Panel Presentation: Human Factors Technologies for Space Exploration

Jeffrey W. McCandless[1], Robert S. McCann[2], Immanuel Barshi[3], Mary K. Kaiser[4]
NASA Ames Research Center, Moffett Field, CA 94035

Anthony D. Andre[5]
San Jose State University, San Jose, CA 95192

The National Aeronautics and Space Administration (NASA) is supporting the next phase of space exploration with new spacecraft, launch vehicles, and ground control facilities. Because of the enormous engineering advances in the three decades since the Space Shuttle was developed, NASA will be able to infuse many advanced technologies into these systems that were not available when the current space transportation system was developed. However, technology infusion comes with many human factors challenges. For example, crew vehicle interactions will become more complex and interactive with potentially variable levels of human-machine function allocation (levels of automation). Crew training techniques will need to take variable automation into account. Advanced extra-vehicular activities may involve communication not only among physically isolated crew-members (perhaps on an orbiting spacecraft and on the lunar surface), but also between humans and remotely situated robots. Human systems integration techniques will use engineering advances and knowledge to ensure that the complex developments associated with this next phase of space exploration are safe and efficient.

I. Introduction

The Vision for Space Exploration (2004) calls for the development of innovative technologies to support human space missions to the moon and beyond. Technology innovation has a particularly strong impact on the field of human factors, which focuses on the design of systems, operations and work environments to take the best advantage of human and machine capabilities and compensate for their limitations where needed. By applying human factors principles to space exploration systems, NASA intends to ensure safe and efficient space missions, starting with crew training, and continuing through crew interactions with the new vehicles and crew activities in remote and extreme environments. Four key areas of human factors associated with the development of this new era of human space exploration are: 1) developing, testing, and validating operational concepts for crew-vehicle interactions, 2) pre-flight and in-flight crew training, 3) extra-vehicular activities (EVAs) and teleoperations, and 4) tools and models to support human-systems integration engineering. This paper discusses those four areas as well as potential requirements for developing the next-generation spacecraft and accompanying systems.

II. Crew-Vehicle Interactions

When considering human-machine interactions on future space missions, the first concept that probably comes to mind is some form of human-robotic interaction, such as a crewmember working with an intelligent mobile assistant to explore a planetary surface. However, the most famous example of human-machine interactions may be those that occurred between the fictional crew of Discovery and HAL, the spaceship controller in the movie 2001: A Space Odyssey. HAL was an example, not of a robot, but an immobot (Williams and Nayak, 1996), a nonmobile

---

[1] Research Psychologist, Human-Systems Integration Division, Mail Stop 262-2
[2] Research Psychologist, Human-Systems Integration Division, Mail Stop 262-4
[3] Research Psychologist, Human-Systems Integration Division, Mail Stop 262-2
[4] Research Psychologist, Human-Systems Integration Division, Mail Stop 262-4
[5] Adjunct Professor, Departments of Psychology and Industrial/Systems Engineering

intelligent agent that gathers, interprets, and acts on information about a building, a machine, or a spacecraft and performs critical operational and control functions.

We are a long way from having immobots with HAL's capabilities. On today's shuttles, limitations in computing horsepower, flight and systems management software, and 1970s-era cockpit interfaces sharply limit the opportunities for humans and onboard computing systems to work vehicle operations in a cooperative manner. For example, the procedures that should be performed in the event of a systems malfunction are available only in paper form, so there is no opportunity for the crew to work through the activities in partnership with fault management software and interactive electronic information displays, the way it is done on modern aircraft. Similarly, in the event of a serious systems malfunction during the ascent phase of a shuttle mission, elaborate contingency scenarios are designed for aborting the mission and returning the shuttle as quickly as possible to Earth. These abort contingencies change rapidly as the vehicle gains altitude and velocity. On the ground, abort determination software computes real-time abort options for different failure scenarios, such as the loss of one, two, or all three main engines. This software is not available on the shuttle, however, leaving the crew dependent on the ground to call out abort options or, in a no-communication situation, to perform complex real-time mathematical extrapolations based on paper abort tables.

Designers of next generation crewed spacecraft have an opportunity to exploit the power of today's portable computing devices to put these and other flight- and vehicle-health-management software systems onboard the vehicles. These systems will automate many tasks that are difficult or time consuming for the crew. Much more than today, then, vehicle operations will become cooperative ventures between the crew and these onboard software systems, the first generation of immobots. This fundamental change in vehicle operations carries important requirements for human-vehicle interface design. For example, next-generation interfaces must support crew oversight over a much wider range of automated activities than in today's vehicles, while also providing insight into automated forms of reasoning and computation and the health of the automated systems themselves.

