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An Approach for Development and Deployment of Artificial Gravity in Deep Space Exploration Architectures

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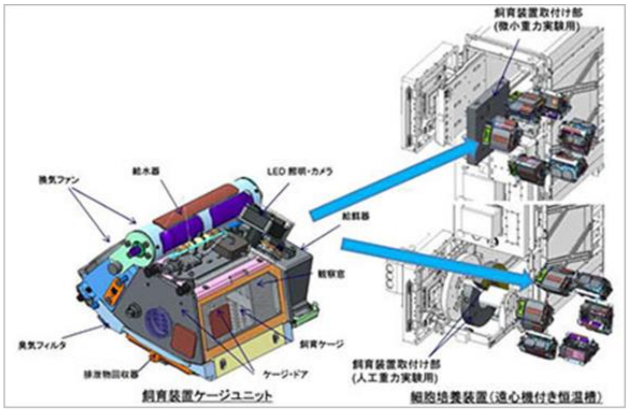
Artificial gravity (AG) systems have long been identified as a potential comprehensive countermeasure to the physiological deconditioning experienced during long-duration exploration spaceflight. However the current state of the art and the lack of substantiating data regarding both the benefits and limitations of AG in zero G preclude practical implementation in current space architectures. Historically, centrifugal AG designs have been limited to spin rates not exceeding tolerable levels of 4-6 rotations per minute (RPM) and thus to produce 1 G, require very large systems (e.g. 110 m diameter). Current investigations at the University of Colorado-Boulder are being conducted to incrementally adapt individuals to higher spin rates by using a repeated exposure threshold adaptation training protocol. Preliminary results suggest that in a few days, individuals can increase the spin rate at which the CC illusion is imperceptible (e.g. 10 RPM). With these investigations, a higher "new limit" of tolerable spin rates will be recommended, allowing for a reduced radius centrifugal design, such as that discussed here. Medium radius (3.5 m to 8 m) AG systems are the only technically feasible implementation for deep space transit based on mass, propulsion, power, keep out zones, and reliability for use in near term deep space architectures. The concept of operation for deep space transits, such as Mars, should minimize the mass required of the transit vehicle. A potentially viable approach, is the one time deployment of an AG system, in the destination vicinity, for reconditioning after arrival with no added mass to the transit vehicle design. Optimal habitat layouts associated with these layouts to address physical performance associated with these rotation speeds are also being designed.

I. Introduction

Artificial gravity (AG) systems have long been identified as a potential comprehensive countermeasure to the physiological deconditioning experienced during long-duration exploration spaceflight. Recently, proposed longer duration missions and new, poorly understood physiological concerns resulting from microgravity exposure have renewed an interest in AG. For example, a portion of astronauts return with visual degradations, a condition now referred to as space flight associated neuro-ocular syndrome (SANS) [1]. While the mechanism of SANS is still not fully understood, presumably the microgravity environment is a casual factor and thus recreating a gravitational environment through AG is a promising countermeasure [2].

The current state of the art and the lack of substantiating data regarding both the benefits and limitations of AG in zero G have precluded practical implementation in current space architectures. Historically, centrifugal AG designs have been limited to spin rates not exceeding 4-6 rotations per minute (RPM) [3, 4] and thus to produce 1 Earth G, require very large systems (e.g., 110 meter diameter). There is a significant gap between the current state of the art, such as the JAXA mouse habitat testing on ISS and the popular depictions of large rotating toroidal shaped space systems and the required capabilities for a deep space mission (Figure 1). The use of higher RPM can reduce the required radius exponentially in making more feasible space craft implementations. However the use of higher spin rates can result in a stronger vestibular cross-coupled illusion (i.e., Coriolis illusion), which occurs when out-of-plane head tilts are made in a constantly spinning environment and leads to disorientation and motion sickness [5, 6]. Thus it remains how high of a spin rate, and thus how short of a radius centrifuge, is feasible for future AG systems. Additional efforts are required for engineering design and development of such a system, as well as the associated concept of operations.



JAXA Mouse Habitat Unit

Van Braun's Space Station 1952

Figure 1: From the current state of the art – JAXA mouse habitat to popular depictions

II. Artificial Gravity as a Countermeasure

We have an increasingly robust dataset for human performance and physiological well-being in space for 6 months or less with some data points up to 1 year. However, we do not completely understand the physiological impact of 1000 day missions. Major human physiological implications due to long-term exposure to weightlessness include: 1) Bone fracture[7] 2) Optic nerve damage/visual changes[8] 3) Kidney stone formation[9] 4) Balance/neurovestibular impairment[10, 11] 5) Muscle atrophy and deterioration of the skeleton (spaceflight osteopenia)[12] 6) Alteration of cardiovascular system functions[13] 7) Decreased production of red blood cells[14] 8) Weakening of the immune system[15] 9) Fluid redistribution (causing the "moon-face" appearance typical in pictures of astronauts on orbit)[16] 10) Loss of body mass, nasal congestion, sleep disturbance[17], and excess flatulence

Countermeasures that reduce the physiological deconditioning of weightlessness have been developed and are being used. For example, resistive and aerobic exercise, extra dietary calcium, and other pharmaceuticals are used to mitigate physiological adaptations to weightlessness due to changes in weight-bearing structures and tissues, redistribution of body fluids, and space motion sickness resulting from gravity transitions. Those countermeasures currently used are primarily focused on musculoskeletal deconditioning. These techniques are time consuming and demand a high degree of individual discipline. These countermeasures may only address short to moderate duration exposures occurring in low earth orbit (LEO).

