combating automated systems.

The addition of activity profiles and automation of the task manager (up to and including the mobile agents concept[9]) is a significant addition to the spacesuit's task management capability. A significant amount of research is required to evaluate and integrate activity sensing into the suit, an 8, for a moderate improvement in EVA efficiency, a 4.

Task Progression Indicators

As alluded to previously, many of the mundane mission management tasks will be automated in a system that has previously been termed mobile agents[5]. This system will provide more information to the task progression indicators whose display will utilize the graphical capabilities of the HMD. As before, the happy/frown face indicates whether the astronaut is completing the current task with the same efficiency as ground training and the background fill indicates their mission task progression.

As an example, consider two EVA astronauts working to repair a system. One astronaut falls behind schedule and his or her fellow cannot proceed until that they have caught up. The idle astronaut would notice that his or her partner's status indicator has become a red, frowned face and would select that icon to investigate the delay. The delayed astronaut's task manager would reply (unbeknownst to the astronaut, allowing them to continue working), showing that the delayed astronaut has four tasks, three of which are interdependent. The fourth is a simple tool errand, independent of the other tasks, which the idle astronaut requests for him- or herself. The idle astronaut has now found new work without interrupting the delayed astronaut.

While this simple example could likely be automated as part of the mobile agents system, the effect is that the idle astronaut was able to query, reassign, and carry out a new task without interrupting the delayed astronaut's work.

This Lunar Suit 2 version is very similar to the CSSS idea; no separate rating is required.

Context Recorder

The Apollo lunar EVAs had recurring difficulty recording the exact situation and surroundings of the EVA astronaut and relaying that information to mission controllers, whether deploying science packages, traversing, or gathering rock samples. Houston had control of the rover's pan and tilt video camera, but this was no substitute for what the astronauts saw in front of them.

Given the significant science objectives and construction tasks awaiting lunar astronauts, conveying their exact surroundings and situational awareness will be much more important. Apollo 17 was arguably the most scientifically-useful mission because of Harrison Schmitt's trained eye; imagine the additional benefit that would come if he were able to fully record what he was seeing for thorough analysis later in the habitat or back on Earth. The core idea here is to enable the astronaut to capture and annotate whatever they find interesting or peculiar while allowing them to continue on their mission[11, 18,21]. This allows the astronaut to immediately postulate and theorize, to record their thoughts as they occur, instead of interrupting those thoughts to describe the location to the ground[24]. It will also shift the rigorous, in-depth analysis from the in-situ astronaut to teams of geologists back on Earth and substantial improvements to Moon/Earth communication are expected[6,9].

Like the Camera Stick, the Context Recorder will capture both the nearby feature (what the astronaut is looking at) and a panoramic view of the land to locate the local view. This visual will be annotated with voice or text notes by the astronaut and the time and location information will be automatically added by the recorder[24]. This record will also include the status or readings of nearby instruments and any other assets to give the fullest experience of the astronaut's surroundings. NASA's Desert Research and Technologies Studies (D-RATS) field tested a three-dimensional sample imager and a team of geologists (in the D-RATS 'backroom') found the images to be highly useful[28].

The Context Recorder has additional utility in documenting the current status of lunar systems and, potentially automatically, updating the associated documents (CAD, specifications, operating procedures, etc.). This is one part of a larger lunar asset management strategy and is essential for the best use of every pound placed there[6].

Some brief examples:

Lunar ice outcropping:

The Context Recorder would assemble packages from the EVA site, including microscope and landscape pictures, readings from astronaut-deployed sensors, the time, date, temperature, Sun's position, irradiation, local surface inclination, and local seismometer history, and would later incorporate satellite images, spectrographic analyses of ice samples, and any previous studies near that location.

Rock collecting:

A mission package consisting of pre- and post-retrieval images (showing any deposits, etc., that were shepherded by the rock), microscope pictures, three-dimensional imaging, multiple panoramic site images, and any local sensor readings. Scientific analyses performed on samples in the habitat would be added to the package before transmission to Earth.

Machine repair:

Consider the difficulties ISS astronauts had in diagnosing and eventually repairing the ISS Solar Alpha Rotary Joint (SARJ), where it took multiple spacewalks to determine the failure of the trundle assemblies and an additional spacewalk to repair both joints. In the future, images of system disassembly, video of troubled locations under operation synched with the machine's readouts, add-on sensors (vibration, current, etc.), and other system-specific measures will help the astronaut and/or mission managers quickly determine what element has failed.

