Human Factors in Spacecraft Design

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This paper describes some of the salient implications of evolving mission parameters for spacecraft design. Among the requirements for future spacecraft are new, higher standards of living, increased support of human productivity, and greater accommodation of physical and cultural variability. Design issues include volumetric allowances, architecture and layouts, closed life support systems, health maintenance systems, recreational facilities, automation, privacy, and decor. An understanding of behavioral responses to design elements is a precondition for critical design decisions. Human factors research results must be taken into account early in the course of the design process.

Introduction

FROM a systems perspective, manned space missions consist of highly interdependent mechanical, biological, and social components. While there are many ways of delineating a complex system's constituent parts, Edwards' simple descriptive framework is of use here.[1,2] The focal concepts are hardware, liveware, and software. Hardware refers to the technical components of the overall system (e.g., spacecraft and habitats, equipment and supplies); liveware to the personnel or human operators (e.g., astronauts and ground support personnel); and software to the policies, rules, and procedures that govern people's relationships to one another and to their habitats and tools. The design goal is to achieve a high degree of "goodness of fit" or congruence among these three elements. Methods include adjusting the liveware (through personnel selection and training), devising new software (through defining roles, structuring tasks, and developing social norms), and, of course, developing new hardware.

The present paper addresses design requirements for a high level of habitability. Although the focus is on space mission hardware, habitability also rests on software and liveware since facilities and equipment must fit the competencies, behavioral propensities, and needs of their human users. The goal is to build spacecraft and habitats that provide a buffer against stress rather than contribute to stress, that allow time to be spent on scientific and other constructive tasks rather than on coping with the environment itself, that work with their occupants rather than against them, and that are sufficiently pleasant so as not to dissuade return visits.

Habitability must be achieved within tight engineering constraints. Spacecraft must maintain structural integrity and function flawlessly during launch and re-entry phases as well as under the temperature extremes and vacuum of space. They must provide protection against lethal amounts of solar radiation, and microgravity has to be taken into account. All work, living, and recreational facilities must be engineered to stringent volume and weight requirements. Designers are limited to flight-qualified materials that do not vent noxious gases, are fire-retardent, and are easy to clean. Given such considerations, it is tempting to cut corners in the interests of simplicity and economy, to lower habitability expectations, and to let the astronauts "take up the slack." However there is only so much that even talented, motivated, and highly dedicated people can do, and the more demanding or debilitating the environment, the more likely that human performance will suffer.

In the sections that follow, we will consider three general design issues that are salient for space station, lunar, and Mars missions. These include designing for the long term, for supporting high performance, and for accommodating human variability. The presentation is shaped by the changing parameters of spaceflight: trends toward increased crew size, increased heterogeneity or diversity of crew composition, extended mission duration, and greater automation.[3,4] Earlier reviews of habitability issues include those by Connors et al.,[3,4] Clearwater,[5] Santy,[6] and Stuster.[7] Also of interest is *The Handbook of Human Factors*,[8] Nicogassian et al.'s recently revised *Space Physiology and Medicine*,[9] and NASA's own evolving human factors compendium, *STD 3000: Man-System Integration Standards.*[10]

Design for the Long Term

Early spaceflight environments were survivable, a level of development that was acceptable in an era when spaceflights were measured in terms of days. Tomorrow's spacecraft and habitats, which will be occupied by the same crews for months or years, will not only have to be survivable, they will have to be livable. This requires establishing new, higher standards of environmental quality and making full provision for aspects of human existence that receive only minimal attention on short-term missions.

Improving Living Standards

Space Station Freedom and explorer craft and habitats will have to incorporate high-quality working and living facilities, good ventilation and odor control, proper illumination, and low levels of ambient noise. Quality provisioning must be given careful thought. The larder should include tasty and varied as well as healthy and nutritious food, and astronauts should not be expected to wear the same kind of clothing day after day.

An increasing need for closed life support systems will pose special challenges. For example, the Shuttle is rarely aloft for

Received Dec. 12, 1989.

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longer than a week; after each mission, it is carefully cleaned and resupplied. The Space Station Freedom, on the other hand, is expected to remain in orbit for about 30 years. Supplies will arrive every few months, and all cleaning and maintenance will have to take place in orbit. Closed life support systems will result in an increased accumulation of odors and increased consumption of recycled water. Psychological factors, along with the quality of the recycled products themselves, will affect user acceptance.