	C	P	N
1. Bone fracture		○	
2. Optic nerve damage/visual changes			✗
3. Kidney stone formation		○	
4. Balance/neuro-vestibular impairment			✗
5. Muscle atrophy and skeletal	✓		
6. Alteration of cardiovascular system functions		○	
7. Decreased production of red blood cells		○	
8. Weakening of the immune system		○	
9. Fluid redistribution			✗
10. Loss of body mass, nasal congestion, sleep disturbance and excess flatulence		○	

✓ C = Complete Mitigation with Diet & Exercise
○ P = Partial Mitigation with Diet & Exercise
✗ N = Negligible Mitigation with Diet and Exercise

Figure 2: AG has potential to address key issues associated with long duration deep space travel

The primary mechanism for physiological deconditioning during spaceflight is the exposure to microgravity, and therefore potentially the best remedy for the problem is to generate AG in space[18]. While AG is not a panacea it can play a significant in improving health and human performance as compared to existing countermeasures which maybe only be partially effective (Figure 2). As previously mentioned, a leading concern for astronaut health during long duration microgravity exposure is SANS. The syndrome, formerly known as visual impairment intracranial pressure (VIIP) syndrome, yields a variety of changes to the structure of the eye and related reduced visual acuity [8]. These include optic disc edema, globe flattening, choroidal and retinal folds, hyperopic refractive error shifts, and nerve fiber layer infarcts. The mechanism of these changes remains unclear. One hypothesis is that the headward fluid shift due to removing the hydrostatic gradient in microgravity causes an increase in intracranial pressure. In any case, it appears that long duration microgravity exposure plays a casual role. Furthermore, current countermeasures (e.g., exercise) appear to either be ineffective or at least insufficient. If microgravity is a primary cause of SANS, then even without fully understanding the mechanism, AG may be a uniquely promising countermeasure [2]. It has even been hypothesized that intermittent (e.g., one hour per day) and partial gravity (e.g., 0.3 Earth G's) AG may be beneficial in preventing or reducing SANS. Specifically, in the "headward fluid shift" hypothesis it would be expected that providing a footward hydrostatic gradient through AG, even intermittently at a reduced load, would alleviate SANS in the same manner as occasionally standing or sitting upright here on Earth apparently does. We briefly reiterate that much of these reasoning is speculative, and that while AG is a promising countermeasure for SANS, it has not been validated in space or in a ground analog.

III. Adaptability to Higher RPM for AG

As noted previously, the design of a centrifuge is constrained by the tradeoff between tolerable spin rate and required radius of rotation. Specifically, if a higher spin rate is tolerable than a shorter radius can be used to achieve a desired centripetal acceleration level (i.e., G-level). However, a higher spin rate (and the associated shorter radius) yields at least three concerns: 1) when the person riding the centrifuge makes any "out of plane" head tilts, they will experience the Coriolis cross-coupled illusion, which is highly disorienting and leads to motion sickness [19], 2) when the person and/or person's appendages translate these masses will be subjected to unexpected Coriolis forces [20], and 3) gravity-gradients along the body longitudinal axis, such that the centripetal acceleration level will be (potentially much) higher near the feet than at the head [21]. Briefly, we suggest that the disorientation and motion sickness from the cross-coupled illusion may be the limiting factor for higher spin rates and thus a shorter radius. Here we build upon a previous incremental approach [22] to increase the spin rate at which subjects do not perceive the cross-coupled illusion (i.e., their cross-coupled "threshold"). We present preliminary results for three experiments, which quantify the effectiveness of this approach and implications for future AG designs.

A. Individualized Adaption to Higher RPM Test Results

In this protocol, subjects repeatedly made 40 degree head tilts in one second while spinning about an Earth-vertical axis in the dark. The spin rate, which the cross-coupled illusion is proportional to, was initially 1 rpm and then incrementally increased. After each head tilt, subjects reported whether they felt any cross-coupled illusion. If the illusion was subthreshold (i.e., not noticeable), the spin rate was increased by 1 rpm, otherwise it was not modulated. The protocol continued for 25 minute sessions with one session per day for 10 consecutive days. This created an *individualized*, incremental cross-coupled training protocol in which the illusion intensity was slowly increased as each subject became adapted/habituated to it. We calculated a cross-coupled illusion "threshold" (i.e., the highest spin rate at which the illusion was not noticeable) at the beginning and end of each session (Figure 3).

