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"Space-BEE: Space Biomedical Exercise Environment" A Personal Centrifuge within an Inflatable Structure

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ABSTRACT

This paper presents a conceptual design of a short-radius centrifuge for orbital application, contained in an inflatable structure.

The objectives of this design are: to support the physical effectiveness of the crew by offering an exercise facility; to provide a test bed for biomedical experiments on human centrifugation in orbit; and to offer recreational benefits during long periods of confinement. The use of a pneumatic structure that can expand in orbit allows maximizing the radius of the centrifuge within mass and launch constraints.

The proposed project is composed of elements with standard interfaces; its environmental design is based on human factor considerations from biomedical literature, and it respects current ergonomics and NASA standards.

INTRODUCTION

Simulating weight by centripetal acceleration has always been a concern since the time of space pioneers, when it was not even known whether humans could tolerate microgravity conditions.

Today it is well known and largely proven [NASA, 1995, 5.2.2.1; Connors, Harrison, Akins, 1985, p. 20-30] that microgravity and confined artificial environments like the space habitats, have two types of inconveniences: physiological and psyco-sociological [Connors, Harrison, Akins, 1985, p. 11-15].

MICROGRAVITY AND CONFINEMENT– Microgravity is proven not to be beneficial to human physiology. Instead, it causes several adverse effects, discussed later on, that are usually counteracted by means of physical exercise, passive devices such as lower-body negative pressure devices, or pharmacological treatment.

In addition, confinement related problems arise from the limited volume of space habitats, lack of sensorial stimulation and monotonous lifestyle. They may cause stress that could impact negatively astronaut wellness and performances. Supplying recreational activities, increasing exercise time, engaging the crew in games, or acting on the quality of the environment and spaces may help providing a higher acceptability of the habitat. Confinement relief, in fact, could be obtained by designing a habitat that gives a perception of spaciousness, paying attention to interior details, or offering a space that the crew can use in a flexible and creative way.

This design project (Fig.1) has the twofold objective of responding to both these human needs by providing weight simulation and greater volume, in addition to providing a platform for experiments.

Fig.1: Space-BEE external view.

CENTRIFUGATION AS A COUNTERMEASURE

EFFECTS OF MICROGRAVITY – Keeping the crew healthy for the mission duration is a critical requirement for the success of space missions. Unfortunately, about 70% of space travelers experience motion sickness soon after going weightless and the body's response can lead to serious problems after the return. Main concerns regard the loss of bone and muscle, cardiovascular deconditioning, loss of red blood and plasma, possible compromise of the immune system, neuro-vestibular adaptation, altered reproductive and hormonal pattern [Young, 1999]. Recovery of preflight physical capabilities takes 1.5 to 2 mos. of the post-flight rehabilitation, and complete bone recovery may take up to 2 years [Kotovskaya, Vil'-Vil'iams, Luk'yanuk, 2003].

TRADITIONAL COUNTERMEASURES – To counteract this, the crew performs daily physical exercise, uses inflation of anti-g suits during reentry, and undertakes medical treatment before reentry, like ingestion of ionically balanced water [Young, 1999]. Physical exercise in particular, as shown on the Kosmos-782 flight in 1975, is mostly effective in stopping deconditioning.

The importance of this problem regards the fact that, assuming that the duration of future space missions will increase, there is no evidence that the current countermeasures will be able to maintain the crew's physical condition [Kotovskaya, Vil-Viliams, Shipov, 1997]. They are effective within the limits of current missions, but they may show a limited effectiveness or even insufficiency in future, long-duration missions of planetary exploration, leading potentially to mission failure or even crew loss [Kotovskaya, Vil'-Vil'iams, Shipov, 1997]. In concluding this, Shipov made a strong case for experimenting with centrifugation in orbit, in order to develop ways to protect astronauts during and after space travels, and before engaging in a Mars exploration [Young, 1999].

HUMAN CENTRIFUGATION – A possible countermeasure that is encountering renewed interest among scientists is the simulation of gravity by centrifugation, that results in the perception of weight due to centripetal acceleration, experienced by a body in a rotating frame of reference.

This possibility presents many engineering challenges. From the realization standpoint there are two ways to simulate weight: linear and centripetal acceleration. The former is a constant acceleration of linear motion that according to the Equivalence principle is indistinguishable from gravity. The latter is rotationally induced, and it can be achieved by either rotating the spacecraft or only an internal part of it.

Current trends propose the simultaneous use of different countermeasures in an integrated approach. According to biomedical studies, better results could be achieved by combining centrifugation with traditional countermeasures such as physical training on a bycicle-ergometer and induced hydration [Vil'-Vil'iams, Kotovskaya, 2003].

DESIGN SOLUTIONS

Centripetal gravity, or spin gravity, inspired a great number of design projects. The first to suggest this solution was the Russian pioneer of space travels Konstantin Tsiolkovsky. He proposed the use of centrifugal force to simulate weight and configured the first rotating station for habitation. After this, many other concepts using rotation were proposed. They can be generally divided into the following architectural typologies.

LARGE RADIUS WHEELS - Because of its large radius this configuration is the one that better simulates Earth gravity, although it presents the highest technological and budget challenges. It features a hub with service modules and a rim that usually hosts the habitats. Docking is carried out at the hub port. The designs of Von Braun (1952), O'Neill (1975) and many others belong to this typology, up to the most recent Space Hotels designed by WATJ and by the Construction Company Shimizu [Matsumoto, Mitsuhashi, Takagi, Kanayama, 1989].

MULTIPLE BODY SYSTEMS CONNECTED BY A TRUSS OR TETHER - The need of reducing launch mass leads to other large-radius concepts, formed by central bodies and multiple habitation or counterweight units at the rim. Hub modules and rim habitats are connected by rigid trusses, or by flexible tension cables (tethers), and elevators. Although they certainly reduce the mass, these concepts create other potential problems regarding the transfer of energy and materials, and the transportation of crewmembers between modules. Among the many projects that have been proposed, Korolev, who was influenced by Tsiolkovsky, designed a cable system for the Voskhod program in the 1960s. Willy Ley also designed a spacecraft that once in orbit could split in two parts to form a two-body system [Young, 1999]; several designs propose truss-connected modules or tethered vehicles like RING, a multipurpose exploration prototype [Chen, Galvez, Pinni, Pognant, 2004]. There are other concerns upon stability, potential meteoroids damage, and increased complexity of the retraction and attitude control systems. Nevertheless, among the large radius configurations, the use of tethers offers the great advantage of a remarkable mass reduction.

