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Electrodynamic Gravity Generator for Artificial Gravity Modules

Predrag Jevtovic
Bezares S.A., Casarrubios del Monte-Toledo, SPAIN, 45950

Weightless environment is causing numerous deleterious effects on human health. It complicates activities and material handling in space. It is necessary to design a kind of artificial gravity generators as life support systems to enable space exploration and colonization. Rotation is in the focus of all artificial-gravity research as generated centripetal acceleration can be substitute for gravity. The aim is to obtain controlled rotation to achieve at least partial levels of artificial gravity. A very effective way to spin objects in space is to use electrodynamic technologies suitable to be optimized and applied in favourable conditions of cold vacuum without gravity. Artificial gravity will provide opportunities for life sciences and advanced technology research. It will enable sustainable exploration and colonization of deep space.

Nomenclature

AGSH	=	artificial gravity space habitat
a	=	relative acceleration
a_{cor}	=	Coriolis acceleration
a_{cp}	=	centripetal acceleration
B	=	magnetic induction
c	=	vacuum speed of light
E	=	electric field strength
EDGG	=	electrodynamic gravity generator
EDS	=	electrodynamic suspension
EMS	=	electromagnetic suspension
EVA	=	extra-vehicular activities
E_A	=	induced voltage in rotation generator
e	=	loop voltage
F_P	=	propulsion force
Fx	=	magnetic drag, *X* component of the magnetic force between moving SCM and null-flux coil
Fy	=	total guidance force, *Y* component of the magnetic force between moving SCM and null-flux coil
Fz	=	null-flux centering force, *Z* component of the magnetic force between moving SCM and null-flux coil
g	=	acceleration due to gravity
g_a	=	total artificial gravity acceleration
I	=	loop current
I_A	=	armature current in rotation generator
I_{xx} , I_{yy} ,I_{zz}	=	principle moments of inertia
i	=	circuit mesh current
L	=	inductance
LEO	=	low Earth orbit
Maglev	=	magnetic levitation
MGS	=	Mars gravity simulator
M_s	=	mutual inductance between super conducting magnet and loops of pair of null-flux coils
n	=	spin rate
P_A	=	active power

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PGS	=	propulsion and guidance system
R	=	resistance
RMS	=	rotating modular set
r	=	radial distance from the center of rotation
SC	=	superconductor
SCM	=	super conducting magnet
SFS	=	space frame structure
TRL	=	technology readiness level
Δ	=	Laplace operator
v	=	relative tangential velocity
ω	=	angular velocity
ψ	=	phase angle between the armature current and induced voltage

I. Introduction

EXPOSURE to weightlessness conditions provokes a significant number of harmful effects on human health and important health concerns: vertigo, nausea, headache, lethargy, skeletal and muscle reconditioning and atrophy, loss of bone mineral density, cardiac problems, loss of cardiac mass, cardiovascular changes, red blood cell loss, fluid redistribution and loss, weight loss, facial distortion, changes of the immune system, and disruption of vision and taste. There are physiologic problems of adaptation to micro gravity conditions and of renewed adaptation to Earth's normal gravity conditions. The psychological effects of living in space are stress, insomnia, fatigue, sleep loss, and depression. Weightless environment in space is complicating all human activities and material handling as objects are floating in completely independent orbits.

It is necessary to generate artificial gravity sensation to resolve or reduce all or a major part of problems present in weightless conditions in Earth orbit and deep space, and to design a kind of artificial gravity generators as a life support and habitation systems to enable sustainable exploration and colonization of space. Gravity sensation can be induced by the inertial reaction to the centripetal acceleration that acts on a body in circular motion. Spinning habitats will provide centripetal force that always points toward the center of rotation causing inhabitants and objects to behave as if they had weight while keep moving in uniform circular motion, where centripetal acceleration acts as artificial or simulated gravity.

The idea of using rotation to create artificial gravity in space was introduced by Konstantin Tsiolkovsky in 1903. Hermann Oberth was the first to use the term space station for a wheel-shaped facility in 1923. By 1929, Hermann Noordung introduced concept of rotating wheel station and suggested it to be positioned in a geostationary orbit. Wernher von Braun and Willy Ley upgraded the idea in the 1950s, popularizing the concept of spinning wheel shaped station to provide artificial one-third Earth gravity. In 1968 the film "2001: A Space Odyssey" by Arthur C. Clarke and Stanley Kubrick described spin-generated artificial gravity aboard a space station and on a spaceship.

For long-term stays in space it will be needed to achieve at least partial gravity conditions. It is necessary to prove ability to generate gravity with rotation and to show that humans can live and work in artificial gravity conditions. Artificial gravity will provide opportunities for life sciences and advanced technology research.