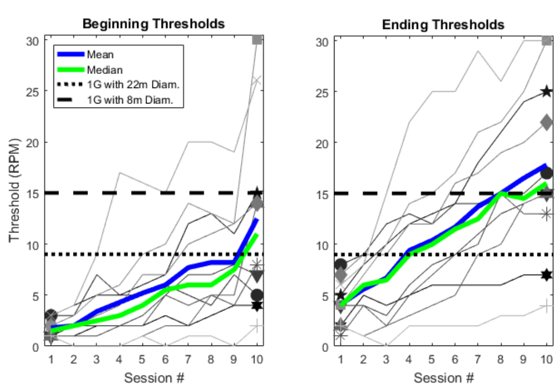


Figure 3 Increased cross-coupled illusion thresholds across sessions. Gray lines with shapes represent individual subjects, blue shows the mean, green the median, and the horizontal dotted lines show required spin rates for potential centrifuge design.

We found that at the beginning of the first session, all 10 subjects had thresholds of 1, 2, or 3 rpm. However, all subjects increased their thresholds across the 10 sessions, such that by the end of day 10 the mean threshold reached 17.8 rpm. While the increase in threshold was quite variable across subjects, by the end of day 10, 7 of 10 subjects had a threshold of at least 15 rpm, which corresponds to a 8 meter diameter centrifuge to produce 1 Earth G of centripetal acceleration. Finally, we note that all ten subjects were able to comfortably complete the protocol without experiencing excessive motion sickness.

B. Group Adaption to Higher RPM Preliminary Test Results

While the individualized, incremental protocol (Figure 3) was effective, for practical reasons it may not be feasible to individualize the protocol to each subject. For example, if there is a single centrifuge in microgravity that multiple astronauts utilize simultaneously it may still be possible to increment the spin rate, but presumably not on an individualized basis. To assess the feasibility of this approach (i.e., group adaptation), we calculated the median spin rate across time in each of the first 9 sessions for the personalized protocol above. Seven new subjects completed this incremental, but not individualized, protocol. On the 10th session, we assessed the beginning and ending thresholds (Figure 4).

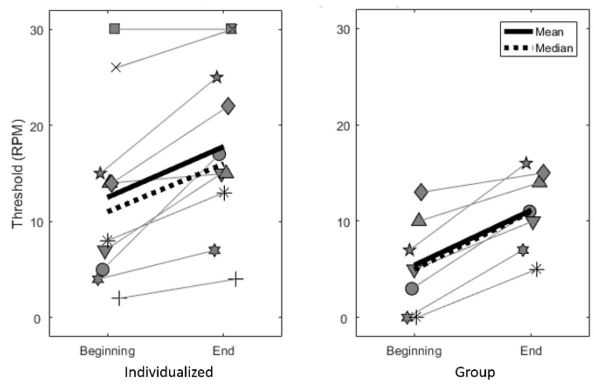


Figure 4 Comparison of cross-coupled illusion thresholds for Individualized vs. Group protocols on the 10th session. Shapes show individual subjects (different subjects in each protocol), mean is thick solid line. and median is thin dotted line.

After 9 sessions of incremental, but group (i.e., not individualized) exposure to the cross-coupled illusion, preliminary data suggest the thresholds tended to increase (Figure 4). Recall the thresholds were 1-3 rpm at the beginning of the first session. At the beginning of the 10th session, the median/mean is approximately 5.5 rpm. By the end of this session, it is up to 10 rpm. Nonetheless, the increase in threshold across the 9 sessions appears to be less in the group protocol than the individualized one (compare panels in Figure 4). If a group protocol is required, additional sessions may be necessary to increase subjects' cross-coupled illusion thresholds to higher spin rates.

C. Retention of High RPM Adaption Preliminary Test Results

Various mission scenarios may require the increases in cross-coupled illusion threshold to be *retained* for a period of time. For example, one might imagine astronauts performing a training protocol pre-flight in preparation for centrifugation after reaching microgravity. Alternatively, increased thresholds due to centrifugation in transit might need to be retained for the time course of a planetary stay without access to a centrifuge. As a preliminary investigation for if or how much the increased thresholds were retained, we brought four subjects (who completed the 10 session group protocol) back after 30 days (+/-3) and further assessed their thresholds over three consecutive days (Figure 5).

