Reduction of Space Exploration Risk - Use of ISS as a Test Bed for Enabling Technologies

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During the developmental phase, the Space Exploration Program will have to undergo the capabilities-based assessment, where along with the fundamental mission capabilities, tasks, attributes and performance metrics, the gaps, shortfalls, redundancies and risk areas will be identified and proposed. Many of these solutions require extensive validation of the underlying technology in space. Even though many technical tools may and will be tested on the ground, the effects of microgravity, radiation, and human factors cannot be easily reproduced with the desired duration and accuracy. Presently, the only operational platform that offers the best approximation to crew exploration vehicle conditions is the International Space Station. An array of existing proven mature technologies that are used in commercial and military applications can be introduced to improve the safety, reliability, affordability, and, ultimately, capability of upcoming and increasingly complicated space exploration systems.

I. Introduction

The idea for this paper came to us after reading the Andrew Koehler's paper, called "Safety, Reliability, Stewardship, and Regret: Contributions to Dependable System Design from the Study of Highly reliable Organizations."[*] In his paper, Andrew Koehler discussed inseparability of human and equipment causes for system hazards, the dynamic relationship between the systemic and human-induced hazards was established in multiple publications.

With future international crews on board the exploration spacecraft and changing character of human-spacecraft ecosystem interactions, it is impossible to eliminate the operations risk, or even to reduce it to the predetermined low value. It is important and feasible, however, to augment this risk with tools that will help crew manage it.

A fundamental unpredictability of failures is amplified by their social character. With long duration space flight the system may continue operating precisely as designed, but its behavior may no longer be what the crew wants.[1]

II. Technical Solutions

During the developmental phase, the Space Exploration Program will have to undergo the capabilities-based assessment, where along with the fundamental mission capabilities, tasks, attributes and performance metrics, the gaps, shortfalls, redundancies and risk areas will be identified and solutions proposed.

Many of these solutions, essential for the long duration Space Exploration mission phase, require extensive validation of the underlying technology in space. The validation phase has to include specific technologies, integrated and utilized in an environment that is very similar to future space flight both environmentally and in the context of human factors. Even~~t~~ though many technical tools may and will be tested on the ground, factors such as microgravity and radiation environment cannot be easily reproduced with the desired duration and accuracy. Presently, the only operational platform that offers the best approximation to crew exploration vehicle conditions is the International Space Station. While the Exploration system goals and objectives will determine if the

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[*] 1st Intl Forum on Integrated System Health Engineering and Management in Aerospace, NAPA, California, November 7-10, 2005

development or use of new technologies is required, there is an array of existing proven mature technologies that are used in commercial and military applications but have not been utilized in human space flight. These technologies are needed to improve safety, reliability, affordability, and, ultimately, capability of upcoming and increasingly complicated exploration systems. Specifically, we considered an array of technologies that can be tested in the environment of the ISS, which is inclusive of flight and ground operations with emphasis on integrated products that impact IVA, EVA, nominal operations, and the commonality of hardware/software system components. The four criteria that we imposed for the evaluation of applicability to Exploration systems are as follows:

A. System has been tested in a high fidelity laboratory environment or in a simulated operational environment. Technology Readiness Level (TRL) should be 6 or higher[†]
B. Reconfigurable in flight or autonomous operations
C. Must address risk associated with Exploration
D. Can be validated in the environment of ISS flight or ground operations

Throughout the history of spaceflight, we recognize faults due to failure of hardware, software, processes, operations and human factors. The two major areas that would allow to address aspects of the mentioned faults, as well as deliver, in our opinion, the highest value for investment are Augmented Reality (AR) and Integrated System Health Engineering and Management systems (ISHEM).

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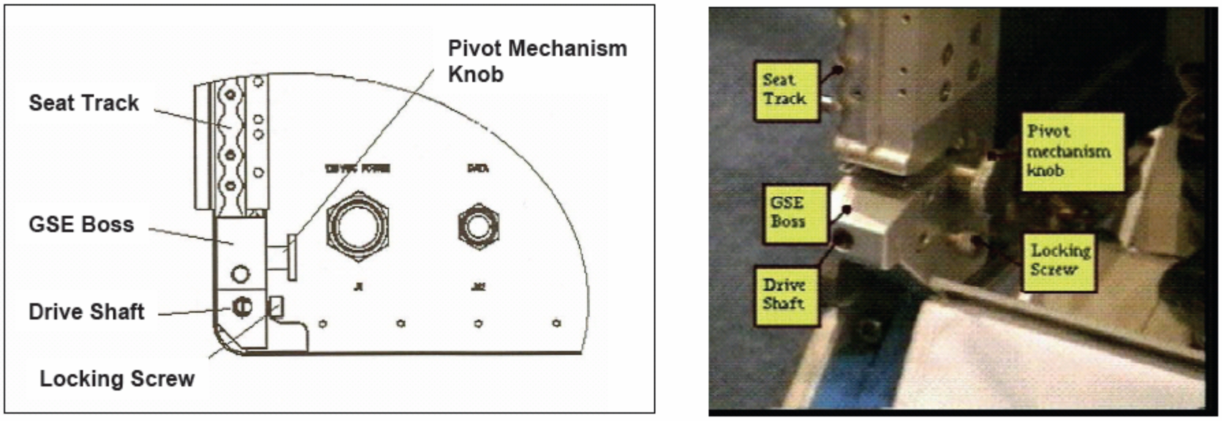
III. Augmented Reality and Wearable Computing for Space Exploration