II. Superconducting Electrodynamic Technologies Applied in Space

A very effective way to spin an object in space is to use electrodynamic technologies, as it is cold vacuum without gravity. The aim is to obtain controlled rotation of a habitat and to generate gravity sensation by means of guidance and velocity control managed by a unified trajectory control system made of propulsion and guidance subsystems. Employing superconducting electrodynamic technologies in space could result in development of a new critical technologies needed to enable human exploration missions and design of human habitats in space.

The superconducting Japanese EDS Maglev trains technology in which vehicle is suspended, guided, and propelled by magnetic forces and fields, is especially suitable to be optimized and applied in space to spin an object by controlled rotation. The term "Maglev" refers to magnetic suspension already in use for Maglev trains, wind generators, and bearings. The most distinguished Maglev train technologies are servo-stabilized EMS developed in Germany and EDS systems developed in Japan. EMS is based on attraction forces generated by conventional electromagnets while EDS is based on repulsive forces and it use powerful SCMs. Although EMS energy consumption is lower, obtained gaps in EDS are much larger enabling this technology to be used in circular paths. EMS is unstable and it needs active electronic stabilization while EDS is stable.

A. Low Temperature and Super Conducting Electromagnets

Generally accepted temperature in space is approximately 2.725 K or almost -270 Cº that is less then 3 K above absolute zero temperature at which molecules themselves stop moving. Although there are slight variations of this value, it is the accepted temperature in space being so-called cosmic background radiation, which is the energy still left over from the Big Bang. Space is nearly ideal heat sink. Such a low temperature makes very interesting and meaningful use of superconductors in space environment. Superconductivity occurs in certain materials at very low temperatures followed by zero electrical resistance and exclusion of the interior magnetic field (the Meissner effect). Superconductors' electrical resistance decreases gradually when temperature decreases and drops strongly when the material is cooled below its critical temperature. Their conduction losses are greatly reduced so resultant power densities are considerably increased. The use of superconductors in cables, motors and generators is highly efficient. These materials could carry high levels of the required electrical current, while still meeting lightweight performance requirements. Electrodynamic systems do not need expensive cryogenic systems to cool SCMs in the frigid space environment. SCMs provide powerful electromagnetic fields with strong repulsive forces resulting in larger and safer operating gaps between rotating modules and rotation generators making possible completely contactless and frictionless rotation. Superconductors can conduct electricity even after the power supply is cut off. Use of SCMs in space will be highly economical and with highly improved efficiency.

B. Lack of Gravity

Levitation is natural condition in weightless deep space and the only target to achieve is to obtain controlled rotation. Electrodynamically propelled system suited in space will need one and unified trajectory control system to achieve fully controlled rotation for deliberate acceleration that will replace natural gravity in space environment. The only clearances to be controlled are between propelled rotating module and rotation generator. Important technical requirements such as lift-off speed, lift-off force, and weight sensitivity, are senseless. Once achieved fully controlled rotation, the weightlessness conditions will facilitate its maintenance making it highly efficient. Propelled modules have no weight in space so required propulsive power consumption will be reduced as well as a size of implemented SCMs and coils. Gravity sensation generated by rotation will be gradual, starting from zero in the axis of the rotation and ending with designed values in rotating habitats.

C. Vacuum Conditions

Outer space is hard vacuum and the closest natural approximation of a perfect vacuum environment. Electromagnetic fields are influenced by matter fields and the influence is specified by Maxwell equations, while matter fields are influenced by electromagnetic fields by the Lorentz force as a feedback. Electrodynamics is a linear theory and electromagnetic waves in vacuum are determined by the following equations:

$$\left(\Delta - \frac{1}{c^2}\partial_t^2\right)B = 0 \tag{1}$$

$$\left(\Delta - \frac{1}{c^2}\partial_t^2\right)E = 0 \tag{2}$$

where $c \approx 3\times10^8$ m/s is vacuum speed of light in vacuum, B is magnetic induction, and E is electric field strength. In vacuum both the electric field and the magnetic field obey homogeneous wave equations. No medium is required for propagation of electromagnetic waves as they can propagate in vacuum traveling at the speed of light, which increase the efficiency of electromagnetic and electrodynamic technologies in space. Strong magnetic fields generated by superconductors in vacuum conditions will result in smaller SCMs. Electrodynamically propelled contactless rotation in space will be completely loss-less and frictionless with highly improved power efficiency.

D. Abundant Solar Energy

Space is the most favorable environment for unobstructed use of abundant solar energy. The Sun is unlimited, clean and very convenient energy source. Essentially a vacuum, space itself is a kind of "superconductor" for photon energy transmission. Energy supply needed for an electrodynamically propelled system can be obtained directly from the Sun to convert the energy contained in the Sun's radiation (mainly light and ultraviolet rays) into electrical power. Energy generation is safe, reliable, renewable, and highly efficient.

