HUMAN FACTORS INTERFACE WITH SYSTEMS ENGINEERING FOR NASA HUMAN SPACEFLIGHTS

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Topic

How does Human Systems Integration fit into the Systems Engineering process?

ABSTRACT

This paper summarizes the past and present successes of the Habitability and Human Factors Branch (HHFB) at NASA Johnson Space Center's Space Life Sciences Directorate (SLSD) in including the Human-As-A-System (HAAS) model in many NASA programs and what steps to be taken to integrate the Human-Centered Design Philosophy (HCDP) into NASA's Systems Engineering (SE) process.

The HAAS model stresses systems are ultimately designed for the humans; the humans should therefore be considered as a system within the systems. Therefore, the model places strong emphasis on human factors engineering. Since 1987, the HHFB has been engaging with many major NASA programs with much success. The HHFB helped create the NASA Standard 3000 (a human factors engineering practice guide) and the Human Systems Integration Requirements document. These efforts resulted in the HAAS model being included in many NASA programs. As an example, the HAAS model has been successfully introduced into the programmatic and systems engineering structures of the International Space Station Program (ISSP). Success in the ISSP caused other NASA programs to recognize the importance of the HAAS concept. Also due to this success, the HHFB helped update NASA's Systems Engineering Handbook in December 2007 to include HAAS as a recommended practice.

Nonetheless, the HAAS model has yet to become an integral part of the NASA SE process. Besides continuing in integrating HAAS into current and future NASA programs, the HHFB will investigate incorporating the Human-Centered Design Philosophy (HCDP) into the NASA SE Handbook. The HCDP goes further than the HAAS model by emphasizing a holistic and iterative human-centered systems design concept.

LIST OF ACROYNMS

ABF – Anthropometry and Biomechanics Facility
CEV – Crew Exploration Vehicle
CxP – Constellation Program
FCI – Flight Crew Integration
GIAG – Government/Industry Advisory Group
HAAS – Human-As-A-System
HCDP – Human-Centered Design Philosophy
HFE – Human Factors Engineering
HHFB – Habitability and Human Factors Branch
HIDH – Human Integration Design Handbook
HMTA – Health and Medical Technical Authority
HRP – Human Research Program
HSI – Human Systems Integration
HSIA – Human Systems Integration Architecture
HSIG – Human Systems Integration Group
HSIR – Human Systems Integration Requirements
ISS – International Space Station
ISSP – International Space Station Program
LED – light emitting diodes
LETF – Lighting Environment Test Facility
NASA-STD-3000 – Man-Systems Integration Standards
OLED – Organic light emitting diode
OpsHab – Operational Habitability
SE – Systems Engineering
SE&I – Systems Engineering and Integration
SFHSS – Space Flight Human Systems Standard
SHFE – Space Human Factors Engineering
SLSD – Space and Life Science Directorate

THE HABITABILITY AND HUMAN FACTORS BRANCH AT NASA JOHNSON SPACE CENTER

A portion of NASA's Human Factors Engineering (HFE) expertise resides within the Habitability and Human Factors Branch (HHFB) of the Space Life Sciences Directorate (SLSD) at NASA Johnson Space Center. The HHFB has been successfully supporting and providing many major NASA space programs technical human factors expertise since 1987.

The HHFB facilitates humans to work safely and productively in space by (i) establishing conceptual designs for space habitats and crew systems, and developing requirements and guidelines for programs to implement, (ii) verifying human-machine interfaces and the operational habitability of spacecraft and habitats, and (iii) overseeing and conducting research in space human factors to improve human performance and productivity.

To fulfill these duties, the HHFB ensures space human factors, including human physical parameters and performance capabilities and limitations, are defined, documented, and applied properly. The HHFB also operates several unique facilities and laboratories to support human factors investigations/analyses and crew-station integrations.

HUMAN-AS-A-SYSTEM DESIGN PHILOSOPHY

The HHFB has been promoting the Human-As-A-System (HAAS) design model to NASA's Systems Engineering (SE) process since 1987. The HAAS model stresses that systems are ultimately designed for the humans; the humans should therefore be considered as a system within the systems. To facilitate human accomplishing mission objectives, the human factors discipline should play a prominent role in the systems design so that human and machine interfaces are properly designed.

