HUMAN-SYSTEMS INTEGRATION CHALLENGES FOR CONSTELLATION

Jeffrey W. McCandless, Ph.D., NASA Ames Research Center, Moffett Field, CA
Mary K. Kaiser, Ph.D., NASA Ames Research Center, Moffett Field, CA
Timothy S. Barth, NASA Kennedy Space Center, Kennedy Space Center, FL
Robert S. McCann, Ph.D., NASA Ames Research Center, Moffett Field, CA
Nancy J. Currie, Ph.D., NASA Johnson Space Center, Houston, TX
Barbara J. Woolford, NASA Johnson Space Center, Houston, TX

The National Aeronautics and Space Administration (NASA) is developing plans for the successor to the Space Shuttle. The Constellation Program within NASA is responsible for developing the Crew Exploration Vehicle (CEV) and related systems to provide astronauts with access to space. The CEV will include many improvements over previous spacecraft, and numerous NASA groups are involved in designing those improvements. For example, the Space Human Factors Engineering (SHFE) project is supporting work on a range of tasks including crew training, cockpit displays, and crew anthropometry. Additional improvements will focus on launch and landing site operations. Within the CEV itself, an upgraded caution and warning system will increase the crew's abilities to diagnose and resolve malfunctions. CEV ergonomics are critical since the vehicle will support several configurations of crew and cargo to maximize its operational flexibility. Work on CEV habitability is being based on numerous factors such as a task analysis to identify critical crew activities. All of these tasks will help ensure that the next-generation spacecraft provides safe and efficient access to space.

The National Aeronautics and Space Administration (NASA) has instituted the Vision for Space Exploration (February 2004) which calls for expanded human exploration of space. In particular, the Vision calls for a human return to the Moon in preparation for human exploration of Mars and other destinations. Project Constellation is responsible for developing the vehicles and related architecture systems for meeting that goal. Its components will include transportation systems (such as the Crew Exploration Vehicle, or CEV), ground infrastructure (such as launch and mission control), communication elements, and robotic assistants. To assess the vehicle requirements and key technologies to enable exploration systems, NASA created the Exploration Systems Architecture Study (ESAS) team in 2005. The ESAS Final Report (November 2005) describes recommendations on the characteristics of the CEV and launch vehicles. For example, the report recommends that the CEV be capable of carrying four crew members to the lunar surface (double the number during each Apollo mission) with a substantially larger habitable volume for the crew. In addition, the ESAS Final Report documents many of the human-systems challenges in continued human space exploration, such as the need to provide the crew with insight over automation and the need for technologies to increase crew efficiency. Further challenges include the necessity of identifying and prioritizing which technology development tasks should be performed over the next several years. In this panel discussion, five participants (from three NASA centers) will discuss the work in progress to address those challenges as their agency continues its path towards expanded human exploration of space. In particular, the panelists will discuss:

1) the Space Human Factors Engineering (SHFE) gap analysis;
2) Launch and landing site operations;
3) an enhanced Caution and Warning system;
4) CEV ergonomics;
5) CEV habitability.

SPACE HUMAN FACTORS ENGINEERING

NASA's Vision for Space Exploration presents significant challenges for Human-Systems Integration (HSI). It is critical, then, that the agency aligns its human-factors workforce and resources to address key questions in a timely, phased manner.

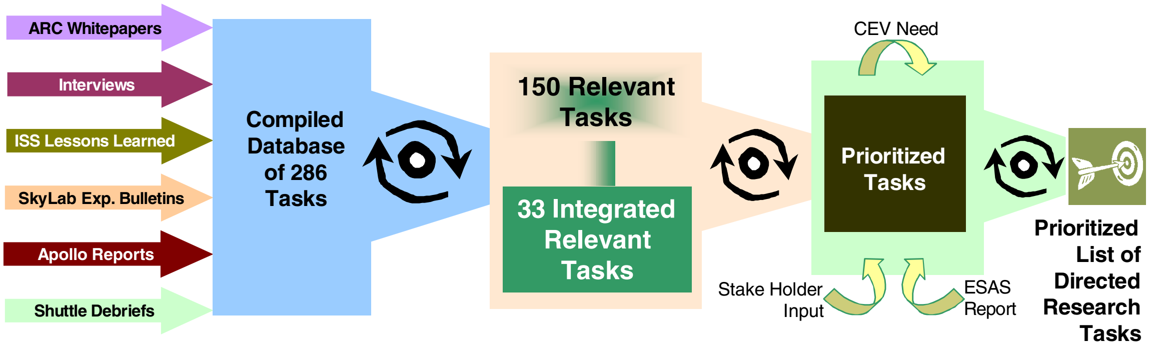

Figure 1. The gap analysis process used by the Space Human Factors Engineering project element to develop a prioritized list of Directed Research Tasks for Human Systems Integration (credit: Barbara Woolford).

