ABSTRACT

Interoperability Trends in Extravehicular Activity (EVA) Space Operations for the 21st Century

Gerald E. Miller, Manager, EVA Operations, United Space Alliance

No other space operations in the 21st century more comprehensively embody the challenges and dependencies of interoperability than EVA. This discipline is already functioning at an unparalleled level of interagency, inter-organizational and international cooperation. This trend will only increase as space programs endeavor to expand in the face of shrinking budgets.

Among the topics examined in this paper are hardware-oriented issues. Differences in design standards among various space participants dictate differences in the EVA tools that must be manufactured, flown and maintained on-orbit. Presently only two types of functional space suits exist in the world. However, three versions of functional airlocks are in operation. Of the three airlocks, only the International Space Station (ISS) Joint Airlock can accommodate both types of suits. Due to functional differences in the suits, completely different operating protocols are required for each. Should additional space suit or airlock designs become available, the complexity will increase. The lessons learned as a result of designing and operating within such a system are explored.

This paper also examines the non-hardware challenges presented by interoperability for a discipline that is as uniquely dependent upon the individual as EVA. Operation of space suits (essentially single-person spacecrafts) by persons whose native language is not that of the suits' designers is explored. The intricacies of shared mission planning, shared control and shared execution of joint EVA's are explained. For example, once ISS is fully functional, the potential exists for two crewmembers of different nationality to be wearing suits manufactured and controlled by a third nation, while operating within an airlock manufactured and controlled by a fourth nation, in an effort to perform tasks upon hardware belonging to a fifth nation. Everything from training issues, to procedures development and writing, to real-time operations is addressed.

Finally, this paper looks to the management challenges presented by interoperability in general. With budgets being reduced among all space-faring nations, the need to expand cooperation in the highly expensive field of human space operations is only going to intensify. The question facing management is not if the trend toward interoperation will continue, but how to best facilitate its doing so. Real-world EVA interoperability experience throughout the Shuttle/Mir and ISS Programs is discussed to illustrate the challenges and illuminate the potential pitfalls present for any technical discipline facing this trend of 21st century space operations.

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Introduction

Extravehicular Activity (EVA) is the space operations discipline providing the most tangible, visceral experience of human space exploration. During EVA's, humans are sent into the vacuum of space to perform those tasks that presently can only be performed by human hands, coupled with human senses and intellect. It is this very human nature of EVA that drives its need for interoperability as space operations expand in the 21st century.

Throughout the Shuttle-Mir Program and now in the International Space Station (ISS) Program, EVA has led the way in demonstrating interoperability. No other space operations discipline has been so deeply integrated between foreign partners. These experiences have proven that the economic and technological realities of human space flight are dictating for any space-faring entities (whether nations, agencies or companies) to succeed in expanding peoples' presence beyond Earth, interoperability is the trend.

As all space organizations struggle to expand their programs, even as their budgets are reduced, this will only continue to be truer.

Hardware Issues

The most obvious sources of interoperability requirements are differences in hardware. Even though equipment and tools have been designed to perform precisely the same jobs, in precisely the same environments, differences in operations philosophies lead to very different design solutions.

The Russian and U.S. space suits (Orlan and Extravehicular Mobility Unit (EMU), respectively) were both designed to sustain human life in the environment of space, while providing the wearer the ability to perform manual tasks. However, while the two suits may look similar on the outside, differences in underlying operational approaches have led to very different systems.

Neither is "better" or "worse" than the other. They simply were designed to fulfill different objectives. The resultant operational differences, which flow outward from these initial design differences like rivers subdividing into multiple streams, permeate virtually every aspect of hardware used for EVA.

Russia's Orlan suit was designed to accommodate a corps of cosmonauts with a very narrow limit on allowable size range. This allowed the Orlan to be built as a "one-size-fits-all" unit. It is a single piece with minimal re-sizing capabilities in the arms and legs. This greatly simplifies on-orbit maintenance, but also limits suit use to fewer people.

The U.S.'s EMU was designed to accommodate individuals ranging in size from the 5th percentile Asian female, to the 95th percentile Caucasian male. In order to meet this requirement, a "one-size-fits-all" design was impossible.

Multiple-sized components (medium, large and extra-large) and sets of sizing rings are needed to individually build up an EMU. Not only does this complicate on-orbit and ground maintenance, but flight manifesting and logistics must now consider the various sizes of crew and when each is scheduled to fly when processing flight hardware. The trade-off is that most people can be fitted to use the U.S. suit.

In order for the U.S. and Russia to combine their EVA expertise and capabilities, their differences had to be assimilated into one another's operations. The two systems had to become interoperable. As the consequences of these fundamental design decisions flowed outward, derived requirements resulted in an ever-widening set of hardware challenges to this interoperability.

Aside from the sizing differences in the two suits' hardware, functional variations had to be overcome. While both suits function perfectly well at vacuum, it is not physically possible for the EMU and Orlan to go to vacuum simultaneously in the same airlock.

Russia's Orlan was developed with a concept of centralized control of airlock and suit life support parameters. During airlock operations, the Orlan's systems are integrated via umbilici into those of the airlock. One individual controls the in-suit life support and airlock for both people in Orlans.

