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DESIGNING FOR FUTURE. SPACE FACILITIES FOR OPERATIONS UNDER DIFFERENT GRAVITY CONDITIONS.

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ABSTRACT

Varying gravity levels experienced by crews in space impose many special design, operations and adaptation requirements. Proper responses to these needs are essential to maintain health during long-term missions, ensure safe and productive performance, and optimize comfort and morale. Special challenges are to facilitate crew adaptation as they transfer between different gravity levels, and to design facilities that optimize use and comfort during long-term orbital missions and voyages to far destinations.

This paper discusses special priorities for planning microgravity facilities in LEO, low-gravity accommodations on planetary surfaces, and artificial-gravity spacecraft for crew transport beyond the Earth-Moon system. Special requirements, and responses related to each are compared, and possible design solutions are proposed to:

- Highlight design problems specific to different gravity circumstances;
- Compare operational and performance advantages and disadvantages of different gravity environments;
- Specify possible ways to optimize physical and psychological adaptation during long-term missions;
- Identify general guidelines for space facilities design.

INTRODUCTION

The purpose of this paper is to explore various facets of spacecraft architecture and human factors design for different gravity conditions, most particularly during long-term space flights. Included are:

1. Partial gravity (Lunar and Mars);
2. Microgravity (Low-Earth Orbit and Phobos/Deimos);
3. Artificial gravity (centripetally induced).

Gravity levels have important influences on the design of all space facilities. These conditions present complex and difficult physical and psychological adaptation challenges for crews who are accustomed to Earth conditions. The designer's responsibility is to plan safe, comfortable facilities that ensure health safety, performance and comfort.

GENERAL DESIGN CONSIDERATIONS

Experiences in Earth orbit and on Lunar surface missions have provided important lessons about altered gravity implications. Variable-gravity conditions affect individual performance, human-equipment interaction, and engineering design. Even after relatively short-term space missions people experience changes in skeleton, muscles and brain neurophysiology [1].

Long-term Russian Mir (Picture 1) and US Skylab (Picture 2) missions revealed physiological changes that included bone deterioration, fluid shifts and muscle atrophy during extended periods in microgravity. Accommodations for exercise were recognized to be important to minimize ill health effects. Yet even with multiple hours of daily exercise, such as on a treadmill under a 1 g load, about 1% of bone mineral content per month is lost during LEO flight missions. Exercise alone may not be sufficient to maintain crew health and conditioning during long-term flights such as to Mars. Artificial gravity is often proposed as a method to minimize the detrimental effects of microgravity.

Picture 1. Russian space station Mir.

Picture 2. US SkyLab galley.

Special Adaptation Challenges:

- Psychological adjustment to unfamiliar conditions influencing task performance.
- Disorientation due to an altered “ground” reference producing head and limbs movement confusion and mistakes [2].
- Maintaining balance in a rotating “artificial gravity” spacecraft with Coriolis forces/cross-coupled accelerations.
- Replacing beneficial effects of gravity that hold people/items securely in place and provide surface traction for pushing.
- Nausea and confusion during transitions from one gravity level to another posing physiological and psychological problems.

Key Design Interventions:

- Appropriate visual orientation cues and other information systems for each gravity condition.
- Convenient and coherent layouts of interior areas, crew work and leisure accommodations and equipment to maximize safety, access and use.
- Personal mobility aids along with proper restraint devices for people, equipment, tools and supplies.
- Exercise systems that are used to counteract deconditioning effects of long low-gravity exposures.
- Planning of all systems for easy operations and maintenance under reduced gravity conditions.

Table 1 correlates some key influences of different gravity levels with human factors and design/engineering requirements.