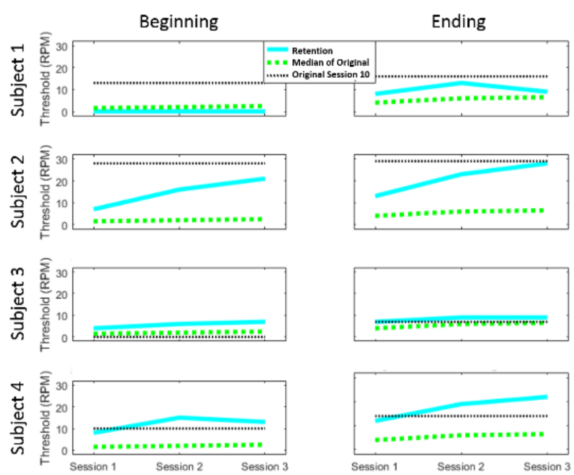


Figure 5 Retention of increased cross-coupled illusion thresholds after 30 days. The thresholds on the retention sessions 1, 2, and 3 are shown in cyan. For comparison, the median of 10 subjects' thresholds on their original sessions 1, 2, and 3 are shown in dotted green and the horizontal dotted black line shows that subject's threshold on the 10th session of the original protocol.

While the results are preliminary and appear to vary between subjects, Figure 5 shows that on average, some, but not all of the increased threshold is retained after 30 days. For example, Subject 2's thresholds after 30 days (cyan) are above the median for subjects on their original first three sessions (dotted green), but lower than Subject 2's threshold was by the original 10th session (horizontal dotted black line). On the other hand, Subject 1 appeared to retain very little (cyan line is similar to dotted green and well below the horizontal dotted black line), while Subjects 3 and 4 retained essentially all of the increased threshold they displayed by the original 10th session (cyan line is at or above the horizontal dotted black line).

Future testing will aim to verify these preliminary results, study different durations of retention (e.g., 60 and 90 days), and protocols longer than 10 sessions. However, it appears that 1) all subjects increased their tolerance to the cross-coupled illusion through a relatively brief protocol that incrementally increased the spin rate, 2) on average, cross-coupled illusion thresholds were increased to a spin rate which would enable greatly reduced centrifuge diameter (e.g., 15 rpm to enable 8 meter diameter), 3) a group protocol was effective, if slightly less so than an individualized version, and 4) there was at least partial retention over the time course of 30 days.

IV. Artificial Gravity Development Program

AG technology readiness level should be raised to TRL-9 as part of NASA's planned "Proving Ground" period utilizing ISS in Low Earth Orbit and a Cis-lunar habitation as a way point to the moon, asteroids, and Mars vicinity. Medium range radius (3.5 to 5 meters) AG systems are the only technically feasible implementation for deep space transit based on mass, propulsion, power, keep out zones, and reliability for use in near term deep space architectures. The ground tests we are performing enable the validation and testing of the limit of human adaptability due to vestibular cross coupling due to higher spin rates. LEO is the next logical step to test configurations and varying rotation speed in order to identify the tolerable radius and associated spin rate that can be supported with the least mass, vibration, acoustic and technical complexity. Such experiments will be necessary in the event that cross-coupled illusion responses may vary in microgravity [23, 24]. Effects of low gravity for both lunar (0.17 G) and Mars (0.37 G) should also be studied with AG in LEO in order to identify the benefit level associated with these G levels as potential alternatives to the need for AG as a countermeasure on the planetary surface. The concept of operation for deep space transits, such as Mars, should minimize the mass to the transit vehicle. A potentially viable approach, is the one time deployment of an AG system, in the destination vicinity, for reconditioning after arrival with no impact to the transit vehicle. Our ground based studies have started to identify not only the tolerable spin rate based on human adaptability but also have identified how quickly the adaptability takes place and suggest that pre-flight training could reduce the adaption time prior to on-orbit AG exposure.

A. Space System AG Design

In previous years, Boeing has designed systems for deep space deployment with a focus on the operational systems that would be deployed by the Space Launch System [25]. In more recent studies Boeing has refined AG designs, but the focus has been on an architecture for LEO deployment that limits the size to fit in a 5 meter fairing that can be launched with just one flight or as modules on ISS resupply vehicles. There are two design alternatives in the most recent AG hardware concept development for test during the proving ground phase.

Thie first concept is the development of small subscale AG system that is sufficiently large to be representation with ~3 meter radius. This would consist of only 1 habitable module with a ~2 meter diameter balanced against a dynamic adjustable counter balance system. Ballast could be added or substracted to habitation module for gross adjustment. This system would be built up from "mini" modules that would fit in the trunk of the improved Dragon for CRS-2 and/or HTV-X. They are similar in size and shape as the Nanorack airlock for ISS that will be flown up in a Space X dragon trunk. The sensitivity to inducing life limiting loads to ISS and/or disturbing microgravity experiments is high on ISS. Loads cells to limit induced loads (similar to active docking system) could be utilized for the mated load. The 2 meter radius for the "floor" would allow testing with limited range of walking motion but still with significant space to support a variety of tactile and balance based tasking. The attachment to ISS would allow for testing across a wider group of subjects with less disruption to on-going ISS operations.

