Preliminary Considerations for Wearable Computing in Support of Astronaut Extravehicular Activity

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Abstract

Preliminary considerations for a wearable computer system for astronauts on International Space Station (ISS) during extravehicular activity (EVA) are discussed. The proposed system acts as a client on a wireless network external to the ISS, and provides text, graphics, audio, and video to astronauts using a near-eye display. Primary design considerations include astronaut safety, comfort, ease of use, operational simplicity, and cost. Requirements are highlighted for electrical design, in-suit thermal issues, the space environment, and EVA displays and controls. A suit-internal wearable computer system prototype is proposed. Suit-external components include a camera, video processor, and wireless access point, which provides access for both the suit-internal wearable and other potential wireless EVA tools. Future plans include development and testing of the prototype system.

1. Introduction

Wearable computing has the potential to enhance astronaut safety and performance by providing new or redundant support mechanisms for astronauts during extravehicular activity (EVA). Current predictions from the National Aeronautics and Space Administration (NASA) EVA Project Office estimate 168 days devoted to EVA for assembly and maintenance during the construction of the International Space Station (ISS) [1]. Wearable computing technologies are ideally suited for use during EVA because EVAs generally consist of well defined, tightly scripted tasks. Even in off-nominal situations, many tasks may be carefully scripted or follow contingency procedures. The requirements for a wearable computing system for EVA are constrained and bounded by a well-defined set of existing operational and engineering requirements.

The authors are currently engaged in a research project with the goal of developing a wearable computer prototype for use initially with the NASA space suit (the Extravehicular Mobility Unit, or EMU) and potentially the Russian Space Agency (RSA) space suit (the ORLAN suit). The system would provide text, graphics, audio, and video to an astronaut via a near-eye display while acting as a client on a wireless network external to the ISS. Figure 1 illustrates conceptual opportunities for visual information delivery during EVA as an astronaut might see them on a near-eye display.

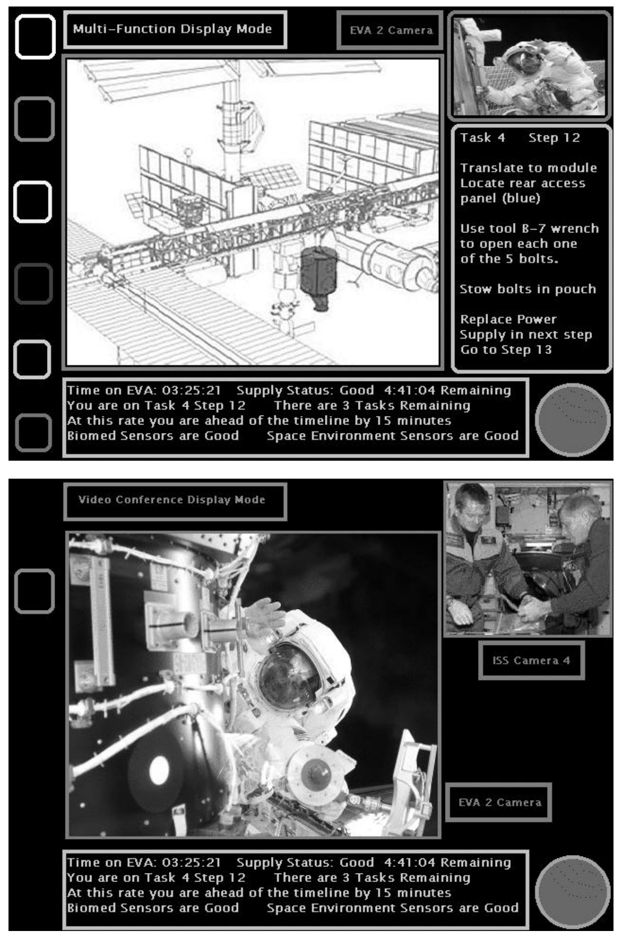

Figure 1 – Visual Information Delivery during EVA

The displayed information (along with audio capability) might be used to guide astronauts through a series of detailed procedures or provide timing, status, and safety information. Video-over-IP and voice-over-IP services could enable real-time videoconferencing between EVA astronauts and other crewmembers, or between astronauts and the Mission Control Center (MCC). Updated procedures, schematics, or images could be "uploaded" to the wearable computer and/or displayed on the heads-up display upon request.

This paper highlights important considerations in the development of a wearable computer system for use with the EMU.