To that end, the SHFE Project performed a research and technology gap analysis. White-paper reviews compared state-of-the-art and state-of-practice with Exploration 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: 1) in-depth reviews with subject matter experts, in both space human factors and the user communities; 2) historical reports from Apollo and Skylab missions as well as debriefs and "lessons learned" from the Space Shuttle and International Space Station.

Over 200 research topics were gleaned from the interviews, white papers, and mission reviews. Experts then rated these topics on multiple dimensions. These ratings were integrated with critical issues raised by the Exploration Systems Architecture Study to yield a final set of critical tasks that now comprise the SHFE research portfolio. Figure 1 illustrates gap analysis process.

This process was not without flaw. Weighting of factors was often subjective; it was often difficult to distill the underlying HSI issues from historical reports of difficulties crew encountered. Finally, the actual task chosen for the current SHFE research portfolio was constrained by program funding and the need to match tasks to current in-house expertise. Nevertheless, the process has produced a portfolio that addresses critical near-term needs of the Exploration Program, and is endorsed by major agency stakeholders.

LAUNCH AND LANDING SITE OPERATIONS

People, including flight, ground, and surface crews, are the critical elements of the system of Exploration Systems. HSI challenges in launch and landing site operations have not been thoroughly addressed during the design and development phases of previous NASA programs. Proactive, substantial HSI efforts in all ground crew operations are essential to support the safety, reliability, sustainability, and life-cycle cost goals of NASA's Constellation Systems. Ground operations include spacecraft and ground support system manufacturing, assembly, test, checkout, and maintenance. Ground crew functions supporting human spaceflight operations are illustrated in Figure 2.

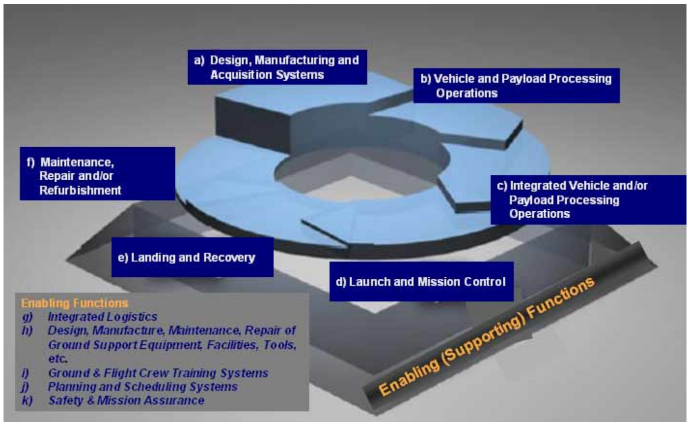

Figure 2. Ground crew operations supporting Constellation systems.

Improving ground crew safety means fewer chances for human error/collateral spacecraft damage in ground processing that could adversely affect flight crew safety, public safety, and the safety of high-value national assets. Specific gaps for ground crews include: HSI design guidelines for unique ground support systems, upgrades to specialized personnel protective equipment supporting hazardous operations such as hypergolic propellant servicing, user-friendly interfaces between ground and flight systems such as quick-disconnects for fluid systems, and intelligent/adaptable procedure systems. Several ground crew HSI gaps are illustrated in Figure 3.

Figure 3. Examples of HSI opportunities for improvement in current ground crew operations.

