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## ABSTRACT

NASA has long recognized the advantages of providing improved information interfaces to EVA astronauts and has pursued this goal through a number of development programs over the past decade. None of these activities or parallel efforts in industry and academia has so far resulted in the development of an operational system to replace or augment the current extravehicular mobility unit (EMU) Display and Controls Module (DCM) display and cuff checklist. Recent advances in display, communications, and information processing technologies offer exciting new opportunities for EVA information interfaces that can better serve the needs of a variety of NASA missions. Hamilton Sundstrand Space Systems International (HSSSI) has been collaborating with Simon Fraser University and others on the NASA Haughton Mars Project and with researchers at the Massachusetts Institute of Technology (MIT), Boeing, and Symbol Technologies in investigating these possibilities. The objectives of this research so far have been to better understand the ways in which an improved information interface may be applied in a variety of mission settings and to refine the definition of system design requirements to best support those applications.

Research efforts have combined the results of concept definition and mission requirements studies with experiments in pressurized spacesuits in the laboratory and in lower fidelity test-beds in field settings. Several promising approaches for the integration of highly capable information interfaces with EVA systems have evolved and have been evaluated in preliminary proof-of-concept tests. The results show considerable promise that an advanced information interface could be adapted to support near-term orbital EVA missions and could be evolved to provide robust support for future planetary exploration missions.

## INTRODUCTION

Extravehicular activity (EVA) uniquely places human intelligence, sensory capabilities, and manipulative abilities where the action is in space missions. The result is a degree of flexibility and capability that has not yet been approached by any remotely operated, automated, or robotic system. Repeatedly, operational experience has demonstrated the value this provides for exploration, science, construction and maintenance in space. However, the key to effectively using this capability is the information that is provided to the human intellect on the scene. In general, the required information extends well beyond what can be directly seen and felt on the objects to be explored or manipulated. Information support systems are required and have, historically, been an important part of every EVA mission.

However, these information support systems have also resulted in additional significant overhead. They have entailed extensive, highly specific training to ensure that the EVA astronaut is armed with most of the needed information before the event. This internal information is supplemented by relatively simple reminders and cues in a "cuff check list" and verbal support over the radio from ground or vehicle-based personnel or another EVA astronaut. Limited real-time information about the status of the EVA systems has been provided by a simple (25 character) text display.

This paper combines insights and contributions from a number of investigators within NASA, industry, and academia who have been exploring alternative ways in which information can be provided to the EVA astronaut to better support his or her work in space. It includes consideration of what information will be most useful in future missions, how it can be presented to best help the astronaut, and how it can respond more flexibly to changing or unanticipated mission needs while reducing the mission cost of providing it.

## HISTORICAL PERSPECTIVE, NEEDS AND POTENTIAL

Experience with current operational systems and prior attempts to develop more capable alternatives provides an historical perspective on both the needs and potential for EVA information interfaces. Seen from the viewpoints of both technology developers and astronaut users, this provides important guidance in identifying goals and promising avenues of exploration for current and longer term EVA information interface research.

EXPERIMENTAL HELMET-MOUNTED DISPLAYS (HMDS) AND CUFF CHECK LIST

Research was conducted at the NASA/Johnson Space Center (NASA/JSA) in the mid-to-late 1980s (References 1 & 2) in order to investigate new spacesuit technologies that could be utilized to provide the astronaut with "hands-free" access to key information while performing an EVA. Specifically, this research focused on incorporating helmet-mounted display (HMD) technology and the use of voice control within the next generation of spacesuits to improve EVA productivity and to reduce training demands. During this period, NASA completed four HMD feasibility development projects for the design and development of an EMU HMD, each resulting in the delivery of a binocular or biocular HMD breadboard unit utilizing conventional optical elements (i.e., glass lenses and beamsplitters) and/or holographic optics. The goal of each project was to provide a low-profile, transparent screen, conveniently located above the EVA crewmember's normal field-of-view that is capable of displaying text, graphics, and video. The HMDs were then coupled with additional research into voice recognition technology (References 3 - 8) in order to provide the EVA astronaut with "hands-free" access to information. Table 1 summarizes the principal characteristics of each HMD design.

The results of these projects were valuable in determining key requirements and identifying key integration issues for incorporation of the HMD into the spacesuit. Unfortunately, HMD integration costs for the Shuttle extravehicular mobility unit (EMU) were exceptionally high, and the decision was made to attempt to integrate the HMD into the next generation of spacesuit only.

**Table 1. Summary of NASA/JSC Experimental HMD Projects Major Design Characteristics**

| | **Wright-Patterson AFB** | **Hamilton Standard HMD** | **APA HMD** | **Technology Innovative Group** |
|---|---|---|---|---|
| Viewing: | Binocular w/ 20 mm exit pupils | Binocular w/ 26 mm cubed eye-box | Binocular w/ 26 mm exit pupils | Bi-ocular w/ 2" x 1" x 5" eye-box |
| Image Source: | 25 mm CRT (2) | LCDs (2) | 17 mm CRT (2) | CRT (modified Sony Watchman™) |
| Resolution: | 525 lines | 320 x 220 pixel | 525 lines | 525 lines |
| Field-of-View: | 47° diagonal (1/3 overlap) | 17° diagonal | 25° diagonal | 25° diagonal |
| Optics: | Conventional only | Conventional only | Conventional and holographic | Conventional and Holographic |
| Image Focal Distance: | ~ 3 feet | ~ 4 feet to infinity (60 feet) | ~ 4 feet | ~ 4 feet |
| Power Consumption: | > 20 watts | ~ 7 watts | < 10 watts | < 5 watts |
| Data input: | RS-170 | RS-170 | RS-170 | RS-170 |
| Volume: | Large, > 18" diameter dome required | Large, > 17" diameter dome required | Small, ~15.5" to 16" diameter dome required | Small, ~15.5" diameter dome required |

As a result, NASA has opted, in the near term, to create an information display system consisting of an electronic version of the paper checklist that is currently flown. This "electronic checklist" is expected to improve astronaut EVA productivity by providing a portable, self-contained information display system allowing the crewmember to have ready access to a much larger database. This database is even capable of being modified on-orbit.

The electronic checklist developed as shown in Figure 1 consists of an off-the-shelf liquid crystal display, touch screen (for screen selection), driver electronics (including micro-controller, memory, and serial data programming port), and battery pack enclosed in an aluminum frame protected, thermally, by softgoods (Reference 9). Access to the memory contents is accomplished via the touch screen through a unique "sextant" screen protocol. Worn over the space suit arm assembly (as is the current paper cuff checklist), the electronic cuff checklist provides an easy access to text and graphics databases of greater than 500 pages. This database is both reprogrammable and expandable via a serial data port to accommodate the data requirements of various Shuttle and expected International Space Station (ISS) EVA mission tasks. Software training tools were also designed to allow efficient creation of "pages" and for loading of the checklist's database.

