Extravehicular Information Interaction

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Executive Summary

Astronauts face a number of obstacles during extravehicular activities (EVAs), but the greatest hindrance to their work is the spacesuit. Engineered to keep humans alive in the extremes of space, spacesuits must maintain the astronaut's life while allowing him or her to do useful work. These requirements are naturally at odds, as rigid structures provide the best protection from space but extreme flexibility reduces astronaut fatigue and increases work pace.

Unlike International Space Station (ISS) crews who perform few spacewalks during their expedition, lunar astronauts are foreseen to conduct long-duration (6-8 hours) spacewalks every other day during multi-month stays while building a lunar outpost, constructing science experiments, or processing the lunar regolith for resources. The frequency, complexity, and duration of these EVAs reduce the ability to prepare on Earth for every action that will be required on the Moon. Instead of rehearsing entire spacewalks as is done now, astronauts will practice a variety of procedures common to the majority of EVAs so that once they are on the Moon the tasks are well-known but performed in varying orders.

The counter to this mission uncertainty is prevalent and easily-accessed information. When faced with a difficult task, the ability to call up additional information on the system being worked on, as well as a suggested procedure and simulation, would greatly help the astronaut correctly perform the task. This information aid falls within the field of Augmented Reality (AR), which is broadly defined as the real-time addition of information to the user's environment. AR techniques can improve spacesuits by presenting information to the astronaut in natural and easily understood ways, through aural, visual, tactile, and other information display devices, while allowing the astronaut to interact with that information, through tactile, verbal, gestural, electromyographic (brainwaves), electro-oculographic (eye tracking), or other computer input methods.

An AR spacesuit needs to communicate with lunar systems and be able to retrieve additional information from lunar or terrestrial databases. Local communication allows the astronaut to command nearby lunar devices so that each device need not have its own, unique human interface. A second component of local communication is the collection and transmission of status and sensor readings which contain all relevant information about an event, sample acquisition, or spontaneous finding.

Long range wireless communication of this rich collection of information allows astronauts, various lunar systems, and Mission Control to work in tight coordination, despite the hostile environment and potentially large distances between participants. This potential will grow in importance as the scale and complexity of lunar operations increase. While one astronaut could deploy the Apollo science experiments, many lunar plans call for the construction of sizeable lunar bases, science instruments, resource collectors and processors, and power generation structures which would require teams of astronauts to erect.

As compared to the Apollo version, the role, purpose, and function of the astronaut is changing from one of a simple, and at times comical, lunar explorer to a highly capable and productive individual unconstrained by the spacesuit. This person, responsible for lunar science installations, resource mining, and maintenance of life-critical systems, will be the most productive when they are given access to the tools and information that allow full interaction with lunar systems over the limits of the spacesuit.

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INTRODUCTION

We are going back to the Moon. The date has not been fixed, but if humanity is to continue its present growth rate and resource consumption we will need to expand beyond Earth's confines. Douglas Adams puts it simply, saying in the Hitchhiker's Guide to the Galaxy "Space... is big. Really big. You just won't believe how vastly hugely mindboggingly big it is..." and though the significant majority of it is empty, our solar system contains sufficient resources to sustain our race through the next millennia. The recently completed Review of U.S. Human Spaceflight Plans Committee reached this same conclusion, stating that "… the ultimate goal of human exploration is to chart a path for human expansion into the solar system."[1]. This potential is incredible in that once affirmatively begun it will mark the next great milestone of our civilization, life living independently of its evolutionary home.

As fantastic as this goal is, our society faces a number of incredible challenges that prevent any significant expenditure on exploration. Some of the many challenges facing our country include the gross inefficiency of our healthcare system, near record-level unemployment rate, decreasing quality of education (to the point that America's graduates will not be able to maintain her current world standing), inability to commit to protecting the environment, and ongoing battle against terrorism. Near term we also face an energy crisis of staggering proportions, one which cannot be solved with conventional energy sources. It is, however, in this area that our space exploration infrastructure can provide an answer by way of cheap and clean fusion power. Our moon, has enough Helium-3 (an isotope of Helium that is rare on Earth) to make fusion power an attractive option for our nation's and world's energy needs. (See Apollo 17 Astronaut Harrison Schmidt's "Return to the Moon" for a fuller discussion on He-3 based fusion [2].) Deposited by the solar wind, Helium-3 can be extracted from the lunar regolith, returned to Earth, and produce power that is well below the wholesale cost of coal, at $0.04/kWhr [2]. Human miners would be an integral part of the Helium-3 extraction process and they would benefit significantly from an improved spacesuit which increases their comfort, safety, and productivity from what is possible in an International Space Station (ISS) spacesuit.