Unfortunately, all these conservative concepts have remained on paper because they are undesirably complex and expensive [Young, 1999].

PERSONAL CENTRIFUGES – A possible trade-off between the need of simulate weight and technological and logistic constraints could be achieved with the use of personal centrifuges. Among the two variants of gravity simulation by centrifugation - rotation of space systems around their center of mass, or short radius centrifuges - the preference is nowadays given to centrifuges as an easier variant for realization [Vil'-Vil'iams, Kotovskaya, Nikolashin, Lukjanuk, 2001].

A **personal centrifuge** is a large, motor driven or powered apparatus with a long arm at the end of which human and animal subjects or equipment can be rotated at various speeds to simulate the prolonged accelerations encountered in high-performance aircrafts, rockets, and spacecrafts. This kind of device, although presents some of the same disadvantages as larger scale projects, such as engineering challenges (perturbations and gyroscopic torques), and human factors issues, it presents them in a smaller scale. Therefore, it constitutes a trade off between technological capabilities, launch constraints and cost feasibility.

PERSONAL CENTRIFUGES PRECEDENTS AND HISTORY – The earliest centrifuges were set up in the 18th century by Erasmus Darwin, grandfather of Charles (1794), and by E. Horn (1818). They were manually powered and used for medical purposes. The first modern centrifuges were built in the 30s and were powered by a motor. Since the 1980s they were used to train military pilots to hyper-accelerations and high-G maneuvers. The research into the physiology of radial acceleration forces and tolerability limits began first in Germany in 1931 with Dr. Von Diringshofen [Kotovskaja, Vil'-Vil'iams, 2004].

Centrifuges on Earth – Centrifuges are built in diverse sizes and capabilities. Today, many of these devices are used in laboratories around the world, for medical experiments and astronaut training.

The largest human-rated centrifuge today is the “TsF-18” Centrifuge set up in Star City at the Yuri Gagarin Cosmonaut Training Center (Fig. 2). It has a 18-meter (59 ft) radius and a weight of 300 tons, which enable it to host up to 4 people and achieve accelerations up to +30 Gz. Its maximum angular velocity is 38.6 rotations per minute, and the maximum allowable load is 350 kg (772 lbs).

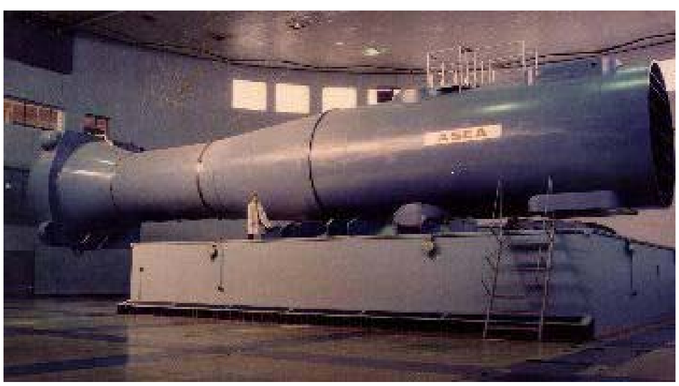

Fig. 2: TsF-18 Centrifuge at Star City (courtesy of Space Adventures, Ltd).

Another centrifuge called the Brandeis Slow Rotating Room (SRR) is in use at the Ashton Graybiel Spatial Orientation Laboratory at Brandeis University. It has a diameter of 6.7 meters (22 feet) and it can rotate at the maximum velocity of 35 rotations per minute, giving a 4-G acceleration at foot level.

NASA has several human-rated devices for artificial gravity experiments at the Center for Gravitational Biology Research at the Ames Research Center. The larger radius device is the "20-G centrifuge” (Fig. 3), which has a radius of 8.7 meters (28.7 feet) and can spin at a maximum speed of 50 rotations per minute. It is human-rated up to12.5 G and can carry a payload of 544-kg (1,200 lb.). Besides this, there is a Human-Powered Centrifuge (Fig. 4) with 1.9 meters (6.25 feet) and a 30-foot Linear Sled for vestibular research.

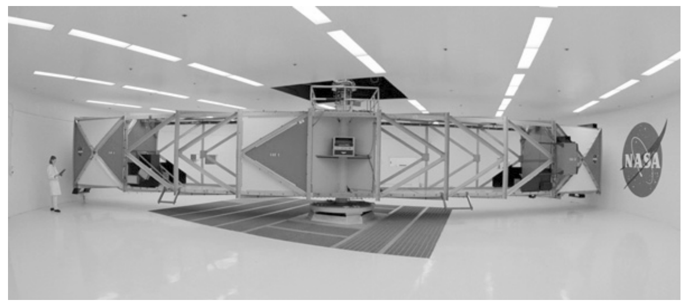

Fig. 3: The "20-G" centrifuge at Ames Research Center (courtesy of NASA).

Accomplishments - The effects of centrifugation on the human body are object of study in many laboratories around the world. They have allowed to obtain very important qualitative though encouraging results for its use as a possible countermeasure. In fact, since the 1960s, experiments on bed rest showed that muskolo-skeletal problems could be prevented by short exposure to centrifugation [Young, 1999].

Other experiments on animals conducted on the Kosmos 936 flight in 1977 showed significantly better performances in animals exposed to centrifugation, associated with rapid recovery and absence of bone loss In human centrifuge studies, periodic centrifugation has shown to be beneficial in preventing orthostatic intolerance and for the bone system [Connors, Harrison, Akins, 1985, p. 33-35].

Other studies have obtained quantitative results on the combination of different countermeasures. They precisely concluded that a 3-day exposure to 1.2 g combined with Water Salt Supplements, and a 6-day exposure to G-loads from 0.8 to 1.6 together with Velo-ergometer training were most optimal [Vil'-Vil'iams, 1994].

Most of these limited but important studies on human centrifugation have obtained qualitative assessment, and need to be quantified before embarking on the next steps of space exploration.

