

Human Systems Integration (HSI) Case Studies from the NASA Constellation Program

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Abstract

The National Aeronautics and Space Administration (NASA) Constellation Program is responsible for planning and implementing those programs necessary to send human explorers back to the moon, onward to Mars and other destinations in the solar system, and to support missions to the International Space Station. The Constellation Program has the technical management responsibility for all Constellation Projects, including both human rated and non-human rated vehicles such as the Crew Exploration Vehicle, EVA Systems, the Lunar Lander, Lunar Surface Systems, and the Ares I and Ares V rockets.

With NASA's new Vision for Space Exploration to send humans beyond Earth orbit, it is critical to consider the human as a system that demands early and continuous user involvement, inclusion in trade offs and analyses, and an iterative "prototype/test/redesign" process. Personnel at the NASA Johnson Space Center are involved in the Constellation Program at both the Program and Project levels as human system integrators. They ensure that the human is considered as a system, equal to hardware and software vehicle systems. Systems to deliver and support extended human habitation on the moon are extremely complex and unique, presenting new opportunities to employ Human Systems Integration, or HSI practices in the Constellation Program. The purpose of the paper is to show examples of where human systems integration work is successfully employed in the Constellation Program and related Projects, such as in the areas of habitation and early requirements and design concepts.

Introduction

NASA, unlike the Department of Defense, does not have a formal acquisition mandate to include HSI activities in human spaceflight programs and projects, or to include HSI deliverables in the procurement process. NASA does, however, have a rich heritage of concern for and protection of their crews, and as a result has considered human health and performance in spacecraft and mission design for many years. In addition, in 2008 NASA updated the Human-Rating Requirements for Space Systems (NPR 8705.2B), a procedural requirements document intended to assure the protection and safety of crewmembers and passengers on NASA space missions, by defining and implementing processes, procedures, and requirements necessary to produce human-rated space systems. The newly updated document is levied on the Constellation crewed space

systems, and lays out a human-rating certification path for the Program Manager and his or her teams to follow in conjunction with selected, traditional milestones.

HSI at NASA

As was previously mentioned, there is no NASA agency-wide or even center-based deployment of the term HSI, or an associated definition. However, the inclusion of the human as part of overall system performance is not only recognized, but supported by the agency.

The Human-Rating Requirements for Space Systems (NPR 8705.2B) contains a set of technical requirements that establish a benchmark of capabilities for human-rated space systems. It directs the Constellation Program to evaluate crew workload, conduct human-in-the-loop usability evaluations, perform human error analysis, prove that integrated human-system performance test results were used to validate the system design, and establish an HSI team to keep these activities on track.

The NASA Systems Engineering Handbook (NASA/SP-2007-6105 Rev 1) provides high level guidance on systems engineering best practices to be applied throughout NASA. It recognizes human factors engineering as a discipline within the Systems Engineering Process, where human factors engineering is described as *the study, analysis, design, and evaluation of human-system interfaces and human organizations, with an emphasis on human capabilities and limitations as they impact system operation*. It counsels that human factors engineering issues relate to all aspects of the system life, including design, build, test, operation, and maintenance across nominal, emergency, and contingency operating conditions.

The Human-Systems Integration Requirements (HSIR) document (CxP 70024) which was developed specifically for the Constellation Program from NASA Standard 3000, or NASA's Man Systems Integration Standard, provides a key mechanism for Constellation to achieve NASA's agency-level human-rating requirements. The proper flow down of the HSIR calls for the design of Constellation systems to be centered on the needs, capabilities and limitations of the human. So while the human-rating certification focuses primarily on the integration of the human into the system to prevent catastrophic events during the mission, and the Systems Engineering Handbook provides guidance on the processes, tools, and techniques to be used during the system lifecycle, the HSIR is intended to ensure proper integration of human-to-system interfaces for all mission phases. The human systems integration requirements in the HSIR are allocated as appropriate to each Constellation Project. They define parameters of a habitable environment, capabilities and limitations of the flight and ground crew that drive the design of Constellation systems to achieve mission objectives, and provide the parameters that protect the health and safety of the crew and allow them to perform their functions in an efficient and effective manner.