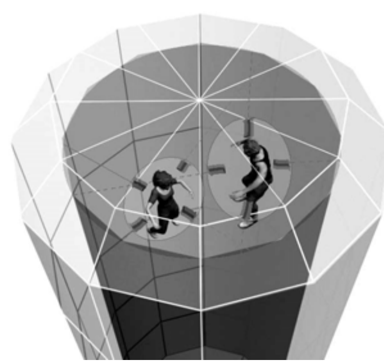
Considerations	Microgravity	Partial Gravity	Artificial Gravity
Human mobility and operations	Movement is effortless but restraint systems are needed for people and equipment	Mobility (e.g. lifting and climbing) will be facilitated by reduced gravity conditions	Mobility can be handicapped by Coriolis forces and cross-coupled accelerations
Psychological adaptation	Need visual cues to establish a local vertical and avoid spatial disorientation confusion	Provides a gravitational up/down reference similar to conditions on Earth	Need cues to define direction of spacecraft rotation for crew orientation and balance
Physical adaptation	Loss of muscle mass, bone density and body fluids produce deconditioning	Some deconditioning may result due to reduced physical exertion in reduced gravity	Transitions from normal to AG conditions may produce nausea and sense of imbalance
Engineering design challenges	Microgravity influences fluid systems and negates heat convection	Reduced gravity can make traction and excavation processes more difficult	AG can complicate spacecraft docking, add structural mass, and cause vibrations
Housekeeping and maintenance requirements	Dust and other contaminates float freely and are difficult to control	Abrasive dust particles can degrade equipment and visibility	Dust and other contaminates float freely during de-spin operations

Table 1

SPECIAL MICROGRAVITY CONSIDERATIONS

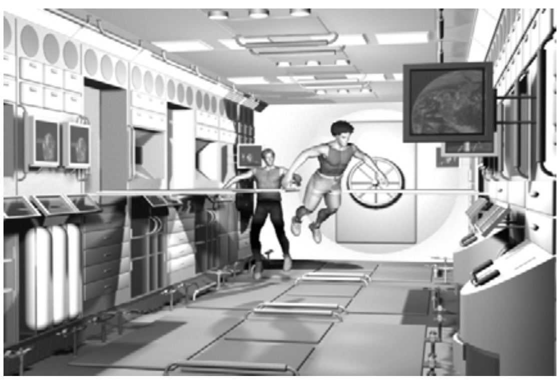
While life under microgravity conditions is very different than what we experience on Earth, long-term space missions have demonstrated that most people adapt quite rapidly and easily to this environment. Mobility is facilitated, with access to normally underutilized areas such as ceilings for a variety of functions, including work, sleep, housekeeping, equipment maintenance and storage. Since zero-gravity imposes needs for securing people and loose items from floating away, restraint devices must be provided to serve diverse requirements. Included are means to secure individuals in place while performing stationary tasks; devices to provide leverage while exerting forces that have reactive consequences; and storage containers that restrain contents from becoming scattered when opened.

The sizes and configurations of internal volumes also require consideration. In very large areas it is possible for astronauts to become stranded somewhat helplessly in the middle of an open area. (Picture 3) It is important to plan interiors and equipment layouts to minimize such risk.



Max reachable radius is approximately 0.8 m
Picture 3.

Crews in early stages of orbital space flights have reported upside down and head movement disorientations. These feelings are usually experienced soon after gravity level transitions and are overcome through physical and psychological adaptation over time. Based upon astronaut and cosmonaut reports, there are two types of weightless orientation references [1]: 1. in relation to architectural visual verticals and 2. in relation to feet position. In both cases it is necessary to offer visual cues, such as using floor and ceiling colors that differentiate a local vertical. Lighting systems and the design and layout of equipment can also reinforce a desired vertical orientation (e.g. work stations and information displays). (Picture 4)



Picture 4. SICSA's Orbital Industrial Space Facility concept.

Microgravity and partial-gravity conditions demand facilities and accommodations for exercise to offset deconditioning effects that include losses of muscle mass, bone density and shifts/losses of body fluids. A special design challenge is to combine exercise with recreation to encourage crews to regularly engage in these activities and to minimize the area used in a limited space module environment.

Planning of all systems must consider special housekeeping and maintenance requirements under microgravity conditions. Inventory control for tools and supplies is particularly challenging due to a tendency for loose items to become scattered and lost.

SPECIAL PARTIAL- GRAVITY CONSIDERATIONS

While experience in creating habitats on other planetary bodies is very limited, the Apollo program revealed some important issues in planning human facilities on the Moon and Mars. One important lesson is a need to protect hardware devices and systems from suspended dust particles, which can create problems for EVA operations and equipment reliability. These micro static particles interfere with visibility and cause abrasive friction that damages moving parts. This condition is of special concern on the Moon due to long periods of low gravity suspension, and also on Mars due to the prevalence of dust storms.