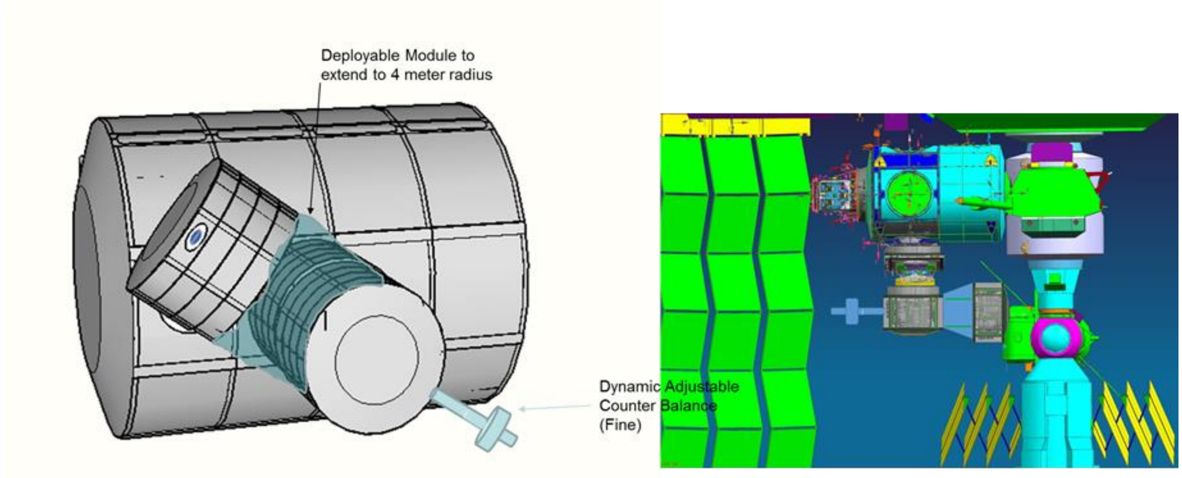


Figure 6 CRS-2 or IP Trunk Delivery for On-Orbit Assemble

Another concept for LEO testing is a cylindrical design rotating about the center with a rotational radius of ~4 meters generating 1 G at 15 RPM. there is continuous ladder access between the two opposite floors of the either ends of the rotating unit. This system comes with a simple habitation module with a spacecraft bus to maintain it. The concept of operations would be ISS assembly and then testing in a free flyer configuration with a commercial crew vehicle for access to the free flyer. This system can be implemented with either a fixed, monlithic structure or with a a deployable mechanism using inflatable materials. Optimal habitat layouts associated with these layouts to address physical performance associated with these RPM can also be tested. This concept can be deployed as either a monolithic design that fits in an Expendable Launch Vehicle (ELV), such as an Atlas V or Falcon 9, with a 5 meter long fairing or as a deployable module in a standard ELV fairing. This design uses counter rotating mechanisms in concert with Control Moment Gyros (CMGs) to mitigate excessive attitude control propellant expenditures. While passive dampening concepts have been developed, active dampening is in the trade space for vibration control. Acoustic impacts are another sensitivity to the design approach. The module size would be close to full scale and allow a complete set of tasking in a high RPM environment and potentially for longer duration than the attached mini-module concept for ISS. As a free flyer its impact on ISS ports and microgravity utilization would be limited during testing.