Human systems integrators at the Johnson Space Center and other centers across the agency are involved not only with the allocation and interpretation of the HSIR, and with the human rating certification process, but also with the processes associated with human centered design and human systems integration. They work with subject matter experts in areas such as acoustics, vibration, medical operations, occupational health,

anthropometrics, and more to ferret out cross-cutting issues that could affect the crew. Working with vehicle and habitat designers they ensure that such issues are included in trade studies and analyses to determine how best to balance vehicle and mission design while meeting the needs of the crew and considering human health and performance limitations. They use HSI tools and practices such as net habitable volume analysis and verification techniques, human-in-the-loop testing, and usability, handling qualities, and workload testing and analysis techniques to mitigate the risks to mission and crew and to optimize vehicle design.

Based on agency level approval and acceptance of the documentation mentioned above, as well as success in previous programs, human systems integrators have made extensive inroads into Constellation Program and Projects. Work has begun to standardize the processes, tools, and techniques used to support HSI, as well as developing a definition or culture aimed at formalizing the term HSI and its practice as a NASA discipline. For the purposes of this paper, HSI will be defined as the integration of human health and performance concerns, including but not limited to areas such as: health; environmental factors; habitability; survivability; human factors; and adaptation, as opposed to the traditional Department of Defense domains. This is an evolving definition being steered through benchmarking outside of NASA, also rooted in NASA's history, and due in great part to the emerging needs of current programs and projects. Much work remains to be done for the early integration of training and personnel selection, and therefore they are not included in this paper. They must be embraced, however, as part of the overall human health and performance considerations and should be included for the future in an HSI comprehensive agenda.

HSI in Constellation Programs and Projects at NASA's Johnson Space Center

General

At the Johnson Space Center HSI practitioners are heavily involved in the Constellation Program and Projects on many levels. In fact, Human Engineering is represented as a subsystem discipline area within the Constellation Program's (CxP) Crew Exploration Vehicle (CEV) Project as part of specialty engineering within the CEV Vehicle Integration Office. Environmental Factors and Medical Operations are also recognized as subsystems, and many human system concerns are represented in ways too numerous to mention here. The CEV Project, or Orion, also formally recognizes an HSI lead who integrates human health and performance concerns by leading or participating in integration forums to coordinate related technical issues with implementers, stakeholders, and subject matter experts in order to characterize risks and potential or realized system impacts, and to provide review of developing designs and architectures. Other Constellation Projects have begun to include human system concerns in their planning and development cycles as well, although on different levels depending on their development progress. The Lunar Lander, or Altair Project, responsible for delivering and returning crews to and from the surface of the moon, thus enabling establishment of a lunar outpost, has used human engineering experts in the early conceptual design phase to

make trades against various architecture options based on analysis of the volume required to perform tasks per lunar operational concepts. The Extravehicular Activity (EVA) Systems Project is chartered to plan and develop all space suit related hardware in support of launch, entry, abort, and EVAs associated with all Constellation Program defined mission phases, tools, crew survival equipment integral to the suit, and suit/vehicle interface hardware. The Project has recently engaged HSI practitioners as part of the Systems Engineering effort to understand trades influencing design, and architecture decisions that are being made based on suited human performance tests and simulations across various Constellation vehicle mockups. HSI practitioners have long been involved with discussions and trades in regard to interfaces between the CEV and the EVA hardware and their effects on crew health and performance. Even the Lunar Surface Systems Project, which is in its infancy but ultimately required to develop lunar surface habitats, rovers, and construction systems, has taken a human centered design approach in developing conceptual designs for the build up of lunar based systems and the overall lunar surface architecture.