Partial-gravity conditions, such as circumstances experienced on other planets, have many features that are similar to those on Earth. Even with the reduced gravity field, habitat occupants will maintain a predetermined and fixed vertical orientation (Picture 5). This means that unlike conditions in microgravity, people will always sleep horizontally in beds rather then potentially be attached to walls in sleeping bags.

Also similar to microgravity, substantial exercise will be required to offset detrimental physiological deconditioning effects. On the other hand, astronauts will be able to lift greater masses than they could on Earth, and will not be as dependent upon restraint devices for physical leverage, making it possible to build greater structures with less effort. These circumstances can enable development of larger and more diverse shapes and structures, and offer opportunities to explore new aspects of architecture. Some other construction activities will be more difficult, however, since surface traction for vehicles used to move the greater masses will be reduced in such environments.

External view on the surface.

Example of interior.

Picture 5. SICSA's Mars Hydroponics Laboratory concept.

SPECIAL ARTIFICIAL GRAVITY DESIGN ISSUES

Scientists believe that adaptation to artificial rotationally-induced gravity will be much more difficult than images that are popularly depicted in science fiction publications and movies. During last years many artificial gravity experiments, simulations and studies have been conducted, using two main types of AG facilities:

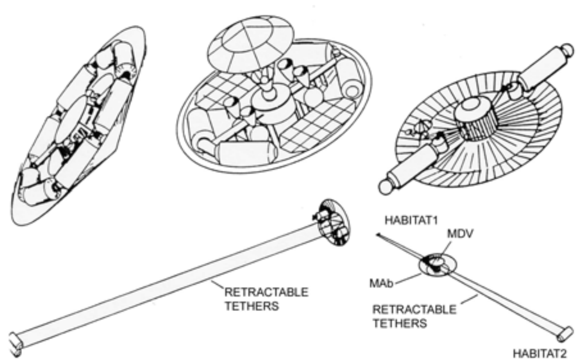
1. Artificial Gravity Sleepers.
2. Rotating Environments, which include:
    a) entire spacecraft rotating;
    b) personal centrifuges.

According to studies conducted at the Ashton Graybiel Spatial Orientation Laboratory [1], artificial gravity sleepers would not be very efficient in diminishing hazardous effects of long-term space missions, such as those to other planets. An important reason is because such devices would not support normal exercise experienced as crews carry out daily activities.

Artificial gravity accomplished by centripetal force is often proposed as a solution to counteract certain health and performance problems that can occur in weightless space environments. Important objectivities are to:

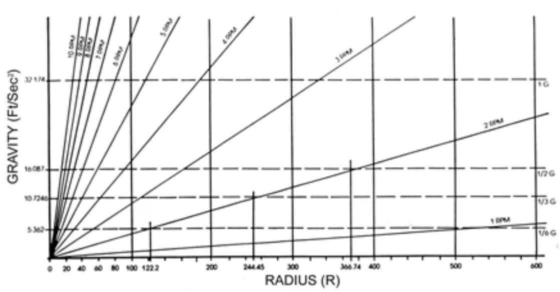
- Prevent deterioration of muscles, including cardiopulmonary systems, which would otherwise occur during long-term exposures to weightless conditions;
- Avoid leaching of calcium which causes long bones (such as those in legs) to become brittle when they are not subjected to gravitational force loads;
- "Normalize" the ease and performance of such activities as locomotion (walking), work tasks and toilet/hygiene functions.

Picture 6 presents some of the concepts for Mars artificial gravity spaceships.