2. Background

2.1 Types of EVAs

EVAs can be grossly characterized as planned, unplanned, or contingency (unexpected, but may be required for crew safety). For ISS EVA operations, there are planned and contingency EVAs [5]. Different flight rules apply for each type of EVA. EVA tasks or components can be characterized by their criticality, such as whether the accomplishment of a specific task would be safety critical, a requirement for mission success, or a mission enhancement. EVAs vary considerably in complexity: some EVAs require only a standard set of tools and skills, while other EVAs require specialized tools specific to a given task or mission. Finally, very complex EVAs may require both specialized tools and a "significant extension of capabilities" including challenging "access (or restraint) problems, or require extended duration or unrestrained translation such as with a propulsion maneuvering unit."[6]

2.2 Origins of the EMU and ORLAN suits

The EMU design has its roots in the space suits of the Apollo program, when an integrated portable life support system (PLSS) was developed to enhance mobility for surface exploration. Previous designs, used during the Gemini program, had provided life support function using a life-support tether. Development of the current-day EMU started in 1973, and it was first used on orbit in 1983. Evolutionary improvements have resulted in the suit that is currently used. The Russian ORLAN suit has evolved from the Salyut-Soyuz program, and has an integrated portable life support system.

2.3 Space Suits as Wearable Computers

In a sense, the EMU and ORLAN suits already meet one definition of a wearable computer[7]: They are portable while operational, capable of hands-free use, able to sense characteristics of the environment (at least the internal environment), are always on (during EVAs), and augment human capabilities.

The display and control module (DCM) of the EMU provides an alphanumeric display of life support status and allows the astronaut to control features of the life support system.

A suit-external independent electronic cuff checklist, developed to serve as a limited mechanism for astronauts to reference procedures or contingency procedures, was flown as a space flight experiment. Despite the success of this project, a wrist mounted paper checklists still serves as the primary written procedural reference during EVA.

2.4 Limitations of Extravehicular Activity

Major limitations during EVA include the need to cope with sensory degradation, the limited duration of EVAs, limited mobility, dexterity, force application, and endurance of suited astronauts, operations time and resource overhead requirements, working volume and access limitations, and hazards to crewmembers [6].

A system capable of mitigating some of these limitations might therefore (1) sense characteristics of the external environment and communicate those characteristics to the astronaut; (2) extend or augment the senses or capabilities of the astronaut; (3) enhance the efficiency with which tasks can be carried out, and (4) minimize any negative impacts on operations time and resource overhead.

The existing systems provide only limited capabilities of information transfer to or from an astronaut during EVA. The primary method of information transfer during EVA has been two-way voice communication over UHF. Life support parameters from the EMU are also sent over the UHF communication system to the Shuttle or ISS and from there via downlink to the MCC. An EMU TV camera has also been used to provide video coverage of EMU worksites. Figure 2 illustrates one of the limitations of the existing communications system:

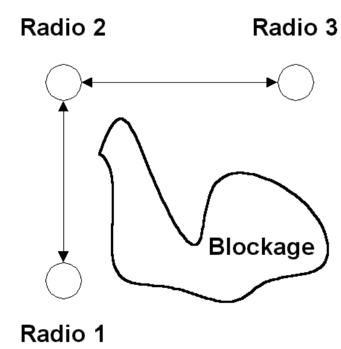

Figure 2 - Blockage scenario (redrawn from Extravehicular Activities Space-To-Space Communication System Training Workbook, p. 2-6)

Because of blockage, Radios 1 and 3 are unable to communicate with each other, although each can communicate with Radio 2. Radios 1 and 3 can have audio contact with each other only indirectly: the user of Radio 2 must relay audio messages.

Augmenting the existing time division multiple access (TDMA) UHF system with a wireless network would greatly enhance the ability to deliver information to astronauts during EVA. This information might be in the form of text, graphics, audio, or video and could provide up to date procedures or enable real-time bi-directional videoconferencing. Making wireless access points available at a number of points external to the ISS could eliminate the blockage scenarios possible in the current system by bridging external wireless LANs using the internal ISS network.

3. Design Considerations

3.1 Design Approach

We propose that an initial wearable computer prototype for the EMU should be an information delivery system, requiring minimal input or control by the EVA astronaut, and allowing information to be delivered remotely by an intravehicular activity (IVA) crewmember, or by the MCC. This approach offers significant benefits to EVA astronauts while minimizing any operational impacts of the system in terms of time and complexity. Incremental addition of capabilities could then be pursued commensurate with training and experience. Furthermore, the wearable computer system would function as an element for mission enhancement: not required for any EVA tasks, but used to support well-defined tasks at varying levels of complexity. It would serve to augment existing systems, not to replace them.