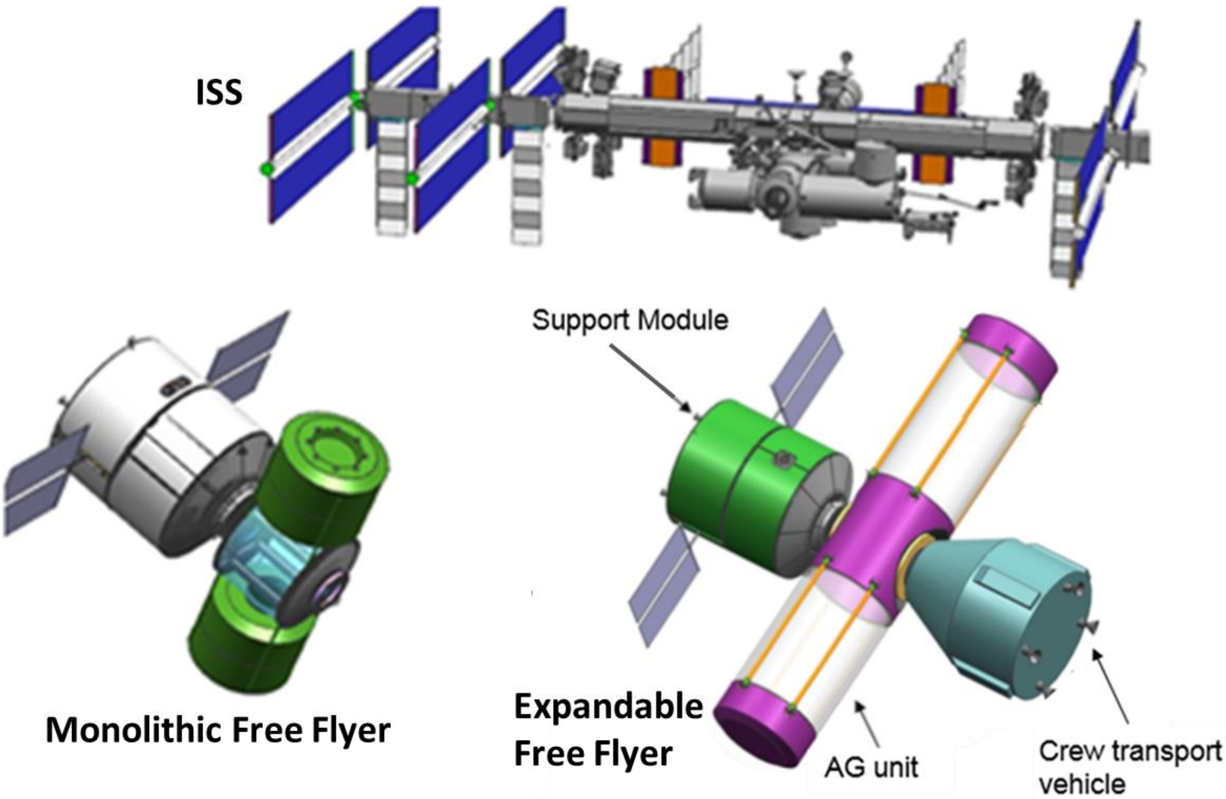


Figure 7 AG free flyer systems for use in LEO as part of exploration "Proving Ground" with and without inflatable sections

For deep space applications, the use of SLS will enable other options that can reduce the complexity of multiple launches through smaller commercial vehicles. Larger habitation diameters enabled by SLS can use either internally housed AG units or externally integrated units to reduce Coriolis effects, vestibular cross-coupling, and gravity gradients while staying within the pressurized habitation walls. Rotating annular parts of the gravity chambers will be configured in a way that allows for most crew functions to be in 1 G while allowing other crew tasking in an inner core to still be accomplished in microgravity. Since the drive mechanism and mount bearing will be internal, the drive units can be maintained through intra-vehicular activity (IVA). Access and exit to the gravity chambers will be simplified and safer since they are all inside one large unit. The deep space transport with AG modules has a functional allocation that reflects those activities that are best performed in microgravity and those that are optimally performed in a gravity-rich environment. The traditional subsystems such as ECLSS, avionics, and ATCS are located in the base habitation module. These subsystems and storage are best supported and accessed in a microgravity environment. An exercise treadmill was located in the microgravity environment in order to avoid unstable loads on the AG system. Crew systems such as galley, crew quarters and non-microgravity science were located in the AG modules that benefit or are neutral to 1 G environment. The safe haven was placed in the middle of the modules to minimize the additional radiation shielding required for deep space radiation protection (Figure 8).