Personal hygiene systems are a particularly vexing space problem. Under conditions of microgravity, water and human waste do not progress downwards to a collection point. Instead, shower water must be vacuumed or sponged, and exotic means must be used to channel human waste toward the proper receptacle. Because the commode's user tends to float, seatbelts or foot restraints are necessary. Commodes themselves may be located in public areas (in the case of the Shuttle) or in tiny cramped quarters. The deficiencies of personal hygiene systems are will known to astronauts, designers, and engineers, and, along with biomedical needs, should be considered in determining the requirements for artificial gravity on multiyear flights.

Spaceflight environments need not be sterile or ugly environments. Color and lighting can be used to create pleasant working and living conditions, and an illusion of spaciousness. Viewpoints, including windows and cupolas, are essential not only for allowing astronauts to orient themselves to the outside world, but also to help crews maintain a feeling of contact with Earth and reduce feelings of being cramped. Artworks can be chosen for appeal and their ability to maintain interest over time. Posters can be carried aboard and changed at different points during the mission, and crew members can be given personal compact disk or tape players so that they can enjoy the music of their choice.

Increasing the Range of Habitability Provisions

Under normal conditions, the activities associated with life's three spheres – work, self-maintenance, and recreation – tend to cluster around different locations or settings and even involve different groups of friends and acquaintances. Spacecraft, however, are among a limited number of settings that hold people on an around-the-clock basis and must make provision for all aspects of life. In the early days of spaceflight, design efforts centered around work and survival, and whole segments of life were given minimal attention or ignored. Among the provisions needed for the future are expanding the range of health maintenance services, developing appropriate leisure time activities, and affording greater personal privacy.

Health Maintenance

Spacecraft and habitats must be engineered to preserve physical and psychological health. Requirements include establishing health maintenance facilities to handle ailments and injuries, and devising special protections and countermeasures against space-related hazards. Of course, medical provisions have been made for past missions, but services must be more extensive and refined for advanced space missions in which there will be more opportunity for illness or injury to occur and less opportunity to speedily return patients to Earth. Current research projects include 1) selecting the facilities, equipment, and supplies that will be of the greatest use given severe volume and weight restrictions; 2) designing medical equipment and procedures that will work under conditions of weightlessness; 3) developing telecommunications and automated systems that will expand the range of medical services; and 4) solving problems of medical staffing given crew-size limitations.

Spacefarers may be exposed to dangerous doses of galactic cosmic and other forms of radiation, especially during solar flares. Both the opportunity for exposure and the cumulative effects of exposure will increase as a function of mission length. One alternative to heavy shielding of the entire craft is the preparation of a small "safe haven" where all of the crew members can gather to ride out the storm.

Microgravity poses medical risks because it leads to bone decalcification and cardiovascular deconditioning. Although some of these changes are adaptive in the sense that they help adjust the body to the spaceflight environment, they put strain on the individual and make it difficult for the body to readjust to normal gravity following return to Earth. Vigorous exercise can offset the osteopathic and cardiovascular effects of weightlessness. However, given the close confines of the spacecraft, limitations in odor control systems, and restricted shower facilities, exercise has not been a popular spaceflight activity. Progress here hinges on the development of exercise equipment that is intrinsically motivating or inherently "fun," as well as improvements in personal hygiene maintenance.

Leisure-Time Activities

Leisure time is a likely feature of highly automated, extended-duration flights. Much recreation consists of sports or other activities that are not available in space. Competitive games, which are fun and exciting under normal conditions, may provoke conflict under conditions of isolation and confinement. In general, isolated and confined people tend to prefer passive to active forms of recreation, but preferences vary as a function of occupational background and may shift over time.[3] One recreational possibility is video or other games that help players test or hone flight-related skills.

Privacy

Privacy defines the degree of social exposure or interaction that one person has with another. To support a range of human activities, tomorrow's space habitats will need locations that afford varying degrees of privacy.[11–13] These include ward rooms and other public areas that can simultaneously accommodate all crew members; semiprivate areas such as libraries or study areas that can accommodate small subsets of crew members; and individual areas such as sleeping quarters that will afford individuals separation.

On lengthy space missions, the opportunity to restrict accessibility to others will be a necessity, not a luxury. Restricted social access contributes to a high degree of concentration that is necessary to perform complex scientific and technical tasks, provides "down time" for rest and recuperation, and helps people manage interpersonal relationships.

Large areas and a multitude of walls and doors are not necessary to achieve privacy.[11,12] The use of lightweight or "soft" features (e.g., screens, moveable partitions) and the availability of small personal items that can be used to "stake out" personal territories along with the careful planning of "hard" architectural features (e.g., interior dimensions, walls, doors) can do much to regulate social distance. Low illumination, which obscures facial features, and background music, which lowers the intelligibility of nearby conversations, can increase psychological distance as can the presence of windows, interesting works of art, television shows, reading materials, and other distractions that people use to mentally tune out each other.