Our design approach relies heavily on near-term operational simplicity. This is consistent with the recommendations of Conners et al. [2] for future EVA system development based on interviews with the lunar surface astronauts. The astronauts recommended that future information displays should be simple and relevant to the current task, and desired safety related status information on a call-up basis. They were also supportive of visual displays for supporting operational tasks, and felt that both visual and aural communication links would be valuable.

3.2 Design Goals and Challenges

Maintaining and promoting safety is the primary EVA wearable computer system priority: First do no harm. Second, it is critical that the system is both comfortable and easy to use. Third, the system should have minimal negative impact on existing operational processes. Fourth, the system should be based on existing technologies and should require minimal modifications to existing flight hardware.

3.2.1 Safety

For components inside the suit, safety considerations include operation of electronics in a 100% oxygen atmosphere, out-gassing off-gassing issues, thermal restrictions, and the severe space constraints imposed by the close-fitting hard upper torso of the suit. Components outside the suit may have fewer environmental constraints, but must withstand the harsh environment of extreme temperatures and vacuum, and, to a much lesser degree, exposure to elemental oxygen, plasma, and micrometeoroids. Safety considerations will be addressed further in the technical requirements section.

3.2.2 Comfort and Ease of Use

Achieving comfort and ease of use requires an innovative user interface (both displays and controls) and form factor. For an in-suit wearable, comfort dictates that the computer be body-conformable and maintains a comfortable surface temperature. Ease of use requirements imply that the user should interact with the computer in a way that is natural to the EVA environment and requires little mobility on the part of the astronaut. Voice control is one option, but is an unlikely candidate because of the potential for interference with existing audio communications, especially given the central role that these communications have played throughout the history of EVA. A solution that requires no movement on the part of an astronaut, and only indirectly may involve audio communication, is remote control of information delivery to the EVA astronaut by IVA crewmembers or the MCC. IVA crewmembers and MCC flight controllers follow EVA progress very closely, and could direct specific information to an EVA astronaut either by prearranged understanding or at the request of the EVA astronaut.

Locating and positioning a visual display is also a significant challenge. There are many objects inside the suit near the eyes and face including the communications carrier assembly (CCA, or CommCap, which is basically a pair of headphones and redundant noise canceling microphones), a drink bag, food stick, and a valsalva device (used for equalizing pressure in the ear canals during suit pressure changes). This limits the space that can be allocated to a suit-internal display. Implementing an effective suit-external display would also be a significant challenge because of positioning and illumination requirements. An external fixed position display does not allow the display to move along with head movements of the astronaut, while an internal display embedded in a pair of standard EVA glasses (with proper prescription for a specific astronaut, or a blank prescription for astronauts who do not require glasses) enables a display to occupy a constant solid angle relative to the head of the astronaut. This could be accomplished using an eyeglass or clip-on micro-display. The varying lighting conditions external to the suit, and the visors used to limit light entry into the helmet, further complicate the development of an external visual display.

3.2.3 Operational Simplicity

Operational simplicity in the donning, utilization, doffing, and maintenance of a wearable computer system for EVA is imperative. Integrating the operational procedures of the wearable computer system into preexisting EVA procedures drives what hardware interconnect configurations are desirable. If a suit-internal wearable computer is used exclusively for EVA (as opposed to a dual use system for both IVA and EVA) the wearable computer system CPU could be stowed attached to the liquid cooling and ventilation garment or LCVG (which regulates internal suit temperature during EVA and assists in circulation of breathing gases) so that donning of the wearable computer would be accomplished by simply putting on the LCVG. Similar considerations might apply for other components of the system.

Operational simplicity during EVA requires careful choice of audio or tactile controls. Traditional hand-based user interface tools may be extremely challenging and generally undesirable due to the physical exertion requirements of moving stiff space suit gloves. Internal tactile controls, or simple external controls (such as buttons or switches) are possible, but must be evaluated with respect to the burden they impose on the astronaut. External tools also pose system integration challenges such as crossing the suit pressure barrier. External tools could also act as additional wireless network clients – this, however, increases the checkout and maintenance burden by requiring battery change-outs or tool recharging, and may also complicate software development.