ENHANCED CAUTION AND WARNING

Every spacecraft has a Caution and Warning (C&W) system, and the vehicles that will support the Vision for Space Exploration will be no exception. In general, C&W systems can be thought of as complex signal detection devices, continuously searching for indications of off-nominal system functioning (signal plus noise) from a noisy "nominal background". The noise in the nominal data comes from many sources, including measurement error, data feeds from failed or degraded sensors, and natural perturbations in system function over time. In today's spacecraft, nominal versus off-nominal discriminations are made via simple limit-sensing algorithms that continuously compare sensor values against preset high or low limits. Because limit sensing operates at the individual sensor level, there is little or no data fusion, leaving the system vulnerable to false alarms (cockpit annunciations, such as written fault messages and/or auditory alerts) based on failed sensors. Similarly, adding to the "false alarm" rate, if a malfunction occurs that results in off-nominal readings from sensors associated with systems components located downstream of the instigating failure (such as fans or pumps that stop operating due to a failure in the power supply system), caution and warning systems based on simple limit sensing will produce a cascade of caution and warning events, as many as one for each off-nominal reading. This situation is distracting and annoying to the crew, and can greatly interfere with their ability to determine the root cause of the problem. In sum, limit-sensing systems are relatively poor signal detection devices.

The designers of caution and warning systems for VSE spacecraft have much more powerful signal-and data-processing tools at their disposal than simple limit sensing. These tools hold great promise for improving the discrimination and classification capabilities of C&W systems. Space limitations will force us to consider just one example of how these algorithms could bring improvements.

Many spacecraft sensors provide data on the functioning of physical components that vibrate, yielding signals that vary systematically in the time-frequency domain. Mathematical techniques such as short-time Fourier analysis and discrete wavelet transforms can now analyze temporally extended samples of sensor values, comparing their time-varying characteristics against patterns that correspond to off-nominal system functioning *and to nominal system functioning*. A classification algorithm that is actively trying to match a pattern against nominal modes as well as off-nominal modes could be a very powerful identifier of failed sensors (versus sensors that are supplying bona fide evidence of a true off-nominal condition). Suppose three sensors are redundantly sensing the same operating parameter for the same system. If one the three sensors fails outright, and begins to provide off-nominal readings, a sensor fusion algorithm could be quickly recruited to attempt to match the off-nominal readings against patterns associated with known failure modes, while simultaneously determining the degree to which the characteristics of the most recent readings from the remaining sensors match those associated with nominal operation. The probability that data from a failed sensor would retain many patterns associated with nominal operations is remote, particularly if the nominal signature included components at multiple harmonic scales and amplitudes. Meanwhile, the probability that the sensor in question is indicating a valid off-nominal condition would become infinitesimal if the remaining sensors were exhibiting highly similar complex patterns that were consistent with nominal operations. Thus, this type of sensor and data fusion could quickly iterate on a failed sensor diagnosis, reducing the false alarm rate of the overall system.

While modern techniques and algorithms offer great promise for C&W improvement, much of the devil will be in the human factors (interface) details. When machines are making safety-critical decisions, such as whether off-nominal indications are genuine or due to sensor failures, and the classifications are being made on the basis of complex data processing and analysis techniques, the danger is that the crew will have no insight into the basis for the C&W decisions, and so no basis for troubleshooting these decisions and detecting possible errors. These considerations may set requirements for new features on system summary displays that capture critical aspects of the algorithmic functioning within the displays themselves. An example might be to provide digital sensor readings in an intermediate level along a grey scale, and represent salient aspects of the natural time-varying patterns in the sensor readings via small changes in brightness up or down the scale. Only when the algorithm determined that these changes fall outside the realm of nominal functioning would the digital change from grey to a caution and warning hue, such as yellow or green.

These and many other issues associated with advanced caution and warning systems remain to be explored.

CREW EXPLORATION VEHICLE (CEV) ERGONOMICS

CEV design must support several configurations of crew and cargo to maximize operational flexibility for missions to and from the International Space Station, to and from lunar orbit for missions to the moon, and, eventually, transport crew members to and from a Mars Transfer Vehicle in low earth orbit. Ergonomic design considerations for the spacecraft's cockpit layout include maximizing the range of anthropometric accommodation for both male and female American populations; task performance and operations in both high and reduced gravity conditions; range of motion, work envelopes, and visibility in both unsuited and suited/pressurized conditions, and mitigation of physiological responses during specific mission phases such as spinal elongation in reduced gravity (g) conditions.