PAST SUCCESSES IN PROMOTING THE HAAS MODEL

Since 1987, the HHFB has successfully introduced the HAAS model into the programmatic and SE structures of many NASA programs. Below is a summary of these success stories:

Creation of the NASA-STD-3000 Space Human Factors Standards

According to Tillman (1987) the Man-Systems Integration Standards (NASA-STD-3000), created by Tillman et al. (1995), was released in 1987. It is a human factors design guide for developers and designers of space equipment to achieve better integration of humans and the equipment in space.

The NASA-STD-3000 provides a single comprehensive document defining all generic requirements for space facilities and related equipment interfaces with crewmembers. The document was assembled for NASA by the Boeing Aerospace Company and subcontractors Lockheed Missiles and Space Co., Essex Corp., and CAMUS, Inc. The team consisted of thirteen authors, a team of six human factors and space flight experts (including two Skylab astronauts), and a Government/Industry Advisory Group (GIAG). The GIAG was a panel of experts and users from NASA centers and Headquarters, prime aerospace contractors and support contractors, other Government agencies, and non-aerospace contractors.

The standard was compiled as follows: The author of each chapter researched publications and prepared the draft. A review group for each chapter, which was formed by experts and advisers from industry and NASA, then reviewed the draft. Comments, questions, and recommendations from the review group were directed to the respective authors, who then made corrections and conducted necessary research to address the problems detected by the review groups. Consequently, the technical contents of these chapters were thoroughly reviewed and the data can be used with confidence.

The NASA-STD-3000/T International Space Station Flight Crew Integration Standard, also called SSP 50005, is a special version of the NASA-STD-3000. The data in this document are a subset of the data in 3000 and serves as the ISSP contractually binding human systems integration design requirements.

Although written for the space environment, much of the information contained in the NASA-STD-3000 has obvious applicability to human interface and engineering problems encountered in terrestrial environments as long as the document users keep in mind those instances that are tailored to the micro-g environment.

International Space Station Program Flight Crew Integration

Besides creating the NASA-STD-3000/T (SSP 50005) for the ISSP, the HHFB also formed the Flight Crew Integration (FCI) group to provide human factors analyses to the International Space Station (ISS). Analyses are performed through participation in design review proceedings, international partner activities, and the Analysis and Integration Team meetings.

A critical component of the FCI group is the Operational Habitability (OpsHab) team. The OpsHab team collects and analyzes information from space flight missions to identify human factors and habitability lessons learned, validate HFE requirements and designs, solve operational challenges, and improve habitability and human performance for future ISS missions.

The OpsHab team's other responsibility is to identify and analyze human-related data captured through crew debriefs, previous findings from long-duration space flights (e.g., Skylab, Mir, ISS) and space-analog environments (e.g., the Antarctic, Submarines, etc.), as well as research findings from behavioral sciences. Moreover, the team conducts focused evaluations on the ISS to identify human factors and habitability improvements. The information from the OpsHab data collection activities is used to create better human factors requirements to ensure better human-centered hardware and systems designs, provide lessons-learned related to human habitation in space, and offer tracking and resolution to human factors issues on the ISS. In fact, the data is now being incorporated in the Human Interface Design Handbook, a companion to the NASA Standard 3001 (see the "NASA Standard 3001" section.) The lessons-learned data from the ISS also benefits future space programs such as the Orion Crew Exploration Vehicle (CEV).

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NASA's Systems Engineering Handbook Updated to Include the HAAS Design Philosophy

The staff at the HHFB was the major contributor to the human factors sections in the 2007 Systems Engineering Handbook (NASA/SP-6105). Initially published in 1995, the handbook describes the fundamental concepts and techniques of SE in a way that recognizes the nature of NASA systems and its environment (Woolford et al., 2007).

The 2007 revision updated the Agency's SE body of knowledge, providing guidance for insight into current best Agency practices, and aligning the handbook with the new Agency SE policy. The update encompasses a top-down compatibility with higher level Agency policy and a bottom-up infusion of guidance from the NASA practitioners in the field. This approach facilitates the opportunity to obtain best practices from across NASA and bridges the information to the established NASA SE process for the handbook. The material for updating this handbook was drawn from many different sources because SE is a holistic, integrative discipline involving a multitude of engineering disciplines including human factors.

The success in the ISSP indirectly offered the HHFB the opportunity to update NASA's Systems Engineering Handbook in December 2007 to include HFE as a recommended practice. Based on the HAAS model, the 2007 version now stresses the roles of the humans in SE. In human spaceflight, the humans, both as operators and maintainers, are critical components of the mission and systems. Human capabilities and limitations must enter into the designs the same way properties of materials and characteristics of electronic components do. Humans are initially integrated into systems through analysis of the overall mission. Mission functions are then allocated to humans as appropriate to the system architecture, technical capabilities, cost factors, and crew capabilities. Once functions are allocated, human factors analysts work with other system designers to ensure that humans are provided the proper equipment, tools, and interfaces to perform their assigned tasks safely and effectively.