Helium-3 mining is one of the many possibilities enabled by the reestablishment of a lunar transportation and habitation infrastructure. The future of the United States' manned spaceflight program (currently Constellation, composed of the Ares I crew launcher, Ares V cargo launcher, Crew Transportation Vehicle, and Altair Lunar Lander) has just undergone a fundamental review of its purpose, destinations, and national contributions.[1] This review has raised a number of questions on America's future in space, however the overriding factor was one of money. The National Aeronautics and Space Administration does not have sufficient funding to permit "…human exploration to continue in any meaningful way."[1] With the Space Shuttle due to retire during 2011 and at least an eight year gap until the next launch system can be deployed, America will have a number of years to plan for a return to the Moon, one that is based on sound economic analyses and steadfast national priorities.

If we go to the Moon equipped with systems slightly adapted from Shuttle and International Space Station hardware, time and money will be wasted because current spacesuits and the mission management architecture are based solely on spoken radio communication. These radios are easy to operate and highly reliable, but their ability to communicate information is greatly limited. 'A picture is worth a thousand words;' this is especially true when exploring the unknown. The ability to transmit high-fidelity visual and aural information will greatly improve this communication and regardless of the form of the next exploration architecture, it will be designed on computer-based systems and include innumerable computerizes systems. As we consider here a collection of lunar hardware, every system an astronaut touches will also exist somewhere as information and every new experiment, structure, or other lunar asset will have some computerized control or status-reporting function. Astronauts need to be able to interact directly with these systems and their information.[3] This capability cannot be realized with spacesuits derived from the Shuttle Extravehicular Mobility Unit and ISS suits. Instead, a new spacesuit designed to allow communication, collaboration, and information display that also improves operator safety while reducing suit maintenance is required.

Improving on Apollo

Returning to the Moon will not be "…a retro-reenactment of the Apollo program…" just as the recent Phoenix Mars Lander was not a dusted-off Viking II. As the overall goal of human exploration is expansion into the solar system, our departure from Earth will be oriented towards developing the necessary technology to enable self-sufficient lunar habitats. Prime among these technology requirements is the ability to construct and maintain lunar equipment which requires a lunar spacesuit.

First Challenge: Perceiving and Interacting with Information

To allow for significant human-information interaction, the spacesuit must be able to present data to the astronaut in a variety of visual and aural ways (tactile actuators allow some unique possibilities and will be explored[4]). Augmented Reality (AR), broadly defined as the real time addition of information to the user's environment, combines computation, display, and human factors concerns to present information in natural ways (e.g., choosing notification color, size, entrance, etc. depending on severity so as not to interrupt the user for a trivial notice) to the user.[6,7] These technologies require the combination of computers, databases, and human-computer interfaces to determine what information is relevant to the user and allowing them to explore and seek additional information if their current task needs it.

If AR concepts are used in the development of the next spacesuit, astronauts will be able to interact naturally with both physical and technological systems for the safest and most efficient completion of their mission. 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]

Constellation Space Suit System (CSSS) engineers at the John H. Glenn Research Center are developing a see-through, helmet-mounted, grayscale monocle with >640x480 resolution that is capable of displaying indicators, graphics, and video. [9] 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.

