Artificial Gravity for Manned Mars Mission: Applications & Designs

Jose Jourdain

Embry-Riddle Aeronautical University

Abstract

For future extended Mars missions and the effective performance of the astronauts' tasks, optimal conditions for their physiological wellbeing, as well as their overall mental health will be highly imperative. This will inherently be the case in a closed and confined environment for an extended period of time. In this sense, artificial gravity would represent one of the most important variables a mission of this nature can have, since it will provide intrinsic benefits for the space habitation of humans and the ability to perform their day-to-day tasks more efficiently. After identifying the inherent technical limitations we currently have of implementing artificial gravity, this report will then make an attempt to render new conceptual technology and methods being considered by the industry, thus closing the gap in allowing artificial gravity to become a reality.

ARTIFICIAL GRAVITY FOR MANNED MARS MISSION: APPLICATIONS & DESIGNS

Introduction

Definition

According to Bukley, Paloski& Clément (2008), artificial gravity is defined as the simulation of gravitational forces aboard a space vehicle in free fall (in orbit) or in transit to another planet. The term artificial gravity is reserved for a spinning spacecraft or a centrifuge within the spacecraft such that a gravity-like force results. Nonetheless, it is important to point out that artificial gravity is not gravity at all; rather it is an inertial force that is indistinguishable from normal gravity experience on Earth, in terms of its action on any mass (Bukley, Paloski & Clément, 2008).

The basic difference is that what’s experienced is a centrifugal force proportional to the mass that is being accelerated centripetally in a rotating device, rather than a gravitational pull. Although the effect of artificial gravity on a human body differs from that of true gravity, therefore, we can think of artificial gravity as the imposition of accelerations on a body to compensate for the forces that are absent in the microgravity of spaceflight (Bukley, Paloski & Clement, 2008).

Problem

One of the major impediments for human Mars missions is the development of appropriate countermeasures for long term physiological response to the micro-gravity environment. Multiple approaches have been proposed, everything from large diameter rotating spacecraft that would simulate a 1-g environment to pharmacological measures. Being the former the most conservative from a human health perspective.

According to Bukley, Paloski & Clement (2008), the different approaches have significantly different implications not only on the overall system design of a Mars Mission Vehicle (MMV) but on the necessary earth-orbiting platform that would be required to qualify the particular countermeasure system. Thus, these different design options can be conveniently categorized in terms of the order of magnitude of the rotation diameter required (100's, 10's, 1's, 0 meters). From this, the different mass penalties associated with each category can be generally compared.

The overall objective of the countermeasure system should be to maximize crew safety and comfort, minimize exercise protocol time, in other words the time per day that each crew member would have to participate in the exercise/countermeasure, maximize countermeasure effectiveness, and minimize the associated system mass penalty of the Mars Mission Vehicle, in terms of fraction of Injected Mass in Low Earth Orbit (Bukley, Paloski & Clement, 2008).

After pointing out the general problem that might impede us to obtain artificial gravity, the author will describe below specific areas which currently experience inherent problems, but that would be directly benefited from the presence of an artificial gravity environment.

Subproblem/Benefit 1: Physical

While the vestibular system should be well-adapted to bed rest, a condition experienced approximately 8/24 hrs each day, questions would remain regarding the degree to which repeated exposures to the unusual gravito-inertial force environment of a short-radius centrifuge might affect central processing of vestibular information, used in spatial orientation and balance control. Should these functions be impaired by intermittent AG, its feasibility as a counter-measure would be diminished (Bukley, Paloski & Clement, 2008).

Subproblem/Benefit 2: Psychological

In addition to the physical problems exerted on the body, other elements play a crucial role for humans in space, such as difficulties from stress prolonged weightlessness, isolation, and confinement (Clement, 2007c). And although they presumable exist, most of the reports are anecdotal. In fact psychiatric problems during space missions, such as anxiety, depression, psychosis, psychosomatic symptoms, and postflight personality changes, have been rare or not methodically documented (Clement, 2007c, p.205).