Traditionally, spacecraft systems have communicated their functional mode and operational status to the crew via a limit-sensing caution and warning system, which alerts the crew only when a sensed value exceeds a predetermined limit (high or low). Such a system is only capable of doing a crude classification of an off-nominal situation; there is no active computation to enable a real-time determination that the spacecraft systems are operating in their nominal mode. By contrast, modern vehicle and flight management software agents can perform real-time computations on sensor feeds that enable them to classify the incoming signals as consistent with either nominal or off-nominal operating modes. With such systems, spacecraft operations could be actively characterized as "nominal."

With the right interface design, the computations involved in making the nominal determination could be turned into useful information for the crew. For example, most sensor values vary over time, even when the underlying system is operating nominally and there is no change in the system's operating mode. Assuming these values are displayed to the crew in white digital form (the traditional format for sensor data), this normal variability could be depicted via small but perceptually noticeable changes in the brightness of the digits (McCann and Spirkovska, 2005) around an intermediate brightness level. When only brightness is changing (but not color), the luminance changes would be "informing" the crew that analyses of current variability in the signal are consistent with (or even provide strong support for) the hypothesis that the system is operating normally. At the same time, assuming that, with training, the continuous fluctuations in brightness form a temporal pattern that becomes recognizable to the crewmember, the fluctuations would provide a salient indication that the immobotic system responsible for assigning the current operational state to the nominal category is itself "live" and functioning normally. In this and many other ways, new technologies will influence the design of a new generation of user interfaces to support effective crew-machine teaming for vehicle operations.

III. Crew Training

As is evident in the previous section, future crew members will be interacting with automated systems which are very different from those currently available to the Space Shuttle, or to the International Space Station. The distribution of functions between human agents and machine agents will be very different from current practices, and communication including modes, channels, and symbology will be very different. These differences may give the impression that only slight content adjustments would be necessary to adapt crew training to future missions. However, as is evident in the following sections on extra vehicular activities and on human-systems integration, there is a lot more to the story: the environment and modes of operations of future missions will be very different from what we know today. Most importantly, the Vision for Space Exploration represents both qualitative and quantitative departures from current missions. These very departures pose the greatest challenges to crew training.

Current shuttle missions allow for many months of training on the ground followed by a short (about two weeks) space flight. Under these conditions, crew members are able to rehearse most tasks to the point of near-automaticity. Furthermore, low-earth orbit allows for continuous real-time communication with mission control. In that situation, mission control can remotely perform many operations, and provide real-time support and guidance in cases of unexpected events. These luxuries will not be available to crew members on future space missions.

Future space missions are expected to last much longer and travel much farther than current missions, introducing significant skill retention issues as well as communication delays. Thus, rather than rehearse specific tasks and rely on mission control for support and guidance, future crews will have to train for generalizable skills and rely on themselves and on on-board support systems. Performance of specific tasks will require refresher and transfer training, and unexpected tasks will require on-board creation of training.

Ground-based pre-flight training and in-space just-in-time training and task rehearsal will continue to be enablers of exploration missions. On-board training systems will enhance the autonomy and effectiveness of exploration crews. Given the nature of the missions, onboard training opportunities for individuals and teams will be needed, some embedded in actual operational devices, others in reconfigurable training and mission rehearsal systems. These systems will enable the crew to maintain skill levels and to develop new skills or practice new procedures to resolve new challenges as they arise. Tailored training approaches and new operational procedures and software will be uploaded to the flight crew from mission control or be devised by the flight crews themselves as needed. Research required for training systems includes: concept development and validation for embedded just-in-time training systems; methods and technologies to assess and maintain performance readiness; technologies and techniques for adaptive, individualized, skill-based training; methods and techniques for the acquisition, development and retention of generalizeable judgment, decision making, and creative problem solving skills; and human performance modeling and prototype development of the continuum from training to decision support.

IV. Extra-Vehicular Activities

In EVA and teleoperations, the human-systems integration (HSI) issues are associated with a broad range of activities, including:

- suited astronauts conducting in-space EVA;
- suited astronauts conducting surface operations on the Moon, Mars, or a near-earth orbit;
- astronauts in a spacecraft or habitat conducting in-space or on-surface teleoperations;
- Earth-based controllers conducting in-space or on-surface teleoperations; and
- Earth-based or spacecraft-based controllers teleoperating equipment within a spacecraft.