Design for Performance

To help offset the high cost of each person-hour in space, NASA sets high performance standards for all missions. A major design goal is to find ways to arrange conditions so that astronauts can perform as efficiently and effectively as possible and to concentrate on creative, productive tasks.

Increasing Efficiency

Cramped quarters, limited supplies and equipment, little or no resupply, the need for cumbersome protective equipment outside the craft, and microgravity or "weightlessness" are among the factors that can impair productivity. Microgravity is of particular interest here, because it is a condition peculiar to space. In microgravity, astronauts can "float" and assume any position relative to their work setting. This could offer the opportunity for greater efficiency and for making use of "walls" and "ceilings" as well as "floors." However, microgravity can require extra effort on the part of astronauts just to stay in place, and there is always some risk that, in the course of moving from one spot to another, an astronaut will lose momentum and get "stuck" where walls, handholds, or other fixtures that would make it possible to resume progress remain out of reach. Floating within an environment can also reduce the environment's visual coherence and hence the ease and speed with which occupants can orient themselves within it. It has not yet been determined whether it is preferable to encourage use of the full 360-deg multiplane environment of microgravity or to supply cues that provide astronauts with a true vertical.

Compensations for microgravity include tethers, air jets, or other means to ensure that astronauts do not get "stuck" midway between interior surfaces; adequate clearances at all work stations; easy-to-operate, secure, and comfortable positioning devices and restraints; simple-to-operate, highly reliable tools and equipment; and adequate storage facilities. As much as possible, personal restraints, tools, and aids should be adjustable and relocatable to accommodate anthropometric variations and personal preferences. Furthermore, it is necessary to satisfy needs for interpersonal coordination, e.g., by providing high-quality, hands-free systems for communicating with co-workers.

Volume requirements, the appropriate allocation of space per person and per activity, are reasonably well understood for short duration flight but pre-existing guidelines are probably inadequate for future space missions. Efforts are under way to devise a set of volumetric standards that reflect: 1) the effects of microgravity and partial gravity; 2) appropriately lengthy time intervals; 3) cultural variability; and 4) future work requirements.

Interior architecture, physical layouts, the location of equipment, and traffic flow are crucial. The preferred planning sequence is to use planned operations as a basis for design. Analyses of crew functions and support needs have provided the basis for module layouts,[5,14] and computer simulation models have been developed for evaluating the behavioral effects of such factors as interior space allocations and equipment.[5,15]

Automation, the use of "intelligent" machines that process information and can contribute to or make decisions, can also enhance productivity. Automated systems will be essential if we are to accommodate the many tasks required for exploration missions. Such systems can assist with work, free up astronauts' time for other activities, and increase the educational or interest value of the activity itself. On the other hand, monitoring automated systems can be boring, encourage complacency, and lead to the loss of skills through disuse.[16]

Basic questions in developing systems that include both human and automated elements concern what roles to assign to each and how to combine their activity.[16] Simply stated, what should the human being be doing, what should the machine be doing, and how should they work together?

In general, intelligent systems can handle quickly those data that are clearly and accurately defined. Machines have an added advantage in that they are unaffected by threat or other stressful conditions. Although less reliable in repetitive operations, humans exhibit far more *plasticity* in response, a characteristic that has particular value in dealing with unanticipated events.

In order to fully understand how to combine human and intelligent machines, we must better understand what humans are capable of doing, under what conditions, and for how long they are able to do it. For instance, humans are capable of great creativity. However, creativity is a characteristic that seems to peak at unexpected times and to resist attempts to sustain it. It makes little sense to load humans with tasks that require them to be consistently creative. Overall, humans seem to need cognitive as well as physical and emotional balance, and human factors research can help identify where the balance lies. We must determine if and how intelligent humans and intelligent machines can complement, buttress, and monitor each other, and how to offset crew complacency in a high-tech environment. Once we have a more complete understanding of the capabilities and limitations of human and intelligent systems, we will be able to address operational questions regarding separate and combined human and automated activities.