The operational philosophy of the U.S. EMU is based upon individual control. While umbilici are used as access to consumables (oxygen, power and water) during airlock operations, all mechanical functions are under control of the individual wearing the suit.

Thus, in developing interoperability between the U.S. and Russian EVA systems, a new airlock was required. The Joint Airlock onboard ISS can accommodate either the Orlan or EMU by changing out control panels in the airlock.

The resultant interoperability provides a more robust EVA capability for the station. Depending on the tasks required, suit familiarity, consumables conservation or suit failure contingencies, the ISS Joint Airlock can be used for space walks by crewmembers wearing either suit. As derived requirements for interoperability propagate further outward from differing suit design philosophies, hardware outside the airlock becomes affected.

Because EMU's make use of custom gloves to accommodate individual crewmembers, higher dexterity is possible. Differing hand dexterities between suits mean when a common tether hook (for use by either suit) was required, significant design challenges arose.

Adding to the dexterity challenges are differences between handrail (where hooks are attached) specifications of Russia and the U.S. By the time differences in reach, access, visibility, stowage locations on the two suits and varying load limits are factored in, a seemingly simple redesign of common tether hooks becomes a significant engineering challenge.

Identical considerations propagate into designs for every piece of hardware that is used interoperably. But hardware differences affect more than just other hardware. Hardware differences also affect people.

With two types of functional space suits and three separate functioning airlocks (only one of which accommodates both suits), plus hundreds of EVA hand tools in use, the requirements on instructor, crew and flight controller certification training are enormous. For personnel to be interoperable using such a wide variety of hardware requires several thousand hours of initial certification training and follow-on proficiency work.

The lessons learned by designing and operating within such a blended hardware system demonstrate that added capabilities can be realized when differing systems are made interoperable. However, such benefits come with a cost to both hardware and personnel. Managing the cost/benefit ratio of interoperability in light of hardware issues is a significant factor in this trend of space operations.

Non-Hardware Issues

Another significant factor in the trend toward EVA interoperability is the effect of non-hardware issues.

No other space operations discipline is so uniquely dependent upon the individual as EVA. Even when crewmembers are from the same country, trained on exactly the same hardware, by precisely the same instructor, to perform the exact same tasks, they will have different results.

This is because no two individuals are anthropometrically identical. They do not have the exact same span of reach, nor identical range of motion, nor precisely matching upper body strength, nor ankle flexibility, nor mechanical aptitude, nor manual dexterity, nor height, etc. When the new interoperability variables of non-native languages, training facilities on separate continents, different task development philosophies, etc. are added, the scale of non-hardware hurdles comes into focus.

An inescapable element affecting EVA interoperability is language. When people are wearing a space suit during EVA, they are for all practical purposes operating a single-person spacecraft. Virtually all major subsystems of a spacecraft (closed-loop life support system, active cooling/heating system, on-board computer, electrical system, caution-and-warning system, communications, propulsion system, etc.) are incorporated into space suits.

The mechanisms for controlling these systems, both on the ground and in orbit, are created in the language of their developers. Simultaneously, supporting documentation (hardware specifications, training manuals, drawings/schematics, systems handbooks, etc.) is also printed in the hardware owners' language.

The effects of such a reality upon interoperability go far beyond the inconvenience and expense of translating documents. Though even these considerations are not insignificant for training and certification purposes.

As discussed, during an EVA the suited crewmember is operating a single-person space vehicle, while performing manual tasks. These suits are their soul source of life support while outside. In periods of nominal operations, the crewmembers' and ground controllers' fluency in a non-native language are less important.

However, in emergency situations it becomes much more significant if there are language barriers present. These barriers may exist between crewmembers or between a crewmember and the hardware being used. They may exist between the ground controllers and on-orbit crew. There can also be language barriers between ground controllers.

Interoperability multiplies the number of places where language differences can create difficulties. Other non-hardware difficulties of interoperability are encountered under the umbrella of what is generally labeled Mission Operations.

Mission Operations encompass all the work necessary to plan/integrate, train (ground and flight crews) and fly (execute) an EVA. Mission Ops are the source of extensive challenges for interoperability. This is demonstrated very clearly by ISS.

During the planning phase of an interoperable EVA for ISS, Mission Ops personnel must integrate requirements from numerous foreign and domestic sources. For example, Russian and American crewmembers might be operating U.S.-manufactured suits while performing EVA tasks on the Canadian-manufactured robotic arm.

Such an EVA, which is not at all unusual aboard ISS, demands interoperable planning and integration to resolve task/procedures responsibility, timeline development issues, integration of the event into overall ISS operations, establishment of Flight Rules, etc. Coordination of this pre-mission planning and integration becomes complex.

To minimize this complexity, the EVA Mission Ops personnel for ISS have implemented interoperability under the following general guideline. Lead responsibility for EVA planning and integration lies with the organization whose suit is being used.

This is because expertise for telemetry monitoring/interpretation and command/control authority for these life support systems resides with the organization that created them. Since control of EVA events is under the authority of this organization, it holds the lead responsibility for planning and integration of the space walk.