Lastly, the 2007 version also provides a summary of the human factors engineering analysis techniques and methods including task analysis, timeline analysis, modeling and simulation, usability testing, workload assessment, as well as human error and human reliability assessment.

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Space Human Factors Engineering Project's HSI Contribution

The HHFB manages the Space Human Factors Engineering (SHFE) project, which is an element under NASA's Human Research Program. The SHFE is a project under the Space Human Factors and Habitability element of the Human Research Program (HRP). The HRP uses a balance of laboratory, flight, and ground analogs to understand the impact of the space exploration environment on the human system. (Grounds et al., 2007) The goal of the SHFE is to develop standards and models to ensure that the design of spacecraft, habitat systems, and hardware are compatible with the physical and cognitive capabilities of crewmembers during space flight.

In 2005 the SHFE performed a research and technology gap analysis to address key questions on HSI in preparation for the CxP Orion space vehicle development (McCandless et al., 2006). The project conducted white-paper reviews to compare state-of-the-art and state-of-practice with CxP requirements for six critical domains (Manufacturing & Launch Site Operations, Mission Control Operations, Spacecraft Systems & Operations, Extra-Vehicular Activity & Teleoperations, Training & Decision Support, and HSI Engineering Support.) These white papers were supplemented with additional sources of expert knowledge, including (i) in-depth reviews with subject matter experts in both space human factors and the user communities, (ii) historical reports from Apollo and Skylab missions, as well as (iii) debriefs and "lessons learned" from the Space Shuttle and the ISS. The project now sponsors a variety of research and technical development tasks to resolve the lacks and gaps identified in those reviews.

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Shuttle and ISS Lighting Improvements

With the ever-increasing complexities in space operations, the Lighting Environment Test Facility (LETF) at the HHFB felt it would be a great improvement in operation efficiency to mount state-of-the-art lights on all cameras on the current Space Shuttle.

The challenge was that the light sources must be bright, durable, light weight, and low-power. With the birth of bright yet low-power white Light Emitting Diodes (LED) technology in 1995, the LETF immediately adopted this new technology for general illumination in the Shuttle's camera systems several years ahead of the industry. These early LED camera lights were designed as rings mounted around the lens of each camera.

Now, each of the four Shuttle payload bay cameras has LED light systems capable of being pointed with the camera's pan and tilt unit. The two robotic arm cameras were also outfitted with LED rings. In June 1998 on STS-91, the first illumination system of forty white LEDs was flown; in May 1999 on STS-96, a white 180-LED system was flown. These lighting systems are extremely reliable and are still in use today.

Age and increased maintenance cost of the fluorescent lights on board the ISS has prompted NASA to introduce white LED lighting to the ISS. In 2008, NASA flew the first prototype LED system the LETF helped develop on the ISS for evaluation.

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CURRENT ENDEAVORS IN PROMOTING THE HAAS MODEL

Success in the ISSP and other activities mentioned in the previous section provided the HHFB an experience base that further triggered other NASA programs to recognize our effort. This section summarizes some of the current endeavors at the HHFB in promoting the HAAS model.

NASA Standard 3001

In 2007, the HHFB began the development of the NASA-STD-3001, or NASA Space Flight Human Systems Standard (SFHSS), and an accompanying handbook through the SHFE project. The documents are in final review and edit and are expected to be published in 2009.

The SFHSS will be a two-volume Agency-level standards document established by the Office of the Chief Health and Medical Officer that defines system design standards to achieve acceptable crew health and performance in spaceflight. SFHSS Volume I, Crew Health, sets standards related to crew health. Volume II, Habitability and Environmental Health, defines the environmental, habitability, and human factors standards related to environmental health and human-system interfaces for human spaceflights.

A companion document to the SFHSS is the "Human Integration Design Handbook" (HIDH). The handbook provides the detailed data and guidance needed to derive and implement program-specific requirements that are SFHSS compliant. Much of the information in the HIDH comes from the corresponding updated and expanded information in the SFHSS. The HIDH will provide guidance for crew health, habitability, environment, and human factors design of all NASA human spaceflight programs and projects. The two primary uses for the handbook will be (i) to prepare contractual program-specific human interface requirements, and (ii) to develop designs and operations standards for human interfaces in space vehicles and habitats.