While this list describes a variety of mission scenarios, all involve humans performing physical actions on an environment through a mediating interface. Although EVA astronauts are physically onsite, their sensory inputs and motor capabilities are mediated (and typically impoverished) by the very suits that allow them to survive in the mission environment. The astronauts in the spacecraft or habitat may be working in shirtsleeves, but they are controlling devices in a remote environment – an environment that may differ greatly in thermal and gravitational/inertial properties. The Earth-based controller faces these same conditions, plus the additional challenge of communications latency and bandwidth limitations.

The overarching challenge in this domain, then, is to minimize the impact of mediation on operator performance. This can be done via the development of advanced interfaces that compensate for cognitive, perceptual, and motor losses. In fact, properly designed interfaces may even augment capabilities; astronauts can "see" beyond the range of visible light, exert forces with precision and magnitudes beyond normal human capabilities, reference information sources far more vast than their own memory stores, and better resolve complex problems via decision support systems. Properly configured, then, the abilities of human-robotic teams can far exceed the capabilities of the individual agents.

The preservation and possible enhancement of crew sensory-motor capabilities during exploration activities is a critical requirement for the entire endeavor, dramatically enhancing scientific productivity and the opportunity for serendipitous discovery. Fully robotic exploration systems simply do not have the sensitivity, knowledge base, agility, and flexibility that an unencumbered, computationally augmented, human explorer would have. Even human-operated earth-based telerobotic systems, which essentially transport the intellect of entire crews to planetary surfaces, are significantly impaired with respect to direct fieldwork.

Much of the impairments due to mediation originate from an inability to perceive and react to the surrounding spatial environment in a timely manner. Indeed, one of the principal challenges to teleoperated exploration is to develop general strategies for managing system response latency to enhance scientific productivity. Mars Exploration Rover (MER) Project Scientist Steve Squyres has commented, for example, that, “what our magnificent robotic vehicles can do in an entire day on Mars, these guys [human geologists] could do in about 30-45 seconds" (NASA, 2004). However, such optimized productivity will not be realized if the EVA suits that are used have the dexterity, tactility, endurance, and flexibility characteristics of current suits. Indeed, deployment of suits that highly degrade the astronauts' normal sensory-motor capacities undercuts the justification for sending crew to the surface in the first place.

In addition to this general "mediation challenge," each of the aforementioned operational scenarios has unique HSI issues, as does the integration of the scenarios in mixed-agents team (e.g., an on-site astronaut working in concert with a teleoperated device). Task allocation among these agents must recognize the strengths and unique capabilities of each team member; the end goal is to maximize the productivity and creative opportunities for the human explorers while ensuring their safety and health. The sequence and timeframe for exploration missions will help to define where principal research and technology investments should be made.

V. Human-Systems Integration

HSI engineering includes the development, implementation, and integration of data, knowledge, tools, techniques, methods, and models to reduce risks due to physical and cognitive mismatches between crew, equipment, environment, tasks, and procedures. Successful employment of HSI engineering methods and products can yield increased operator safety and increased efficiency in terms of design cycles, mission operations, and training. Stated directly, HSI engineering support is needed for systems to be usable and effective. We have identified several key challenges that need to be addressed in this area, as well as gaps that currently exist between NASA's expected HSI engineering support needs and its current capabilities.

The first and primary need is data that pertains directly to human performance issues in the planned future exploration missions, as these create new HSI considerations. For example, future missions will require a small number of crew-members to operate with greater autonomy than in the past (given the delay in communication between Mars and Earth), and for longer durations. Thus, crews will need to be more self-reliant and possess more varied skills sets than past missions. Crews must be selected and trained accordingly and on-board systems must be designed to enable long-haul, self-sufficient operations. Further, it is anticipated that many mission activities will be conducted by, or in parallel with, robots and other forms of automated computer-based agents. This creates new human factors requirements regarding the allocation of function of tasks and missions to humans and robots, as well as interface and interaction design issues.

The second key need is the establishment of human performance requirements for the unique and extreme environments that are not encountered in any other domain. Along with requirements associated with hardware and software accuracy and reliability, a priori criteria for the performance, behavior and subjective aspects of the human experience must also be identified early on in the requirements phase.