The implementation of successful leisure activities would counteract the effects of interpersonal conflicts in a confined microsociety, as is a spacecraft. Thus, the ability to have artificial gravity on board would undoubtedly represent a wider array of opportunities to implement such leisure activities to assist in the adaptation process.

Subproblem/Benefit 3: Cardio-Vascular

The cardio-vascular system has the primary function of circulating blood through the body, and is composed of the heart, the circulatory system, the lungs and the kidneys. Although the responses of the cardio-vascular system to microgravity seem to have been relatively free of major threats to well being and performance during flight, problems such as orthostatic hypotension and diminished exercise capacity are commonly observed after return to Earth (Clement, 2007a, p.139).

Orthostatic hypotension has been noticed since the earliest human spaceflights. Orthostatic intolerance affects about two-thirds of the astronauts returning from spaceflight even of relatively short duration (Clement, 2008a, p.139). The latter is even greater for shuttle pilots, and pilots of future manned Mars missions, who would perform complex reentry maneuvers in an upright, seated position. Thus, the presence of artificial gravity would alleviate the effects of orthostatic intolerance, and the subsequent recovery to preflight levels of tolerance, without the need to wait the traditional period of about a week or so. Not to mention the elimination of predispositions to vital organs like the heart, kidneys or lungs, as well as the effects of blood accumulating in the legs or head.

Subproblem/Benefit 4: Musculoskeletal

Spaceflight directly affects muscle tissue, and those most affected are the ones attached to the skeleton (i.e., skeletal muscles). Skeletal muscles are the largest tissues of the body, accounting for 40-45% of the total body weight (Clement, 2007b, p.173).

As for the bones, we have to consider these as living tissues, because that’s precisely what they are. Bones are constantly being broken down by certain cells, and much of the activity from these specialized cells comes in response to the stress put on bones, during walking or exercising. Thus, we can clearly see why bones play such an important role during spaceflight, due to the inherent strenuous activities they are subject to.

With the advent of artificial gravity, the problems which the musculoskeletal system is subject to would no longer be present. For instance, since muscles represent more than 30% of the body mass (Clement, 2007b, p.173), elements like muscle atrophy, changes in body weight, and decrease in leg volume “chicken legs”, would no longer be present.

Significance

Gravity is of particular importance not just for the basic ability it would represent for astronauts to perform their tasks on a more efficient manner, but more so due to the inherent mental and physical problems it would solve for humans in space. Humans will go into space as part of the human drive to explore, expand, research and colonize. This is an intrinsic part of being human in the broadest sense, and science is just one part of that experience. Nevertheless, the use of technology and science as a mean for us to obtain artificial gravity will signify the great opportunity for humans to feel much safer and able to do things in a familiar environment, where being far from home, we would actually try and make the space environment our new home for an extended period of time.

Thus, the report at hand is to be considered as a grain of salt along with all other written throughout the years, which should serve future generations of aeronautical engineers a laconic snapshot on the subject at hand, so that one day we will be a step closer to having artificial gravity as a common element of spaceflight.

Review of the Relevant Literature

As the main purpose of this review is to analyze scientific works and journals by other researchers in the field, it is worthwhile pointing out that in contrast to the logical concerns of engineers when the space program first began (Phillips, 2002), specifically the ability of a human pilot to perform the tasks required for space operations; parting from this latter notion, the attempt should now be made on analyzing the potential shift in mentality, specifically of doing things from a different perspective, not just points on a checklist, but rather a more familiar and comfortable work environment brought on by the presence of artificial gravity, which may very well lead to day to day tasks becoming significantly simpler, which in turn will reduce workload and human error.

Especially attempt to further investigate the validity of relevant technical notes on pilot-controlled simulation of rendezvous of spacecraft and command modules with the absence of gravity and physical strains exerted on the body (NASA, 1963).