Voice communications have played, and will continue to play an integral role during EVAs. In addition, IVA crewmembers and MCC flight controllers are often focused on supporting EVA astronauts during EVAs. As such, audio requests for information delivery fit naturally within the current operations framework and allow for a natural language interface not yet possible through voice recognition systems.

3.2.4 Cost

A reasonable delivery cost estimate for the flight version of an EMU might be between $10-20 million. The ORLAN suit is significantly less expensive and is designed to support a higher number of sequential EVAs, but supports a lower number of lifetime EVAs because it lacks a refurbishment capability. Changes to existing hardware are both prohibitive in cost and in risk: any changes must undergo lengthy evaluation especially when such changes may involve any risk to human life. Reducing programmatic risk will therefore tend to reduce development and certification costs. The major limitation this imposes upon a wearable computer system for EVA is a minimization of physical connections across the pressure barrier of the suit. This implies that it is necessary to carefully segment the wearable computer system into suit-internal and suit-external components.

4. Technical requirements

This section highlights some of the existing NASA requirements for EVA systems and outlines their relevance to the development of a wearable computer system for EVA. Prototype development need not produce a wearable computer system that meets all of these requirements. However, the prototype system should be consistent with the design implications of the flight system technical requirements.

4.1 Applicable NASA Requirements Documents

NASA's extensive experience with human space flight systems has resulted in an extensive set of guidelines and requirements for human space flight systems called the Man-Systems Integration Standards[6]. However, for EVA, a more detailed, definitive, and up-to-date source of requirements has been developed by the NASA Johnson Space Center EVA Project Office: the *EVA Hardware Generic Design Requirements Document*[4] is designed to assist project implementation from "concept through development, fabrication, and certification" and is consistent with EVA requirements for both the Space Shuttle and International Space Station programs. Both references are considered for the wearable computing system to assist EVA.

4.2 General Electrical Design

For fire safety in the oxygen-enriched interior of the space suit, currents are limited to 0.5 Amps at a (maximum ground level) operation pressure of 130 kPa (20 psia, due to atmospheric pressure and standard suit differential pressure operations). Current limiting circuit protection devices are also mandatory to preclude fire, smoke, explosion, or arc-over. The NASA standards (JSC-26626A and NASA-STD-3000) recommend against mating or de-mating powered connectors, and require that connectors have key and positive-locking mechanisms, and protective caps when connectors are uncovered. Electronics must be designed to survive in the ionizing radiation environment of low earth orbit. Batteries must be two-failure tolerant to catastrophic events, and are typically lot-checked to achieve well-matched cell capacities. Keep-out zones need to be developed near non-ionizing radiation sources such as transmitters. Existing translation paths incorporate knowledge about recognized dangers, including intentional transmitters.

Current limitations suggest that a low power CPU core will be required for an suit-internal wearable, and that careful power design will be required to ensure all currents are less than 0.5 amps. Compatibility of existing wearable computing technologies with the low-earth-orbit ionizing radiation environment needs to be evaluated. Few space qualified battery technologies can be packaged in a body conformal profile – lithium polymer batteries show great promise but have not yet been flown in space. Finally, the low power requirements for relatively short-range wireless networking should pose little direct risk of exposing crew members to non-ionizing radiation.

4.3 In-Suit Thermal Requirements

In suit surface temperature (or "internal touch temperature") must be between 10? and 43? C. An internal wearable computer tends to reduce the maximum metabolic heat removal capability of the LCVG because the LCVG would need to remove both excess body heat and waste heat from the wearable computer system. However, since the use of the Apollo-era LCVG, cooling has not been a limiting factor in meeting metabolic load requirements. Currently the EMU must support sixty minutes at a metabolic load of 293 watts, and a sustained minimum metabolic load of 73 watts[6].

Our present design criteria of < 15 watts should not have a significant effect on the ability of the LCVG to adequately cool an astronaut in the EMU. The flat profile required because of in-suit volume limitations will provide a large surface area for cooling of the CPU (a primary generator of waste heat) and may even enhance astronaut comfort: The external ISS EVA environment is, on average, significantly colder than the Space Shuttle EVA environment. In addition, the space station will not be rotated to provide optimum sunlight conditions for temperature regulation during EVA (as is often done during Shuttle operations).