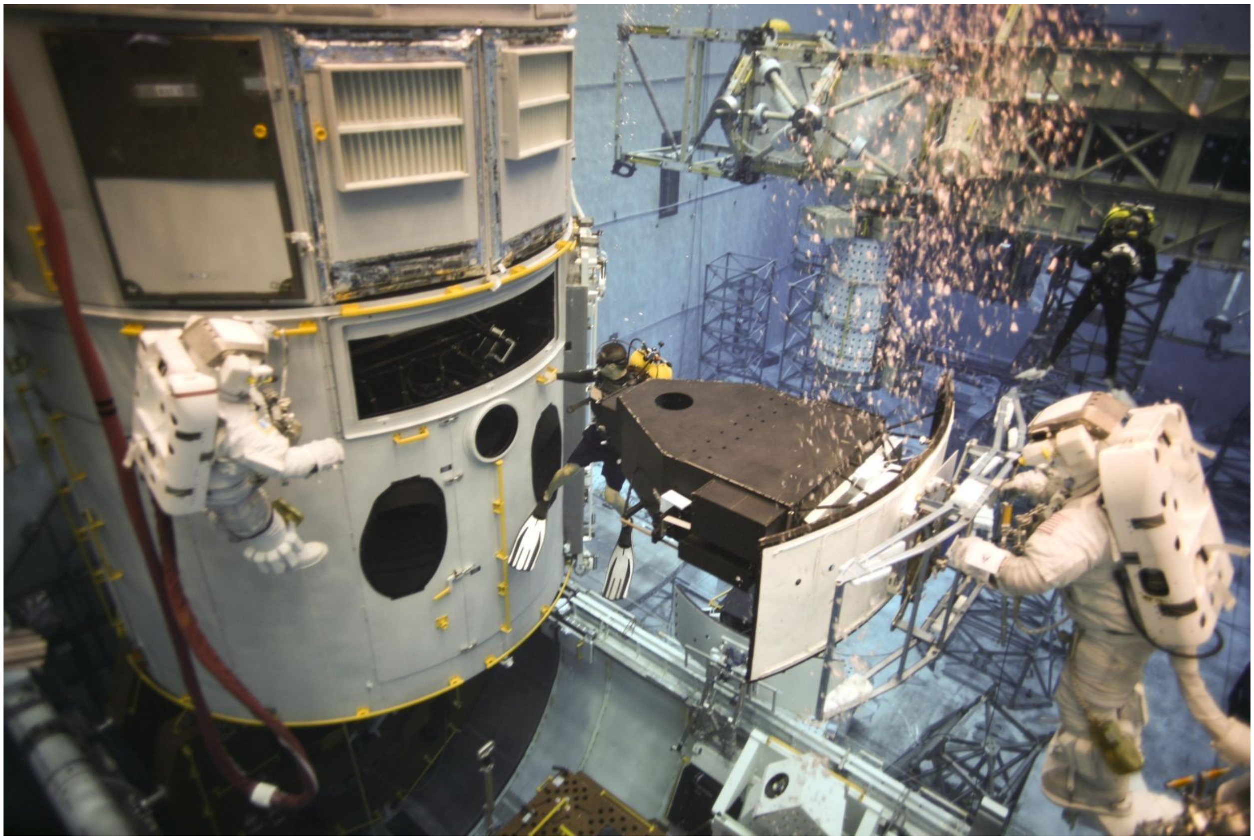
The Context Recorder significantly improves the astronaut's ability to record, transmit, and later recall what they encountered during the EVA. They will be able to reconstruct their thought process as they learned about the system/environment and this will enable them to better prepare for future EVAs; this concept leverages the astronaut's presence in ways not possible today, a 9. The primary difficulty with this proposal is the collection of information from multiple systems, but much of this will be accomplished by the Suit Area Network, leading to a research rating of 3.

Perspective Trading

Once the astronaut's is able to record their surroundings (context), this should be able to be streamed to fellow lunar-walkers, rovers, and the habitat to aid in joint maneuvers[11]. Much as mission control monitors spacewalkers via their helmet cameras, this would provide substantially more information to all actors in a procedure and includes displaying streaming information from deployable cameras and sensors.

One recent example of the utility envisioned is from STS-125, the final Hubble servicing mission. Mission Specialist Andrew Feustel was attached to the end of Columbia's remote manipulator and as he replaced the Wide Field and Planetary Camera 2 with the Wide Field Camera 3 (WFC3), his entire field of view was occupied by WFC3. Fellow spacewalker John Grunsfeld positioned himself on Hubble near the camera bay to guide WFC3 into place and tell Feustel when it was fully inserted. While this arrangement achieved success, Feustel could have been more fully utilized if he were able to view Grusfeld's perspective.

This concept allows astronauts to understand their environment and the effect of their actions, while lowering EVA support and coordination requirements, a leveraging factor of 6. The primary difficulty envisioned is integrating various camera feeds from multiple assets and allowing the astronaut to easily select between these feeds. The communication will be handled by the Suit Area Network, but a research rating of 4 is appropriate to determine how these feeds should be presented to the astronaut.