An AR-enabled 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 extravehicular activities (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.[3,10] Seamless integration with and command of lunar systems is envisioned, figure 1 provides an example.[11]

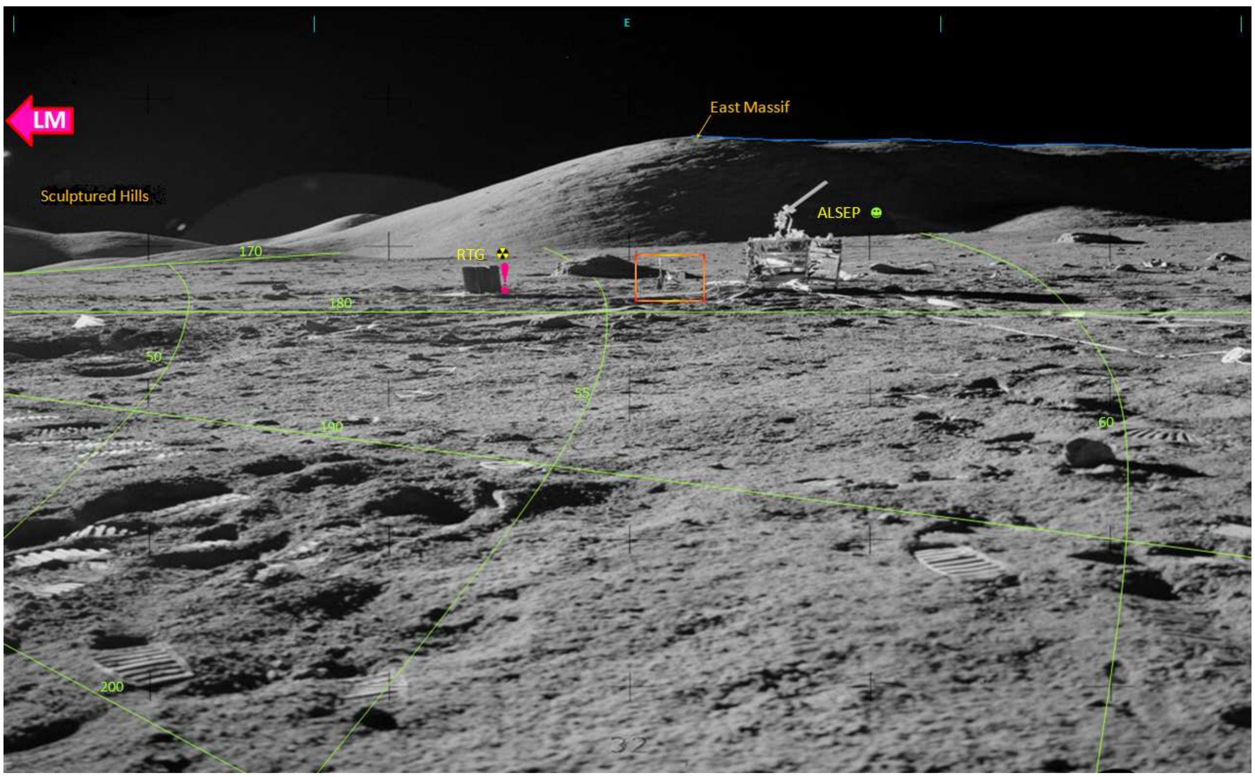

Figure 1. Sample conception; actual display would cover the astronaut's entire field of view:

	path to safety, the Lunar Module (LM) here		next task item
	radial 'mile markers;' 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 operation is normal

The hostility of space is well known and this significantly complicates the integration of new technologies in the spacesuit. 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.

Second Challenge: Communicating Understanding

The physical limitations of the Apollo spacesuits are readily apparent in astronaut accounts and EVA videos, but an equal hindrance was the astronaut's limited ability to communicate their surroundings and discoveries to Earth. As described in the preceding section, future lunar astronauts will have a significant need to interact with all kinds of information, some of which can be predicted now, as mission prototypes are being developed, while the utility of others will not be apparent until we have boots on the Moon. Meaningful human-information interaction will enhance the astronaut's understanding of the environment and ability to deal with unexpected situations, allowing them to act with greater confidence and focus on the delicate and risky elements of the particular mission.