Furthermore, for the benefit of this report and to further substantiate with valuable literature on the subject, it is worthwhile mentioning that according to Paloski (2006), the choice of artificial gravity design depends on a basic decision whether the crew is to be transported with continuous artificial gravity, requiring a large-radius spinning vehicle, or exposed to intermittent artificial gravity, in which case a small centrifuge can be employed. The latter evaluations are based to a significant extent on material contained in the final report of the International Academy of Astronautics Study Group 2.2 entitled “Artificial Gravity as a Tool in Biology and Medicine” (Paloski 2006).

Application, Technology & Operational Overview

Hereunder the author will discuss the potential technologies for achieving artificial gravity in a space vehicle. First, a series of definitions and general description of the rotational dynamics behind the forces exerted on the human body during centrifugation will be rendered, such as gravity level, gravity gradient, and Coriolis force. Second, considerations and comfort limits associated with a rotating environment will then be discussed. Finally, engineering options for designing space vehicles with artificial gravity will also be presented.

Linear acceleration: Is one means by which artificial gravity in a spacecraft can be achieved. By accelerating the spacecraft continuously in a straight line, objects inside the spacecraft are forced in the opposite direction of that of the applied acceleration (Bukley, Paloski & Clement, 2008). This phenomenon is experienced by astronauts routinely during orbital adjustments of the Space Shuttle and other orbital spacecrafts when the thrusters are fired (it is also experienced by people in cars as the force pushing them back into their seats when they step on their gas pedal after the traffic light turns green).

The result is intermittent impulsive artificial gravity imposed on the astronauts (or car driver) that is equal to the acceleration level achieved by the thrusters. However, the duration of this artificial gravity is too short (a few seconds) to be considered as a potential countermeasure.
If, however, a continuously thrusting rocket could be constructed that would accelerate a spacecraft for the first half of the journey to Mars and decelerate for the second half of the journey, a constant artificial gravity situation would result.

According to Bukley, Paloski & Clement (2008), ideally, the acceleration level would be at 1 g during both phases of the flight so that the explorers would feel “normal” gravity loading throughout their trip and arrive on Mars ready to go to work1. But most rockets accelerate at a rate several times that of Earth’s gravity. This acceleration can only be maintained for several minutes because of limits on the amount of fuel that can be carried on board the launch vehicle as well as the specific impulse of the fuel.

Theoretically a propulsion system employing very high specific impulse fuel and the key characteristic of a high thrust-to-weight ratio could accelerate for long periods of time. The result would be the production of useful levels of artificial gravity over longer periods of time, rather than very high gravity loads for a very short period of time. As an added bonus, such a constantly accelerating vehicle could provide relatively short flight times through the solar system.

A spaceship accelerating, then decelerating, at 1 g would reach Mars in 2-5 days, depending on the relative distance. In a number of science fiction plots, acceleration is used to produce artificial gravity for interstellar spacecraft, propelled by as yet theoretical or hypothetical means.

<u>Mass</u>: Is the key component in producing gravity. Any mass has an associated gravitational field associated with it, be it ever so small for particles, or so overwhelming as the gravitational field associated with infinitely massive black holes (Bukley, Paloski & Clement, 2008). Hence, yet another way that artificial gravity might be achieved is to install an ultra-high density core into a spacecraft so that it would generate its own gravitational field and pull everything inside towards it. In reality, this is not artificial gravity because it is gravity.

Most of us all very familiar with popular science fiction movies or plots, which have played a positive role in opening our imagination for greater things related to spaceflight. And all of these plots are achieved with the concept of artificial gravity, implying that there are artificial gravity generators that create a gravitational field based on a mass that does not exist. In a practical sense, the story is helped because an Earth-like environment is apparently present on the spaceship.

According to Bukley, Paloski & Clement (2008), an extremely large amount of mass is required to produce even a tiny gravitational field. For example, fairly large asteroid produces only several thousandths of a g3. We can therefore imagine that by attaching a propulsion system of some kind to this asteroid, it might loosely qualify as a space ship. The downside is that gravity at such a low level is not likely to have any practical value. Furthermore, the mass would obviously need to move with the spacecraft. Thus, we can conclude that any significant acceleration required for such a craft would come with the disadvantage of an increased fuel consumption.