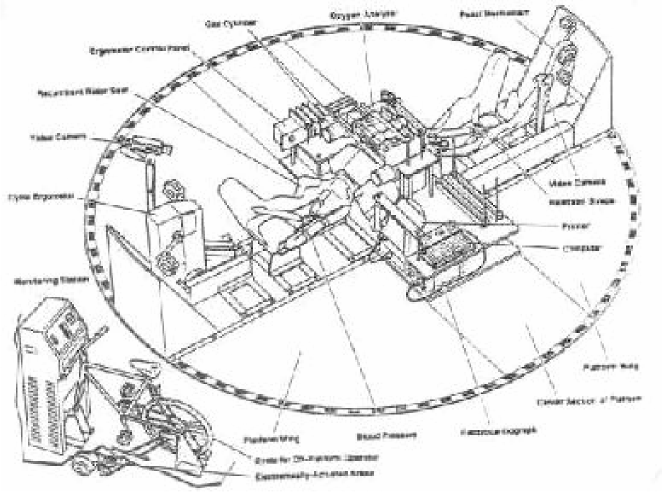

Fig. 4: Human Powered Centrifuge at NASA Ames Research Center (courtesy of NASA).

<u>Centrifuges in space</u> – One of the reasons why artificial gravity is not very well understood is that it has been tested very little in microgravity conditions, where the component of Earth Gravity is absent. In fact, there are only few occasions in which humans experienced some degree of centripetal acceleration in orbit.

It was achieved first in 1966, during the Gemini 11 mission when astronaut Richard F. Gordon linked a tether to an Agena rocket and to the Gemini, putting them in rotation around each other. The almost non-perceptible acceleration was only 1.5 thousandth of the Earth Gravity. Previously, on Gemini 8, a similar test failed because of a thruster's malfunction, and only the ability of Astronaut Neil Armstrong lead to overcome this problem [Young, 1999].

A higher acceleration experienced by humans in space was the self-generated by the Skylab 2 crew in 1973. The large diameter of the Skylab module (6.3 meters, 21 feet), enabled Astronauts Conrad, Weitz and Kerwin to "run" around the perimeter of the Orbital Workshop, on the lockers of the upper compartment, combining exercise and recreation (Fig. 5). The acceleration they experienced was almost the same as lunar gravity (0.165 G).

Tests on the vestibular system in orbit were only performed during the "Neurolab" mission in 1998, on board of Spacelab. They were conducted on the D-1 Vestibular Sled, exposing humans to linear acceleration and rotation on IML-1 and Neurolab experiments [Young, 1999].

Some design concepts were proposed for Short Radius Centrifuges powered by cycling to be installed on the Space Shuttle. Its size would allow the crew only to sit and not to stand up [Meeker, Isdahl, Helduser, 1996]

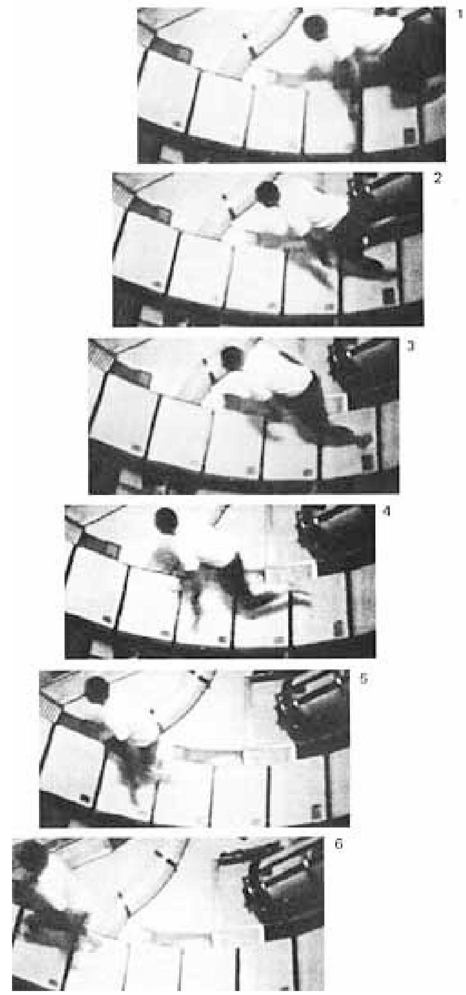

Fig. 5: Skylab "track path", May-June 1973, crew: Conrad, Weitz, and Kerwin (courtesy of NASA).

HUMAN ADAPTATION AND TOLERABILITY LIMITS

The initial phase of space exploration will probably take place through sequential, objective limited enterprises followed by the return to Earth. Nevertheless, even in this phase, astronauts will have to pass through gravitational fields of various intensities, and therefore they should be trained to adapt and operate in them [Cardus, 1994].

Centripetally induced gravity calls for other effects arising from rotation that may cause disorientation and motion sickness. These effects could make a habitat even more environmentally complex than weightlessness, both for the crewmembers, who have to adapt to it, and for designers, who have to take many parameters into account.

TOLERABILITY LIMITS- **G-acceleration** at any radius is proportional to the radius times the square of the angular velocity. Apollo missions provided information regarding the adequacy of 1/6 G for locomotion [Young, 1999].

Under this level, in fact, the acceleration is so low that perambulation is not possible. Most researchers then assume that a minimum acceleration of 0.2 G would be necessary for a comfortable locomotion [Young, 1999].

The level of comfort during centrifugation also depends on the **gravity gradient**, that is, moving from the rim to the hub, the difference of the radii divided by the radius at the rim. In a module where radius is double an astronaut's height, G-level would be double at foot level than it is at head level, and the gravity gradient would be 50%. An object carried up at head level would appear lighter than at foot level and also the head and arms would appear light. Therefore, in short radius centrifuges, the gravity gradient factor sets an upper limit for acceleration, because above 50% it may create "awkward materials handling problems" for people engaged in activities [Young, 1999].

Another problem is **cross-coupled rotations**, as one moves his head during rotation about any axis except parallel to the spacecraft spin axis. This produces an angular acceleration with a magnitude equal to the product of the spin velocity and the head velocity out of the plane of the spacecraft rotation. It leads to a sensory conflict between vestibular system and surrounding visual field due to the unexpected acceleration. Habituation to this visual-vestibular conflict may not occur for all subjects [Young, 1999].