4.4 Space Environment

Extreme non-operating temperatures for EVA in the ISS space environment range from -157?C to 149?C while operating temperatures range from -129?C to 121?C. External pressures can range from a surface maximum of 15.23 psia to $1x10^{-10}$ torr in the near vacuum of low earth orbit. Equipment in a suit or an airlock may also need to survive emergency pressurization or depressurization at rates of 0.76 psi/sec and –0.3 psi/sec respectively. Equipment in the space environment will also face high levels of solar ultraviolet exposure, natural and induced plasmas, corona, and atomic oxygen ($5.0x10^{21}$ atoms/cm^2/year). Collisions with micrometeoroids and debris ranging in mass from 1g to 10^{-12}g are also possible.

Design criteria for suit-external wearable components are clearly extreme, and constitute a major reason to design a suit-internal wearable, even given the challenges associated with that option.

4.5 Controls and Displays

Suit-external controls and displays must be located in specific work envelopes defined by NASA standards [6]. These work envelopes are cylindrical boundaries within the EVA astronaut field of view, which is shown in Figure 3. Work envelopes related to space suit joint torque constraints, perhaps more functionally relevant than the existing NASA standard, can also be constructed [8].

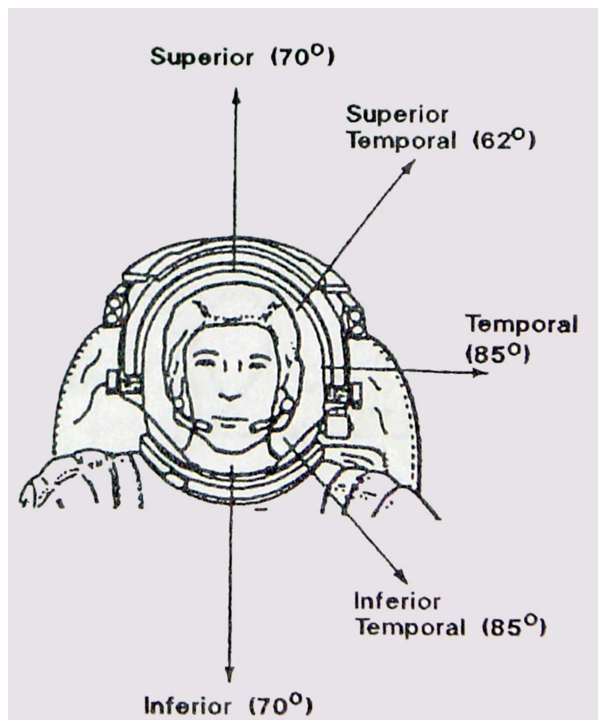

Figure 3 - EMU Field of View (from NASA Man-Systems Integration Standards, page 14-20)

Standard worksite tools can be used to help position tools within these work envelopes. Controls and displays should also be reachable from a neutral body position, compatible with the bulky EMU gloves, and should have a maximum finger actuation force of 9 to 44 N or a maximum required torque of 3.4 Nm (this torque includes only the torque required to manipulate a worksite tool and does not account for the torque required to hold a given body position within the space suit). Battery powered tools should be designed for battery replacement capability at the EVA worksite and should have charge status indicators.

An external visual display (and the apparatus required to secure its position) may obscure a central portion of the astronaut's field of view and work envelope. An internal display may present similar difficulties unless a see-through display is available. A near-eye micro-display integrated into a pair of standard EVA glasses could provide an adequate visual display that could be turned off or adjusted to prevent visual conflicts between the display and the physical environment. It would also be easier to ensure that a suit-internal display would be readable in a variety of external lighting conditions.

A camera and video processor mounted on the helmet of the EMU could provide perspective to the ground of the EVA worksite. Currently, an EMU helmet-mounted camera (EMU TV) can provide a one-way EMU-ISS video link. Views captured by the EMU TV are therefore limited by the position and orientation of the space suit, and no video images can be provided to an astronaut during EVA. A wireless remote camera system could be used to extend the senses of the astronaut or ground crew to locations that are difficult to see because of scale or reach: this new EVA tool might be called something like a "wireless camera on a stick" and could complement free-flying micro-satellite-type video cameras that have recently been proposed and demonstrated such as the NASA Johnson Space Center "Aircam."

4.6 Operational Life

Operational life specifications require that non-suit EVA hardware be designed for up to 100 space shuttle missions (for Space Shuttle specific equipment) and up to 10-year on-orbit durations (with required maintenance). Space suit operational life requirements are suit dependent: EMUs are designed for single-mission, multiple-EVA usage followed by refurbishment prior to re-flight. Operational life requirements for a wearable computer system have yet to be defined.

