NASA Exploration Systems Enterprise
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Architectural Design to Promote Human Adaptation to Artificial Gravity

A White Paper
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Abstract

Habitat design might mitigate the cost of artificial gravity by aiding human adaptation to higher rates of rotation at shorter radii. Such design strategies have remained largely unexplored. This paper presents arguments for more research in this area.

Background

Decades of experience in low Earth orbit have amply demonstrated that prolonged exposure to micro gravity is detrimental to human health. Current countermeasures focus only on certain organ systems and symptoms, require specially adapted therapeutic equipment, are time consuming, demand a high degree of individual discipline, and yet are only partially effective at slowing the crew's physical decline over a period of months [Connors, Harrison, Akins, 1985; Covault, 1983; Covault, 1988; Diamandis, 1987; Gunby, 1986 a; Gunby, 1986 b; Keller, Strauss, Szpalski, 1992; Lenorovitz, 1989; Marwick, 1986; Merz, 1986; Oberg, Oberg, 1986; Raymond, 1986; Wickelgren, 1988; Woodard, Oberg, 1984; Woodard, 1985]. Artificial gravity has long been proposed as a means of holistically maintaining the entire human organism and avoiding all of micro gravity's adverse health effects. Yet it has not been implemented, in part due to concerns with system complexity and cost in mass and energy.

It has been suggested that artificial gravity may be unnecessary for manned Mars missions because some individual cosmonauts have survived a year or more in micro gravity. These long-duration missions are milestones of human endurance. To adopt them as models for future missions, while disregarding other cases that fared worse on shorter flights, would be something akin to the "normalization of deviance" described by the Columbia Accident Investigation Board [2003 August]. In this case, the deviance being normalized is not in the spacecraft, but in the crew – whether discounting extraordinary endurance, or accepting a serious decline in health, as if they were normal.

As NASA prepares to send humans far beyond Earth on missions lasting a year or more, it should investigate vigorously the cost and complexity of providing artificial gravity versus the cost and complexity of avoiding it through continued application of other countermeasures. Current practice does not avoid complexity but merely defers much of it from mechanical engineering to space medicine – a field of endeavor that's less well understood and much harder to control. Meanwhile, design strategies that might mitigate the cost of artificial gravity, by aiding human adaptation to higher rates of rotation at shorter radii, have remained unexplored [Hall 1999 July; Hall 1999 Sep.; Hall 2002 July; Hall 2002 Oct.].

From studies in ground-based centrifuges and rotating rooms, researchers have estimated that the maximum angular rate for "comfortable" rotation is between 2 and 6 rpm [Cramer, 1985; Gilruth, 1969; Gordon, Gervais, 1969; Graybiel, 1977; Hill, 1962; Stone, 1973]. Higher rates permit a shorter radius, less mass, and less kinetic energy for any particular centripetal acceleration (apparent gravity). Unfortunately, higher rotation rates also yield higher levels of Coriolis acceleration and cross-coupling with normal head rotations. These distort the apparent gravity and can lead to motion sickness due to a sensory mismatch between the vestibular and visual senses of motion. Because the Coriolis effects and rotational cross-coupling occur only intermittently, during relative motion within the rotating habitat, they may take a crew member by surprise if he or she has become disoriented with respect to the axis and direction of rotation.

Architectural design may promote the crew's adaptation by minimizing the need for off-axis motion and by providing consistent visual cues (color, form) for orientation. These cues would allow a crew member to prepare for the consequences of an action before initiating it, thereby improving coordination and comfort.

It's not clear that the rotation studies cited above have made any attempt to design the test environment to promote adaptation. At best, the designs may have been neutral. At worst, they may have inflicted sensory mismatch by isolating the subjects from visual cues to the rotation. In any case, the wide variation in estimates of the comfort zone suggests that other aspects of the environment, besides the basic rotation parameters, may have influenced the subjects' comfort.