Spacesuit Area Network (SAN)

Many of the Lunar Suit 2 ideas require or significantly benefit from integration with surrounding systems. In light of the difficulties of physical interconnects, this communication will be wireless[6,11,18,29] and resemble Bluetooth®, Radio Frequency IDentification (RFID), Wireless-Fidelity (Wi-Fi), and related consumer technologies. Several capabilities are enabled by a flexible, short range wireless network:

As alluded to in the description of Lunar Suit 2, the lunar astronaut will transition from a role of physical labor to a perceiver and operator of systems, once the basic infrastructure is established. The ability to command many and varied assets while on EVA is critical[1]. The SAN should integrate with nearby systems (say within 10-15m, useful sight), presenting their various functions and current tasks to the astronaut upon request[7]. The astronaut can then select a particular system and give it a new task (for automated completion) or manually operate it, perhaps negotiating it through particularly delicate task before returning to pre-assigned tasks.

As astronauts interact with various systems, any operational data should be able to be displayed in the astronaut's helmet. There are many motivations for this (notably obviating the need to design a new user interface for every system and instead using a single user interface and the astronaut's helmet), but the present interest is displaying the status of systems in a much more usable way.

Hand tools are essential for every EVA; consider here the oft-used pistol-grip tool (torque wrench) and what improvements can be made to the lunar version[11]. When astronauts use the torque wrench, they set the fastener's rated torque level on the wrench and then torque until exceeding the torque setting, at which point they read out how much torque was applied before release. If insufficient torque was applied, several attempts are made (each requiring the removal of the tool to read the applied torque) before deciding whether to advance to the next torque level. This process is tedious and slow; the astronaut likely spends more time reading the applied torque and returning the tool to the fastener than actually torqueing. To leverage the SAN, the lunar torque wrench will include a low-power transmitter to communicate both the set torque level and currently-applied load. This information would be displayed on the astronaut's HMD, appearing whenever the tool is held. An electronic torque sensing system could be further developed to verify the integrity of the fastener by recording the applied torque and the fastener's response for comparison against standard load curves. The astronaut can now apply precise torques and learn something about the status of the fastener before leaving the worksite (the applied toque level and torqueing curve would be saved for future analysis, if need be, by the Context Recorder, and the Task List would update as soon as the prescribed torque is reached).

Another very simple and useful application of the SAN is to track tool and equipment positions. Each device would have a simple (perhaps RFID-based) transmitter to broadcast its identity when queried. While attached to the astronaut via tether or holster, the tool would be 'checked out' for use. Once the astronaut is finished the tool would be untethered and moved to a tool rack, also supporting a local

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[1] Thorough implementation of Perspective Trading would allow the habitat crew to direct these assets while the EVA astronauts provide good view angles, but this requires participation in the EVA by the habitat crew, who should have other tasks to do. The overriding goal of Lunar Suit 2 is to free the astronaut from dependence on the habitat or Mission Control. Requiring habitat participation in the EVA runs counter to this objective, though both operating modes should be possible.

wireless network. In this way, every tool and reusable piece of equipment can be tracked by its wireless profile to reduce the inventory management and tool-hunting tasks. Object transmitters could be active or passive; if powered they could communicate device status information so that, for example, the number of fully charged pistol grip tools is always known. It is difficult enough to manage the many items required for brief orbital assembly missions; without a rigorous and automated inventory management system the Moon will become littered with misplaced objects.

If the SAN is developed early and found capable of fault-tolerant operation, it becomes an easy way to communicate between various modules on the spacesuit. One of the main difficulties in designing new systems for current spacesuits is the need to use existing connectors and suit pass-throughs while not interrupting or impairing the operation of any current system. If the communication is wireless, these concerns are diminished, allowing suit designers to spend more time designing the mechanical aspects of the suit and less time creating holes for various applications.

As envisioned, the SAN provides a critical service to other suit systems and allows the astronaut to be fully engaged with the lunar environment and lunar systems, a 9 on the leverage scale. A significant amount of research will be required to support the ‘ad-hoc’ networking envisioned and to harden it for lunar operation, a 9.

HMD Highlighter

Between NASA's acronym soup and the emplacement of significant quantities and varieties of hardware on the Moon, lunar astronauts are going to find it difficult to remember the name, function, and related information of systems and their subcomponents. As described in the SAN, nearly every non-expendable item will have a radio marker which will identify module and their functions, but for many repair missions this information will not be sufficient (the lunar rover would have one radio tag, but any number of subsystems could break and need repair).