NASA's Human Systems Integration Requirements (HSIR) which governs the design of all Constellation elements currently specifies that all aspects of the vehicle with which a crewmember may physically interact with shall accommodate stature, mass, and specified body components which are representative of the 1st to 99th percentile points of the male and female population in the 1988 Anthropometric Survey of US Army Personnel (ANSUR) database projected forward by NASA to 2015 to account for the expected small growth in the size of members of the US population. Critical anthropometric dimensions have been identified for specific elements of the cockpit design including the integrated seat layout, seat and restraint systems, and pressure suits. For example, seven dimensions were identified as critical for CEV seat layout: seated height; seated acromial height; bideltoid breadth; forearm breadth; knee height; buttock-knee length, and foot length. Five additional dimensions were identified as important but not critical for seat layout: seated eye height, thigh clearance, seated popliteal height, buttock-popliteal length, and hip breadth. Using these parameters, three-dimensional digital human models in representative pressure suits were then created to enable computer-aided design and analysis of proposed seat layouts to accommodate up to six crewmembers in the cockpit environment. Proposed seat layouts were then evaluated with respect to human g-load tolerance limits, crew ingress and egress (nominal and time critical), adequate clearance from vehicle subsystems components, adequate clearance between suited crew members, crash load attenuation, operator visibility and operability of displays and controls, and proximity to windows to provide adequate external fields of view.

An important aspect of CEV cockpit and cabin design is the consideration of the extreme range of potential gravity environments encountered by the crew - from great than 10g during some launch abort scenarios to microgravity conditions in low earth orbit. To ensure proper design interfaces all controls, input devices, and switches in the cockpit and cabin will be assigned to a specific "reach zone". The reach zones are defined by conditions, such as functional reach encumbrances associated with elevated g flight, that affect the operator's ability to reach and operate controls. Fields of view within the cockpit have also been defined using a similar approach to assist in the placement of displays and controls. Crew interface items deemed most critical for ascent and entry flight phases must be located in the operator's primary field of view while seated, restrained, and wearing a pressure suit. The primary field of view is defined as a 30 degree cone extending ± 15 degrees left/right and up/down about a central line that is depressed 15 degrees from the line perpendicular to the sagittal plane of the face as measured from the design eye point. The primary view of considers head rotation limitations incurred by elevated g flight and pressure suit helmet designs.

Ergonomic considerations are a critical element in the human-centered design approach to CEV cockpit development to ensure that human performance capabilities and limitations are considered for all vehicle systems requiring crew interaction.

CREW EXPLORATION VEHICLE (CEV) HABITABILITY

NASA's space human factors team is contributing to the habitability of the CEV in a variety of ways. First, we provided anthropometric data based on all prior candidates considered for crew selection to use in establishing that indeed, six suited crewmembers can fit into a conical capsule with the specified inner diameter. Now we are refining models of physical size and range of motion for crew in various pressure suits to assess candidate designs. Specific tasks during launch and landing will be identified as critical, and designers will evaluate layouts based on reach and field of view.

Crew consumables such as food, water, clothing, and hygiene supplies will be critical to the habitability of the CEV and to crew survival and comfort under a variety of scenarios. The human factors team provides data on minimum quantities, as well as estimates of effects on performance and well-being when the amount and variety of these are limited. We are conducting studies of stowage techniques to minimize packaging weight and volume, and to reduce crew time lost to looking for and accessing supplies. A low-fidelity mockup has been constructed to enable current crew members and managers to experience the effects of various layouts. Computer models quantitatively compare free volume between configurations and facilitate visualizing tasks being performed under high gravity conditions during launch and landing, and under micro-gravity conditions on orbit.

Task analyses are under way to identify critical crew activities. Lessons learned from the International Space Station underscore the importance of well-designed procedures and schedules. New display and navigation concepts are being evaluated to provide crew procedures in more effective ways, to reduce both on orbit crew time requirements and pre-flight training. The reduced volume of the CEV, relative to the space shuttle and space station, will significantly limit dedicated displays and controls. On the other hand, as systems become more sophisticated and sensors become more easily embedded, leading to far more information potentially available to crew members, the competition for interface space increases. Task analyses and understanding of human perception and cognition are critical to sound decisions about interface design.

Task analyses combined with measuring envelopes for physical performance of the tasks are determining 'keep out' volumes that must stay free of fixed equipment to enable suit donning and doffing, and emergency operations in case of medical emergencies, or fire or depressurization. Formal internal volume configuration control for the space station did not begin until long after the station was inhabited and science operations were initiated. Only later did the realization that deploying multiple payloads simultaneously impeded crew travel in case of emergencies lead to a formal assessment of operational scenarios. CEV, with its much more restricted free volume, is addressing the issue in the earliest design stages.

ACKNOWLEDGMENTS

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