Figure 1. NASA's electronic cuff check list prototype used a liquid crystal display and touch screen control interface.

An in-flight EVA evaluation of the electronic checklist was performed on Shuttle Flights STS-63, STS-64, STS-69, and STS-72. Although some design modifications were made between these experiments to address design deficiencies identified, in the end, performance of the electronic checklist was only marginal. The key areas for improvement for the electronic checklist were packaging (around the suit arm) and the need for a more robust display.

A second-generation electronic checklist is currently under development by NASA/JSC and is expected to be flown in late 2004.

## A USER'S PERSPECTIVE, ISSUES AND FUTURE NEEDS

The environment in which EVAs are conducted is hostile, unforgiving of mechanical failures or human errors. The ultimate goal of EVA suit designers is to make suiting up for EVA no harder than putting on the sort of protective gear needed to go outside in other hostile environments such as Antarctica or cold-water SCUBA diving. However, this EVA utopia is probably several generations of new materials in the future, and at present part of the task of an EVA astronaut is to learn through training how to use a spacesuit as a tool through which to interact with the environment. The perception that "I am making my suit move in such a way as to accomplish this task" is fundamentally different from "I am doing this task." Familiarity with spacesuits gained during years of training allows astronauts to use spacesuits without a lot of conscious thought about suit mechanics, just as drivers learn to use a standard gearshift almost subconsciously. But a competent EVA astronaut can never forget a spacesuit's limitations, and the fact that in a sense he is ultimately a tele-operator, using the suit as an intermediary to manipulate the environment.

A critical factor in successful tele-operation activities is to maximize situational awareness. An EVA astronaut has far more situational awareness than observers inside the Shuttle/Station or on the ground, but suit constraints severely limit this awareness. Even a simple act like turning one's head to see what is behind is impossible in a spacesuit. Astronauts carry TV cameras on their helmets to share views of their workspaces with their colleagues, but they currently have no way of using this TV capability to increase their own situational awareness. Even if they had pointable helmet- or body-mounted TV cameras that could in principle show them what is going on in different directions, astronauts have no way at present to display such information for their own use. The same would be true if a "god's-eye view" were made available by a Sprint-AERCam (an experimental tele-operated free flying camera flown by NASA on STS-87) or some similar technology. Such a view can be immensely useful to observers for monitoring clearances, path planning, and numerous other purposes, but the astronaut, who could probably make the most use of such a view, currently has no way of seeing it.

Moreover, even if they could see the views, astronauts have no capability to use the images generated by their TV cameras to communicate with their colleagues with any precision. Suppose, for example, that an astronaut is working on a repair task and comes across a detail worth bringing to the attention of ground experts. A camera can be pointed at the work area and the astronaut can try to describe in words the detail at issue, or if the geometry is favorable the astronaut may be able to point with her finger. How primitive! TV sports viewers are used to seeing cursors used all the time to point out areas of interest in a scene, but this elementary form of telecommunication is beyond the scope of EVA astronauts.

When an astronaut is communicating with human beings, the use of verbal descriptions to indicate an area of interest in a visual scene, while often inefficient, is at least possible. The situation changes if we imagine future astronauts trying to interact with robotic systems. The efficiency of space-suited explorers on remote planetary surfaces will be enhanced immeasurably if they can work with robots accompanying them on their geological traverses and carrying out tasks at their request. Imagine setting up a temporary sample collection base at a strategic location. Rather than have to walk or drive around from rock to rock, an astronaut could work at a central location and tell a robot to “Go bring me that rock.” But how can you indicate which rock you are talking about? Describing the size, shape and color of the rock might work with a human assistant, but until artificial intelligence becomes a lot more sophisticated, it won’t work with a robot. A simple cursor placed on a scene generated by the robot’s TV vision system would be far more efficient. Dealing with computer displays is second nature to even elementary students these days, but this technology is not available to astronauts.

How can an astronaut constrained in a spacesuit control computer displays: select pages, scroll up and down, and move cursors? A glove-compatible keyboard is one possibility, but an astronaut’s hands are too valuable to have their time consumed by controlling computer displays. Hand control might be reasonable as a backup, but it is appropriate to consider what other effectors are available. Voice is a possibility, but you can’t talk to your computer and your colleagues at the same time, and you don’t want your computer to mistake a comment to a colleague for a command. Astronauts inside the Shuttle or Station have “push to talk” buttons, but using these takes up one hand. To avoid this, EVA astronauts currently are always on “hot mike.” Could one create the vocal equivalent of a “push to talk” button? Other effectors are possible. For instance, EVA astronauts periodically sip on a straw connected to a water bag inside their spacesuits. Could blowing or sucking on a straw be an efficient hands-off way of controlling communications modes and computer displays?

If we have learned anything from complex EVA activities such as repair and servicing missions for the Hubble Space Telescope or ISS construction missions, it is that where EVA is concerned, the most valuable and limited resource is “useful human time outside.” Part of the quest to maximize the ratio of useful time outside to the total time devoted to EVA is to reduce the overhead involved in pre- and post-EVA activities such as suit preparation, prebreathing, and suit cleanup. However, it is just as important to increase the efficiency of the time astronauts spend outside, and the efficient use of information technology can be an important aspect of this effort.

Many new EVA information technologies can be tested on the ground and in water tanks. However, real confidence in space systems only comes when they have been used in space. The International Space Station is the focus of a huge amount of EVA activity. Once construction is complete, the ISS will hopefully become not only a valuable scientific laboratory but also a test-bed for new space technology, including EVA technology. When we have demonstrated in space the ability of EVA astronauts to use advanced information technology to increase their situational awareness, to communicate with their colleagues, and to control robotic systems, then we will be much farther along in our readiness to extend human exploration farther from the Earth.

## EXPANDED UTILITY IN EXPLORATION SETTINGS – DESIGN IMPLICATIONS

As suggested by the preceding user’s viewpoint discussion, information interfaces for future exploration EVA and near-term orbital missions may be expected to share many demands and design characteristics. The fundamental functional needs and constraints are not expected to change dramatically. However, significant growth in the need for flexibility and autonomy can be anticipated and must be supported by increasingly flexible information interfaces.

EVA information interfaces must support basic activities such as life support and comfort control, communications, mission and task planning, localization and situational awareness, navigation, and task execution. Information interface requirements are strongly dependent upon the desired level of autonomy, flexibility, and coordination (with other crewmembers, robotic agents, and other mission support elements), as driven by the uncertainty of the environment and requirements of the EVA system (Figure 2).