To improve communication and speed system repair, augmented reality techniques can overlay computer aided design (CAD) information on the astronaut's view to annotate the real world. Thus, as the astronaut opens an interconnect box and requests more information, a perspective camera[2] captures what each eye sees, identifies the subcomponents by comparison with CAD assemblies, and draws annotations on the HMD to provide the requested information. The astronaut's view of the interconnect box is not obstructed by this process, but graphical arrows and text appear to identify which connectors correspond to the failed subsystem. These annotations surround without obstructing components needed for the procedure and they can be selected to display more information[30]. If operational, system status information should be included on these annotations, allowing the astronaut to critique its real time operation and, optionally, compare it to simulations. This application of augmented reality will be of significant use while diagnosing system failures because it allows the astronaut to pull apart complex systems and inspect each subsystem's function virtually, before beginning physical disassembly.

Beyond repair missions, the object recognition and annotation capabilities of the HMD Highlighter will be used to recognize prominent surface features in collaboration with the location-finding system. Some elements of the HMD Highlighter were included in the sample Mile Markers conception on page 16; these include the East Massif & terrain profile, Sculptured Hills, ALSEP & status indicator, and RTG & warnings.

As envisioned, the object recognition component will require significant research while the annotation positioning component will significantly depend on the interface choice; adopting eye gaze tracking will lessen this research requirement. The HMD Highlighter contains the primary information presentation mechanism of Lunar Suit 2 and it improves the astronaut's ability to quickly understand their surroundings and systems they are working on. A research rating of 9 and a leverage rating of 8 summarize the utility of this concept.

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[2] The perspective camera will see what the astronaut sees, the world from their point of view. To avoid placing a camera on the bridge of the user's nose, simultaneous images from multiple (2-3) helmet mounted cameras would be combined with eye tracking to replicate the astronaut's viewpoint without obscuring their sight. To the author's knowledge this has not been tested in the research.