Within the Constellation Program's System Engineering and Integration Office, a Human System Integration Group (H-SIG) has been established with responsibility and authority, and accountability equal to other discipline area SIGs (e.g. Thermal/Life Support, Integrated Loads Structures and Mechanisms, Power, Software and Avionics, etc.) The HSIG leads the human system integration across Projects for both hardware and software for all Constellation crewed space systems, including the operability and usability of interfaces and hardware and software requiring human/operator interactions by the flight crew during ground and flight operations, as well as ensuring cross-systems, cross-mission support of human health and performance, including crew habitability accommodation and human interfaces. The H-SIG also acts as the book manager to maintain the HSIR, which, as mentioned above, drives the design of space vehicles, their systems, and equipment with which humans interface in the Constellation Program. Work is underway within Constellation to establish the H-SIG as the functional lead of the Human Systems Integration Team, or HSIT, which, according to the Human-Rating Requirements for Space Systems, consists of *astronauts, mission operations personnel, training personnel, ground processing personnel, human factors personnel, and human engineering experts, with clearly defined authority, responsibility, and accountability to lead the human-system integration (hardware and software) for the crewed space system.*

As is evidenced above, HSI practitioners across NASA centers are recognized within the Constellation Program and Projects as valuable, key team players who bring methods and tools to help identify, quantify, and provide solutions or trades for human related concerns. Much work still lies ahead to standardize HSI processes, as well as products or required deliverables, that are less reactionary and more proactive in terms of Program and Project Management, and are more systematic. There are, however, numerous examples outlined below where human systems integration work is successfully employed in the Constellation Program and related Projects. Although the examples cited below are arranged by Project, in reality most of the issues and proposed solutions actually lie across the Projects, making the listing more one of convenience than practicality.

Crew Exploration Vehicle (CEV) – Orion Project

- Task-based analysis of Net Habitable Volume (NHV) in Phase One of the Project illustrates that a proposed crew/cargo design reference mission (DRM) is not practical, eliminating the proposed DRM, saving time and money.
- A handling qualities team is established to develop test criteria, required personnel, methods, and facilities for review of the control algorithms, thruster placement, displays, and design of the CEV, ultimately resulting in Level 1 handling characteristics for CEV manual control scenarios, as levied per HSIR requirements.
- A verification method for NHV is developed to provide interpretation and verification for Program level requirements. The proposed method is dual in nature, to include both volumetric calculations (physically in mockups and computer generated) and task-based analysis and demonstration to ensure that NHV measurements do not only meet a required value, but also constitute a volume that is usable and optimal for all the tasks the crew must perform.
- Displays and Controls (D&C) are prototyped and tested, enabling D&C conceptual designs (for both devices and display formats) to be iteratively built, tested, and redesigned quickly and efficiently.
- Conceptual food system menus are validated against historical menus using statistical analysis to determine the amount of hot water required per crewmember per meal, affecting the environmental life support system, power, and consumables. The total amount of water required per crewmember per day either in food or in a beverage form is also analyzed in regard to total vehicle weight constraints versus human health needs under various operational concepts.
- Health and performance trades are performed to review emergency egress, and post landing survival in sea states in light of trade offs between cabin temperature, acoustic noise, suit and vehicle design, and crew health and performance.
- Subject matter experts in acoustics review design concepts, including proposed materials and geometries, to provide inputs on vibro-acoustic effects.
- Discussions are held with Constellation Ground Operations regarding required pre-launch integrated vehicle off-gas testing in pre-launch preparation flow as described in CEV Concept of Operations.
- Valuable insight is provided to Project Managers for requirements verification via human-in-the-loop (HITL) testing methods employed successfully on previous Programs to reduce cost and mitigate risk.

Lunar Lander –Altair Project and Lunar Surface Systems Project

- Various conceptual designs of the Altair's Ascent Module and Airlock are analyzed using variable diameter mockups and based on subjective and objective performance measures taken as part of the HITL testing of tasks and mission scenarios. Functionality of the vehicle from a functional task performance

- perspective is determined and fed into future design and operational considerations.
- Support is provided for early design analysis and testing in desert trials of the Small Pressurized Rover (SPR) mockup, collecting habitability data for various proposed mission scenarios. Results are used to guide design and layout of next generation mockups and improvements for the next round of trials. Methods are considered for adding a psychological aspect to the testing regime.
 - HSI practitioners work with the Lunar Integration team to identify analysis and requirements gaps in support of Human Lunar Return efforts, including: Crew strength and mobility for lunar surface operations, automation and robotic interaction with crews on the lunar surface, radiation detection and protection requirements, maintenance requirements, biological sample return, and many others.
 - Habitability subject matter experts help the Lunar Surface System team develop and refine lunar surface architecture concepts with models, including several lunar outpost habitat concepts, and early human design consideration enables trade decisions.