In addition, **Coriolis force** is an undesired effect experienced by a body moving in a rotating frame of reference, with the exception of movements parallel to the spin axis [Young, 1999; Hall, 2002]. Its magnitude is the body mass times twice the product of the spin rate and the astronaut's relative speed in the plane of rotation. This force acts on to push astronauts toward or away from the rotation center, or toward or away from the direction of spacecraft spin, depending on the astronaut's relative motion. Free-falling objects follow a curved path relative to a rotating observer.

Regarding the **rotation rate**, subjects without any preparation can tolerate 6 rpm, while for higher rotation rates (12-30 rpm) a graduated exposure schedule is required [NASA, 1995, 5.3.2.3; Connors, Harrison, Akins, 1985, p. 33-34]. The rotation rates of 60 rpm for up to 3 or 4 minutes around the pitch axis (y-axis) and around the yaw axis (z-axis) have been described by subjects as being not only tolerable but pleasant [NASA, 1995, 5.3.2.3, Human Responses to Rotational Accelerations]. Above 80 rpm rotational rates are considered intolerable. NASA Standards recommend to: keep radial traffic at minimum; not cross the hub unless it is non-rotating; keep habitats far from the center; arrange living areas parallel to spin axis; and, finally, orient workstations so that the axis through the ears is parallel to the spin axis.

Experiments at the Pensacola Slow Rotating Room also concluded that most people could adapt to 6 rpm on Earth. Nevertheless, this is considered a level estimated in early research [Young, 1999]. In fact, Graybiel's early studies on visual adaptation give reasons to believe that short-term adaptation to a specific direction is gradually replaced by a general long-term non-direction-specific adaptation. Developing adaptation techniques could bring rotation rate to 10 rpm, and consequently allowing a significant reduction of spacecraft radius [Young, 1999; DeHart, 1985].

RESULTS FROM EXPOSURE TO CENTRIFUGATION - Lackner [1998] studied the effects of accelerations generated by centripetal gravity on execution of arm, leg, and head movements, and concluded that adaptation occurs readily, especially arm and leg control, while control of head and neck takes longer.

Other experiments have been made at MIT Artificial Gravity Lab, at NASA Johnson Space Center and at Wyle Laboratories. All these experiments were made to test the psyco-physiological response of humans to centrifugation and acceleration, the response to Coriolis force and adaptation to the consequent disorientation, the changes of the vestibular system, and nystagmus (rapid eye movements). Most experiments, although showed motion sickness, inappropriate vertical nystagmus, illusory tilt, and heart rate changes, they also showed significant adaptation following head turns in the light, and reduction of all symptoms in time [Young, Hecht, Lyne, et al., 2001].

Human tolerance of +G in a short arm centrifuge with a high gravity gradient (100%) was found no worse than on a mid-arm centrifuge with a lower gravity gradient (20%) [Vil'-Vil'iams, Kotovskaya, 2003]. Some studies concluded that even a very short radius of 1.5 meters (5 feet) could be used to measure G tolerances, in on-ground experiments and in space [Burton, Meeker, 1992].

These experiments could have interesting consequences for possible simulated gravity environments, even though disorientation and other negative effects could suggest limiting their use to intermittent and brief sessions in orbit [Young, 1999].

The adaptation to centrifugation is under study also from the psychological standpoint. A design proposal of MIT [Kim, Robinson, 2001] analyzes the concept of "intuitive physics", a branch of cognitive psychology that studies the people's commonsense beliefs regarding how the physical world works. The preliminary study includes test evaluation on different candidates about linear and accelerated motion of objects. Candidates are tested on the path of objects in inertial and in non-inertial systems. The thesis is that, even if Coriolis force defies intuitive understanding, people can be trained, improve their knowledge of the physics, and learn to deal with objects that do not "behave" in the way we are used to in our every day life.

DESIGN RECOMMENDATIONS

NASA RECOMMENDATIONS – The main problem of testing centrifuges in orbit is their volume. The sizes of current launchers do not allow a diameter of more than 4.5 m. The larger diameter considered for installation on board of Spacelab, as already mentioned, was less than 2.5 meters that could have enabled an astronaut to sit or cycle, but not to stand up.

The NASA Artificial Gravity Working Group suggests, as a long term recommendation, the use of a centrifuge of 7.2 meters (24 feet) diameter, equipped with a treadmill and an ergometer spinning in the direction opposite to the rotation of the module. The centrifuge, in order to maximize the radius, was designed for installation inside an inflatable pressurized module (Fig. 6).

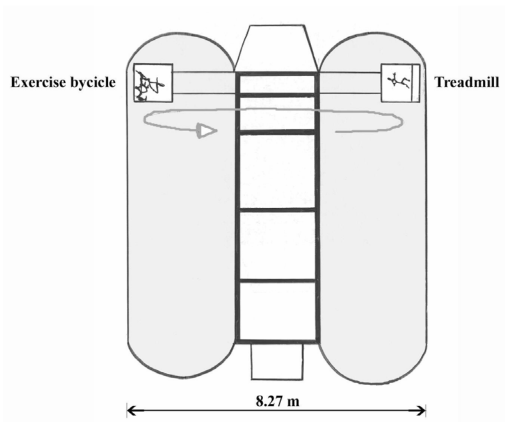

Fig. 6: NASA long-term recommendation for a Powered Exercise Centrifuge within a Transhab-like module (courtesy of NASA /W. Schneider, 1999).

M.I.T. RECOMMENDATIONS – An MIT design for a short radius device describes similar features: a radius of only 4 meters, a G-level of 0.5 requiring a spin rate of 10 rpm. This device could be spun up to 10 rpm over a period of several weeks in the early phase of a long space mission [Young, 1999].

With regards to human adaptation capability, Dr. Laurence Young states: “if we are right about the ability of astronauts to adapt and maintain the adaptation, it may be possible to achieve a measure of protection from an intermittent artificial gravity exposure with a radius as low as 4 meters, rotating at 10 rpm to produce about half a g at foot level”. [Young, Hecht, Lyne, et al., 2001; Young, 1999]. Following this recommendation, this project proposes a 24-foot centrifuge contained in an inflatable structure.