III. Electrodynamic Gravity Generator (EDGG)

General theory of moments for electrodynamic magnetic levitation systems based upon the dynamic circuit principles and emphasized on the loop-shaped coil and the figure-eight-shaped null-flux coil suspension applied in Maglev EDS trains in Japan can be modified and fully applied to spin objects in space environment of cold vacuum without gravity. It is characterized by very low magnetic drag at low speed, high suspension stiffness, high lift to drag ratio and high guidance to drag ratio. EDGG is axial thrust rotation generator designed to be included into larger space structures with artificial gravity. Generation of controlled magnetic forces and rotating magnetic fields between rotating modules and rotation guideway will obtain stable, controllable, and contactless rotation.

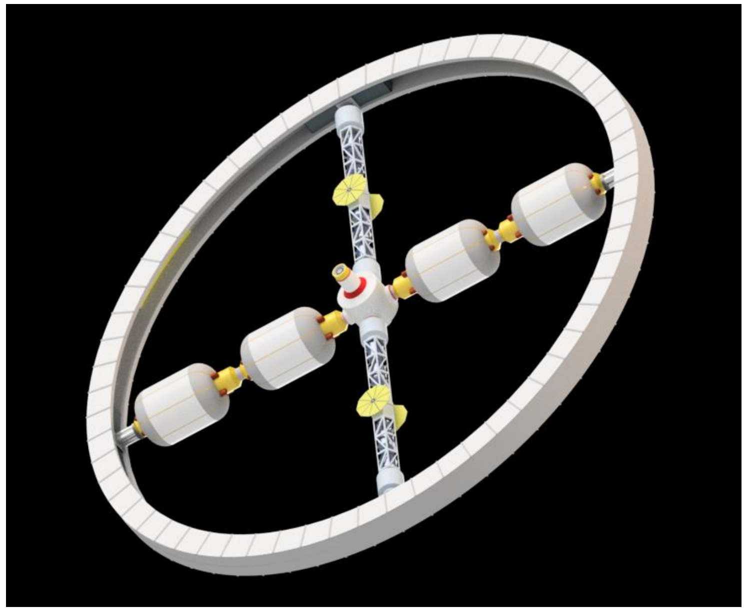


Figure 1. Electrodynamic Gravity Generator (EDGG).

A. Propulsion Guidance System (PGS)

Electrodynamic Gravity Generator (EDGG) consists of EDGG guideway and Rotating Modular Set (RMS), as shown in Fig. 2.

Controlled rotation is obtained by means of guidance and velocity control by a unified trajectory control system made of propulsion and guidance subsystems.

EDGG guideway contains null-flux coils, null-flux cables, and electromagnetic chucks, where null-flux coils and cables are part of the Propulsion Guidance System (PGS). RMS includes propelled SCMs modules, another main part of the PGS, as shown in Fig. 2. The aim of spinning the RMS is to generate artificial gravity sensation in Artificial Gravity Modules (AGMs) located on its endpoints. Detailed composition of the RMS is described in the Chapter IV.

Propulsion and guidance are achieved by electrodynamic interactions between SCMs and null-flux coils. The guidance consists of axial and radial centrings.

Propulsion Guidance System (PGS) is composed of superconducting coils (SCs) located on propelled SCMs modules, and figure-8 shaped null-flux coils on the sidewalls of the guideway. The 8-figure null-flux coils located on the opposite walls are connected by null-flux coils to make a null flux circuit, while those null-flux coils located along the guideway are connected to

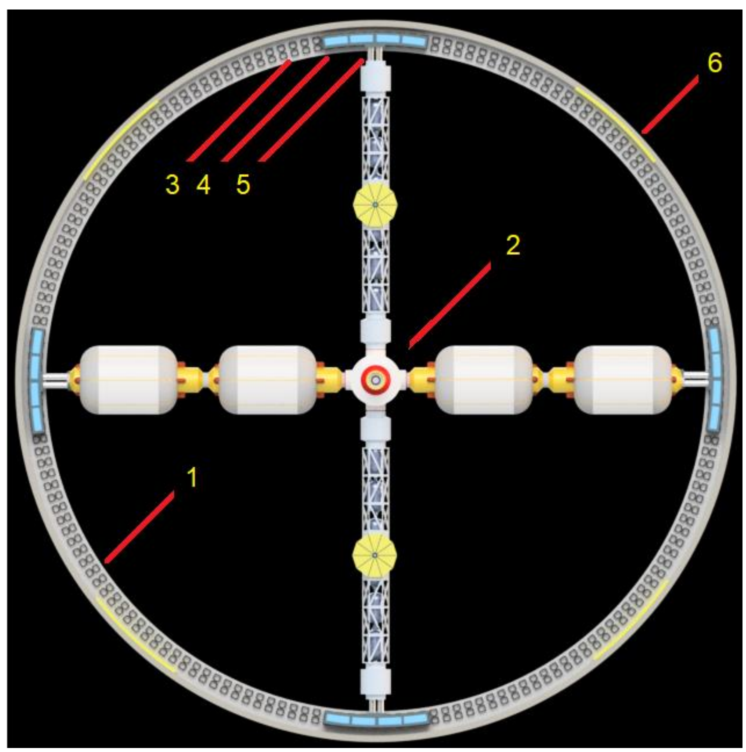


Figure 2. Coils arrangement in propulsion and guidance system.
1 – EDGG guideway. *5 – Clampers.*
2 – Rotating Modular Set (RMS). *6 – Electromagnetic chucks.*
3 – Null-flux coils (schematic).
4 – Propelled SCMs module (blue colored SCMs, schematic).

make serial circuits for alternating current (AC) supply of high nominal voltage (33kV), as shown in Fig. 3. Propulsion current is 390 A.