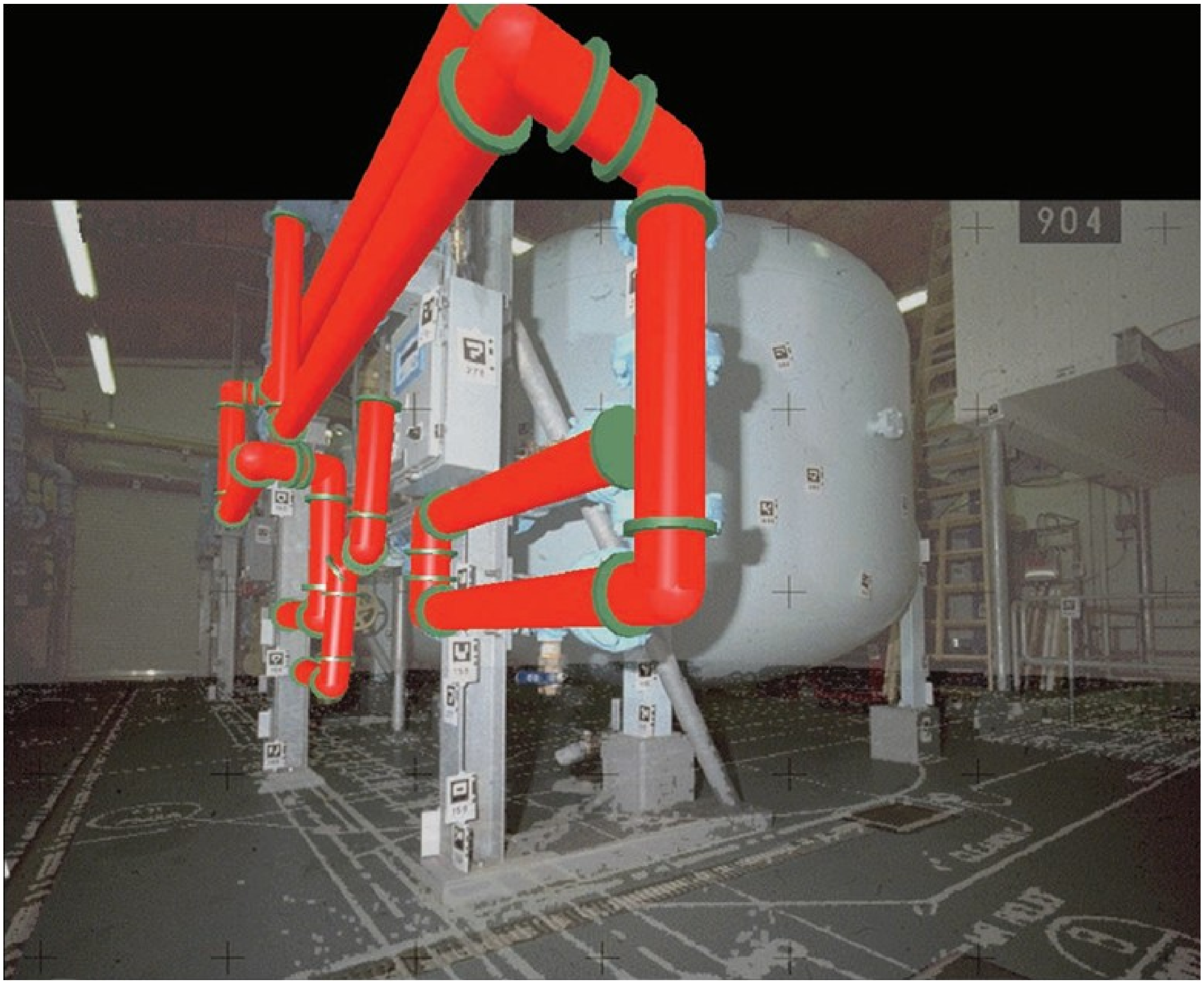
Virtual Checks

The information systems envisioned for Lunar Suit 2 will be able to paint high-resolution graphics onto the astronaut's view of the surface and recognize objects within their field of view. The astronaut should be able to display, manipulate (rotate/pan), and annotate CAD models with the suit's computing resources and interface. With the object recognition system described in HMD Highlighter, these CAD modules could be scaled to match objects near the astronaut, allowing astronauts to practice assembly missions before launch and, during the assembly, verify that the next component will fit.

A similar application of the CAD/scaling system is to aide structure and system positioning before moving begins. As conceived, the EVA astronaut would call up a model of the structure and virtually position it in his or her view of the lunar surface. Once positioned, the astronaut could walk around the model, seeing its perspective change with his or her position, looking for any complications. Systems similar to this have been developed and tested in the literature, see Azuma[19].

This is a comparatively small extension of the HMD Highlighter which warrants a 2 for required research. Through this idea, astronauts will be able to plan, practice, and evaluate future missions; this is a significant capability that will be required for Mars operations, receiving a 5 on the leveraging scale.

Sample conception, showing a proposed pipe location; coutesy Azuma[31]:



Night Simulation

As missions advance in complexity, operating in locations other than the South Pole will become desirable, necessitating a means to operate during the lunar night. A brief search yielded no information on stellar irradiance during the lunar night; it is assumed that some vision aide will be required. This can be accomplished using light amplification techniques (especially if the suit camera's dynamic range is sufficient) or by the integration of simulation.

Light amplifying 'night vision' systems are well established so the simulation concept is developed here. The lunar surface is static on human time-scales and will only be altered by prescribed human actions. Topographic information will be captured autonomously by orbiting assets and relayed to the habitat for stitching into a continuous map[6]. With the previously discussed display, modeling, and location-determination capabilities of Lunar Suit 2 and the static nature of the lunar surface, the astronaut does not necessarily need to see the surface to navigate it. A robust simulation of the surface terrain that is accurately scaled and aligned to the lunar environment (registration) would be indistinguishable from the fully-lit landscape, except for the reduced fidelity of small features. No studies have considered this application and it would likely only enable crude assembly tasks.

This Night Simulation concept is offered as a prospect for additional research and cannot be fully evaluated due to its many, significant unknowns. It is expected that the rover will be able to provide local illumination and may obviate the astronaut's need to see in the dark.

6 – Human-Computer Interface Technology Summary

The complete implementation of the previously mentioned ideas will require the integration of several technologies that allow the astronaut to fully interact with and manipulate information required for the mission[11]. At the same time, the spacesuited astronaut faces many of the same difficulties as quadriplegics when interacting with computer-based systems, since every body movement is resisted by the suit. A new computer input system is needed that does not require hand motion yet approaches the accuracy and speed of the mouse and keyboard combination. Similarly, the display must also approach the resolution and display capabilities of modern L.C.D. monitors and occupy as little space as possible, so that the astronaut is able to see the real world while interacting with the computer system.

Input

The traditional keyboard and mouse paradigm is entirely inappropriate for a spacesuited astronaut and the performance of extravehicular tasks. This requires a rethinking of input devices to allow the astronaut to interact with information while performing a manual task and with minimal additional mental or physical exertion. Considering the mouse and keyboard, mouse actions are highly flexible (due to the graphical user interface), precise, and slow whereas each keyboard key has a specific function whose operation is precise and very fast to the trained user. Thus, specific tasks for which the user knows the exact command are quickly accomplished via the keyboard (*nix command line), while unknown and poorly-recalled tasks are best accomplished graphically with the mouse, where various options and explanations can be presented. The astronaut needs both capabilities to interact with dynamic, graphical information (pictures, maps, and video) and give specific information to systems (system commands and annotations).

Positional Input

Eye gaze tracking (EGT) may lend the astronaut functionality approaching that of the computer mouse and uniquely leverages the graphical nature of the mouse to create a natural interface. The current desire is to directly move a computer cursor in response to eye movements, though future versions could employ three-dimensional focal point tracking to allow the astronaut to operate their graphical interface and also ‘select’ physical objects (rocks, rovers, instruments, etc.) visible in the foreground.