Gravity Generator: No verified technique currently exists to produce gravity, apart from mass itself, even though there have been many claims over the years that such a device has been developed and exists. Eugene Podkletnov, a Russian engineer, has claimed since the early 1990s to have built such a device consisting of a spinning superconductor producing a powerful gravitomagnetic field (Bukley, Paloski & Clement, 2008). However, no verification has been provided and third parties have even purported negative results.

According to ESA (2006), reports arose that a similar device was created that demonstrated positive results for the production of gravitomagnetism. The device produced only 100 millionths, which is not really a usable level of gravity in any application.

Centrifugal Force: Centrifugal force results from the centripetal acceleration generated by circular motion (rotation). Examples of circular motion include artificial satellites in geosynchronous orbit, a racecar going through a curve on a racetrack, an aircraft executing a coordinated turn, or an object tied to the end of a rope and twirled about in circles (Bukley, Paloski & Clement, 2008). We have experienced this force of the one that pushes us to the left (right) as we make right (left) hand turns in our cars.

The term “Spinning motion” or rotational motion refers to a special case of circular motion that occurs when an object rotates or spins about its own center of mass. The spinning produces centripetal acceleration in a radial direction away from the center (Bukley, Paloski & Clement, 2008).

Centripetal force is the product of the centripetal acceleration times the mass of an object. Artificial gravity could therefore be generated in the following ways:

1. by a spacecraft spinning about its axis
2. by the rotation of two spacecraft connected by a tether (Figure 2-03, left).
3. by a short-radius centrifuge on board a spacecraft

In the case of a spinning spacecraft (1 and 2), anything inside would be forced toward the outside radius of spin by centripetal acceleration, which is the source of the artificial gravity. In the case of an internal short-radius centrifuge (3), only the subject and the objects on the centrifuge will be exposed to artificial gravity.

Artificial Gravity Generated by Rotation: As previously stated, throughout this book the term artificial gravity is used to describe the centrifugal force generated by a spinning spacecraft or by a centrifuge within the spacecraft. In a rotating system there are forces present other than the centrifugal force that influence how objects move in the rotating environment and, consequently, how humans feel in such a rotating frame (Bukley, Paloski & Clement, 2008).

Nevertheless, we should keep in mind that we are assuming that any movement by an astronaut or particle in a rotating coordinate frame is at a constant velocity. Furthermore, we will not consider accelerations in an inertial frame, but only in the rotating coordinate frame associated with the rotating centrifuge or spacecraft.

Gravity Level: Circular motion is characterized by a radius *r* and an angular velocity *ω* (in rad/s). The radius is measured from the center of gravity of the spinning object to its edge, which will henceforth be assumed to be circular with the center of mass exactly in the middle. The angular velocity is simply how fast the spacecraft or object is spinning. Most people are familiar with angular rate being expressed in revolution per minute, or rpm (Bukley, Paloski & Clement, 2008).

According to Bukley, Paloski & Clement (2008), the magnitude of the tangential velocity is $r\,\omega$ and it is oriented in the direction of the rotation of the rim of the spacecraft or object. The magnitude of the centripetal acceleration is simply the product of the magnitudes of the tangential and angular velocities, and is always directed radially outward from the center of the rotating body. Therefore, the magnitude of the centripetal force is:

$$F = m\,\omega^2\,r$$

Gravity Gradient: Because the gravity level varies along the radius of the centrifuge, an astronaut lying in a centrifuge along a radius with her feet positioned at the rim will have her head closer to the axis or rotation than her feet. The head will have a smaller radius of rotation. Consequently, the gravity level at the head will have a smaller magnitude than the gravity level at the feet. The difference in artificial gravity level with distance from the center of rotation is referred to as the gravity gradient (Bukley, Paloski & Clement, 2008). For an astronaut of height *h*, lying in a centrifuge along a radius with his feet positioned at the rim and his head pointing towards the center of rotation, his head has a radius of rotation equal to *r - h*. The ratio of head acceleration to foot acceleration can be simply expressed as:

$$\text{Ahead//Afoot} = \omega^2 r\,(r - h) / \omega^2 r = (r - h) / r$$

Therefore, if a person standing on the outside rim of a centrifuge or spinning vehicle and she jumps off the "floor" with a velocity directed radially inward towards the axis of rotation, she would not come straight "down", rather she would land a few centimeters to one side.