PLG null-flux coils for propulsion, guidance and levitation, developed for EDS trains in Japan, can be applied in space where the levitation function on Earth becomes guidance function in space, used for radial centering and path control. Guidance and propulsion forces are generated by letting electric current into the null-flux coils and by connecting a couple of facing coils by a null flux cable at the same time, as shown in Fig. 3. When the direction and the intensity of the currents going through the null-flux coils are controlled, the sign and the intensity of the created magnetic field are also controlled.

Null-flux coils are to be installed on the inner surfaces of the circular rotation generator guideway and covered with aluminium curved-shaped panels. This concept includes high guidance-to-drag ratios and very low magnetic drag at low speed. The null flux makes the power losses from the induced currents in metal loops very low resulting in smaller magnetic drag forces. The null flux coils enable strong and fast acting trajectory control forces being inherently and passively stable. The coils must have high mechanical strength to bear magnetic forces so they are wound aluminium conductors moulded out of unsaturated polyester resin reinforced with glass fibber and electrical insulated. The null-flux coils can be symmetric or asymmetric. In this paper is accepted symmetric configuration 0.75 x 0.72 meters, with 0.9 meters coil pitch, 120-degree-pitch, with 0.1 x 0.04 meters coil's cross section.

SCMs are sequentially mounted under the outer surface of propelled SCMs modules, as shown in Fig. 2. SCMs are made of superconducting coils made of conventional superconductors that require very low temperatures. Permanent direct currents (DC) go through them generating a strong magnetic field that enables both, the guidance and the propulsion thanks to their interaction with null-flux coils. The coils are closed and the magnetic field they generate is hence constant and does not change over time. In this paper is accepted 1.07 x 0.5 meter SCM with 1.35 meters pole pitch, and 700 Ka magnetomotive force.

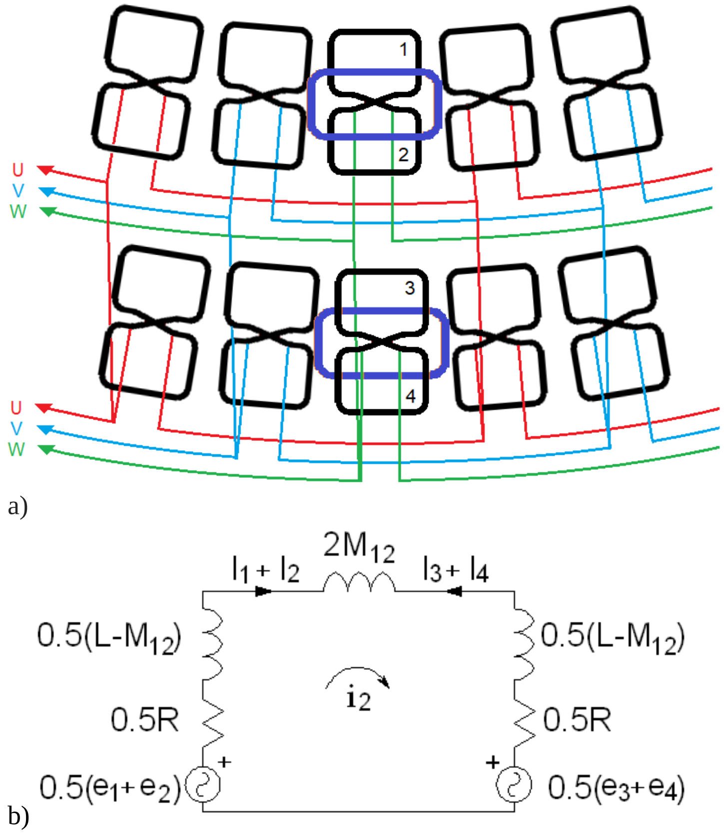


Figure 3. Null-flux coils arrangement.

a) Cross-connected facing pairs of null-flux coils for guidance. Serial-connected null-flux coils for propulsion. Pair of SCs running over the null-flux coils.

b) Simplified equivalent circuit of cross-connected null-flux coils.