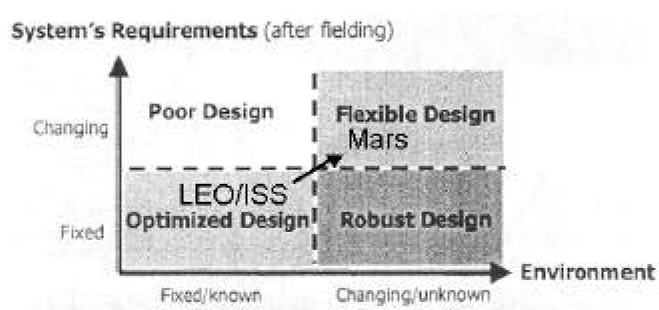


Figure 2. Flexibility allows a system to respond to change in its objectives and requirements after it has been fielded. Information interfaces must support operational flexibility in dynamic environments when uncertainty is high. Adapted from [Reference 10].

Because the spacesuit is such a physically constraining environment, information interfaces must also minimize the movement and forces required for their operation. This is especially important during long-duration space flight when an astronaut may be operating with reduced physiological capabilities. Because of the exposure risks and mental concentration required to work in the EVA environment, information interfaces should be designed to minimize the cognitive load required for operation.

Here we discuss challenges and opportunities for information interfaces to support the aforementioned basic activities as we move beyond operations in Low Earth Orbit (LEO) (including Shuttle and ISS), and toward extended operations on the Moon or Mars.

Life Support and Comfort Control

Life support control and comfort control for the EMU are provided by the chest-mounted DCM, which can interfere with the work area of the astronaut. Life support information can be viewed by the EVA astronaut on the DCM or by support personnel monitoring telemetered life-support data. Current limitations of the DCM display make its presentation of life support data useful primarily for intermittent status checks in which it is scrolled through the various parameters of interest or for the investigation of alarms or warnings automatically generated by fault detection logic. Routine awareness of activity levels, thermal state, expendables status, etc., is primarily maintained by support personnel and, to the extent that the EVA astronaut's involvement is required, communicated by voice link.

Future EVA information interfaces for life support control and comfort control are likely to maintain dedicated controls for critical life support functions. Integration of life support status information into improved information displays could reduce communications chatter, and provide the capability for more autonomous operation in environments with reduced real-time mission-control type support (e.g., reduced local mission support crewmembers and/or long light-travel-time delays). This would provide astronauts with the capability to monitor and manage their own work rates and to manage constraints including thermal loads and consumables margins.

Communication

Current EVA communications interfaces are limited to voice communications, one-way telemetry of astronaut life support and physiological data, and one-way video via the EMU helmet-mounted camera [Reference 11]. Data automation during the Apollo lunar mission was limited by technological capabilities. Current operations suffer from a dearth of communications infrastructure components, which have the potential to dramatically improve the flexibility and robustness of future EVA operations.

A wireless network is required for future EVA systems to provide the backbone for information delivery, data automation, synchronization, and coordination between components of the EVA system. In LEO/ISS operations, blockage by space structures may limit network coverage, but network optimization can minimize blockage and maximize performance. During future planetary exploration, wireless network coverage may be limited by topography, power, multipath propagation, and mass and deployment complexity of communications infrastructure components [References 12-15]. Future EVA information interfaces should function across a range of communication data rates and should permit a variety of interaction modes including voice communications, text, graphics, video, and perhaps inter-conversion between modes [Reference 16].

Mission and Task Planning

During current operations, astronauts participate in mission and task planning as part of their training, but do not generally plan whole sequences of actions or tasks on-orbit because of the extensive verification and validation required to develop a viable EVA plan. Current operations can be described as an attempt to "dance a ballet" – the goal of the EVA is to execute a predetermined, practiced plan, follow rehearsed contingencies when necessary, and improvise only as absolutely required.

Future EVA's are likely to entail dramatically increased task uncertainty and an increased number of potential contingencies, making current levels of preparation impractical. EVA astronauts will take on a larger mission and task planning role by making observations and measurements that will affect the remainder of their EVA goals and objectives. One example might be the inspection of a failed piece of equipment external to the ISS; the remaining goals and objectives for the EVA could depend strongly on a surface inspection or electrical measurements made by the astronaut. During planetary exploration, a geologic traverse could be driven largely by observations made earlier in the geologic traverse. Thus, information interfaces should enable astronauts to acquire, record, analyze, and communicate the data required to support mission and task planning (see Task Execution, below).

In addition, when more autonomous operations are required, EVA information interfaces should enable astronauts to perform their own mission and task planning to the extent required to maximize the value of EVA within operational constraints. With one-way line-of-sight light-travel-time delays of 4.5 to 21 minutes between Earth and Mars, EVA operations on the Martian surface are likely to be autonomous or semi-autonomous. One might imagine a geologist replanning the rest of their geologic traverse for the day based on an important discovery. The geologist might use an information interface to specify limited temporal, spatial, and other characteristics of their new planned traverse and submit an 'EVA plan' (analogous to a pilot filing a flight plan) after validating that the new traverse meets all applicable 'flight rules' including expected thermal loads and consumables margins [Reference 17].

Localization and Situational Awareness

Localization and situational awareness continue to be a problem in microgravity EVA operations due to spatial disorientation (including inversion illusions), a lack of direction cues, contrast challenges, and limited visibility (especially to the rear of the spacesuit). While the same orientation challenges experienced in microgravity are not encountered in partial gravity, the Apollo lunar surface astronauts had difficulty with localization because of the undulating and self-similar nature of the lunar surface.

The EVA information interface should assist in localization by providing cues to astronaut orientation and position relative to visible landmarks. Likewise, information interfaces should enhance situational awareness by making available to the astronaut basic status information (for example, time on EVA or time on task), progress compared to plan, consumables, upcoming events (for example, time to events like sun-up or sun-down), or other contextual information.

In microgravity, tactile displays [Reference 18] and visual displays have been proposed to provide localization cues. Visual displays could also highlight landmarks, keep-out zones, or other hazards, and could illustrate the location and characteristics of other EVA events. Providing behind-the-back clearance sensing might also be useful – because of suit-limited visibility and proprioception, astronauts may bump into and potentially damage objects that are behind them.

Many traditional localization techniques can be applied to planetary surface operations, including identification of landmarks, observation of sun-angle, radiolocation, and localization schemes like the global positioning system (GPS). Because localization is likely to be such a routine activity during planetary surface exploration, EVA information interfaces for localization should be highly automated. Localization schemes can be built upon surface-based communications and networking infrastructure if a GPS-like localization scheme is not available.

Information interfaces for planetary exploration could use a traditional map view to illustrate topography, landmarks, keep-out zones, locations of ongoing EVA events, and temporal events such as comparing actual progress on a geologic traverse to the nominal planned traverse. A visual display might serve as the EVA equivalent for planetary exploration to today's multifunction flight displays for pilots, integrating temporal and spatial data into a single view. An augmented reality display would also be highly desirable.

Navigation

During microgravity operations, translation routes are learned during ground-based training or via study prior to EVA. Nevertheless, translation can be disorienting over significant distances on large space structures. During Apollo lunar surface exploration, navigation was hampered by a lack of landmarks, self-similarity of the terrain, hummocky ground, reduced line-of-sight distances, and visual challenges with some sun-relative directions of travel [References 19 and 20]. In addition, reliance on dead-reckoning navigation sharply reduced navigational accuracy until the deployment of the lunar rover.