A design that actively seeks to promote adaptation may allow for a higher rotation rate, with a correspondingly lower radius, structural mass, and kinetic energy, thereby reducing the cost of artificial gravity with respect to other countermeasures.

Considering that half of all astronauts require one to three days to adapt to micro gravity, a similar period of adaptation to artificial gravity is not unreasonable, especially since artificial gravity promises substantial health benefits with less demand on crew time and motivation.

An alternative to rotating the entire habitat is to provide a short-arm centrifuge within the habitat to provide therapeutic doses of artificial gravity. It's difficult to say whether this would result in an overall simpler or more affordable design. The on-board short-arm centrifuge has implications for mass and momentum balance, pressurized volume, and crew scheduling. The intensity and duration of the required dose remain unknown. It remains a worthy research topic. Nevertheless, this paper aims at continuous rotation of the entire habitat.

Candidate Technology

Architectural design to promote comfortable habitation at higher angular rates should be tested in Earth-based rotating rooms, before attempting to design a flight test. Earth-based tests are somewhat encumbered by the constant vertical surface gravity: it dominates the artificial component, prevents testing at sub-normal gravity levels, and changes the orientation of people and actions with respect to the rotation axis. (In a true artificial-gravity environment, the axis would be horizontal and overhead in the crew's frame of reference. In Earth-based tests, it's vertical and usually in the center of the room.) Nevertheless, experiments can account for these differences.

The tests should be conducted in a rotating room that provides ample space for the subjects to sit, stand, walk, and engage in various activities in different orientations with respect to the rotation axis. Furniture and wall panels could be arranged variously to create one or more rooms within the rotating room. Two facilities in particular have implemented the necessary technology:

- the slow rotation room at the Naval Aerospace Medical Research Laboratory, Pensacola, Florida (used by Graybiel in the 1960s)
  HTML: http://www.federallabs.org/servlet/FLCLPRODisplayServlet?wLPROID=1185

- the slow rotation room at the Ashton Graybiel Spatial Orientation Laboratory, Brandeis University, Waltham, Massachusetts
  HTML: http://www.graybiel.brandeis.edu/facilities/facilities.html#SRR
  HTML: http://lsda.jsc.nasa.gov/scripts/cf/hardw.cfm?hardware_id=1138

A space-based test would probably involve tethers. Gemini 11 demonstrated the basic technology in 1966, when the crew connected the capsule to the Agena booster with a 30-meter tether and put the assembly into a slow rotation to produce a miniscule amount of artificial gravity. A longer tether or faster rotation, or both, would be needed to produce a useful amount. The Gemini 11 tethered vehicle exercise revealed some unexpected tether dynamics that will need to be considered in designing an artificial-gravity space habitat [Wade, 2003].

Applications

The principal application of artificial gravity is to preserve human health during multi-month space flights – especially during transits between Earth and Mars or other celestial bodies, in which long exposure to microgravity is a nuisance rather than a mission objective.

Relevance to H&RT Strategic Technical Challenges (STCs)

This addresses the following challenges:

- Office of Space Flight (Code M):

  + Habitats, Habitability, and Human Factors: to provide safe, affordable, and substantial habitable volume for human operations beyond Earth's neighborhood.

  + Adaptation and Countermeasures (Microgravity): to understand potential countermeasures for adaptations to microgravity.

- Office of Biological and Physical Research (Code U):

  + to counteract the whole body's adaptations to microgravity, and enable "healthy astronauts to accomplish missions objectives and return to normal life following a mission."

Figures of Merit

Figures of merit for comfort, in artificial gravity or elsewhere, include: biomedical measures of stress hormones, heart rate, and breathing; ergonomic and psychological measures of performance in standardized tasks; and self-assessments of satisfaction.

Current State of the Art: Technology Readiness Level (TRL)

The slow rotation rooms cited above are at TRL 9 – they're operational.

Experiments to be conducted within such facilities are at TRL 2. There is a large body of research in "environment and behavior" (E&B), including human perceptions and reactions to color, form, and other architectural parameters. However, the application of these concepts to promote adaptation to rotation is still speculative.