Once an interoperable EVA has been planned, it must be trained. In this phase, the lead organization has two primary training responsibilities, training operation of the suit and training the EVA tasks to be performed.

In training suit operations, the lead organization functions virtually autonomously. As developers of the suits to be used, they retain ultimate expertise on the requirements to operate it.

However, in training the EVA tasks to be performed, the lead organization must be interoperable. In the example sited, while the task will be trained by U.S.

instructors, technical expertise for the task lies with Canadians. The instructors must interact heavily with the hardware experts to develop and train procedures that fulfill technical objectives, while adhering to EVA operational (airlock, vehicle and suit) constraints.

The final phase of Mission Operations, execution, is also heavily impacted by interoperability. Following planning and training of an EVA, it is executed by the on-orbit crew under the direction of flight controllers on the ground.

In the example being discussed, command and control of the suits, airlock and task will be performed from Mission Control Center-Houston (MCC-H) with augmented flight control support by Canadian robotics experts. However, interoperability yields the possibility for a more complex EVA execution scenario aboard ISS.

Simply changing the choice of which suit is used in the present example presents increased challenges for interoperability. Should the capability be enabled for the same crewmembers to use the Russian Orlan suit in the U.S. Joint Airlock, it would become necessary to hand off control authority between MCC-H and Mission Control Center-Moscow (MCC-M) during the EVA.

The reason such a hand-off would be required is that expertise for the Joint Airlock resides with the U.S., while expertise for the Orlan resides with Russia. Airlock systems issues during its operation would be controlled by MCC-H. However, once the crew egresses the airlock, MCC-M would control the EVA tasks. In this circumstance, Canadian expertise may be required to augment Flight Controllers in both locations.

A matrix created in 1999 delineating the complexities of ISS EVA interoperability for Mission Operations is displayed in Figure-1. Clearly the issues affecting EVA interoperability include significant non-hardware considerations.

Management Issues

Technical issues, both hardware and non-hardware, are not the only ones demanding consideration for EVA interoperability. In fact, for the 21st century, EVA is not the only space operations discipline that must face questions of interoperability.

Management within space-faring organizations is challenged by both decreasing budgets and increasing complexity of human space flight to consider interoperability in general in order to meet their objectives. This means management must develop methods to effectively expand international and interagency cooperation if human space exploration is to thrive in the 21st century. The key term here is *effectively*.

Interoperability lessons learned during the Shuttle/Mir Program, and those being learned onboard ISS, must be applied when mapping future space endeavors. EVA, being the most heavily integrated space operation, is an outstanding source of interoperability lessons which can illuminate potential pitfalls facing other disciplines.

For example, examining the downstream consequences (both financial and technical) of suit design decisions upon crew assignments and hardware logistics/processing illustrates previously unforeseen factors impacting management's schedules and budgets. Seemingly minor choices made early in development of interoperable systems can lead to far-reaching operational issues.

Another EVA interoperability experience from the Shuttle/Mir and ISS Programs with applicability across other disciplines is personnel training and certification. If interoperability is achieved by simply increasing the number of systems simultaneously in use, the requirements for ground and flight personnel to achieve and maintain operational proficiency will soon become unwieldy. Management must scrutinize the cost/benefit ratio (not only financial, but also in terms of logistics and practicality) as it applies to the people who must operate such a system.

Management must apply this same level of scrutiny when considering real-time mission execution using an interoperable system. Decisions about the division of responsibilities and authority have a profound impact on mission safety, as well as mission success. This is particularly true in off-nominal or emergency situations when consequences of operations are most critical.

As humans strive to increase their presence in space throughout the 21st century, the technological and economic hurdles they must overcome are increasing correspondingly. The next steps by humans beyond their own planet will require investments that are as demanding financially as they are intellectually.

It is virtually assured that meeting such demands will require agencies, organizations, institutions, corporations and nations to pool their collective resources. The team that has effectively learned the lessons and facilitated its implementation will meet the inevitable need for interoperability in space operations for the 21st century.

Figure-1
ISS EVA Interoperability Matrix

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MATRIX VARIABLES: **SUIT - E** (EMU)/**O** (ORLAN)
PROCEDURES, TIMELIINE AND TRAINING - u (U.S.)/**r** (Russia)
AIRLOCK - ***J*** (Joint)/***R*** (Russian)/***S***(Shuttle)

COMBI-NATIONS	DEVELOPMENT/TRAINING (responsible location)	REAL-TIME CONTROL	SCHEDULED TO OCCUR?	LANGUAGE IN USE
Er*J/S*	sys-U.S./task-Russia	sys-Houston/task-Moscow	yes	A/L ops-Eng/post egress-Rus
Eu*J/S*	U.S.	Houston	yes	Eng
Or*J/R*	JA/L sys-U.S. task, RA/L & suit sys- Russia	JA/L sys-Houston task, RA/L & sys-Moscow	yes	Rus
Ou*J/R*	task & JA/L sys-U.S suit & RA/L sys-Russia	task & JA/L sys-Houston suit & RA/L sys-Moscow	yes	A/L ops-Rus/post egress-Eng