DESIGN PROJECT FOR A PERSONAL CENTRIFUGE IN AN INFLATABLE MODULE

GOALS OF THE PROJECT– An onboard Short Arm Centrifuge (SAC) on ISS, if technically and economically feasible, could be a useful tool to test human centrifugation in microgravity. This proposal for an orbiting centrifuge has the following main goals:

- Serve as an orbital exercise facility to support the crew’s health during space flights.
- Offer a test-bed for biomedical experiments on human centrifugation in orbit.
- Provide recreational benefits during long periods of confinement.

The use of a pneumatic structure that can be compressed at launch allows maximizing the radius of the centrifuge within mass and launch constraints.

OVERALL REQUIREMENTS – The system drivers and requirements of this concept can be summarized as follows:

<u>Inflatable module requirements:</u>

- The main system driver is the capacity, in mass and volume, of the launch system, which drives the maximum size of the centrifuge. The maximum launchable diameter is currently 4,5 m, equal to the maximum capability of the Shuttle cargo bay, if using a rigid approach. An inflatable module, instead, can expand from 4.5 m up to 9 m in diameter (27 feet).
- The module should have a rigid hub to provide a structural support for rim attachments and transmitted loads.
- The hub should contain a passageway for circulation, because the space between hatches must be free from obstacles [NASA, 1995, 8.10.3.1].
- The hub should provide one access or more to the centrifuge environment.
- The module, as an additional feature, could potentially work as an adapter, and could be equipped with a Common Berthing Mechanism (CBM); and with an Androgynous Peripheral Attachment System (APAS).

<u>Centrifuge requirements:</u>

- The centrifuge should be designed for assembly by crewmembers in orbit, during IVA activity, and it should be composed by modular components of a manageable size and with fast and safe attachments.
- It needs a power system with control panel placed in the hub.
- It should be equipped with a vibration damping system.
- It should be provided with the capability to add other devices to be placed on the rim, such as treadmills or workstations.

- It should be equipped with a restraint system for the transition to and from microgravity, and for circulation.
- It should be designed with a signal system to keep the crew aware of their position and movements.

GEOMETRICAL DEVELOPMENT– From the analysis of the needs and requirements of the project, the following hardware is needed:

- 7.2 meters (24 ft) diameter centrifuge (radius 3.6 m)
- Common Berthing Mechanism (CBM)
- Androgynous Peripheral Attachment System
- Aluminum hub
- Inflatable membrane (9 m diameter)

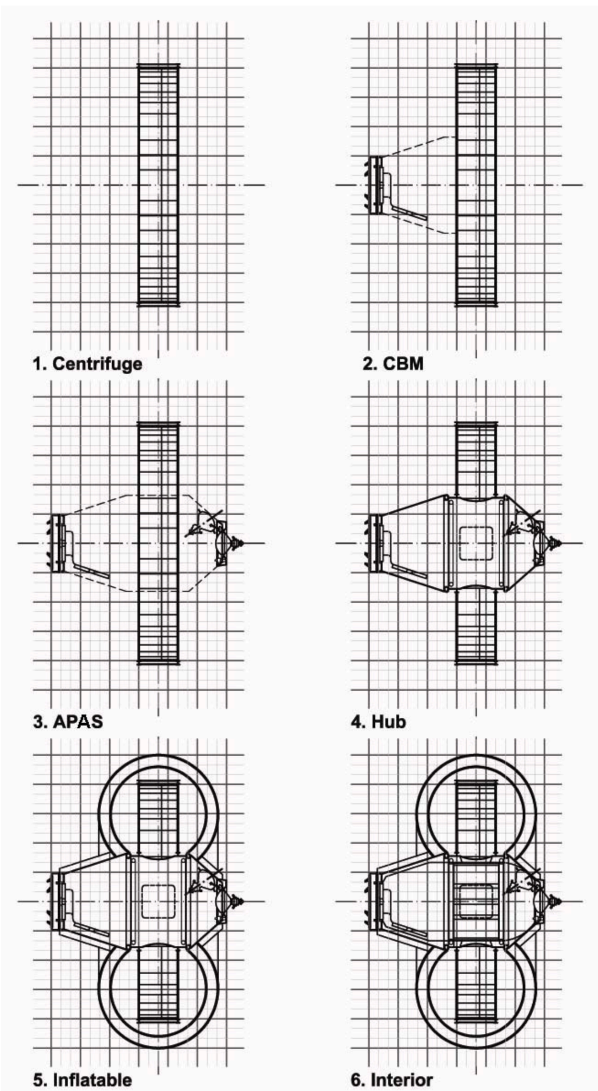

Fig. 7: design sequence: (1) centrifuge; (2) CBM; (3) APAS; (4) hub; (5) inflatable membrane; (6) interior covering.

The architectural ***parti*** of the project (a non-reducible pattern that overarches the proportional organization and the geometry of the parts) is based on a standard module of 90 cm (35,43 inches). Figure 7 shows the design sequence of the main module components. Figure 8 shows the cross sections.