Previous EGT studies determine the user’s gaze by imaging the user’s eye (usually with a commercial or disability focus) or measuring the change in local electrical fields due to eye movement[6,32,33,34,35]. Camera-based methods generally require placing a camera and light source in the user’s field-of-view to illuminate and track each eye’s position. Functionally, these techniques process images of the eye to locate the edge of either the pupil or cornea for comparison to a circle. When the user is looking directly at the camera the pupil/cornea appears as a circle; as they look elsewhere the circle distorts and the magnitude of this distortion is characteristic of the new line of sight vector. This is a moderately computer-intensive task whose accuracy is heavily dependent on the resolution and clarity of the acquired image. The camera and illumination source must be within the user’s field of view and would significantly obstruct the astronaut's field of view.[3] It is doubtful if a camera-based method can be adapted to operate within the confines of the spacesuit helmet.

Electrooculography (EOG) methods determine where the user is gazing by measuring the orientation of the corneoretial potential (CRP), a small electric dipole developed across the eye ball by the eye's metabolism[32]. When the subject looks at different objects, sensors surrounding their eyes measure changes in the CRP. Whereas camera-based methods require image processing to determine eye position, the CRP signal varies in proportion to the movement, allowing the new eye position to be determined much more quickly while requiring fewer computing resources than camera-based methods[34].

Determining the user's line-of-sight has previously necessitated that the subject's head remain stationary, but if both eyes are tracked this requirement can largely be eliminated[4] and provide a useful indicator for when the user is using the interface and when they are viewing the environment. When both eyes are focused on an element of the HMD, the position vectors derived from each eye measurement will intersect at the display, and when the eyes are focused anywhere else they will not intersect at the display.[5] This can be used to tell when the astronaut is using the interface and may control when the other interface elements are active.

EOG-based eye tracking is a relatively new technique and there remain a number of hurdles before the technique can approach mouse functionality. As it relies on sensing electric fields, the raw CRP signal must be processed to remove brain and muscle activity, changes in skin moisture, and variations in the dipole strength (as the retina's metabolism changes in response to fatigue and illumination[6]). The absolute accuracy and long duration usability of an EOG-based system have not been previously investigated[34].

While this discussion has focused on EGT, no other projects show the same promise as EGT for positional interfacing without requiring external hand controllers. Wrist-mounted track pads and a magnetic sensing system have been tested in a spacesuit application, but these and similar input methods are avoided here because their use is physically taxing and requires the astronaut to set down their current task before performing the interface functions.

Discrete Input

A number of alternative interface methods can be applied to the spacesuit to enable discrete input without physically or mentally taxing the astronaut. As stated before, the goal is to provide a fast and

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[3] If designed similarly to systems in the literature; an imageguide-based system could significantly reduce this obstruction and is worth further exploration.

[4] The position is indeterminate only in the case when the center of rotation of the user's head and the center of the helmet coincide; when this is the case and the user is focused on the display, rotation of their head will not be detected by the interface and allowing the graphical cursor to be displaced from the user's focal point.

[5] To reduce eye fatigue the display will appear to be approximately a foot away from the user by slightly offsetting the image to each eye; the EOG-derived position vectors will not intersect at the helmet's inner surface but rather at this virtual point outside of the helmet.

[6] Though considered a difficulty here, EOG's susceptibility to fatigue can provide another measurement of astronaut performance to ensure mission completion[32].

definite input device approaching the utility of the computer keyboard (and including mouse click function). As with the mouse replacement, greater operational similarity to the traditional keyboard will allow many of the same mouse-keyboard paradigms to be used in the spacesuit interface.

Discrete Input: Voice Recognition

Voice recognition is one of the most appealing technologies for both near- and long-term computer interfacing and has previously been tested on orbit. Voice recognition enjoys a substantial commercial motivation which will continue to drive its development; it is the most mature interface technology discussed in this section. Despite moderate commercial success, substantial further work is required to expand the system's vocabulary, improve accuracy, mitigate the effects of dialect, accent, and any changes caused by reduced gravity, and reduce training time for both the system and astronaut[3,36].

For the near-term Constellation architecture, any voice recognition system would be integrated into the crew transport vehicle or habitat with inputs and responses given over the radio. The astronaut would verbally request information to be displayed in the suit HMD which the vehicle/habitat computer would send as data to the suit's HMD for display. This unfortunately requires the astronaut to memorize a series commands before being able to use the system or a dialogue of prompts and expected responses, similar to systems used in automated call centers.