During microgravity operations, visual display of preferred translation routes or techniques could be used to assist astronauts while translating from site to site, for example, during an unplanned EVA. Visual displays have also been proposed for navigation of the Manned Maneuvering Unit (MMU) [Reference 2] or use of the Simplified Aid For EVA Rescue (SAFER) system [Reference 21]. Extensive surface data is likely to be available for most, if not all, future planetary surface missions. An integrated display of these data combined with aforementioned data such as landmarks, hazards, and keep-out zones could provide a highly functional aid to navigation.

Task Execution

Task execution during extravehicular activity has been enhanced by continued (but limited) improvement in mobility of spacesuit joints and gloves, standardization of mechanical interfaces, and evolution of a limited but powerful set of tools that provide position and orientation control and mechanical advantage. Task execution often includes one or more (and often many repetitions of) steps including physical manipulation, measurement, recording, processing, communication and verification. During Apollo, astronauts read out measurements from a gravimeter over their radios. LEO operations still utilize the same techniques – when tightening a bolt, an EVA astronaut will count out loud the number of cranks and degrees per crank made while turning a torque wrench.

EVA information interfaces should be developed that reduce the time and energy (mental and physical) required to execute a task. Significantly improved data automation is required to achieve this goal by improving the task efficiency or the efficiency with which task outcomes are communicated.

Efficient task execution requires that EVA astronauts have access to accurate task-related information, especially for complex tasks or for tasks for which an astronaut has not recently trained. EVA information interfaces could deliver video, text, and graphics, possibly acquired in real time over a wireless network, to the astronauts. These information interfaces should also permit real-time collaboration among members of the EVA team to support routine discussions, troubleshooting, and contingency or emergency operations. Delivery or display of information could be initiated by a remote operator on request by an EVA astronaut [Reference 21], in response to voice commands [Reference 3], or based on contextual data such as tool usage, position, orientation, posture, or time.

For example, an electronic torque wrench could measure and wirelessly transmit the total number of degrees of rotation it has been turned since being reset. Grasping or resetting the torque wrench could wirelessly activate a torque-wrench display, and data from the device could be displayed on a visual display in the space suit or viewed by support personnel.

In the context of planetary exploration, geographical information systems (GIS) may serve as a useful model for automation of many of the components of task execution. Physical manipulations, observations and measurements can be tied to contextual data (such as position, time, etc.) and integrated into a virtual world-model that can be subsequently analyzed or communicated. Attempts should be made to enable activities that are common during terrestrial field work such as imaging, note taking and sketching. Interfaces for these activities may require some physical movement or may be based on voice commands (e.g., limited annotation of images, with opportunity for sketching upon doffing of the spacesuit).

## RECENT ENABLING TECHNOLOGY DEVELOPMENTS AND NEAR TERM POTENTIAL

Challenges that face engineers when designing wireless information systems for the current generation of spacesuits include:

- Safety,
- Human Factors,
- Reliability,
- Form Factor,
- Systems Integration,
- Power Consumption,
- Thermal Characteristics,
- Electromagnetic Interference,
- Operational Performance, and
- Mechanical Engineering.

There is a high degree of interdependency for these issues. At the core is power consumption which is central to achieving safety, size, thermal and operational targets.

Advancements in low-power microprocessors (Reference 22) and wireless network chipsets (Reference 23) used in current mobile computers have enabled substantial improvements in miniaturization and performance. Embedded, hand-held and wearable computer systems are now used in a variety of applications to collect, process and deliver information in mobile work environments (References 24- 26).

Display technology has a considerable impact on engineering issues and selection of components is tightly coupled with system design. Silicon Microdisplays (Reference 27), available in sample quantities since the early 1990's and combined with appropriate optics (Reference 28), have been used in near-eye applications to enable "Hands-Free" and "Head-Up" operation of mobile information systems. Sizes have ranged from .2-inch diagonal, 320x240 qVGA (Reference 29) Active Matrix Liquid Crystal Displays (AMLCD) embedded inside of prescription eyeglasses (Reference 30) to 1.3" 1280x1024 SXGA resolution in helmet-mounted systems (Reference 31). AMLCD with .4-inch diagonal, 640x480 VGA resolution, sequential color LED backlit displays have been shown to function with the EMU pressure suit in ground tests. A color monocular display using an articulated arm can be attached to non-corrective or prescription eyeglasses (Reference 32) and worn inside the EMU helmet with a field-of-view of 17 degrees, positioned between 5-10 degrees above line of sight.

Distribution of components with body conformal packaging can be achieved using a modular electronic design using flexible interconnections (Reference 33). Placement of the flexible modules was found to be optimum attached to the upper back of the liquid cooling and ventilation garment (LCVG) between the $O_2$ vent return plenums that extend to the arms (Reference 34). This allows for minimum cable length between the electronics and the near-eye display and maintains comfort given the minimal space available.

Currently available commercial off-the-shelf (COTS) components have been evaluated for power consumption. This has shown that a complete system can be operated as an I-Safe device (Reference 35) with electrical characteristics within the safety constraints required for use in the $O_2$ pressure suit. Currently available COTS components require separate power and fusing for the computer with display, wireless network client and micro-drive (Reference 21), but recent advancements in components due to be available during 2003 would clear the way to design a single device capable of meeting the constraints (Reference 36).

Additional features that can be enabled using this technology include Voice over Internet Protocol (Reference 37) for redundant voice communications, voice recognition, text to speech, enhanced biomedical sensor interfaces (References 38 & 39.), remote streaming video / mega pixel imager over IP and location aware services (Reference 40.) over 802.11 wireless network to support context-driven applications. Improvements to the communications carrier assembly (CCA) headset performance by inclusion of Blind Source Separation or ICA, phased array microphones, and noise canceling earphones can be incorporated along with the wearable computer system (Reference 41).

It has been demonstrated that a wearable computer and wireless communications system can be made from available commercial components to meet functional requirements for delivering text, graphics, images and video to an individual inside of a ground test EMU pressure suit (Reference 42). Constructing a space qualified version now appears to be achievable in the near term using COTS components.

## INTEGRATION AND INFORMATION FLOW MODELS

The preceding discussion of EVA information system applications and needs makes it evident that much of the potential value they offer is connected with the ability to share information in real time. The ability to store and access data and images and to display the output of sensors and systems that are part of the spacesuit system has great value. However, the ability to share that information in effective collaboration with other EVA or support personnel and to gain effective access to information generated outside the spacesuit system in response to changing mission needs and conditions significantly multiplies the benefits. In addition, the information interface will be most valuable if it can also serve the astronaut's need to interact directly and effectively with supporting robotic systems.