Design and Development

As follows the author will present various conceptual designs and sketches of human space habitation considering the presence of artificial gravity. These will go from spinning rings to complete large scale conceptual cities based on artificial gravity exerted on "O" rings.

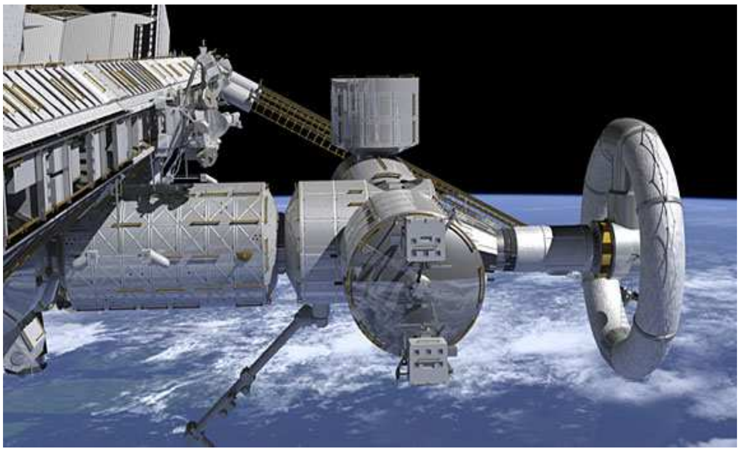

Figure 1-1. Conceptual image of an artificial gravity producing ring. Retrieved from "Discovery News", 2011, *Launching a Space Station to Other Worlds*.

From the concept above, the trickiest piece of engineering is the inflatable spinning torus that would provide partial artificial gravity. The ring would need to spin at 10 RPM to provide a force one-half Earth gravity. The bearings, slip rings for power, liquid metal seals, and counter-rotating flywheel would be an engineering challenge. A scale working model of the centrifuge would be externally attached to the ISS for testing.

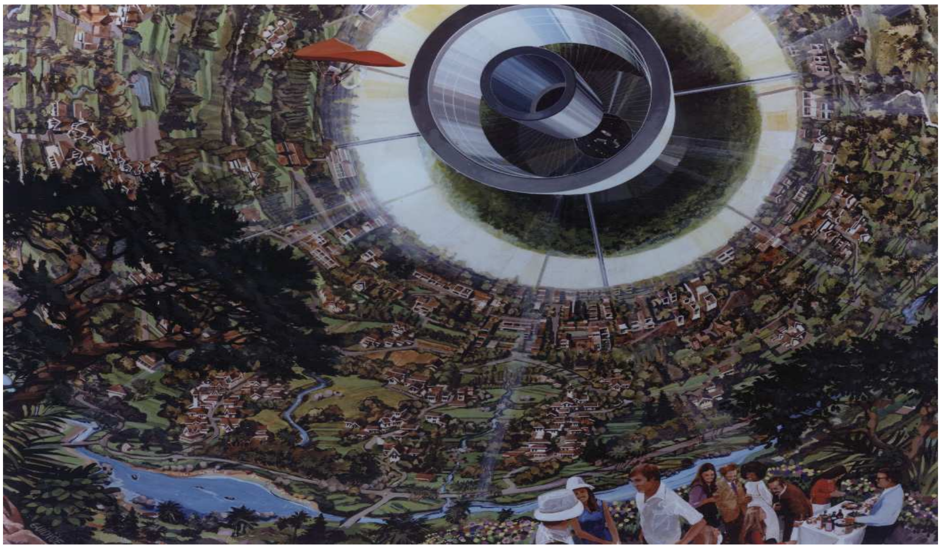

Figure 2-1. Conceptual image of a city in space with artificial gravity. Retrieved from Astroprofspage.com