5. Prototype Development

The above requirements suggest that a suit-internal wearable computer system would be potentially more advantageous than a suit-external wearable computer system because of display positioning issues, the challenges of connections across the suit-pressure barrier, the less stringent environmental extremes within the suit, and the flexibility for an suit-internal design to evolve into a dual use EVA/IVA design at some point in the future. A suit-internal design does suffer from a lack of access during EVA: safety is the primary concern here that will need to be addressed as the design evolves. Admittedly, a suit-internal wireless system might require multiple antennas (because of potential blockage), and would increase astronaut non-ionizing radiation exposure and complicate donning and doffing procedures.

Figure 4 illustrates one possible prototype system under consideration that would utilize a suit-internal wearable computer system with a suit-external wireless access point and helmet mounted video camera and encoder. A low power CPU core and batteries would be packaged in a body conformal form factor (potentially in the abdominal area or in the small of the back). Potentially, something not too dissimilar from StrongARM™ technology found in recent commercial products could be used. A near-eye display could be integrated into a standard pair of EVA glasses: this might be not unlike the current VGA-resolution embedded-glasses display prototypes produced by MicroOptical Corporation. Cabling could be routed through the LCVG so that it would not interfere with existing donning and doffing procedures. The audio and display cabling might also be physically integrated with the CommCap (CCA) cabling to simplify donning and doffing procedures.

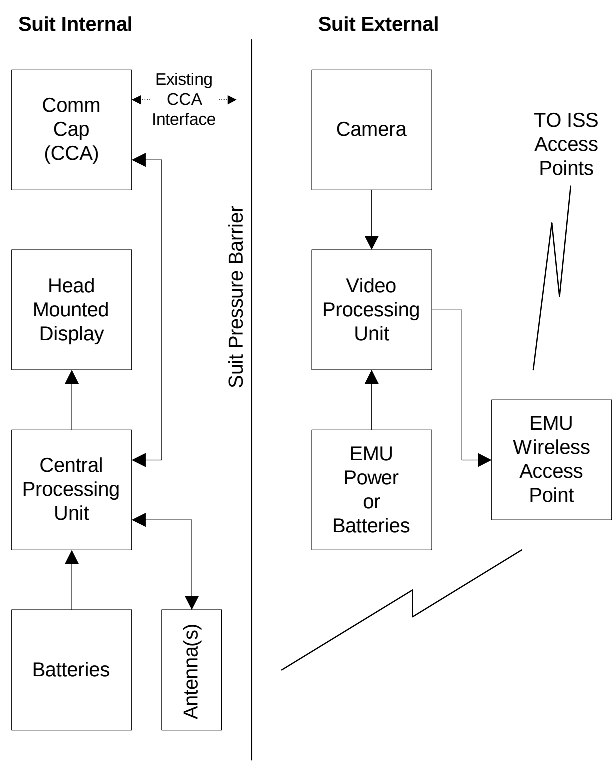

Figure 4 - Potential Prototype Block Diagram

Significant functional integration of the wearable computer system with the existing CommCap (CCA) would raise the criticality of the wearable computer system: it may be desirable to physically but not functionally couple the wearable computer system with the CommCap (CCA). Modifying the existing CommCap design slightly to include an additional independent audio in/out capability would allow for functional independence between the existing audio system and the wearable computer audio system.

The suit external camera system would be similar in function to the current helmet mounted EMU TV, but it would also serve as an wireless access point for the suit-internal wearable computer system and possibly for other wireless EVA tools such as the "camera on a stick" to which we have previously referred.

6. Conclusions & Future Directions

The research project to develop this system is still ongoing. While a preliminary concept for a prototype system has been developed, we are still in the process of trying to understand how our proposed wearable computer system can best support astronaut safety and performance during EVA. Over the next couple of months we will further refine our wearable computer system prototype design, with significant input from astronauts and other stakeholders. Over the next year we seek to deploy a prototype system for test and evaluation.

7. Acknowledgements

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8. Glossary of Terms

CCA	Communications Carrier Assembly
CPU	Central Processing Unit
DCM	Display and Control Module
EMU	Extravehicular Mobility Unit
EVA	Extravehicular Activity
IP	Internet Protocol
ISS	International Space Station
IVA	Intravehicular Activity
LCVG	Liquid Cooling and Ventilation Garment
MCC	Mission Control Center
NASA	National Aeronautics and Space Administration
RSA	Russian Space Agency
TDMA	Time Division Multiple Access
VGA	Video Graphics Adapter
UHF	Ultra-High Frequency

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