Longer-term, voice recognition will likely not be the primary interface since many tasks can be performed more quickly by some muscular action; instead, voice recognition will be implemented on an application-by-application basis. Recording spontaneous insights and observations is one of the most obvious and best applications of voice recognition, permitting the astronaut to freely describe whatever they are seeing and thinking while the system transcribes the comments and links to external information mentioned in the comment[9,11]. STS-41 tested a voice-controlled camera system and "…astronauts commented that the system created a lot of disruptive 'chatter'"…"and interfered with communications"[3]. If voice recognition can be performed locally, the system could determine whether comments are directed to the system or meant for broadcast to other spacewalkers. Voice recognition is one of the few technologies that can be implemented with today's technology and no modification to the spacesuit but substantial research needs to be performed before it can be routinely used in EVAs.

A voice recognition system could also respond other sounds generated by the mouth, such as teeth clicking, pop and clock sounds made by the lips and tongue, respectively, whistling, and humming.

Discrete Input: Electroencephalography (EEG) / Electromyography (EMG)

Closely related to EOG eye gaze tracking are electroencephalography (EEG) and electromyography (EMG) interface systems. Whereas EOG relies on the measuring the CRP, EEG and EMG sense brain activity and facial muscle movements, respectively, for comparison to pre-recorded events. These systems are being actively developed by motor disability researchers for HCI and as a tool to learn more about how the brain functions. As applied to a spacesuit interface, recognized EEG/EMG patterns would trigger specific actions, potentially including mouse clicks, yes/no responses, radio mode selector, and other simple actions.

Many of the brain and facial muscle activities that must be removed from the EOG-based eye tracking could be used for discrete inputs with the same EOG hardware. Eyebrow movements and eye blinks are easily controlled and able to be detected by EGT systems in either the EOG signal or directly from camera images of the eye. Movements tied to interface commands would need to be carefully chosen to ensure that they are significantly different from the user's normal facial expressions and should initially be restricted to non-critical commands, until system performance is well understood.

Discrete Input: Gloved Interaction

As is commonly known and alluded to previously, a moderate to significant exertion is required to grab and manipulate objects through the spacesuit glove. While glove research continues, the inherent stiffness could be taken advantage of by integrating sensors into the innermost glove layer. This layer is envisioned to fit closely to the astronaut's hand and would contain flex, tactile, or other movement sensors to record small movements of the astronaut's hands. In this way, small movements that are insufficient to move the glove can be used for the interface while large movements are ignored by the system.

From a relaxed position, each finger can be straightened and curled with potentially four movements for each thumb. Through a multi-level key matrix full alphanumeric operation is possible, though a moderate learning period would be required. Designs that allow a tactile response would likely be learned and operated more quickly than those that provide visual or aural indication of a key event. The system must be easily turned off while the astronaut is manipulating an object and quickly turned on once the task is finished.

This concept is the complete creation of the author and no examples have been found in the literature, though this bears some semblance to a few 'haptic glove' projects. As compared to a voice recognition system, a glove interface device would likely allow faster, more accurate input at the expense of being able to manipulate the interface when hands are not holding anything.

The interface technologies considered here represent technologies under active development, but this discussion does not attempt to be authoritative. Other technologies may exist and should be evaluated according to similar parameters as these.

Display

The helmet-mounted display (HMD) will become an essential spacesuit component, beginning with the CSSS and continuing until direct brain interfaces are possible. As noted previously, the CSSS display is sub-optimal for AR applications and will not be discussed further here. While many lessons will be learned from returning to the Moon, a number of display recommendations are clear from the literature.

Display graphics must be highly visible and readable and adjustable with changing exterior conditions[11,12]. To reduce eye fatigue, a constant brightness and contrast should be maintained by an adaptive filter. While outside the present area of research, this is envisioned to be an electrically-controlled layer on the helmet bubble that variably filters the outside environment to a consistent illumination, possibly by polarization-changing electronic ink technology. Such a filter would shield against all harmful radiation whilst only varying the visible spectrum transmission.

A number of optical technologies could overlay graphics onto the astronaut's view of the environment though resolution, dynamic range, and transmissibility are the primary factors. First, the display should exceed current computer resolution (> 9000 pixels / square inch) so that individual pixels cannot be discerned. Secondly, the display should be capable of photo-realism, having sufficient color range for the seamless merging of real and computer-generated objects. Lastly, to the greatest extent possible the display mechanism should not impair the transmission of the natural environment through the helmet bubble. A few technologies may be developed to meet these criteria but their ultimate applicability cannot be determined without further fundamental research; furthermore, this effort did not significantly research optical display technologies and the following discussion is based largely on the author's general familiarity with these technologies.