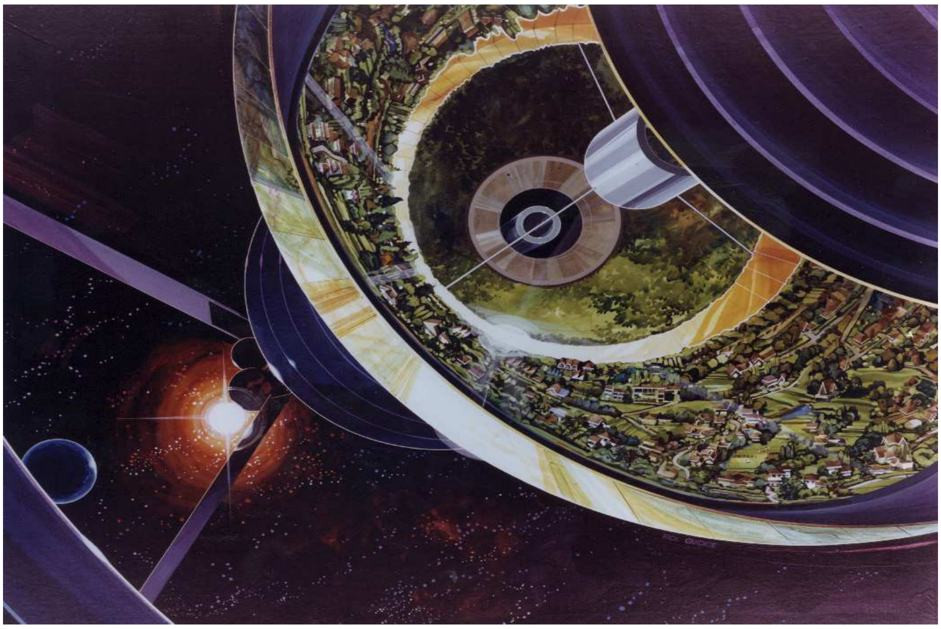

Figure 3-1. Conceptual image of a city in space with artificial gravity. Retrieved from Astroprofspage.com

Conclusions

Summary

In this report an attempt has been made to thoroughly examine the advantages and disadvantages of artificial gravity in a spaceflight environment. For this, the researcher first provided a basic definition of technical terms, followed by the main technological problems and limitation we currently lack to obtain artificial gravity, as well as the immediate benefits which would be obtained with its presence. Following this rendition, the researcher also expressed his personal interest on the subject, as well as the significance it represents to the aerospace industry and the future of mankind in general. A further attempt was to thoroughly read professional publications on the subject in order to render an objective comparative review.

Thus, the overall report addresses the many problems introduced by a topic of very large magnitude by leveraging off existing expertise while at the same time establishing a data format for simulation that enables a deeper contribution to this debate.

This contribution will, in the author’s opinion, make it possible for any reader or analyst to make a quick judgment and analysis of artificial gravity, and to further research and investigate on the matter.

Future Outlook

According to Bukley, Paloski & Clement (2008), for this to work, it would involve avoiding any non-diamagnetic materials in or near the strong magnetic field that would be required for diamagnetism effects to be evident. Magnets of incredible strength would also be required for the implementation of such an artificial gravity system. As a matter of fact, we can actually levitate a frog using such devices, implying that up to 1 g can be produced. But this is accomplished using a magnet system that weighs thousands of kilograms and must be super cooled using very expensive cryogenics to keep it superconductive. The latter is obviously not practical for implementation on a spacecraft.

If we take as a parameter science fiction, we often see spacecraft in which artificial gravity, or the cancellation of gravity, is clearly present, yet the spacecraft is neither rotating nor accelerating. Current magnetic technologies have not yet developed to the point that such an artificial gravity system can be created in this way. Nonetheless, similar effects can certainly be created through the mechanism of diamagnetism (Bukley, Paloski & Clement, 2008).

The only pragmatic way to implement artificial gravity based on the principle of mass is to find as of yet undiscovered materials with very high densities such that significant mass is present in a low volume of space. However, we would still need to grapple with getting so much mass into orbit in the first place.

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