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Constellation Program Human Systems Integration Group

The HHFB's success in the ISSP has drawn attention from other NASA space programs. Among them is NASA's Constellation Program (CxP) and its project elements.

NASA's CxP is developing new human-rated space vehicles that can reach and operate on the moon and eventually on Mars. The HHFB now leads the interdisciplinary Human Systems Integration Group (HSIG) for the CxP.

The HSIG is a program-level authority of the CxP Systems Engineering and Integration (SE&I) group. The HSIG develops and maintains the CxP Human Systems Integration Architecture (HSIA) by ensuring commonality through integration and application of the HSIA among the CxP's program level, project level, and external entities. Through the CxP SE&I's Program Technical Integration Office, the HSIG analyzes, integrates and dispositions technical changes and issues affecting the application of Human Systems Integration (HSI). The group also works with NASA centers and/or external agencies to resolve lower-level issues concerning CxP HSI-focused technical integration work. Today, the HSIG is intimately involved in the following CxP project elements: Crew Exploration Vehicle (CEV) development under the Orion Project, Extra-Vehicular Activities (EVA) spacesuit development under the EVA Project, lunar vehicles development under the Altair Project, ground operations and facilities development under the Ground Operations Project, and the rocket development under the ARES I Project.

DEVELOPING THE CXP HUMAN SYSTEMS INTEGRATION REQUIREMENTS (HSIR)

One of the important contributions of the HSIG to the CxP is the creation and management of the CxP HSIR document (CxP 70024, 2006). The HSIR is a CxP document that defines requirements to ensure proper integration of human-to-system interfaces and is a key mechanism for achieving human rating of CxP systems. The requirements within the HSIR document apply to all CxP mission phases.

During the early stages of the CxP, the HHFB saw the need to tailor the NASA-STD-3000 for the Orion CEV spacecraft development. The CxP's Orion Project element is developing the CEV, a replacement for the current Space Shuttle. The Orion CEV will extend humanity's reach to the moon and Mars. The goal for the tailoring was to use the Standard to create a requirements document with the specificities and the right legal languages for the CEV. In 2004, the HHFB drafted a CEV requirements document. Later, the HSIG was formed, which led to the promotion of the project-level Orion CEV requirements document to the program-level CxP HSIR document. The current version of the HSIR includes an allocation matrix (Appendix J in the HSIR), which allocates requirements as applicable across all CxP projects such as Orion, EVA, and Ground Operations.

DEVELOPING THE CXP CREW INTERFACE LABELING STANDARD

HSIG's other responsibility is to develop and maintain the Crew Interface Labeling Standard (CxP 70152, 2007). The document presents the standards for labeling and coding of all crew interfaces on flight hardware in the CxP. It drives the design of labels for space vehicles, their subsystems, and equipment that humans interface. These standards ensure the labels designed for the CxP systems can facilitate locating/identifying interfaces, interpreting/following procedures, and avoiding hazards.

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Orion Project CEV-HSI Team

The HHFB also leads the Orion Project's CEV-HSI team by managing all things related to Orion's human health and performance concerns. The team's major roles are summarized below:

CEV RESOURCE PLANNING AND ALLOCATION

The CEV-HSI team supports the Orion Project Office with resource planning and subject matter expertise for the HFE subsystem and ensures that all assigned resources are allocated and managed properly for human health and performance concerns. The team works with all Orion team members including civil servants, contractors, and other NASA centers. Team members are always ready to provide content for and assist with modifications to the Orion Prime contract as the spacecraft designs and interfaces evolve.

OVERSIGHT OF ORION REQUIREMENTS, VALIDATION STUDIES, AND STRATEGIC SUPPORT

Another contribution of the CEV-HSI team is to manage the children flow-down requirements from the HSIR to the Orion Project. This role involves assisting Orion stakeholders in the interpretation of requirements, as well as addressing HSIR issues and determining their impacts on CEV subsystems designs. With their human factors expertise, the HSI team members participate in design reviews and validation studies such as needs assessments, cost credibility studies, and flight demonstration projects.

SAFETY OVERSIGHT AND RISK MITIGATION PLANNING

The CEV-HSI team also serves as the liaison for the SLSD in all things related to Orion's human health and performance concerns by being the conduit to the Orion Project Office's Health and Medical Technical Authority (HMTA). The team identifies specific human health and performance related risks and develops the appropriate mitigation plans. When technical concerns regarding human health and performance are unresolved, the CEV-HSI team members serve as an independent entity on Orion boards and panels to address those issues.