EVA Systems Project

- HSI practitioners work with Environmental Control and Life Support system, EVA system, and CEV Project teams to identify and resolve issues related to transitioning the crew from a portable breathing apparatus onboard the CEV to an EVA space suit used in contingency mode within a contaminated CEV to prepare for depress/repress to remove toxic atmospheres.
- HSI practitioners are key participants in the EVA Suit-to-Seat Working Group and review human related issues such as accommodation for the minimum and maximum crew sizes, sensitivity of these interface issues to variables in the suit and seat architectures, and trades between restraint of the crew for landing protection and mobility for flight operations. Resolution plans are discussed and proposed for specific issues such as: definitions of keep-out zones for suit shoulder bearings to ensure secure restraint fit, identification of attach locations for suit umbilicals and survival equipment, including the emergency breathing system, and suit pressurization effects on mobility, reach, and control.
- The mobility of various proposed and existing suit system designs are benchmarked using digital video and motion capture methodology for consideration in future conceptual designs. Subject matter experts also provide interpretation to the CEV Project on anthropometric requirements from the HSIR that drive both suit and spacecraft design. Novel techniques and methods are employed to establish minimal functional mobility and strength characteristics essential for successful human systems integration.

Constellation Program

- Verification strategies are developed with Program and Project test and verification personnel for HSIR requirements which require multiple system

- resources for verification testing, including acoustics, vibration, translation paths, ground processing, and suited crewmember water consumption and telemetry requirements.
- A Human Systems Integration Technical Forum is established to provide interpretation of HSI requirements and verifications methods to the CEV prime contractor.
 - Risk mitigation strategies are provided for mission level and occupational health risks due to crew exposures to radiation.
 - HSI practitioners analyze the influence of combined whole-body vibration plus G-loading on visual performance of the crew as part of the total system performance capability of the CEV. HITL performance testing under vibration is performed and analyzed to determine performance impacts due to thrust oscillation during Ares-I first stage burns. The results provide insight into safe vibration levels, constraints on display and task designs for first stage operations, and insight into the degree of performance after-effects due to vibration. Results are provided as part of an analysis to determine required Thrust Oscillation mitigation plans.
 - HSI practitioners work with ground emergency escape system, ground operations, personnel, crew, and other stakeholders to develop the appropriate requirements for crew acceleration and restraint during emergency egress from the pad, and to identify the appropriate level to hold those requirements. Requirements must balance a variety of objectives, including protection of the crew from dynamic events in emergency scenarios, ease of use, and accessibility and versatility to accommodate different occupant sizes and types, including EVA-suited flight crew, fire and rescue crew with their PPE, and SCAPE-suited ground crew.

Conclusions

NASA human systems integrators have made much progress within the Constellation Program and Projects to mitigate risks to mission and crew, and to promulgate consideration of human health and performance in design and throughout the system lifecycle, especially in light of a lack of formal recognition of the discipline area or a widely accepted definition of HSI. There are multiple agency level documents that require human health and performance to be considered in spacecraft and mission design, enabling human systems integrators to contribute to the Constellation Program. Most efforts have been at the grass roots, or bottom-up level, however, and are successful due to the nature of the integrators and subject matter experts themselves as much as due to the practices they use. Program and Project needs are creating an environment ripe for the development of NASA HSI tools and standardized processes. In a climate of ever-shrinking budgets and accelerated schedules, however, HSI practitioners must show their worth early and often. They must diligently integrate across discipline areas and work within the constraints of Program and Project Managers, using language they understand, to show cost and or schedule benefits as well as risk mitigation. More work needs to be done to integrate operations and training early in the design process so that these discipline areas do not become expensive band aid fixes. However, overall, partly in thanks to NASA's culture and rich history to mitigate loss of crew or loss of mission, as well as to recent changes to agency requirements and processes, HSI practitioners are

meeting success in the Constellation Program and Projects and paving the way for a more standardized approach in the future.

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