Apollo 17 was arguably the most scientifically useful mission of the Apollo program because of Geologist Harrison Schmitt's trained eye, yet his observations were limited to the degree to which he could record and communicate his surroundings. During his second spacewalk Schmitt described a nearby rock by saying "The mineral texture appears to be subophitic ... like a good diabase, although a little coarser… ."[19] While this description is useful to field geologists, there may have been additional characteristics that guided Schmitt's diagnosis yet were not communicated, either due to his need to describe the rocks in geologic terms that originated on Earth or danger of delaying the EVA by pausing for an extended analysis and report. Significant additional science would have been possible if he had been able to fully record what he was seeing for thorough analysis later. A high-fidelity recording system that automatically integrates readings from any nearby sensors, imagers, and cameras, will enable astronauts to document whatever they find interesting or peculiar without disrupting the mission.[12] This field data could later be combined with additional observations from orbiting craft as well as any relevant previously-know characteristics, as shown in figure 2. The key requirement is that lunar sensing devices be able to communicate with each other so as to automatically produce a single, cohesive picture of astronaut's surroundings and object of interest. This recording system would operate continuously to allow the astronaut to speculate immediately on their findings, recording thoughts as they occur, instead of interrupting those thoughts to describe mundane features such as location to mission control, as was done during Apollo.[3,11,12,13] Useful Earth/Moon communication requires the collection of information from disparate systems into cohesive packages which can be easily transmitted to all parties. These packages will shift the rigorous, in-depth analysis from the in-situ astronaut to teams of scientists back on Earth who could add specific tests later EVAs.[14,15]

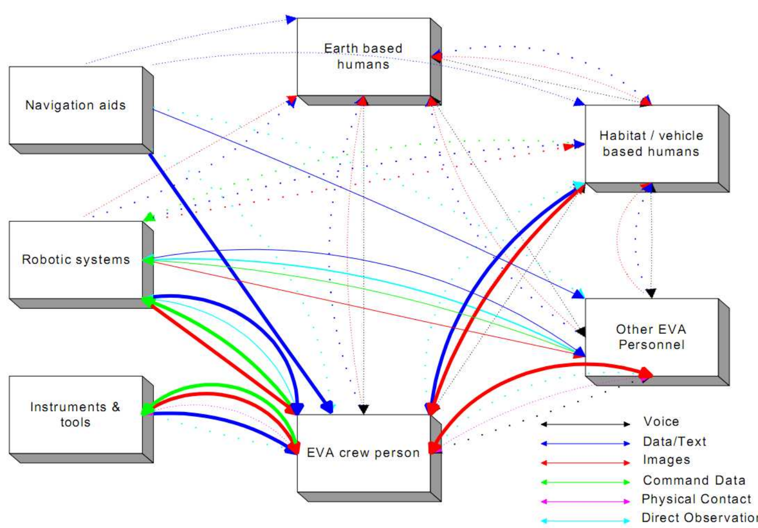

Figure 2. Communications web in support of extravehicular activities. Courtesy Boucher, et. al.[8]

The recording system just described and other new spacesuit systems have the common difficulty of trying to utilize existing electrical connectors and suit pass-throughs (holes between suit layers for wires to pass through) while not interrupting or impairing the operation of any current system. In light of the difficulties of physical interconnects, future non-life support subsystems as well as assets near the astronaut will communicate by wireless technologies, likely resembling Bluetooth®, Radio Frequency IDentification (RFID), Wireless-Fidelity (Wi-Fi), and/or other common protocols. If the communication is wireless, spacesuit engineers can spend more time designing new capabilities and less creating holes for various applications.

Another very simple and useful application of this suit area network (SAN) is to track the physical location and status of tools and other implements. 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 wireless node which would update the tool's status to 'checked-in.' In this way, every tool and reusable piece of equipment would be tracked by its wireless profile, with the goal of sparing astronauts from inventory management and tool-hunting tasks during EVA. 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 (drills) 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.

One exciting prospect enabled by the SAN is the display of operational data from EVA tools and system controls.[16] Consider here the oft-used pistol-grip tool (drill and torque wrench) and what improvements can be made to the lunar version.[3] When astronauts use the torque wrench, they set the fastener's rated torque level on the wrench and then pull the trigger until the torque setting is exceeded, at which point they read out how much torque was applied before release. If the fastener did not respond as expected, the operation is repeated (each requiring the removal of the tool to read the applied torque) before the astronaut consults with mission control to decide whether to advance to a higher loading. 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 while updating the virtual record for the individual fastener with the applied torque. Near-suit communication between tools and the astronaut's display and recording systems will verify the completion of the present EVA while building a component history which may be useful should that component later fail.[15]