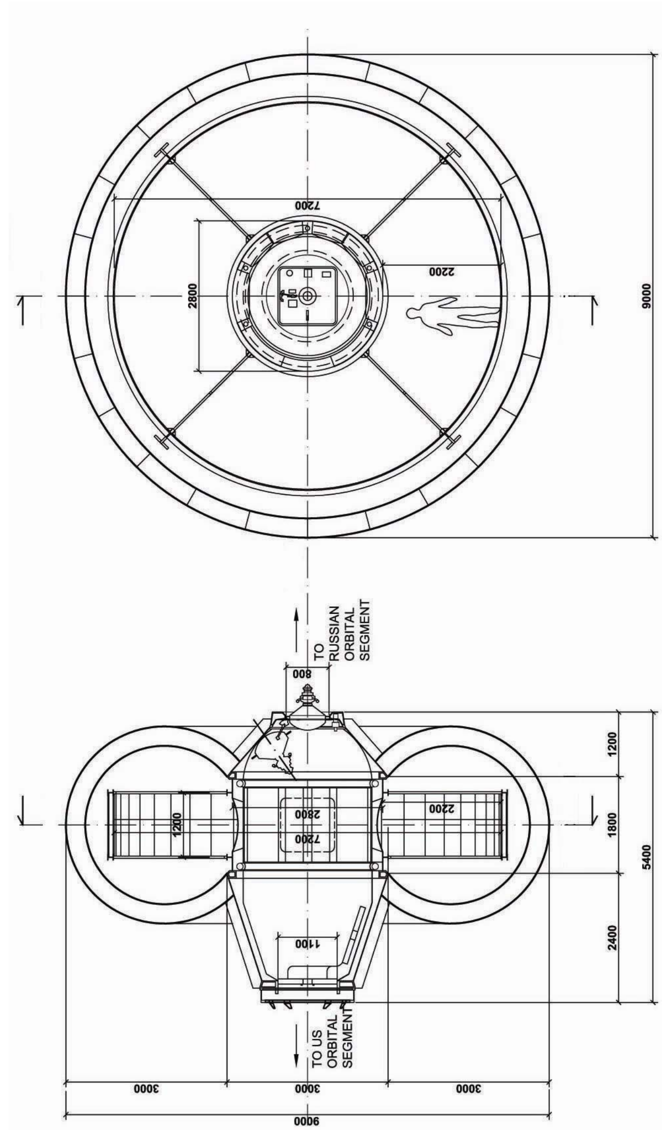

Fig. 8: Space-BEE cross sections. The module spin axis is inertially fixed.

COMPONENTS OF THE INFLATABLE MODULE – Common Berthing Mechanism: The CBM is a standard attachment system, designed with a square opening (hatch) of 110 cm, which serves for passageway of racks and equipment. The CBM that appears in this project uses as reference the non-standard hatch of the inflatable Transhab module. Its special attachment system is designed with an inclination of 70°, instead of the standard one of 25°, for logistical purposes.

Androgynous Peripheral Attachment System: This attachment system is a Russian standard. A compatible attachment is used on the Shuttle. This hatch is much smaller than CBM that was developed later for the Space Station. Its axis-symmetric design enables to stand greater loads and perturbations due to space operations and maneuvers.

Hub: The hub is designed in aluminum, and composed of modular panels and rings (Fig. 9). It supports end cones and hatches, and has three openings to access the inflatable volume. It contains the power and control systems, in order to leave the inflatable volume free from equipment and enable control, repair and maintenance in comfortable and safe conditions [NASA, 1995].

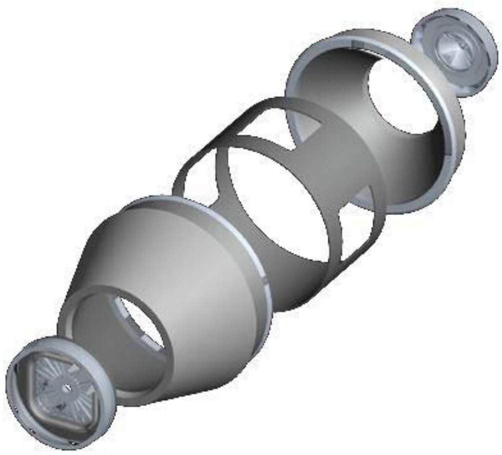

Fig. 9: Hub exploded view. Assembly of hub components takes place on the ground.

Membrane: One of the assumptions of this project is the use of the inflatable technology developed in the Transhab program. The 36 cm-thick membrane is made of a multi-layer fabric made of advanced materials that should guarantee the same or higher requirements as a rigid shell: pressure containment, thermal insulation and micrometeorites protection. The safety factor in the design of every gossamer structure is equal to 4 [Jenkins, 2001]. It is composed of 24 sectors, united by a special index system.

Living volume: The membrane and rigid structure enclose a pressurized volume of 128 cubic meters.

Volume at launch: The module is designed for transportation in the orbiter's cargo bay. According to this system driver, it is designed with a diameter at launch of about 4.5 meters. Although it is difficult at this phase of the project to individuate a gross mass, a first estimation ranges between 8 and 12 tons.

CENTRIFUGE COMPONENTS – The components of the centrifuge are:

- Two bearings attached to the hub
- 8 spokes attached to the bearings
- Rim composed of external rings (composed by arcs)
- 48 floor panels attached to the inner part of the rings

Assuming that all components are made of aluminum, and although a precise mass estimation could be made only with a structural simulation, a gross estimation of the mass of the centrifuge could give about 500 kg.

Assembly sequence: the bearings are pre-placed around the hub on the ground. The remaining assembly procedure should be carried out in orbit. First, the spokes have to be fixed to the bearings. Then, the arcs that constitute the rim should be attached to the spokes. Finally, the 48 floor panels should be placed on the rings. They are made of an aluminum honeycomb. The assembly should be carried out in microgravity conditions, therefore connection mechanisms have to be simple and safe [NASA, 1995; Vil'-Vil'iams, Kotovskaya, 2003].

Rotation data: In a rotating frame of reference, the tangential velocity is equal to the angular velocity multiplied by the radius, and the acceleration is equal to the square of the angular velocity multiplied by the radius.

$$V = w \cdot r$$

$$A = w^2 \cdot r$$

If the radius is 3.6 meters, to reach an acceleration of 0.3g (0.3·9.81 m/s^2), the centrifuge will have to speed at 8.63 rpm (0.90 Rad/sec) at a tangential velocity of 3.25 m/s.

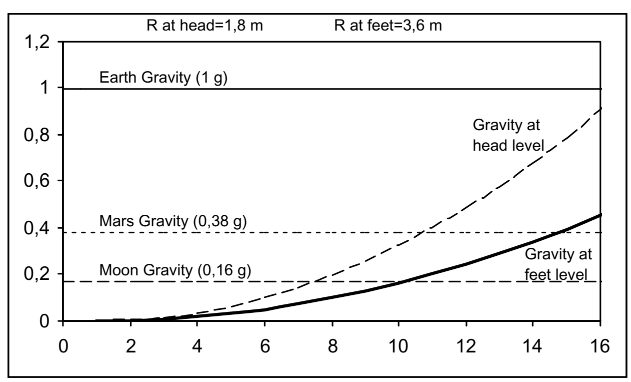

Table 1: Gravity gradient experienced by a body inside the centrifuge.

In order to access the centrifuge, astronauts will enter the hub and pass through one of the three openings. They would propel themselves toward the centrifuge, at 2,2 meters away. The 4-stand-off section of ISS modules is designed with the same dimensional requirement. Once reached the centrifuge they will be carried by the rotating device, perceiving the force as if it were their own weight.