These interactions require the information interface within the EVA spacesuit system to be effectively integrated with a wider net of data communication systems. They demand tools for not only accessing and displaying data, but also for annotating, modifying, and describing them and controlling their transmittal. The development and use of these networks and tools in the context of both the ISS and future planetary exploration missions are being investigated in current research studies.

### POTENTIAL FOR IMMEDIATE AND LONG-TERM ASTRONAUT SUPPORT ON ISS

Wireless communication technology, coupled with recent advances in miniaturization of computers and head-up displays, as well as human factors science, offer us new capabilities that have not been available in the past. Whether we are considering the immediate future, or long-term astronaut support, there are two ultimate goals, interrelated to each other: 1) enhancing crew performance to enable new tasks and operational modes or decrease training requirements and 2) preventing performance deterioration by refreshing or supplementing task training while maintaining safety on at least the same level as before. Below, we outline several opportunities for an EVA information system coupled to an external wireless data network on ISS to support these goals and play an important role in future EVAs.

Annotated Graphics

Published sources indicate that annotations added to features in real-world scenes provide a significant improvement to the technical workflow process. Annotations provide substantial advantages for communicating task details, and in conjunction with the augmented reality (AR) technology, can be used to improve human performance (Reference 44).

A comprehensive database for EVA may incorporate collections of voice annotations, previous EVA still and video footage, Neutral Buoyancy Laboratory training, mockup assembly, or real-time footage from remote cameras deployed at the workplace. The augmentation process would include adding annotations and other media features, as necessary. The end product would be an integrated uplink to the astronaut and could be played on demand. With the envisioned information interface and network, this kind of task support could be provided to an EVA astronaut in real time during an EVA and adjusted flexibly as required by variations in task flow or hardware conditions.

A simple example of such annotation was created for the deployment sequence of International Space Station (ISS) S0 truss segment strut during flight 8A and is illustrated in Fig 3.


Fig. 3 Visual and text aid annotations that identify the locations on the vehicle and operations to be performed. The procedure could be annotated by voice or supported by real-time voice communications.

Spatial Disorientation and Tactiles

When determining orientation in 1-g environments, the human brain utilizes input from a number of sensory channels and vision, the phenomenon known as proprioception. This sensory information also gives us a sense of movement and force. In aerospace environments, however, the proprioceptive sense often provides useless or illusory information (Reference 44). The fact that the U.S. military loses roughly 20 aircraft and 20 officers per year as a result of spatial disorientation mishaps illustrates the seriousness of this problem. As a result, orientation in such environments is currently performed by vision alone. Providing an EVA crew member with an indication of contact with the structure and type of contact (flat surface or sharp, temperature, etc.) and force feedback will significantly contribute to task performance and safety. The concept of a Tactor Locator System (TLS) has been developed to increase an astronaut's situational awareness. The prototype was characterized as a non-intrusive, intuitive display capable of conveying position and velocity information via a vibrotactile stimulus applied to the subject's neck and torso (Reference 18). The ability to track the astronaut's location and orientation and send the resulting data to the tactile display will significantly reduce the level of spatial disorientation and, therefore, improve safety during EVA.

EMU Interfaces

Designing smart interfaces between the EMU and imagery, operational and other pertinent information databases on board the vehicle and on the ground is imperative for improving EVA performance and mission safety. Redundancy, advanced error correction protocols and decentralized approach to the suit information system will allow not just sensors, but entire components to fail without degrading the performance of the entire system. In the long term, the idea of context awareness for the EVA should be extended to better correlate with the EVA location and task. Real-time dynamic link of the context to the specific support information will be crucial to productivity and mission safety. A significant effort on application of a wearable situational awareness terminal for EVA and development of software requirements may be found in Reference 21.

Summary

Based on recent progress in the field of information technology and sensor applications, EVA operational information software and hardware can be easily reconfigurable and, in the long term, plug-and-play, much like modern ad hoc wireless local area networks (WLANs). In order to aid a future EVA crew member to conduct routine or emergency operations, the following features are deemed essential:

- navigational information in the form of local 3D map and astronaut current position and orientation, updated with sufficient frequency (optical tracking, IR, RF, etc.) to the video display (short term) and tactile display (long term)
- Visual information related to the task (short term). Augmented panoramic or local view (long term).
- Audio and text to complement visual information (short term)
- Visual information on the EMU critical systems (long term)
- Real-time collaboration with remote resources (ISS - short term; ground – long term)

TOWARD PLANETARY EXPLORATION EVA INFORMATION SUPPORT

The most significant differences between ISS operations and planetary exploration mission demands on the integration of EVA information interfaces are expected to be in the distances over which information must flow and in the uncertainty that characterizes the process. Together these factors may dictate significant differences in appropriate technology and system solutions.

On ISS, EVA network communication distances can be limited to the scale of the space station itself with relays used for linkage to the Tracking and Data Relay Satellite (TDRS) and ground support. All aspects of the system and its application can be well characterized a priori. The size, shape and arrangement of modules, location of task sites and EVA translation paths, etc., are all well known, and the communications infrastructure supporting the EVA wireless network can be selected to optimize performance. Likewise, the information content and formats required can be anticipated with a high degree of confidence even while providing significant flexibility in information support to a particular EVA.

For planetary exploration EVA missions, network communication distances will be substantially greater. EVA's during the course of an extended planetary exploration mission can be expected to range at least tens of kilometers from the landing site and habitat. With pressurized rovers envisioned in some mission scenarios, these distances could expand to hundreds of kilometers. By the very nature of exploration, the precise routes covered in these EVA's will be subject to change and the terrain characteristics for radio propagation somewhat uncertain. Mission constraints will ensure that data communications must be supported by a sparse infrastructure with a limited number of ground relay stations and orbiting satellites to support network continuity throughout the EVA's. Constraints on EVA system mass and volume also mandate limited power for EVA communications, especially from systems within the EVA spacesuit itself.

To respond to these challenges, it is essential to understand the real needs for EVA information support in exploration mission contexts as accurately as possible. Definition of the types and amounts of data to be transferred, and of acceptable limits on quality of service parameters such as availability, latency, etc., is essential to make sure that the mission can be accomplished without unacceptable penalties.

To minimize the penalties that are imposed to achieve information support, a robust network architecture is envisioned. The system must be flexible and respond to changing links among EVA astronauts, rovers, robotic assets, orbiting satellites, ground relay stations, habitats, and Earth as exploration traverse routes and terrain features open and close specific communication paths in largely unpredictable patterns. Within such an architecture, relatively low-power communications in astronaut-worn systems can be linked to the habitat or landing vehicle, and ultimately Earth through higher power systems on rovers, satellites, or ground relay stations to minimize the adverse effects of distance. Line of sight or other terrain related problems can be overcome through the ability of the system to develop changing relay linkage patterns as conditions change through the EVA and by using next-generation Non-Line-of-Sight (NLOS) communication systems. Advanced radio communication technology will support this architecture by minimizing the adverse impacts and using the positive results of multipath and optimizing the use of available power and bandwidth [References 45 – 47).