Characteristic time for vehicle functions such as electrical power, attitude control, and data computation take time in the order for 10 ms to 500 ms, whereas human response, and particularly human decision making takes anywhere from half a second to days. Consequently, any appreciable reduction in human response time potentially can yield substantial benefits from the standpoint of vehicle performance and fault detection, isolation, and response (FDIR) function. AR systems can enhance the crewman view of the intra and extravehicular environment by adding virtual objects, such as text, 2D, or 3D graphics, to the real world imagery.

An example of application, developed by Boeing to the human space flight is shown on Fig. 1.



Line art from RACK R&R MPLM TO USOS GENERIC, DRAFT, Nov 5,1997 'Figure 2. Lower Attach Mechanism (left side)'

Augmented Reality: real or camera views with labels and graphics under computer control.

Figure 1. Example of virtual reality annotations for ease of assembly (on the right), compared with a standard paper drawing (on the left).[2]

Ideas to use wearable computers in conjunction with head-up displays or other types of portable screens have been around for more than a decade. Wearable computers connected to a wireless network allow delivery of data and imagery to an operator, thus enhancing her mobile access to the content. That content may range from still

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[†] Technology readiness level definition may be found in http://ranier.hq.nasa.gov/Sensors_page/Background/TechLevels.html

imagery to annotated video streams, depending on a task on hand. However, the wearable computer system by itself cannot correlate that imagery with the real world, as observed by an operator. A real benefit comes from proper utilization of the AR and wearable computer technology into one system that would allow to bring the crew response time down and make the space flight safer. Despite the substantial NASA effort to direct Space Exploration toward autonomous spaceflight, certain operations are designed based on the human-in-the-loop concept, proper utilization of AR and Wearable Computing technologies will bring the human response time down.

A fusion of augmented reality and wearable computer-applications has already been used by the industry and academia in terrestrial applications for several years. Besides providing the situational awareness through head-up displays and a variety of digital wireless interfaces, wearable computers enable remote ambulatory astronaut health monitoring and trending, and multi-modal physiologic sensing. In the past, the significant effect of microgravity environment on the crewmembers' capabilities has been “carefully considered not only for each particular task, but also for all the overhead related to the task and the general overhead associated with EVA[3].” Long-duration crew exploration missions require a skills’ based training ability to quickly react to unforeseen workaround and contingency operations. This in turn warrants quick on-the-fly access to the broad information database and display of such information in a convenient, unobtrusive way. NASA considers EVA an enabling operational resource for all human space exploration missions, and its future capabilities and interfaces can be emulated and validated on the ISS.

Use of augmented reality and wearable computers for active systems command and control and other critical functions, such as robotic operations would enable the crewman to expediently make the operational decisions based on the real time situation awareness information flow. Such simultaneous operation would involve a set of authenticating and safeguarding tools to prevent inadvertent mistakes.

A number of human factors must be considered in using the augmented reality for space applications. There has been some progress made on identifying detailed design features of an AR tool, such as the head-up display (HUD), that need to be implemented to make a positive impact on human performance. However, it will take some time and effort to validate the AR tools in zero gravity. Future long duration missions will bring an increase in psychological loads and result in downgraded performance. The new technology to diminish the impact of these factors will be required and the only physical environment where these effects can be comprehensively studied is the ISS.

A critical area to feed information into the crew situation awareness system is advanced integrated vehicle health management (ISHEM). With proliferation of wireless sensors and distributed mesh networks, ISHEM, interfacing with the wearable computer and augmented reality information layer may augment the existing information access in ways that have never been explored before.