With the advance of transparent circuitry that can be applied to any substrate (as compared to being etched from the substrate), it may be possible to emplace light emitting semiconductor devices directly on the helmet bubble's interior in a regular pattern that is similar to LCD monitor technology (see Park, et al[37]). Such a system would be capable of high resolution graphics, but may have difficulty meeting the required brightness. A significant concern with any micro-engineered structure or circuit is its susceptibility to electromagnetic radiation—at the minimum the display (and all other suit systems) must not fail when exposed to radiation considered 'safe' for the astronaut and any quantitative method for determining the received radiation dose would be useful.

A second display technology of merit is using low powered lasers and a scanning optic (mirror or lens, depending on the configuration) to paint images directly onto the astronaut's retina. This system's resolution would be limited by the accuracy of the scanning optic and requires either head stabilization or robust eye tracking. To avoid obstructing the astronaut's view, the lasers and scanning optic would ideally be positioned to the side or above the user's head, but this quickly imposes limits on the helmet configuration. Creative application of this technology may enable the envisioned display technique, further study is required.

The CSSS display being developed at Glenn Research Center uses waveguide optics to conduct the image through a substrate until it reaches a holographic diffraction grating, which sends image out of the substrate to the user's eye[15]. The display's brightness and resolution are controlled by the source and losses in the waveguide optics and difficulties have been reported in adapting to a curved substrate. It is not clear how significantly the holographic grating affects the helmet bubble's transmissibility.

A significant driver of the HMD development, besides augmenting the astronaut, is that its development allows the human-machine interface problem to be solved once. As soon as a rigorous interface is integrated into the suit, any other lunar system needs only to communicate with the SAN for the astronaut to fully control that system.

Tactile Display

As mentioned previously, the astronaut's vision will be over-utilized and often used to compensate for senses inhibited by the spacesuit[10,11]. A few projects have explored using tactile devices (vibroactuators most commonly) to relay the relative position of teammates or for status alerts, but none have explored their integration to spacesuits[38,39]. Two domains exist: applications that augment the astronaut's sense of touch and those that convey non-tactile information in a tactile way.

Consider, as an example of the first domain, an astronaut using a drill (today's Pistol Grip Tool). When one uses a drill on Earth, a significant amount of information about the operation is conveyed by the vibration and pitch of the drill, in addition to its visual progress, which the operator uses to determine whether the force and speed are appropriate for the material. The lunar astronaut, lacking both the tactile and auditory responses from the drill, has no indication whether the bit is fully engaged, has encountered a different material, or has broken through. He or she has only the large scale movement of the drill (i.e. it can be pushed in and out of the hole) or the absence of new chips to tell whether the drill has finished the hole. As one application of the SAN, the drill could contain accelerometers which would drive vibroactuators in the astronaut's glove (perhaps on the back of the hand) to provide analogous, tactile feedback the suit otherwise prevents. Similar benefits are anticipated in sampling missions (boring through regolith), plowing (vibrations when harder surfaces are encountered, proportioned between the right and left hands according to the obstruction's location on the plow), and sense enhancement (where, for example, slight imbalances in rotating machinery are amplified and relayed to the astronaut for diagnosis).

As an example of the second domain, Olson used a vibroactuator belt (distributing actuators around the wearer's waist) to convey position and attitude information to pilots in inclement weather[38]. Pilots affirmed a greater sense of situational awareness, but this was not statistically observed. The difficulty with conveying non-tactile information in a tactile way is that accuracy varies significantly with application location and most people can only distinguish between 5-6 vibration frequencies. It may take a significant amount of training before an inhibited sense is fully replaced by a tactile display system; more research is needed. Tactile matrices are also under development, some as reconfigurable Braille devices, but are again limited by the sensitivity of the selected location as well as the body's tendency to become accustomed to static stimuli[39].

With thorough testing tactile displays could become useful, though in the near to intermediate term any data displayed through a tactile interface should either be non-essential or able to be presented through more exact visual or aural means.

7 – Conclusion

While this discussion has focused on applying augmented reality to lunar spacesuits, many of the concepts could be developed and applied to other lunar systems, notably including the pressurized rover design (interfacing with myriad systems, significant annotation and crew interaction capabilities, surface operation recording and uplink, crew monitoring, etc.).

Many of the technologies required for augmented reality spacesuits have commercial utility, but some fundamental systems are solely motivated by extraterrestrial missions. These include radiation-hardened, low-power computing platforms, interference and fault tolerant communication platforms, multi-asset mission management systems that perform under communication delays, among others. The commercial market will eventually reach to the Moon and these initial technology investments will be returned.

The concepts described here represent some of the capabilities future lunar astronauts will benefit from. They are presented to motivate further research and inspire additional thought on the future EVA demands. Our return to the Moon will teach many lessons and allow the preceding ideas to be refined; it is essential that future spacesuit designs be highly modular and receptive of additional elements so that lessons learned can be tested without requiring suit redesign.

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