Over the past five years, the NASA Haughton Mars Project (HMP) has provided an important venue for evaluating and developing these needs, architectures and solutions. By combining scientific activity and technology in a geographic area and geological setting similar to anticipated Mars planetary exploration sites, it provides an essential complement to existing commercial and military networking and communications development activities. This has included the development of field experience that highlights the limitations of common commercial protocols (such as 802.11b) in this setting [References 16 & 47] and the evolution of advanced collaboration systems (Figure 4) for dealing with the barriers of space and time (including long propagation delays) inherent in earth-based support for Martian exploration EVA's [Reference 45].

SOME RECENT EXPERIMENTATION AND RESULTS

During 2003, collaborative experimental programs aimed at the use of commercially available hardware to develop a better understanding of EVA information interface usage and integration continued with both laboratory and field experiments. Laboratory experiments provided relatively high fidelity experience in a pressurized space suit, while the field program offered lower fidelity testing using mock-ups but took place in an operationally relevant remote exploration setting. Together, they have allowed the investigation of a variety of potential applications and modes of use for the information interface.

Field experimentation (Figure 5) took place, as in the past two years, as part of NASA's Haughton Mars Project (HMP) and built on the results of prior studies (Reference 48) to improve test systems and introduce additional capabilities. Activities took place over a two-week period and involved the cooperation of field scientists and technologists working on exploration communications systems and wireless network development and exploration rover concepts as well as the EVA information interface team. As in previous years, the experimental program took advantage of the

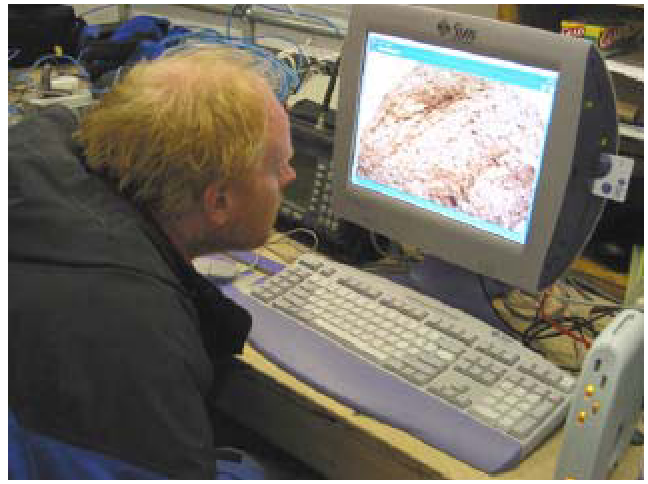

Figure 4. Field experiments have evaluated advanced collaboration systems for planetary exploration. (Photo NASA HMP)

Figure 5. Field experimentation at the Haughton Mars Project provided applications experience in a relevant environment and input from scientists. (Photo NASA HMP)

flexibility provided by the mock-up test bed and the presence of multiple investigators and varied equipment at HMP. Two different display configurations, several computers, and multiple input devices and networking configurations were investigated. Highlights this field season included:

- Integration of sun-visor and sun-shade with the field test mock-up suit to better test information display operation under ambient lighting conditions.
- Tests with augmented vision using a small camera at the end of a staff to produce near real-time images displayed on the EVA information interface.
- Integration of navigation aids and mapping software.
- Enhanced information system voice control experimentation.
- Enhanced wireless networking experiments and extended tests with remote control of information interfaces by support personnel.

In addition, support was provided to NASA experiments comparing the application of telerobotic exploration and telescience to human EVA exploration and field science as part of the NASA Ames Research Center MEX-HORSE study (Reference 49).

Field test results confirmed the advantage of an in-helmet information display. Use of a very low-power, full color VGA display in full daylight was successful with good readability of the display with the use of sun visor and sun-shade as anticipated in an operational EVA system. This contrasted with experience without the sun visor and shade the previous year when it was necessary to operate the display in a higher brightness, monochrome mode under daylight conditions. This earlier experience is indicative of the need for substantially higher power in a display outside the helmet.

Suit-integrated augmented vision tests extended earlier remote camera and wearable computing-based augmented vision experiments at HMP to integrate the camera with the mock-up EVA system. They demonstrated significant potential value for planetary exploration and field science by allowing safe examination of locations (e.g. over the lip of a cliff) that could not otherwise be reached by the EVA explorer. They established the fact that useful visual information could be provided even with rudimentary systems and showed what camera and display control interfaces were likely to be required in the field.

Experimental use of mapping software and navigation aids demonstrated the ability to use topographic map information with the in-helmet display and the potential utility of these tools over a wireless network to enhance collaboration between EVA crew and support personnel in a habitat or vehicle. Unfortunately, software integration issues in the field prevented planned experimentation of mark-up of mapping data using varying EVA information interface input modalities. Collaborative mapping, supported by remote IVA crew control of EVA computer system was, however, successful, consistent with prior years' experience. This demonstrates one use of the wireless networking connection to relieve crewmembers of complex human-computer interactions during EVAs. These and other processing-intensive experiments highlighted the importance of providing capable processors to meet the varied and somewhat unknown demands of the planetary exploration environment (References 16 and 46). Field equipment failures also reinforced the need for robust field hardened equipment like the Xybernaut computers used for some of the experiments. (Reference 50).

Significant progress in information system voice control was demonstrated as a result of work on the development of a limited vocabulary control interface. Results with large vocabulary speech recognition for the capture of field notes, sample records, etc., continued to be disappointing, indicating a need for substantial further development in this area. One significant factor in this result was the impact of wind noise in this year's experiments. This may be an artifact of the terrestrial analog environment (Mars' atmosphere is much less dense) and of the partial mock-up used in these tests which allowed wind and ambient noise to enter at the bottom of the HUT. Base camp-based tests of context-dependent VXML-based speech recognition and interaction with remote computing resources in the windy Devon environment continue to be highly successful.

The results of wireless networking experiments were compromised by interference among multiple commercial systems assembled to implement local and wider area communication nets, but significant progress was achieved. Effective operation of the interface as an EVA support collaboration tool was demonstrated. This included its use to display relevant field science support imagery in response to real-time exploration events. Both remote operation of the display system by support personnel with conventional input devices, (mouse and keyboard), and direct control by the EVA crew using voice control and touch pad were successful, although significant room for interface improvement remains.

Integration and use of a head-mounted information interface in a pressurized space suit was investigated in two tests using a ground test EMU in a laboratory setting. In these tests, a Micro-optical display was mounted to the temple of a pair of eyeglasses (with plane or prescription lenses depending on the needs of the test subject). In the first of these tests, the display was driven by an IPAQ pocket PC inside the suit which, in turn, was networked through a wireless card to test control computers outside the pressure suit. In the second test, the configuration was similar, but the IPAQ was replaced by a similarly sized Toshiba e740 with a more capable processor and integrated 802.11b wireless, and the display was upgraded from 320x240 pixels to a full VGA unit with wider (17° vs. 10°) field of view. This provided an extremely compact hardware configuration in the suit, but in both tests restricted the system control options to remote control of the displayed information by the test operator.