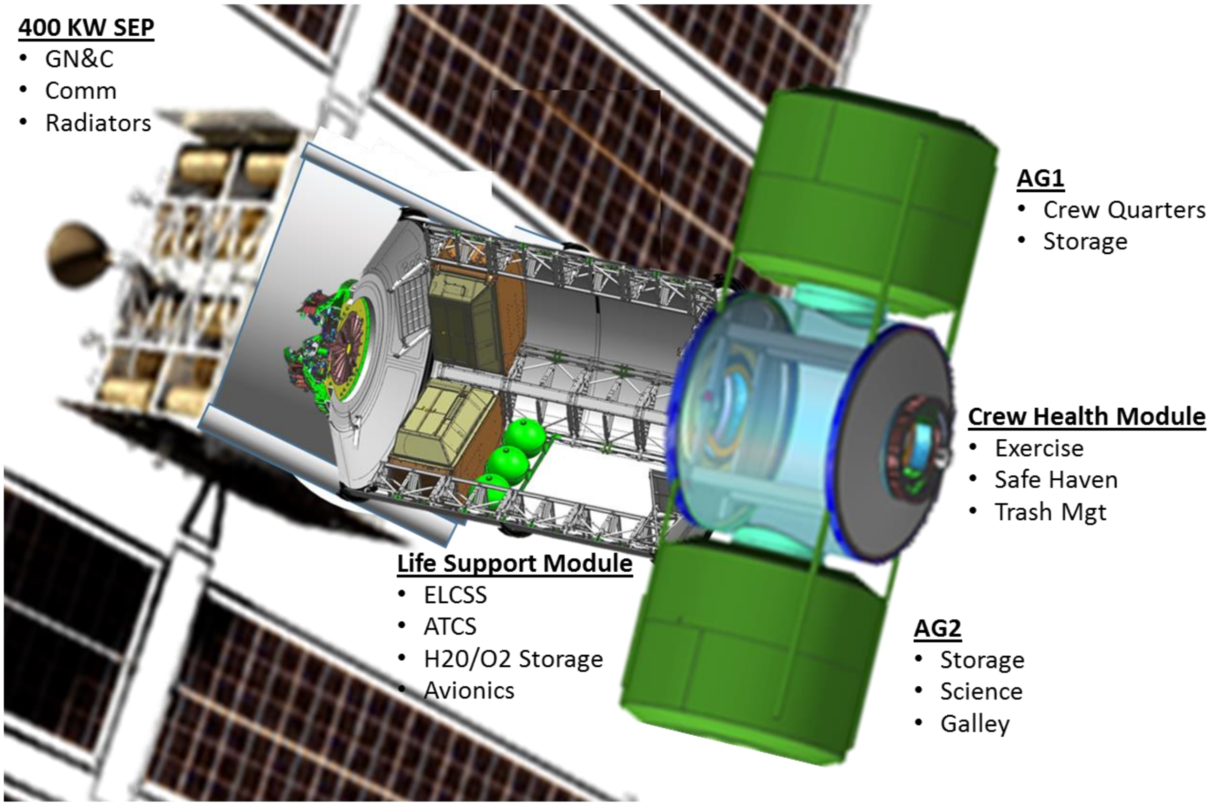


Figure 8 Mars Class Deep Space Transport with AG

B. Deep Space AG Concept of Operations

While not fully determinant until actual in space testing has been performed, based upon bed rest studies, it is plausible that the crew would not be required to be exposed to 1 G for the full 24 hours per day. As a simplifying assumption, 8 hours a day would be reasonable starting point. This would mean that the AG would be utilized for operations that are best or at least adequately performed in 1 G environment with the rest of the activities performed in typical microgravity operations. Examples of operations that are potentially better performed in 1 G are part repair, eating, hygiene, packaging, and medical procedures. Conversely, internal outfitting for crewed modules benefit greatly from microgravity and being able to place subsystems and stowage around the full circumference of the habitation module. Moving hardware and supplies as well as performing maintenance on subsystems are example of operations that benefit from a microgravity environment. A system and concept of operations that blends these has potential increases in crew tasking potential and efficiency, crew health and crew comfort. The design of the AG modules as shown in Figure 9 will have to account for the ergonomics of a 1 G, high spin rate environment, as well as when the AG system is turned off. This sets up that some stowage and operations in the AG modules may be limited while in operation. Examples of design considerations would be a table that on one side is concave to match the radius of rotation so objects could be place on it are balanced (such as a cup) while on the other side would be flat for repair or medical procedures that require a planar surface.

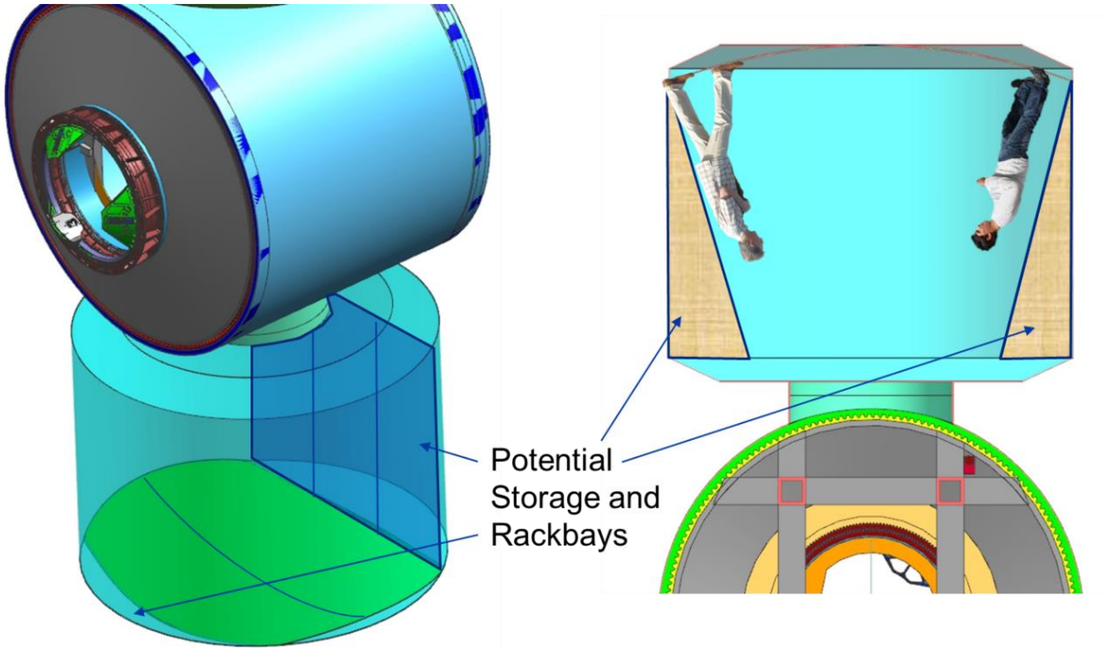


Figure 9 AG Interior Outfitting must address both Zero G and AG induced interior outfitting