The third key need is a suite of conceptual design tools that allows engineers, researchers and designers to easily and accurately model, mock-up or otherwise evaluate and justify proposed system designs. These tools must allow for early evaluation of mission-relevant factors such as protective clothing (e.g., suits, gloves, helmets), gravity, stress, vibration, limited space, extreme temperatures, excessive noise, and sleep deprivation. By fostering the consideration of human needs and design impacts in the early conceptual design phase, critical engineering decisions can be made faster, with less cost and with a lower likelihood of error.

The fourth key need is for new tools and processes to fully document system design objectives, attributes and decisions. An efficient distributed mechanism is needed to document and manage the collection of design knowledge and rationale behind a given system design so that others can access not only *what* decisions were made in the design process, but more importantly *why* the decisions were made. Such a knowledge capture system will lower life-cycle design costs, will allow for more efficient reuse of designs, and will enable the transfer of design knowledge across design teams or generations.

Finally, the proposed NASA missions will rely on a complex organization of advanced systems developed by a diverse group of researchers and engineers between NASA and industry. Care must be taken early in the process to ensure the systems are developed to a sufficient level of consistency, in accordance with established usability principles, and following a human-centered design process, thus accounting for human capabilities and limitations, and minimizing HSI engineering risk and error.

VI. Discussion

Each of the four areas described here will form a key aspect of the human factors challenges faced by NASA in this next phase of human space exploration. For example, within the field of crew-vehicle interactions, the area of cockpit design will be critical because it will be "inherently tied to every system in both the CM [command module] and Service Module (SM) and every aspect of flight operations" (Covault, 2006). Fortunately, NASA's involvement in cockpit design is well underway, and cockpit design will remain NASA's responsibility even after a contractor is selected to build the CEV (Covault, 2006). Other areas presented here are equally important, and history has shown that failure to consider them could lead to catastrophic consequences. For example, Ellis (2000) listed crew training as a contributing factor to the collision between the Russian station Mir and a supply spacecraft. The commander of Mir, who used a teleoperated system to attempt to dock the supply spacecraft with Mir, received his most recent simulator training four months before the collision. Supplementary training approaches such as on-board training and tailored training described in this paper will be considered for the next phase of space exploration to reduce the time between an actual event and the training associated with it.

On a pragmatic level, the development of the human factors technologies described in this paper will need to be balanced against other pressing concerns that NASA will face (such as the development of launch systems). Like many government agencies, NASA's budget is fairly restricted. For example, the President's Fiscal Year 2007 budget request for NASA is \$16.8 billion, of which \$4.0 billion is allocated for Exploration Systems which is responsible for a next-generation spacecraft (source: http://www.nasa.gov/pdf/142458main_FY07_budget_full.pdf). For comparison, the total cost for the entire Apollo Program from 1962-1975 was \$30 billion (Lowman, 1996), which is equivalent to approximately \$150 billion in 2006. This translates to an average annual cost of about \$11 billion in 2006 dollars. Presumably, the planned retirement of the Space Shuttle in 2010 will result in additional funding for Exploration Systems, but in the interim, NASA scientists must judiciously determine the aspects of human factors (and indeed, all areas of technology development) that should be directed towards new spacecraft systems. Fortunately, the cost of developing the types of human factors technologies described in this paper is relatively small compared with the potential payoff in terms of enhanced mission safety and operational efficiency.

Acknowledgments

Dr. Stephen Ellis (NASA Ames Research Center) contributed to the section on Extra-Vehicular Activities. Dr. David Foyle (NASA Ames Research Center) and Ms. Becky Hooey (San Jose State University) contributed to the section on Human-Systems Integration.

References

Covault C (2006) Piloting the CEV. Aviation Week & Space Technology, Vol 164, No 25, June 19, 2006, pp 46-49.

Ellis SR (2000) Collision in space. Ergonomics In Design, Vol 8, No. 1, pp 4-9.

Lowman (1996) T plus twenty five years: a defense of the Apollo Program. Journal of The British Interplanetary Society, Vol. 49, pp. 71-79.

McCann RS and Spirkovska L (2005) Human factors of integrated systems health management on next-generation spacecraft. In Proceedings of the First International Forum on Integrated System Health Engineering and Management in Aerospace, Nov 7-10, Napa, CA.

National Aeronautics and Space Administration (2004) The Vision for Space Exploration, Washington, DC.

National Aeronautics and Space Administration (2004) Proceedings from the NASA Administrator's Symposium: Risk and Exploration: Earth, Sea and Stars. September 26-29, 2004, Monterey, CA.

Williams BC and Nayak PP (1996) Immobile robots: AI in the new millennium. AI Magazine, Vol 17, No 3.