Figure 6. Wireless network operation of a head-mounted display in a pressurized EMU demonstrated potential utility.

The first of these tests (Figure 6), was used to verify the operability of the test system in pressurized suit operations and to verify that display readability in the suit would support useful information transfer throughout a test run. Important results included:

- Wireless networking through the suit with the PCMCIA card link was effective and robust over laboratory scale distances with no evidence of problems due to test subject motions or attitude changes during testing.
- Display visibility and readability was sufficient to support test activities involving both text and graphic image recognition. Text was most readable at 14 font or larger.
- The display did not interfere with direct task and environment visibility.
- The display did not interfere with head mobility or positioning for task activities within the helmet, and display position remained sufficiently constant for readability throughout the test.
- Establishing the desired display position on the head inside the EMU's helmet presented a major challenge. It was not possible to pass through the neck ring without disrupting the desired alignment, and it was reestablished with the helmet partially in place only with great difficulty. This integration challenge requires further work for other than research use of this configuration.

The second pressurized test series was performed after testing at Devon Island and sought to build on that field experience as well as the prior laboratory tests. It was intended to provide a preliminary evaluation of the in-helmet display as an aid for realistic EVA hardware tasks of some complexity for which extensive task-specific training is not practical.

For this purpose, a restored Apollo portable life support system (PLSS) backpack was selected as the "unit under repair", and two test subjects were selected who had substantial experience in the suit, but no specific familiarity with the Apollo PLSS. Two multi-step task sequences were developed each involving a variety of inspection and manipulation tasks on the PLSS. Nominally, each task sequence was planned for approximately 10 minutes total execution time. Each sequence was documented in a step-by-step set of instructions and in digital photographs of the hardware that were annotated to mark the items or locations involved and indicate required actions. The verbal instructions were prepared in the form of a cuff check-list package for each sequence, and combined with the photographic records as a series of images for computer display. An example is shown in Figure 7.

Prior to donning the pressure suit, each test subject was given the opportunity to review the test sequences and photographic documentation (but not the hardware itself) and to ask questions about the hardware and planned operations. This phase of the program continued to the satisfaction of the test subject and was not time constrained.

Subsequently, the suit was donned and the test subject performed one of the test sequences using only the cuff check list information. The other test sequence was performed with the assistance of the in-helmet information interface which displayed the combined verbal and graphical information appropriate for each task operation. In both cases, verbal assistance from an observing EVA support "crew member" was also available throughout the test. In order to minimize test biases, test subjects performed the opposite tasks with and without the display support. In addition, one performed the display-supported task first while the other worked first with the cuff checklist.

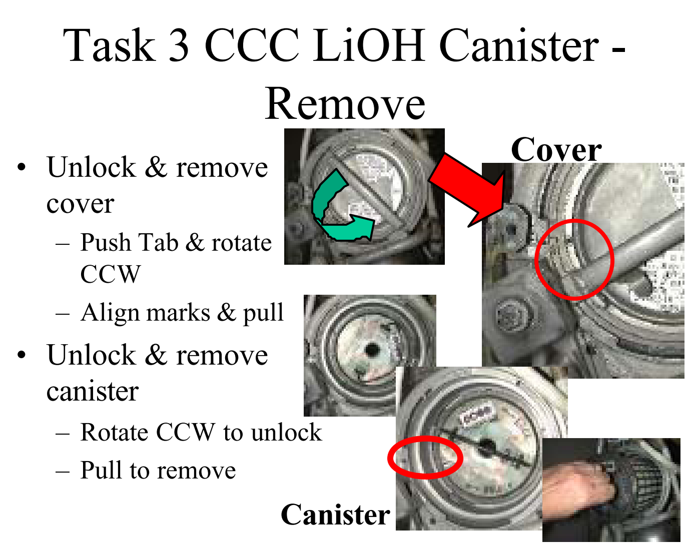


Figure 7. The information interface made both text and graphical task support information available hands-free during task performance.

Post-test comments from both test subjects indicated that task completion was much easier with the in-helmet display and that there was no interference with any direct vision or mobility. Quantitative results illustrated in Figures 8 and 9 were consistent with these comments. There was a significant decrease in the time required to accomplish the tasks with the use of the information display. Results were remarkably consistent for both test subjects and test sequences. There was also a measurable decrease in the need for verbal support.

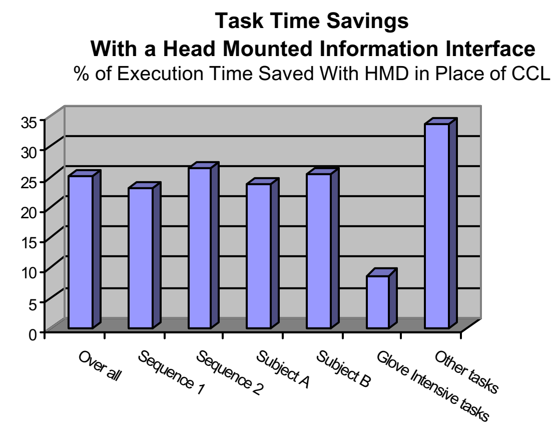


Figure 8. An advanced information interface can significantly reduce task performance time.

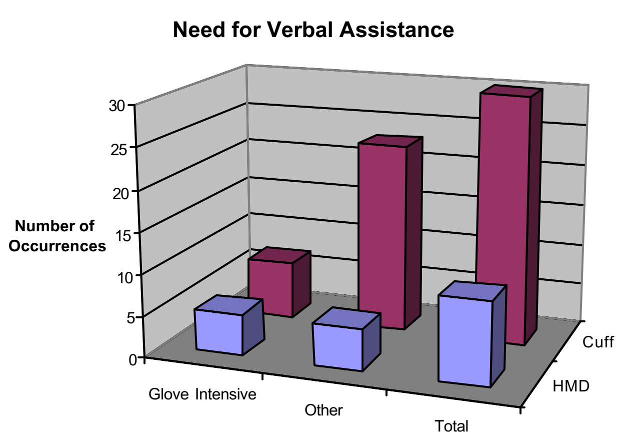


Figure 9. An advanced information interface can reduce the need for IV support to EVA tasks.

## CONCLUSION

Rapid development of hardware and software technologies for the communication, management and display of information has characterized the decades since the design of current extravehicular activity systems. As a result, there is a real potential to provide far more capable information support to EVA astronauts today than was originally included in the system design. Over the same period, the scope and complexity of EVA operations has grown substantially to fit the capability demonstrated by EVA astronauts and the growing needs of NASA's increasingly complex space missions. This growth will continue as missions evolve beyond LEO to deep space construction and planetary exploration. This creates growing needs for EVA information support and the market "pull" to match the technology "push" of growing capabilities.