Real mass advantages can be derived by spending a one-time mass on sending a destination AG system such as a module in Mars orbit or one on the surface of one of the orbiting bodies such as Phobos or Deimos. This allows weeks of rehabilitation upon arrival to Martian orbit after ~6 months of microgravity exposure during transit, similar to those who have returned from an ISS LEO mission. They could then go to the surface of Mars and immediately be effective upon landing. If Martian 0.38 G is determined to have limited or minimal benefit as compared to 1 G, then when the crew leaves the Martian surface they can rehabilitate one more time in the AG system before departure transit. Rotating gravity chambers proven in LEO can also be used as gravitational housing, especially on small space objects that have a milli- or microgravity environment. A good example would be on a moon of Mars, such as Phobos. Such a gravity chamber would be configured on a lander. A Phobos lander could potentially be the support structure for the gravity units as shown below. The very low gravity of terrestrial objects like Phobos will add hardly any vertical component to the centripetal forces induced within the gravity chambers. The lander will have to be designed with legs that will attach sufficiently well to the landing surface for stability. Figure 10 below shows the concept.

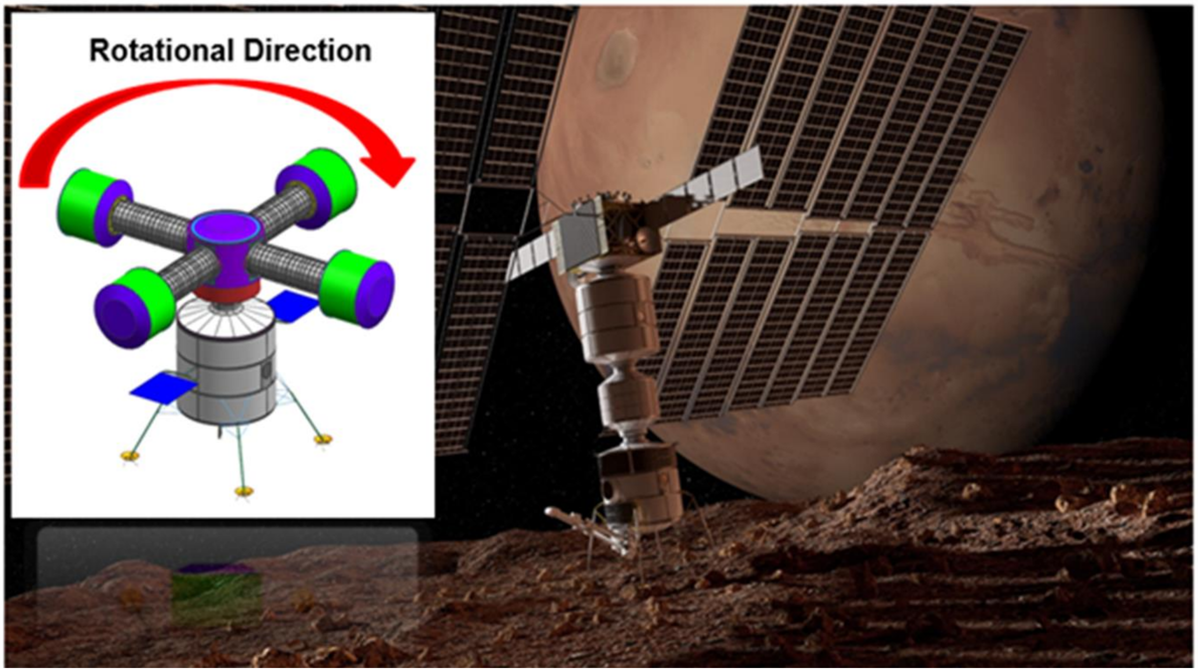


Figure 10 Destination Centric Conditioning could be performed in Mars Vicinity such as Phobos

Conclusion

AG is currently in the Global Exploration Roadmap but not part of NASA's Cis-lunar exploration architecture. AG offers the potential to comprehensively address Human Health and Performance needs for long-duration deep-space exploration. With the increasing data that conditions such as SANS may only be mitigated through AG, it should be considered for adoption as part of NASA's proving ground activities. With our preliminary work demonstrating human adaptability to high RPM there are now feasible configurations that can fit into the current exploration planning. Boeing has developed a number of enabling technologies to make this happen, including 10 AG patent pending concepts. We are currently performing ground-based studies to further inform our AG centrifuge system designs. A human space centrifuge in LEO near the ISS would allow for fundamental scientific and validation experiments, as well as demonstrate necessary technologies for deep space exploration.

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