Increasing the Proportion of Productive Time

We not only want astronauts to get a lot done; we want to make sure that what they accomplish is important and meaningful both to the space program and to the performer. Although astronauts need balance in their work regimens, they should not be hopelessly enmeshed in routine maintenance tasks at the expense of more productive endeavors. Increasing the preponderance of productive to routine activities means eliminating or at least automating inventory control and as many other "housekeeping" functions as possible. It means designing reliable, self-checking, self-repairing, easy-to-maintain systems and equipment. Ease of maintainability is determined by simplicity, accessibility, adequacy of restraints, and the availability of tools and spare parts. We offer two cautions in this area. First, automated functions never proceed as rapidly nor work as flawlessly as initially envisioned. Second, astronauts must not be so separated from the performance of even routine functions that they are unaware of failures occurring or are unable to intervene in an appropriate and timely manner.

Accommodating Human Variability

Over the years, there has been an expansion in the range or diversity of the crews that have been sent into space. The first crews consisted of white male military test pilots. At that time, military test pilots were a logical choice. They were in excellent physical condition, had demonstrated an ability to withstand stress, had known performance records, and already possessed many of the technical skills required for spaceflight. By the mid-1960s the needs and goals of spaceflight began to change. Scientists joined test pilots in comprising the astronaut corps, and in the late 1970s women and minorities followed.[17] The trend toward diversity continues. New work roles are increasing the range of talents and occupational skills required in space, and reduced financial burdens coupled with the promise of heightened scientific and political dividends are increasing the attractiveness of international missions.

Thus, spacecraft design must take physical and cultural variability into account. Whereas the earliest astronauts had to fit in the space capsules of the day, the Space Station Freedom is intended to accommodate all but the largest males and smallest females. Because static anthropometric measurements of bodily dimensions are rarely sufficient to specify requirements, dynamic representations of activity envelopes (spatial representations of volumes and distances required for a given activity) are required. Furthermore, these envelopes must reflect the impact of unusual conditions, such as microgravity. The full range of body movements associated with the normal performance of prescribed activities for the desired anthropometric range is under study at Johnson Space Center.

Cultural factors also complicate the design process. For instance, the same level of noise that leaves it possible for two native speakers to communicate satisfactorily may not permit acceptable levels of information exchange between people who have different native tongues. Because privacy needs also vary as a function of culture, future space habitats must be capable of housing people who are very different in terms of their desires to interact with one another.

The prospect of international crews also raises questions about culturally based preferences and aversions in such areas as work schedules, social distances, recreational activities, religious practices, decor, and foodstuffs. Selections must be tailored for individual astronauts, or be acceptable to a wide range of people.

Conclusions

In this paper, we have described, in general terms, a few implications of contemporary space mission parameters for spaceflight. First, because of the extended length of tomorrow's missions, we can no longer tolerate minimally acceptable living standards nor make do with limited attention to such issues as health maintenance, recreation, and privacy. Second, to offset the high expense of manned spaceflight, design solutions must be found that maximize astronauts' efficiency and expand options to accomplish creative, productive tasks. Third, because tomorrow's space crews will involve men and women from a wide range of occupational and cultural backgrounds, manned space systems will have to accommodate increased physical and cultural variability. Ample volumetric allowances, carefully planned architecture and layouts, high-quality life support systems, attractive decor, and mutually supportive person-machine combinations are among the paths to achieving these general goals.

In order to upgrade spacecraft habitability, research is needed in selected areas. For example, we need to know more about the behavioral effects of microgravity and partial gravity; to develop volumetric norms that reflect such factors as mission duration and crew diversity; and to improve our understanding of human-machine interactions, so that humans and machines support one another and compensate for each other's weaknesses.

There are limited opportunities to conduct research in space itself, and flight time generally should be reserved for assessing conditions found only in space or for the testing and verification of ground-based results. Fortunately, there are a number of environments that preserve many of the elements of spaceflight in that highly talented and motivated individuals perform difficult tasks under conditions of isolation, confinement, deprivation, danger, and risk.[7,18,19] Among the most promising of these spaceflight-analogous environments are subaquatic research vessels and Antarctic bases. There are now about 60 bases in Antarctica, and by choosing among them, one can find today an Antarctic outpost or community that resembles an outer space environment of tomorrow. For example, Antarctica's Dry Valley provides an excellent terrestrial analog for the surface of Mars, and there is interest in developing a prototypical base there for trying out habitats, people, and scientific research procedures prior to deployment to the red planet.[19]

Developing suitable hardware for tomorrow's space missions will require high coordination among design engineers and psychologists. Human factors issues are important, and they will not resolve themselves. It is preferable to take human requirements into account before reaching initial design decisions rather than to address them as an afterthought since the latter strategy encourages piecemeal solutions that tend to perpetuate past design inadequacies.[20] A high level of cooperation among engineers and psychologists early in the course of mission development can lead to high-quality decisions that perfect the system as a whole.

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