The characteristics of these present and evolving needs, as we see them, are summarized in Table 2. "Requirements" will ultimately emerge only as NASA develops concrete mission plans and system designs. Here, the term is used to encompass anticipated functional needs and the attributes and capabilities that will allow them to be satisfied. Both true requirements and desiderata are certainly included in this listing with the ultimate boundary between them to be defined in future study. As the comments on current capabilities in the table indicate, much remains to be done wherever that line is ultimately placed.

The challenges involved in integrating an advanced information interface into a space suit system and operating it successfully in space remain substantial. Finding the best path to making it truly useful to the astronaut will require answering myriad questions about information content, display location and format, control approach, data storage and processing locations, communication architectures and other system aspects. Numerous technology, human factors and operational research programs have been developing answers to these questions and have resulted in significant progress, but there has been no operational implementation to date.

The technology base for a capable system has emerged. Current, as well as future, EVA missions will benefit from its availability. The time is right for aggressive EVA information interface development to create a firm foundation for meeting future mission needs.

**Table 2. EVA information interface requirements and potential capabilities are well beyond those of current systems.**

| Requirements | Major Capabilities / Attributes | Current Operational Capability |
|---|---|---|
| **General** | Non-Interference | No |
| | Environmental tolerance | Yes |
| | System compatibility | Yes |
| | Availability in all light levels | Yes |
| **Task Execution Support** | Hands-free | No |
| | Text display | Yes |
| | Graphics display | Limited |
| | Flexible access | Limited |
| | Data input / capture | No |
| **Situational awareness** | | |
| Safety | Always available | Yes |
| | Real-time graphics display, video? | No |
| Hardware | Text display | Yes |
| | Real time graphics display | No |
| Work Flow | Text display | Yes |
| | Data input / capture | No |
| Navigation | Directional data display | No |
| | Real time graphics display | No |
| | Text display | No |
| **Collaboration** | Real time graphics display | No |
| | Graphics mark-up | No |
| | Verbal communication | Yes |
| | Image transmission | Yes |
| **In-Flight Training** | Graphics display | Limited |
| | Text display | Yes |
| | Authoring / near real time | No |
| **Robotic / Automatic Systems Interface** | Real time graphics display | No |
| | Graphics mark-up | No |
| | Precise positioning display and designation | No |
| | Text generation / mark-up | No |
| **Real-time planning** | Real time graphics display | No |
| | Graphics mark-up | No |
| | Text generation / mark-up | No |
| | Data analysis / real time modeling | No |
| **Documentation** | Real time graphics display | No |
| | Graphics capture | Photography |
| | Graphics mark-up | No |
| | Text generation / mark-up | No |

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Gratitude is also due to the Canadian Space Agency for funding of the PlanetNet and MarsCanada projects, which provided the major funding for Simon Fraser University's HMP-based EVA research as well as the Canadian Space Agency and the European Space Agency for funding under the REMSAT National Extension and REMSAT II projects, respectively, which provided computing hardware for EVA tests on Devon Island, as a component Technical Investigation of those projects.

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## DEFINITIONS, ACRONYMS, ABBREVIATIONS

3D: 3 dimensional imagery. Usually viewed using stenographic, binocular equipment, but can also refer to computer graphics imagery and other specialized electro-optical systems.

802.11: IEEE standard for wireless networking using unlicensed frequency bands. Currently in the 2.4GHz (B and G) and 5 GHz (A) spectrum.

AMLCD: Active Matrix Liquid Crystal Displays. A type of Silicon Microdisplay also common in flat panel and notebook computer displays.

AR: Augmented Reality. The addition of sensory information to real world information found in the use of see through head mounted displays using prisms

CCL: Cuff Check List. Laminated paper checklist attached to the cuff of the EMU in use since the Apollo program.

CCA: communications carrier assembly

CCC: contamination control canister

COTS: Commercial Off The Shelf. Readily available equipment, peripherals, components, software and accessories that can be obtained directly from manufacturers and distributors without special order.

DCM: Display and Control Module

e740: A COTS handheld computer or Pocket PC made by Toshiba with integrated 802.11b and user accessible compact flash adapter socket in a very thin form factor

EMU: Extravehicular Mobility Unit

EVA: Extra-Vehicular Activity. Activities conducted outside of a space vehicle.

GPS: Global Positioning System

Hands-Free: User interface where use of hand controls is kept to a minimum

Head Mounted: Attached to the head by an adjustable band, to a helmet, headset or eyeglass.

Head-Up: Information display superimposed on user's field of view.

HMD: head mounted display

ICA: Independent Component Analysis. A form of signal processing used for blind source separation of audio sources to remove noise and other unwanted sounds from a speech processing system.

IP: Internet Protocol

IPAQ: Brand name for a popular Handheld Computer similar to most Pocket PC products used by consumers for high performance mobile computing.

IR: Infrared

I-Safe: Intrinsically Safe. A rigorous set of standards for spark free equipment used around combustible sources such as oil rigs, gasses and flammable materials.

ISS: International Space Station

IV: Intra Vehicular. Activities coonducted inside a space vehicle.

LAB - ISS Laboratory module

LCVG: Liquid Cooling and Ventilation Garment.

LED: Light Emitting Diode

LEO: Low Earth Orbit

Micro-optical display: A complete optical assembly including silicon microdisplay, optics, head mount and cable produced by the Micro Optical Corporation, Westwood, Massachusetts, USA

MMU: Manned Maneuvering Unit

NLOS Non-Line of Sight

$0_2$: Oxygen

PCMCIA: Personal Computer Memory Card International Association. International standards body and trade association founded in 1989 to establish standards for Integrated Circuit cards used in mobile computers. Evolved into the PC Card Standard.

PLSS: Portable Life Support System used on the EMU

qVGA: Quarter VGA typically found in PDA hand held devices and equal to a resolution of 320x240 pixels

RF: Radio Frequency

SAFER: Simplified Aid For EVA Rescue

Silicon Microdisplays: An electronic display using silicon transistors and optics to present an image in a small form factor. Typically less than 25mm in diagonal

S0: Starboard Truss Assembly Number 0 on the International Space Station

SXGA: Super VGA

TDRS: Tracking Data Relay Satellite

TLS - tactor locator system

Touch Pad: A touch sensitive finger activated input device usually employed as a user interface on mobile computers.

VGA: Video Graphics Adapter. Standard computer graphics display developed in the early 1980s with 640x480 pixels resolution

VoIP: Voice over Internet Protocol. A method of transmitting audio over the Internet.

VXML: Voice Extensible Mark-up Language. Voice xML is a Meta Language similar to HTML (hyper text meta language) that provides for reuse of content across different computing platforms and viewing apparatus and supports a large number of specific implementations.

WLAN wireless local area network