It is important to note that during use, the line through the ears of the user is parallel to the spin axis, thus minimizing cross-coupled accelerations.

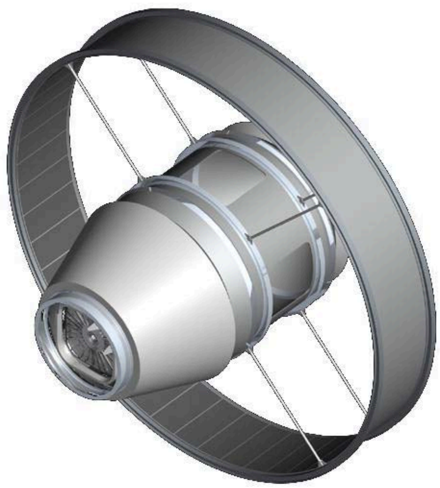

Fig. 10: The hub with the centrifuge (inflatable membrane omitted).

OUTLINE PROPOSAL FOR TRAINING SCHEDULE- A proposed schedule for the use of the equipment could use two groups for training. The first group, the "control" group, could perform exercise as planned for missions in microgravity. This could be done inside the hub, using standard exercise equipment. The second group could test combinations of exercise and centrifugation. After comparing the results, experiment parameters could be varied as required [Burley, Dara, et al., 2003].

SUBSYSTEMS DESIGN

POWER SYSTEM – In order to power the centrifuge, three options were proposed: electric motors placed around the hub shell; air thrusters placed at the rim; air thrusters attached internally on the membrane.

Among those, the second was chosen for its multiple advantages.

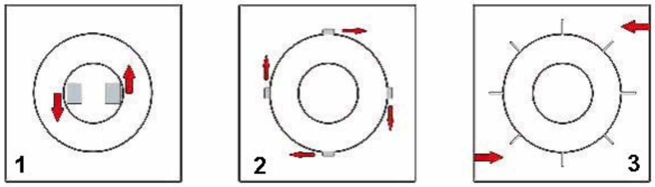

Fig. 11: Three options for power system: 1) Electric motors inside the hub. 2) Air thrusters on centrifuge end arms (squid concept). 3) Air thrusters attached at the inner side of the membrane (windmill concept).

Electric motors: The first option indicates the use of electric motors. Motors should be two for redundancy and would power three gears, placed inside the core in motor boxes. The gears are mechanically attached to the bearings. This would enable all mechanisms to be inspected, repaired or replaced from the central volume.

The expected power requirement, based on comparison with similar devices, may be as low as 500 Watts with 20-30 Amperes [Burley, Dara, et al., 2003].

Nevertheless, this system presents several disadvantages:

- Excessive mass
- Gyroscopic torques caused by perturbations on the core, and consequently on the station on which it is attached.
- Perturbations on the hatches and CBM that has particularly stringent requirements about rigidity. APAS is less problematic being axis-symmetric.
- Perturbations causing potential damage or improper functioning of gears and teeth system.
- Additional mass needed to provide a counter-rotating ring.
- Noise caused by motors, with consequent discomfort for the astronauts.
- Possible corrosion due to difference in electric potential between materials used to build this device, and additional treatments needed on materials.

Air thruster system: a simpler solution, although it would not solve all the listed disadvantages, could be the use of thrusters working with compressed air, placed at the external rings. The variant with thrusters placed on the membrane was discarded because it presents possible compromise of membrane safety due to high local loads.

The air could be compressed in a compressor, placed in the hub or end cone, and conducted to the thrusters through pneumatic lines. Thrusters would apply a small impulse using air, with no need of fuel, tanks, gears or motors. The larger radius would also enable minor leverages, with respect to the motor system.

Air thrusters would also be more silent than electrical motors, providing increased comfort level.

Figure 12: Thrusters power system positioning.

ATMOSPHERE DISTRIBUTION AND LIGHTING SYSTEM – Regarding Life Support System and energy, this module is not designed to be autonomous. The MEP ducts, coming from an adjacent module, run inside the end cones and along the hub, and circulate around it in two main ducts that have interfaces with both environments, central and inflatable. Light fixtures and atmosphere supply and return are placed on these main ducts.

Change of air is object to important consideration in this project, because the main activity performed is physical exercise. An estimation of the diameter of the air duct is determined by the air velocity in current habitation modules (ranging from 4.16 to 6.785 m/s), and by the flow through exchange ducts between adjoining modules, which is between 3.8 and 5.95 m^3 per minute (0.06 and 0.099 m^3/second). The flow rate is equal to the total volume per unit of time, or the velocity of the fluid times the area of the duct:

$$F = V/t = w \cdot A$$

Assuming 6 air changes per hour, for a volume of 128 cubic meters, and for an air velocity of 4,16 m/s (worse case), the diameter of each of the two main duct results to be 18 cm. For an air velocity of 6.785 m/s, each duct would be 14 cm. The design provides tolerances to possibly increasing this diameter.

PERTURBATION CONTROL - Even if powered by air thrusters, the centrifuge in motion with its unbalanced loads causes gyroscopic torques, originating perturbations and vibrations. Therefore, it should be equipped with passive and active damping systems, compatible with the system of the station to which it will be attached. The system should be similar to the one of the International Space Station that enables to compensate vibrations caused by the use of the ergometer and other exercise facilities.

Should these systems be insufficient, the possibility of adding a counter-rotating ring is considered. This design provides spatial tolerance, near the bearings, to add extra equipment at the interface between the centrifuge and the hub.

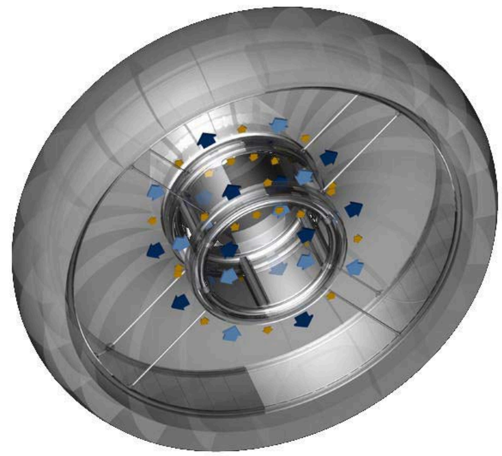

Fig. 13: Air and Light distribution: the two MEP ducts distribute atmosphere and power in both the hub and the inflatable volume.