IV. Integrated System Health Engineering and Management (ISHEM)

One of the most significant discriminators of space exploration vehicles is the ability to sustain long duration autonomous flight with all or most critical health management operations executing in real time without real-time ground communication support. The new smart health management system should not replace the crew, but evolve the traditional C&W system into a decision-and-action support system (DASS) that will dynamically reallocate the level of autonomy and assist the crew with all aspects of health management operations[4,5,6].

DASS will also allow the change of the threshold of crew involvement into fault management decisions, depending on the workload and cognitive function. [7] Such approach requires extensive use of quantitative criteria and Metrics Evaluation Tool (MET) developed under Rotorcraft Industry Technology Association. Health and Usage Monitoring Systems (HUMS) Technology program is now used to evaluate the performance and effectiveness of features typically used in HUMS. This tool was developed specifically for vibration diagnostics in helicopter Health and Usage monitoring System (HUMS), but it can be adopted for the broad array of future spacecraft diagnostics and validated on the ISS. An overview of the candidate algorithms and method of metrics can be found in the referenced source.[8]

A significant body of work in designing smart homes has been done to date in the government, academia, and industry.[9] Most of it is devoted to developing techniques for speech recognition, source localization, and prediction algorithms, based on context aware computing.

A disciplined systems engineering approach that would follow the ISO 13407 Human Centered Design process for Interactive Systems”[10] is necessary for successful implementation. A subsequent Usability Maturity Model was published as ISO TR 18529. This model[‡] that consist of seven sets of base practices can be streamlined and applied at a subsystem level supporting a major requirement. Technically, it does not extend beyond the systems engineering and system of system architecture applications. However, introducing the human factors into the picture makes its development substantially different during the design and validation phase.

The importance of understanding the human factors is imperative not only from the vehicle safety standpoint, it has a profound effect on the economics of future spaceflight. Human factors produce a connection between Operations and Planning, Design, Manufacturing and Testing, (See Fig. 2.[§]).

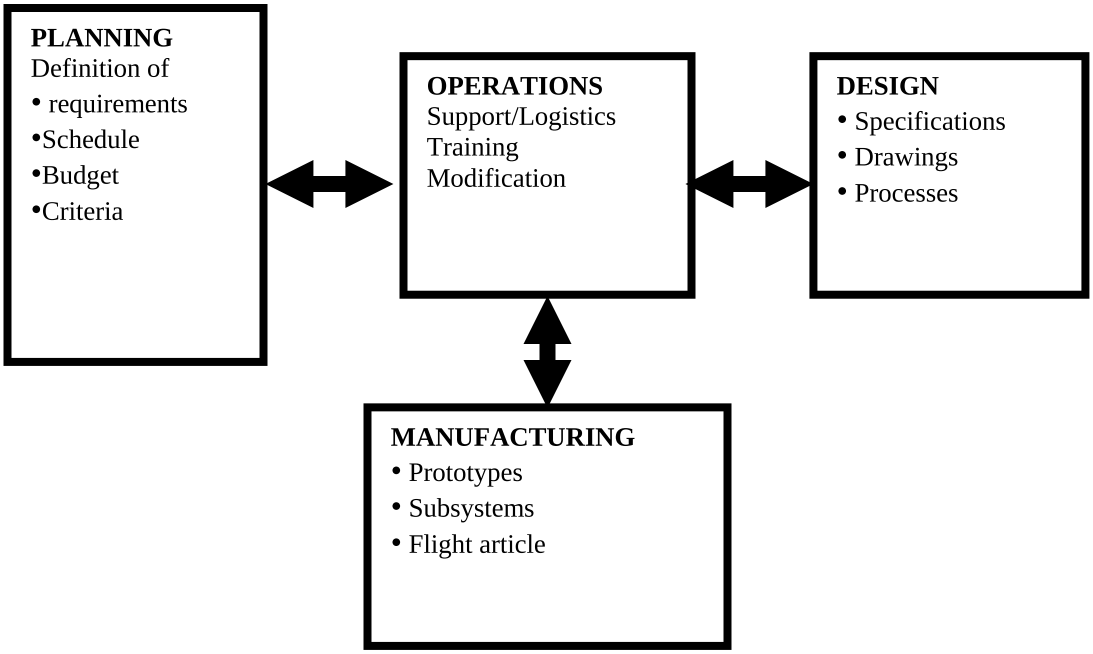

Figure 2. Relationships between operations and other life cycle processes.