This local communication would also eliminate the need to design a new user interface for every lunar system because the astronaut's helmet display would adapt to each controllable system. Instead of having a different human interface on every lunar system, this near-field wireless communication would solve it once for all systems while enabling additional capabilities. As one example, an astronaut could select a particular automated system and either give it a new task or instruct it to prepare for manual operation, perhaps negotiating a rover through particularly delicate dangerous area before releasing it to continue working on its pre-assigned tasks. Implementing a single human interface in the spacesuit that communicates with systems by a standard wireless protocol will greatly simplify human-controlled lunar systems while lessening the training requirements for lunar astronauts because they are using a familiar and individually-configurable interface. Flexibility in lunar systems is a highly desirable quality particularly if something does not go according to plan; a robust human-information interaction capability in the spacesuit is one of the best ways to ensure EVA success.

Third Challenge: Working Collaboratively

When astronauts can engage in useful communication, substantially collaborative activities are possible, increasing the capability of EVA teams while likely decreasing the time required to complete those activities. Multiple types of collaboration are possible during lunar EVAs and should be chosen based the demands of the activity.

The simplest and most apparent is collaboration between spacewalkers as they jointly conduct the mission. Verbal communication mediates collaboration between spacewalkers and is easily seen in Apollo, Space Shuttle, and ISS EVA videos. One particularly clear example of the current system occurred during STS-125, the most recent Hubble servicing mission. As seen in figure 3, 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. Feustel’s and Grunsfeld’s collaboration was enabled by their ability to be in instant verbal contact with each other.

Figure 3. Practice installation of the Wide Field Camera 3 by Mission Specialists John Grunsfeld, left, and Andrew Feustel, right. Astronaut Feustel cannot see around the camera assembly, requiring Astronaut Grunsfeld to give him verbal directions as to the alignment and progress of the camera into the camera bay. Photo courtesy *NASA*.

Many complex and intricate EVAs will require astronaut teamwork; however this collaboration need not be limited to verbal communication. For example, as one astronaut interacts with information relating to the current task, his or her companion should also be able to view and manipulate that information with changes made by either appearing on both helmet displays, as if both astronauts were viewing the information on a single display.

Furthermore, this collaboration should not be restricted to human participants as automated assets can provide data relevant data based on the current task's progress, while also managing mundane aspects of the mission. NASA scientist William Clancey analyzed the transcripts from Apollo EVAs and noted that "…CapCom—the astronaut in Mission Control in Houston, serving as the single point of contact for the lunar crew—was virtually a third person on the moon, often more present to the two lunar astronauts than they were to each other. CapCom maintained a continuous conversation with the astronauts, monitoring and advising nearly every step in deploying equipment, navigating, scheduling, regulating life support, logging data, and interpreting observations."[14] Based on this analysis Clancey classified the types of support CapCom provided and recognized that many of the routine status-keeping and information retrieval tasks could be completely automated, provided by a computer agent. This concept features 'mobile agents' that "…interpret and transform available data to help people and robotic systems coordinate their actions to make operations more safe and efficient."[17] Automating the mundane tasks of mission management would reduce astronaut distraction from the EVA, requiring their input only during abnormal situations.

Solutions to the preceding challenges will allow astronauts to work as they would on Earth without the burden of the spacesuit. Once the required human interface and communication technology has been developed, it becomes possible to design information interfaces and productivity tools that…

Path Forward

The present uncertainty in our exploration plans threatens to delay advances in human space operations, but our eventual expansion into the solar system is very likely. Indeed, Harrison Schmitt considers a privately-developed Helium-3 mining operation to be the most likely to succeed, over any government effort.[2] So the question is not if we will need advanced lunar operation but when will the value of space resources surpass economic barriers to their pursuit.

Notwithstanding the increasing commercial incentives, NASA research into advanced human space operations continues towards many of the concepts included here. The Desert Research and Technologies Studies (D-RATS) is an annual excursion to Arizona desert to field test developments in EVA systems made over the past year. Figure 4 shows a prototype field science station along with an enhanced mobility, rear-entry spacesuit. Similar field tests include NASA's Houghton-Mars Project and the Mars Society's Devon Island research station in the Arctic Circle. Together these tests allow us to reasonably test fundamental concepts and capabilities for EVA improvement and guide further research in these areas.