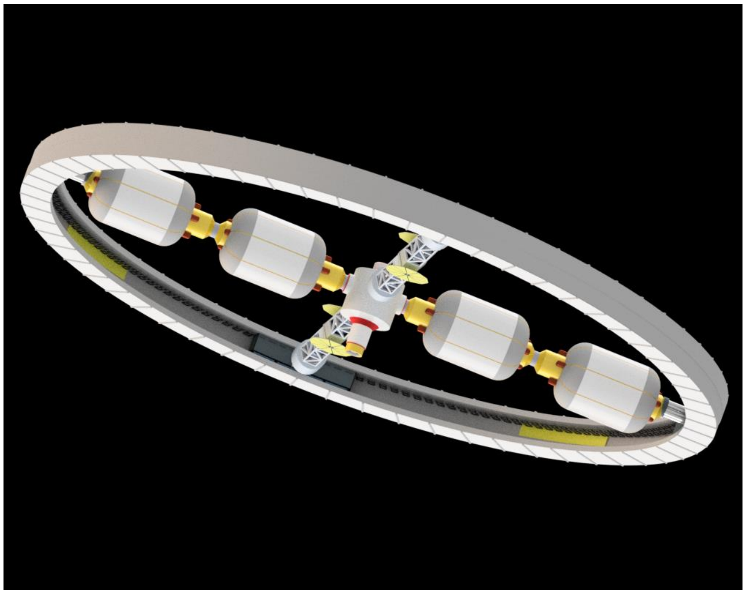


Figure 4. Propelled SCMs module spinning in EDGG guideway.

When the propelled SCMs modules move fast and near the null-flux coils, their magnetic fields created by superconducting coils scans the null-flux coils inducting currents to flow through them, as shown in Fig. 4. These inducted currents create magnetic fields that interact with the magnetic fields induced by superconducting coils in the propelled SCMs modules. The guidance does not require any other energy than the energy required for propulsion. There is voltage induction in the coils due to the relative motion of the magnet-coil system. This voltage creates current flow except at equilibrium position, resulting in a secondary magnetic field in opposition to the change in flux due to relative motion.

EDGG is axial thrust rotation generator of considerable diameter. The coils and the SCs need to be modified, slightly asymmetrical and slightly curved shaped with the lateral sides converging in accordance with the radius of the rotation.

Interactions among the coils are characterized by strong magnetic fields, which enable larger gap between the rotating modular set (RMS) and the rotation generator guideway. The choice of operating gap in space is a design decision. Larger gaps improve safety, allow greater construction tolerances and decrease construction costs. Lower sensitivity is very convenient for circular trajectory and circular paths. The dynamic circuit theory could be extended for curved SCMs and coils. Although the null-flux and superconducting coils are usually flat, use of slightly curved gradient coils would allow instantaneous adaptation to change in the circular trajectory to benefit the electromagnetic fields interactions and the rotation itself. SCMs are not complicated to construct nor to operate. SCMs can conduct electricity even after the power supply has been shut off. Magnetic fields induced by SCMs are strong and with serious effects on humans. Their penetration into interior of habitats must be limited with barriers made of conductive materials as electromagnetic shields to control electromagnetic fields and their dangerous effects. Superconducting materials can expel magnetic fields by the Meissner effect. Protection level directly depends of shield’s material and thickness, volume of the shielded space and existing apertures in it.

The guidance subsystem enables radial centering as well as axial centering being stable, high-precision, and self-aligning system. In stable system, any variation from stable position will push a moving object back to designed optimal position without any active electronic stabilization. EDGG is high-precision system able to provide stable rotation. Spin rate, spin-up and spin-off requirements are easy to meet by simple change of alternating currents frequencies. It is low-speed rotation, self-aligning, high precision, and noiseless system. Rotation is uniformed, completely contactless and practically loss-less while vibration, wobble, and shaking are significantly reduced. EDGG as a low speed electrodynamic system is to be located in space to act in favorable conditions of frigid vacuum without gravity where system efficiency is going to be strongly improved.

Electromagnetic chucks are located in the inner coaxial surface of the EDGG guideway, as shown in Fig. 2. They are designed to hold fixed the propelled SCMs modules before the final phase of the assembly process, as well as for breaking. Their number is at least equal to the number of applied propelled CSMs modules. Clampers are located at the end points of the rotating modular sets and their role in final assembly is fundamental as they attach propelled SCMs modules to the RMS preparing it for spinning in the EDGG guideway. EDGG is not viable as an independent system located in space. It is designed to be applied in complex space structure with artificial gravity, as shown in Fig. 5. It is necessary to apply simultaneously two coaxial EDGGs to generate counter-rotations to achieve angular momentum canceling. The assembly of EDGGs into the space frame structure as a back-bone of the whole AGSH structure, is explained in the Chapter 1V. Power supply issue is also explained in the Chapter 1V.