Today the ISS and Shuttle crews cannot devote their time to perform health management activities; they rely on the ground processing capabilities where flight controllers and mission evaluation room support space operations. Just because of the signal time delay and unavailability of the safe vehicle[**], the future exploration crew self-reliance imposes much stricter requirements to the fusion of vehicle health management and situational awareness. The issue of sensors’ errors extend beyond the scope of this paper; we will just mention here that there is an extensive arsenal of methods to deal with situation assessment that involves incorporation of uncertain evidence from diverse sources.[11] These methods usually comprise a suite of tools for sensor measurement, isolating faulty sensors by assigning a degree of validity to each measurement, estimating faulty measurements, and isolating faults.[12]

[‡] See Attachment A

[§] Adopted with significant changes from Charles D. Mott, The System Life Cycle and ISHEM,1st Intl Forum on Integrated System Health Engineering and Management in Aerospace, NAPA, California, November 7-10, 2005

[**] Such as Soyuz, constantly docked to the ISS and available to the 2 person crew for returning to earth in emergency

V. Conclusion

One of the key factors in identifying the ISHEM methods and their effects on dependability is replicating the system in a controlled environment. The ISS as test bed for space exploration should be viewed as a best available tool to evaluate the acceptable tradeoff between newer technology, manufacturing maturity and applicability for long duration space exploration. Reliance on limited diagnostics and pure heuristics that was prevalent in the days of the early spaceflight is no longer an option. Our understanding of the crewmember interaction processes with other crewmembers and IISHEM, using the AR and wearable computer tools will allow us to engineer adaptable system operations, less prone to the human error.

Today, we have a pressing need and an opportunity to better understand the diagnostic, communication, and cognitive problems that the proposed space exploration vehicle present and how we can explore and validate these challenges on the ISS.

Appendix

A Human Centric Design for Space Vehicle Operations.

1	**Ensure HCD content in system strategy**	**Space Vehicle Operations Design**
1.1	Represent stakeholders	Crew, Mission Operations, Ground test and verification
1.2	Collect market intelligence	Collect relevant information pertaining to other military and civilian programs (Future Combat Systems, Objective Force Warrior, Navy, Air Force, etc.)
1.3	Define and plan system strategy	Assemble representatives from all stakeholders and define top level requirements
1.4	Collect market feedback	Submit system strategy to the authorities in the field of operations and HCD
1.5	Analyze trends in users	
2	**Plan and manage the HCD process**	Make sure that all stages of the HCD process are reflected in the concept of operations
2.2	Identify and plan user involvement	Design operations scenarios for different stages of the spaceflight
2.3	Select human-centered methods and techniques	Methods and techniques are selected based on skills training and cognitive abilities of the crew
2.4	Ensure a human-centric approach within the team	
2.5	Plan human-centric design activities	Human factors and ISHEM expertise must be applied at all stages of vehicle design
2.6	Manage human-centric activities	
2.8	Provide support for human-centric design	Application of specific sensor fusion algorithms and choice of hardware/software solutions for meeting the mission objectives for all phases.
3	**Specify the stakeholder and organizational requirements**	
3.1	Clarify and document system goals	

3.3	Assess risk to stakeholders	Primarily the crew, but also the mission control
3.4	Define the use of the system	This step should be preceded by the assessment of threshold for crew involvement at different FDIR scenarios
3.5	Generate the stakeholder and organizational requirements	
3.6	Set quality in use objectives	Utilize metrics evaluation tools
4	**Understand & specify the context of use**	
4.1	Identify and document user’s tasks	
4.2	Identify and document significant user attributes	
4.3	Identify and document organizational environnent	
4.4	Identify and document technical environment	
4.5	Identify and document physical environment	

5	**Produce design solutions**	Design solutions should be 90% software based and reconfigurable in flight
5.1	Allocate functions	
5.2	Produce composite task model	
5.3	Explore system design	
5.4	Use existing knowledge to develop design solutions	
5.5	Specify system and use	
5.6	Develop prototypes	
5.7	Develop user training	
5.8	Develop user support	
6	**Evaluate designs against requirements**	
6.1	Specify and validate context of evaluation	
6.2	Evaluate early prototypes in order to define the requirements for the system	Results of evaluation must feed the iterative process of refining the software solution
6.3	Evaluate prototypes in order to improve the design	
6.4	Evaluate the system to check that the stakeholder and organizational requirements have been met	
6.5	Evaluate the system in order to check that the required practice has been followed	
6.6	Evaluate the system in use in order to ensure that it continues to meet organizational and user needs	
7	**Introduce and operate the system**	After successful evaluation on the ground and NBL deploy on the ISS
7.1	Change Management	
7.2	Determine impact on organization and stakeholders	

7.3	Customization and local design	Extensive testing of prototypes on the ground and neutral buoyancy lab (NBL)
7.4	Deliver user training	
7.5	Support users in planned activities	Collect extensive data (medical, financial impact, time savings, etc.) from the stakeholders

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