Picture 6. Five concepts for Artificial Mars Spaceships. [3]

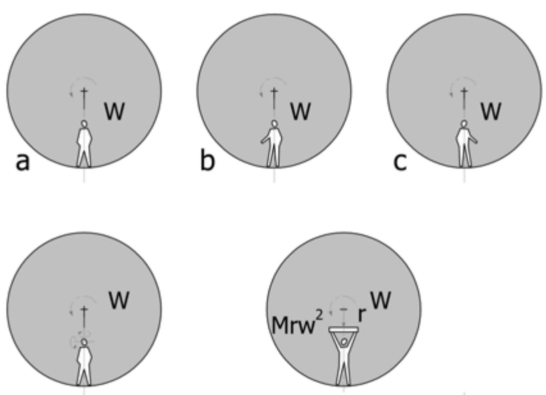
People’s ability to psychologically and physiologically adapt to artificial gravity fundamentally depends upon the angular momentum (spin rate) of the overall spacecraft, and the arc radius of its rotation [3] (Picture 7).



Picture 7. G-Levels as a Function of Radius and Angular Velocity. Rate of Acceleration formula: $\mathbf{A= w^2R}$, where A – rate of acceleration (1G=32.174 ft/sec^2); w – angular velocity (1RPM=0.10472 radian/sec); R – radial position (feet)

Influences of radial Coriolis forces during locomotion resulting from adapting to effects of artificial gravity in space are shown in picture 8.

A) Standing; B) Moving in Direction Opposite of Spin; C) Moving in Direction of Spin. Radial forces push a walker toward or away from the center of rotation.



Cross-coupled Acceleration Through Head Movement

Gravity Gradient Changes Through Positioning

Picture 8. An object of mass **M** “weighs” $\mathbf{Mrw^2}$ at radius **r** and with angular velocity **w**.

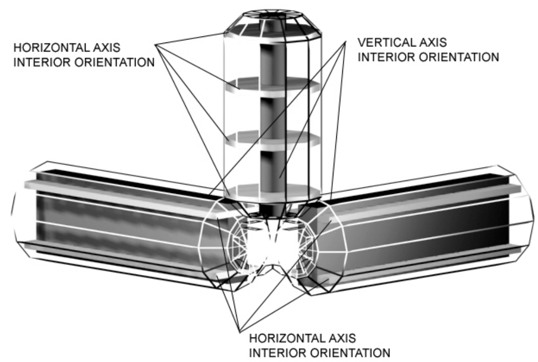
Factors to consider in designing for artificial gravity:

- An object is weightless at the spin axis, and assumes half of its ultimate weight at 1/2 of the spacecraft spin radius (50% gravity gradient).
- People can experience motion sickness, particularly during transfers from zero-gravity to artificial gravity and transitions between different artificial gravity levels.
- Radial and tangential Coriolis accelerations will exert forces upon people as they move in different directions with respect to the rotating environment, potentially causing them to feel heavier or lighter, and throwing them off balance.
- Cross-coupled angular accelerations produced when people rotate their heads or bodies relative to the rotating environment may cause disorientation and a sensation of falling.
- Gravity-gradient changes will cause people and objects to become “heavier” as they move outward from the central spin axis; and “lighter” as they move back to the center.
- In order to anticipate and adapt appropriately to these new conditions, people must constantly remain aware of their orientation relative to their environment’s direction of spin.

IMPORTANT GUIDING PRINCIPLES FOR HABITAT DESIGN

In conclusion, different gravity levels pose many unique issues and challenges that must be carefully considered throughout planning and design processes. These activities must be guided by broad knowledge of mission objectivities and requirements that will be impacted by such special conditions. Examples include:

- Crew size and mission duration (effects upon psychological, physiological and sociological factors), along with a need for entertainment, exercise and privacy.
- Mission objectivities and the gravity environment (crew preparation for adaptation to gravity levels and other factors).
- Spacecraft architecture options: size/volume of habitats, spin radii for rotationally-induced artificial gravity, special maintenance issues and requirements.
- Interior planning and equipment design options (orientation cues, feet and body mobility/restraint devices, housekeeping and maintenance processes and supplies, and means to maintain a clean and safe breathing atmosphere).
- Interior design that defines a clear and obvious vertical-horizontal relationship in all modules regardless of the way they are assembled (Picture 9).



Picture 9. Vertical – Horizontal interior orientation

New types of structures should be considered in developing facilities for different gravity conditions. Designers should maximize advantages and avoid disadvantages presented by special gravity conditions. This is essential to optimize the crew's psychological and mental health during long-term missions in orbit and voyages to planets.

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