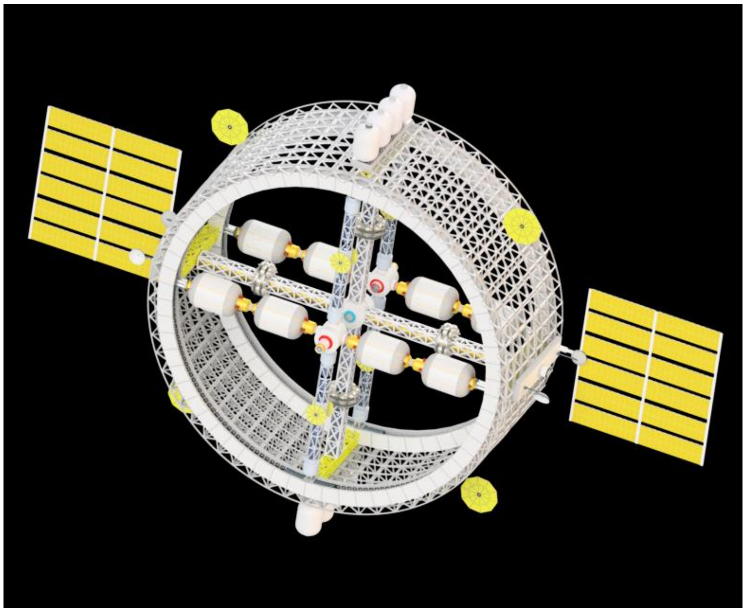
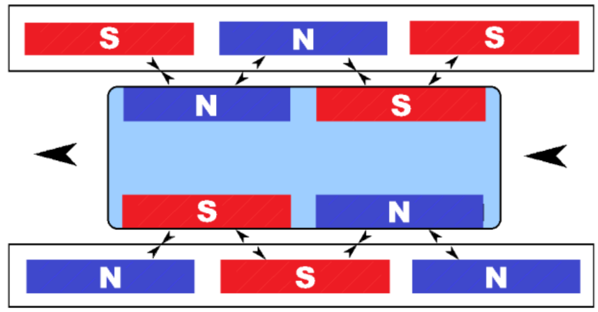


Figure 5. EDGGs in Artificial Gravity Space Habitat (AGSH).

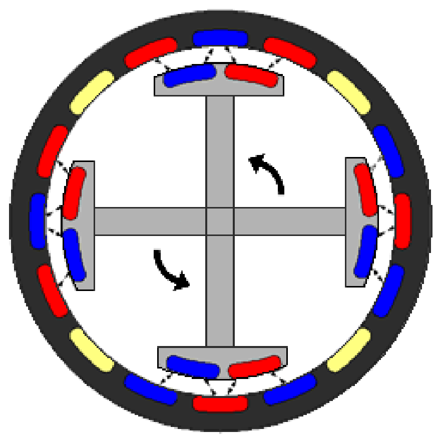
B. Propulsion

The SCMs located on the propelled modules will get excited and spin in a field created by the ring of the null-flux coils suited on the inner walls of the EDGG guideway. They are energized by three-phase alternating current creating a shifting magnetic field. Alternating current is generating a traveling magnetic field, which moves the propelled SCMs module without any contact and rotation is contactless. All propelled SCMs modules will rotate under the same conditions being pushed and pulled by the rotating magnetic fields. The sums of forces acting over each propelled SCM module distributed in two pairs, will create torques to spin the rotating modular set. Repulsive and attractive forces over the propelled SCM modules keep the rotating modular set coaxial with the guideway.

The on-board SCMs are attracted and pushed by the shifting field, propelling the rotating module. They are direct current magnets and their fields do not vary with time. Propulsion is achieved when two magnetic fields are synchronized and locked among them. As a result, the speed of the rotation is proportional to the input frequency of the alternating current. Force that propels the rotation forward is produced by the excitation current in the SCMs and the magnetic field induced by the propulsion null-flux coils' serial circuits. Propulsion forces are controlled by changing the magnitude and the phase angle of armature. Propulsion force F_P and active power P_A are:



a)



b)

Figure 6. Propulsion.
a) SCMs are attracted and pushed by shifting field induced by propulsion coils, to propel the rotating SCMs module.
b) Repulsive and atractive forces over the propelled SCMs modules keep the rotating modular set coaxial with the guideway.

$$F_P = \frac{P_A}{v} \tag{3}$$

$$P_A = 3E_A I_A \cos\psi \tag{4}$$

where v is relative tangential velocity, E_A is the root mean square of the induced voltage, I_A is the root mean square of the armature current and ψ is the phase angle between E_A and I_A. The propulsion force F_P must be stronger then the sum of magnetic drag forces Fx (armature reaction).

The magnetic polarity (direction of the magnetic field) of the SCMs alternates along the module. The guideway loops experience an alternating wave of magnetic flux as the rotating module moves. A downward magnetic flux is followed by an upward flux, then by downward flux, etc. Propulsion of the electrodynamic repulsive system can be described as "pull - neutral - push". The only clearances to be controlled are those between the rotating propelled SCMs modules and the EDGG's guideway.