Assessment of Research and Development Degree of Difficulty (R&D3)

This is at R&D3 level 2. There may be a moderate degree of difficulty in achieving the objectives. A single technological approach is sufficient, but it involves extrapolation from previous research. Moreover, architectural design is not an exact science. Several design iterations should be tested in order to probe the relative significance of various elements, and to improve the design's overall effectiveness.

Exit Criteria

This research might be discontinued in the following circumstances:

- Artificial gravity is shown to be unnecessary, thanks to some new, sufficiently effective, more affordable biomedical countermeasure.

- Intermittent artificial gravity with an on-board short-arm centrifuge is shown to be sufficiently effective and more affordable.

- Arbitrarily long tethers are shown to be safe and affordable, allowing 1 g of artificial gravity at very slow rotations, so that Coriolis accelerations and cross-coupling rotations are insignificant.

- Several iterations of the experiment fail to show any significant results.

Other Relevant Programs

The Man Vehicle Laboratory at the Massachusetts Institute of Technology conducts artificial gravity research with a short arm centrifuge, akin to the sort of device that might be installed within a space habitat as an alternative to rotating the entire habitat.

HTML: http://mvl.mit.edu/AG/

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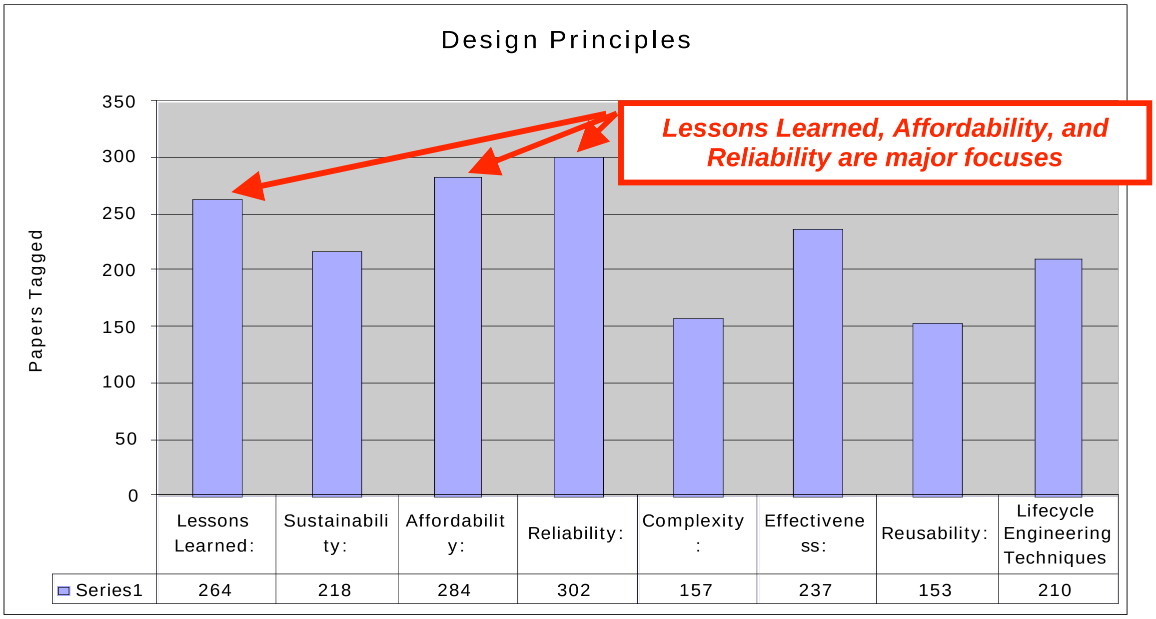
Dear RFI Respondent Theodore W. Hall,

Ten weeks ago, you contributed to a crucial first step in NASA's implementation of the Nation's new Vision for Space Exploration. In a broadly-focused Request for Information, the Office of Exploration Systems sought white papers analyzing key technical and programmatic issues relevant to the execution of a sustained campaign of human and robotic exploration of the solar system.