INTERIOR DESIGN CONSIDERATIONS

Regarding the environmental requirements, two main goals should be achieved: environmental comfort and ergonomics for micro-and simulated gravity conditions.

Environmental comfort in space habitats depends mainly on efficient internal arrangements and shape of habitat, thermal control, acoustic quality, and habitat capability to provide stress relief, for example by means of windows or entertainment activities [Pinni, 2000].

TEXTURES AND COLORS - A balanced variety of colors and textures can increase the quality of the environment, if their number is limited to 4-5 and with moderate texture patterns. [NASA, 1995]. In some cases, rough textures are recommended to provide sound-absorption.

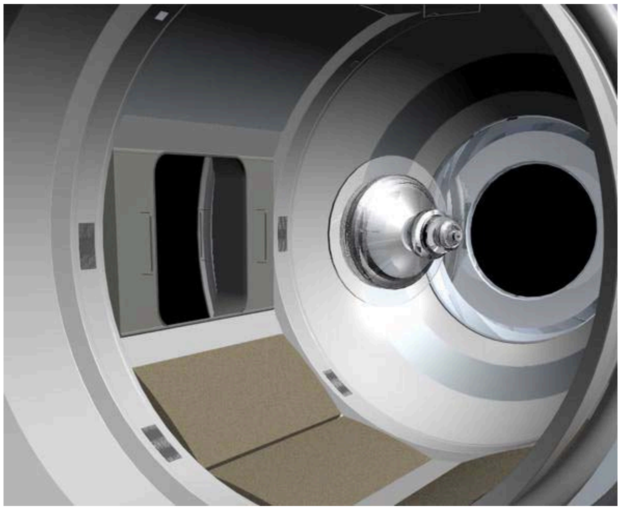

Fig. 14: Hub interior's view. The lower part between the two MEP ducts is covered with fabric. See on the left one of the openings to access the centrifuge, on the right the APAS.

ERGONOMICS FOR HABITATS WITH VARIATIONS IN ACCELERATION REGIMENS –Dealing with design of "empty spaces" in different gravity conditions implies that one has to design two fundamental types of "environmental systems" [Pinni, 2000]:

- An **Orientation Signal System** that should help the crew to remain constantly aware of their positions and movements.
- A **Passive and Active Restraint System**, to support crew's mobility inside the module, especially during transitions in microgravity and between microgravity and centrifugation regimen.

Orientation system: a signal system with distinctive color schemes, studied specifically for a rotating environment, and indicating the direction of spinning, should be integrated in the interior design. It could enable astronauts to identify orientation and spinning directions relative to the spin axis to help them adapt to Coriolis forces and cross-coupled rotation effects [Young, 1999, Hall, 2002]. It should also distinguish right from left and forward from backward, and it should be incorporated in the general interior design without overwhelming the decor. In fact, an excess of stimulation, as well as its opposite, can deteriorate the quality of the design and it may create a sense of over information or confusion [NASA, 1995]. The development of a "semiotic" for simulated gravity environments could be the object of an interesting experimental design project.

Restraints and mobility aids system: This system should support mobility inside habitats in weighlessness conditions. Additionally, it should support mobility during transition between microgravity and centrifugation to ensure an efficient and safe circulation, as well as during centrifugation. Handrails should be provided inside the hub for the microgravity conditions, as specified in [NASA, 1985]. Handrails are also to be placed on the external perimeter of the hub structure, so astronauts can propel themselves toward the centrifuge.

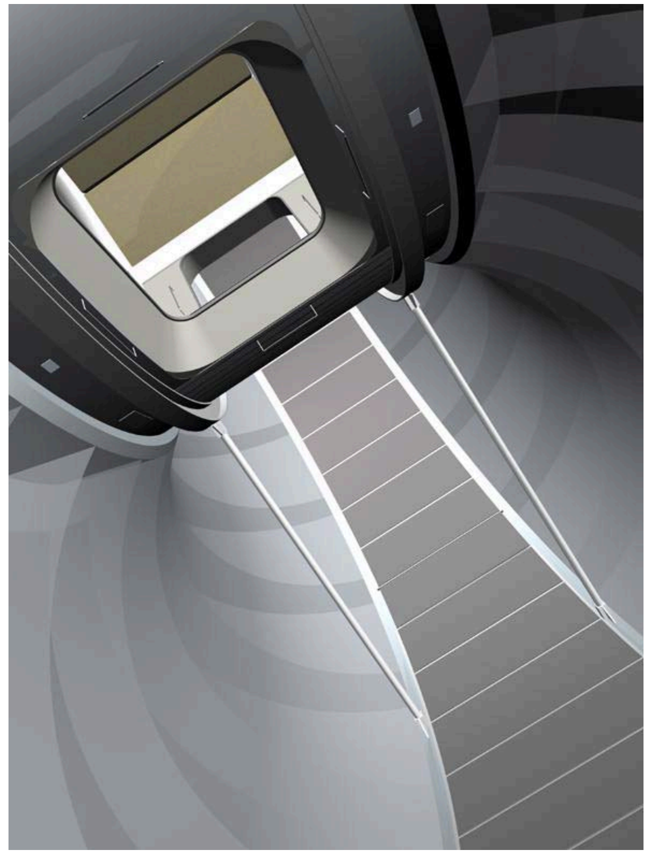

Fig. 15: Interior of inflatable volume, showing the centrifuge "track path".

DEVELOPMENT STRATEGY FOR INTERIOR ARRANGEMENTS

Growth directions: Should this design not present any problems in a possible implementation in orbit, there are some growth directions that could be explored. For example, additional equipment and exercise devices could be installed on the track path. This way the centrifuge could also be used for other activities that may result more comfortable when performed in gravity conditions (computer work, games, other entertainment activities, rest and sleep, dress and undress).

On-ground applications of technologies developed for this device might include new rides and simulators, entertainment devices, new exercise equipment and other clinical and medical applications [Burley, Dara, et al., 2003].

CONCLUSION

In conclusion, this paper highlights many habitation and adaptation issues related to human centrifugation in space. It proposes a design concept that addresses launch constraints and human factor requirements, with the purpose of supporting crew's health during future long-duration missions of planetary exploration.

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