C. Radial Centering

When the propelled SCMs modules are on the correct path and the SCMs are running over the centers of the null-flux coils, no current flows, but any moves off-line will create a changing flux that generates a field that naturally pushes/pulls the SCMs (and the propelled SCMs module) back into projected path, as it is shown in Fig. 7.

Facing null-flux coils are connected under the guideway in the rotation generator guideway, constituting a loop. When the rotating module is displaced from the designed rotation path and the equilibrium position, the SCMs on the side that gets closer to the EDGG guideway will induce an electrical current in the loop resulting in a repulsive force acting on the null-flux coils on the side near to the displaced rotating module and an attractive force acting on the null-flux coils on the side farther apart from the rotating propelled SCMs module. Thus, a running module is always located at the center of the guideway. The repulsive forces between the two magnetic fields will push the rotating module from the guideway toward the designed position. The opposite set of the SCMs on the opposite side of the rotating propelled SCMs module where the gap has increased, will have the opposite polarity then the facing null-flux coils. Resulting repulsive force produces inherently stable support and guidance because the magnetic repulsion increases as the gap between the rotating module and the rotation generator guideway decreases. At the same time will be induced attractive forces from the coils in corresponding loops. The farther the module moves from the projected rotation path, the stronger will be the induced repulsive and attractive forces bringing it back, as it is shown in Fig. 7.

All propelled SCMs modules will rotate under the same conditions. If only one of them gets out of the projected path, all propelled SCMs modules will get under the same reaction simultaneously being pushed and pulled to bring back the whole rotating modular set back into the designed coaxial trajectory to preserve controlled and contactless rotation of the rotating modular set inside the EDGG guideway.

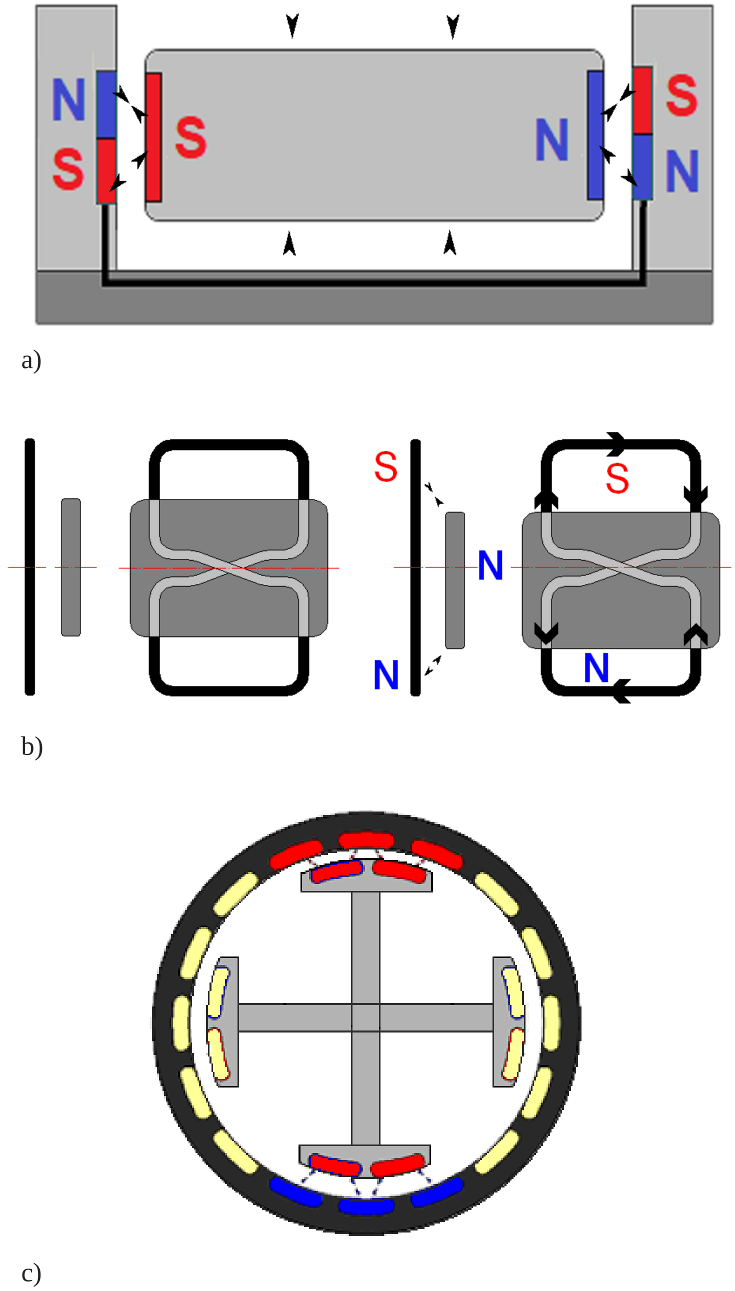


Figure 7. Radial centering.
a) Repulsive and attractive forces keep the rotating module centered.
b) Interactions between SCM and null-flux coil. SCM runs over and of-line the projected path.
c) Repulsive and attractive forces over the propelled SCMs modules keep the rotating modular set coaxial with the guideway.