The complement of 998 responses that we received have not only affirmed a high level of external interest in the Vision, but have stimulated and refined our formulation of requirements, technology portfolios, and acquisition strategies. Responses came to us from a diverse array of government research centers, private companies, university research laboratories, student organizations, non-traditional sources ranging from architects to computer game developers, and at least two Nobel Prize winners.

Upon our receipt of the responses, we commenced an evaluation process that judged submissions on their demonstrated effectiveness, innovation, and potential to improve performance in cost, schedule, or risk. In this process, our evaluators also tagged submissions for relevance to multiple RFI focus areas, Work Breakdown Structure (WBS) elements, and technology types. In combination with keyword searches, these evaluation metrics and metadata now support our utilization of RFI contributions for purposes of formulating requirements and program plans.

Generally, we were impressed by the high number of quality submissions provided in the "Program Management" RFI Focus Area, where responses focused on Requirements Formulation, System-of-Systems Development Strategies, and Modeling & Simulation. We noted that a high number of submissions emphasized the importance of lessons-learned, affordability, and reliability in the "Design Principles" Focus Area. Among "Cross-Cutting Design Drivers," respondents cited commonality, autonomy, and mission operations as critical elements of optimal exploration architecture. (See following charts.)


Design Principles
Lessons Learned, Affordability, and Reliability are major focuses
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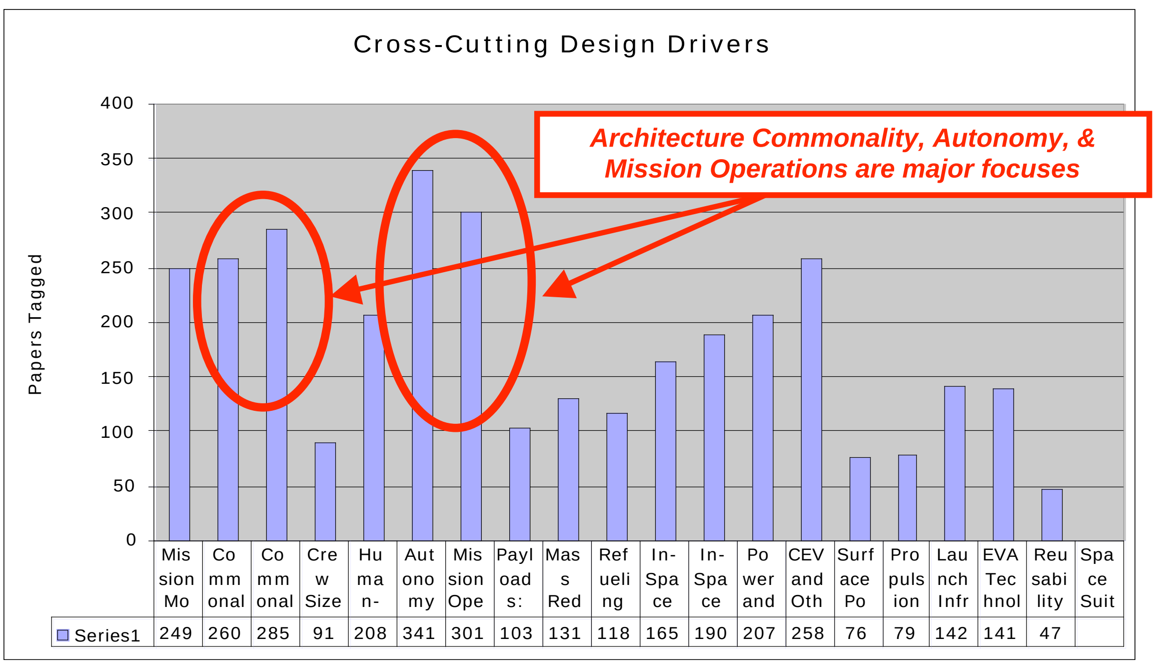
Cross-Cutting Design Drivers
Architecture Commonality, Autonomy, & Mission Operations are major focuses
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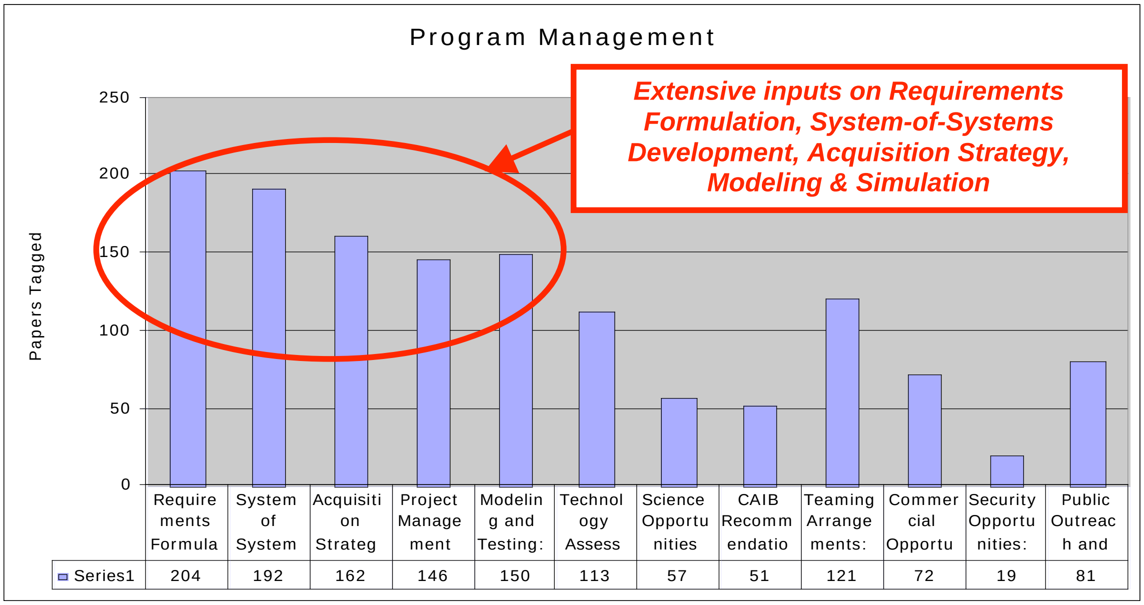