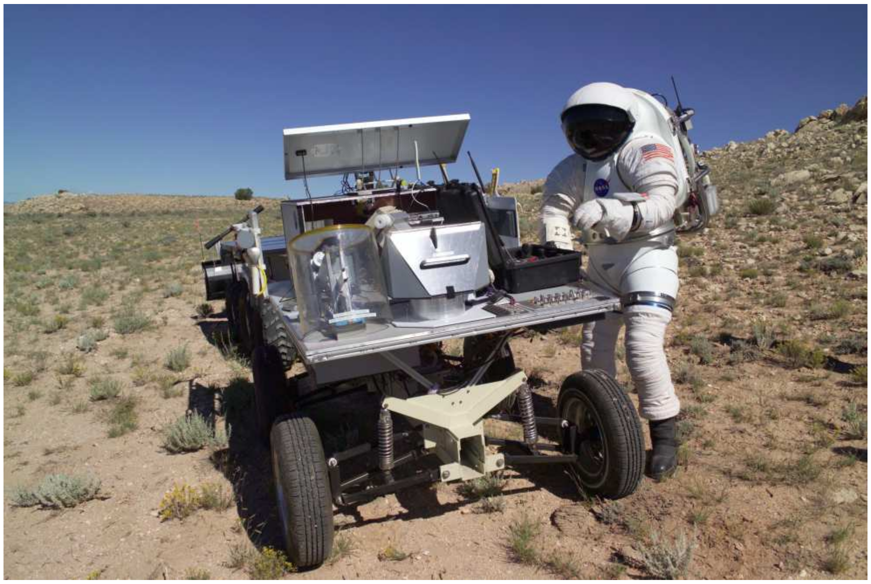

Figure 4. Prototype spacesuit and mobile experiment station.

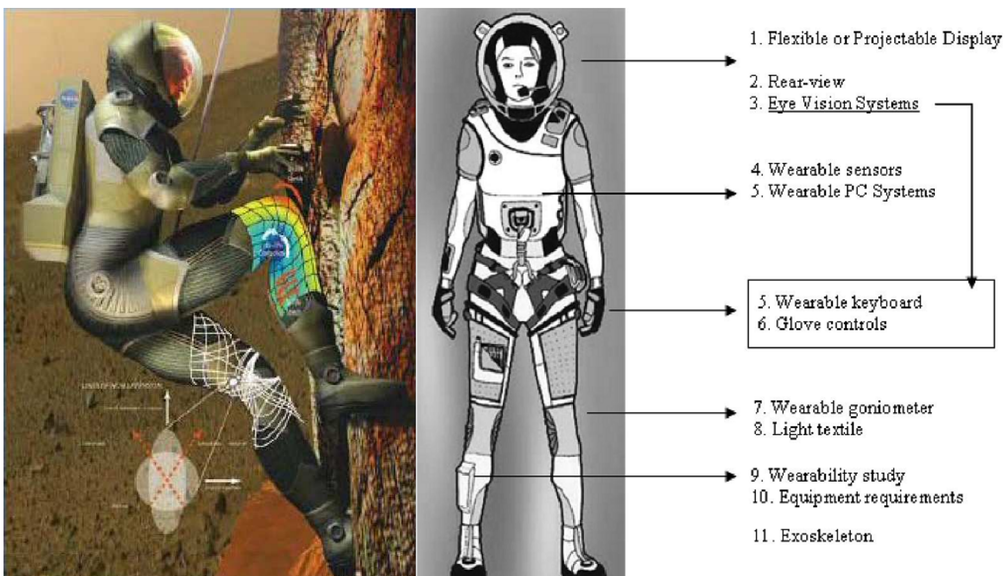

Figure 5. MIT's form-fitting unpressurized BioSuit concept. Courtesy Canina, Newman, and Totti.[18]

CONCLUSION

Manned exploration of the Moon will benefit significantly from the development of human-information interaction and communication systems. These will enhance the safety, productivity, and work quality of EVAs by allowing astronauts to more completely understand their surroundings and potential effects of their actions. This environment understanding will only increase in importance with the placement of more and more equipment on the Moon.

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