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Anthropometry in Constellation Spacesuit Development

The Anthropometry and Biomechanics Facility (ABF) at the HHFB has initiated an effort to overcome the existing limitations of the current spacesuit architecture. The ABF has identified several key anthropometric factors to improved crew-interface accommodation (Jeevarajan and Rajulu 2008): (i) the minimum mobility needed to perform all necessary tasks; (ii) the minimum strength a suited crew population is capable of exerting; and (iii) the dexterity and tactility capabilities and limitations existed on the pressurized gloves.

By benchmarking the existing suits on those critical factors, the human factors engineers at NASA can gauge the constraints of the current spacesuits. From a SE perspective, the data allows human factors engineers to work closely with spacesuit designers and engineers in developing requirements that would eventually eliminate or minimize the potential injuries as well as improve the safety and comfort of the new spacesuits.

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OLED Emergency Egress Lighting System Development

The newest activity from the Lighting Environment Test Facility (LETF) at the HHFB is the emergency egress lighting system that uses Organic LED (OLED). OLED composes of long-lasting photo-luminescent material and extremely low power organic polymer. The system will greatly reduce maintenance costs without compromising safety for future space vehicles.

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FUTURE: INCORPORATING THE HUMAN-CENTERED DESIGN PHILOSOPHY INTO THE NASA SYSTEMS ENGINEERING PROCESS

As evident in the success the HHFB has made in the past two decades, the HAAS model has gained much visibility at NASA. Besides continuing the endeavor in the upcoming years to promote the HAAS model, the HHFB plans to take a step further by making HFE an integral part of the NASA SE process through introducing the Human-Centered Design Philosophy (HCDP). As a first step, the HHFB plans to update the next version of the NASA SE Handbook with HCDP-relevant language. This first step will enable the NASA engineering community to be more aware of the concept. Through the HHFB's effort on the new Handbook and the introduction of the HAAS model into past and current programs, future programs will be more receptive to the HCDP and hence more likely to adopt the idea into their systems design.

Unlike the HAAS model, which emphasizes the importance of incorporating the human into the systems design, the HCDP goes further by recommending a holistic and iterative systems design process with the humans as the center the systems development process (Wong 2008). With the HCDP, the entire system is considered as a whole and designed with humans as the ultimate customers.

An effective holistic/iterative systems design process should follow a spiral pattern where more effort is spent on the early design stages to explore feasible concepts. A holistic systems design process looks at the entire system life-cycle in its entirety. The systems development team should be composed of a multidisciplinary team of professionals. An iterative approach with multiple design cycles is more effective than the traditional linear approach to systems design for today's highly complex systems. Multiple design cycles ensure sound designs in each cycle given the maturity level.

The HHFB plans to provide detailed descriptions of the HCDP for consideration of incorporation into the next version of the NASA SE Handbook.

CONCLUSION

The HHFB has come a long way in the past two decades to convey to major NASA programs the benefits of the HAAS model in SE. While the HHFB efforts have been successful, introducing the HAAS model is only the interim solution to HSI. The HHFB's ultimate goal is to introduce the HDCP into the NASA SE process. The HCDP will greatly enhance the qualities of future NASA human and non-human rated space systems with higher efficiency, reduced cost, and increased safety.

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Biography

Douglas Wong is an aerospace human factors engineer at the NASA Johnson Space Center's Habitability and Human Factors Branch in Houston, Texas.

Doug has been with NASA since 1989. His first position at NASA was a wind tunnel instrumentation research engineer at NASA Langley Research Center in Hampton, Virginia. His career on human factors began in 1998 when he joined the Crew/Vehicle Integration Branch at NASA Langley. At the time, he worked on many research projects related to aviation safety, especially in the area of Synthetic Vision Systems. In 2005, he joined NASA Johnson Space Center and has been working on spacecraft related human factors projects. One of his current major projects is the Orion spacecraft, which will be the Space Shuttle replacement. His prime focus on this project is human model validations. Besides the Orion project, Doug has been involved in advocating a human-centered system engineering philosophy at NASA.

Doug is a licensed Profession Engineer in the state of Virginia. He received his Master of Science degree in Mechanical Engineering from the University of Maryland in 1989. He also has both formal and on-the-job training on human factors and statistics.