In the evaluation process that concluded in June 2004, your paper, which was submitted in the Design Principles, Objectives, and Guidelines category, received the following scores:

Demonstrated Effectiveness / Technological Maturity: 2
Innovativeness / Variation from Historical Approach: 5
Potential Improvement in Cost, Schedule & Risk: 5

These scores were based on a one- to five-point scoring system, five being the highest possible rank. The scores were compiled based upon comprehensive evaluation guidelines, which can be viewed with other relevant updates on the RFI at the Acquisition Portal of the Exploration Systems website at http://exploration.nasa.gov. While these metrics are a useful piece of metadata that we use in searching our RFI database, they are only one element of the techniques we employ in mining high-value ideas and proposals.

In the coming months, we will be using your RFI response in concert with hundreds of others to inform government analyses and priorities as we bring on an increasingly large population of contractor teams through Broad Agency Announcements and Requests for Proposals. We hope that you will continue to contribute to our nation's implementation of the Vision for Space Exploration by submitting proposals through the mechanisms appropriate to your organization and domain of expertise.

Your input has already served an important role in kick-starting our efforts at NASA, and will continue to be a valuable resource as we proceed. Thank you, and please join us in the years ahead, as we design and build the next generation of systems that will humans and robots on exciting missions to the moon, Mars, and beyond!

Very respectfully,

Craig Steidle
Associate Administrator
Exploration Systems Mission Directorate
NASA Headquarters