The three components of magnetic forces acting between moving SCM and null-flux coils are:

$$F_x = \sum_{j=1}^{4} I_s I_j \frac{\partial M_{sj}}{\partial x} = I_s \left\{ i_1 \left(\frac{\partial M_{s1}}{\partial x} - \frac{\partial M_{s2}}{\partial x} \right) + i_2 \left(\frac{\partial M_{s2}}{\partial x} - \frac{\partial M_{s3}}{\partial x} \right) + i_3 \left(\frac{\partial M_{s3}}{\partial x} - \frac{\partial M_{s4}}{\partial x} \right) \right\} \tag{5}$$

$$F_y = \sum_{j=1}^{4} I_s I_j \frac{\partial M_{sj}}{\partial y} = I_s \left\{ i_1 \left(\frac{\partial M_{s1}}{\partial y_1} - \frac{\partial M_{s2}}{\partial y_2} \right) + i_2 \left(\frac{\partial M_{s2}}{\partial y_1} - \frac{\partial M_{s3}}{\partial y_2} \right) + i_3 \left(\frac{\partial M_{s3}}{\partial y_2} - \frac{\partial M_{s4}}{\partial y_2} \right) \right\} \tag{6}$$

$$F_z = \sum_{j=1}^{4} I_s I_j \frac{\partial M_{sj}}{\partial z} = I_s \left\{ i_1 \left(\frac{\partial M_{s1}}{\partial z} - \frac{\partial M_{s2}}{\partial z} \right) + i_2 \left(\frac{\partial M_{s2}}{\partial z} - \frac{\partial M_{s3}}{\partial z} \right) + i_3 \left(\frac{\partial M_{s3}}{\partial z} - \frac{\partial M_{s4}}{\partial z} \right) \right\} \tag{7}$$

where i_1, i_2 and i_3 are circuit mesh currents, M_{sj} (j=1,4) are mutual inductances between the SCM and the four loops of a pair of figure-eight null-flux coils connected by null-flux cable, as shown in Fig. 3. I_s is SCM current while I_j (j=1,4) are currents in the loops. The relations between the mash and loop currents are: $I_1=i_1$, $I_2=i_3-i_1$, $I_3=i_3-i_2$, $I_4=-i_3$. The coordinates for the corresponding gaps are specified by y_1 and y_2 in Eq. (6), and z_1 and z_2 in Eq. (7). Equation (6) represents magnetic force acting over one rotating SCM applied for radial centering of the rotating module. As the trajectory is circular, the *Y* component of the magnetic force acting between moving SCM and null-flux coil is the guidance force. All guidance magnetic forces induced over the rotating SCMs are directed toward and from the center of the rotation tending to be completely equilibrated. The result is radial centering of the rotating module (RMS) keeping it coaxial with the rotation generator (EDGG guideway).

As mutual inductances between the null-flux coils and rotating SCMs are time-dependent and space-dependent, these equations can be further developed based on harmonic approximation to obtain simplified analytical expressions. The voltage e_1 has the same polarity as e_2, and e_3 has the same polarity as e_4, as shown in Fig. 3. The null-flux guidance force will be generated when $e_1 + e_2 \neq e_3 + e_4$, or when $I_1 + I_2 \neq I_3 + I_4$. The current flowing in the cross-connecting cable between the two null-flux coils can be determined from Fig. 3. b) by the voltage equation:

$$Ri_2 + (L - M)\frac{di_2}{dt} = \frac{1}{2}\left[(e_1 + e_2) - (e_3 + e_4)\right] \tag{8}$$

The cross-connection part of the null-flux guidance force is:

$$F_y = \frac{1}{2} i_2 I_S \left\{ \left(\frac{\partial M_{s1}}{\partial y_1} + \frac{\partial M_{s2}}{\partial y_1} \right) - \left(\frac{\partial M_{s3}}{\partial y_2} + \frac{\partial M_{s4}}{\partial y_2} \right) \right\} \tag{9}$$

Taking in account that the null-flux system usually operates near vertical equilibrium, it can be assumed that $\delta M_{S1}/\delta y_1 = \delta M_{S2}/\delta y$, and that $\delta M_{S1}/\delta y_1 = \delta M_{S2}/\delta y_1$. Equation (9) is simplified:

$$F_y = i_2 I_S \left(\frac{\partial M_{s1}}{\partial y_1} + \frac{\partial M_{s3}}{\partial y_2} \right) \tag{10}$$

It should be noted that Eq. (9) and Eq. (10) represent only the guidance force resulting from the current flowing in the cross-connecting cable (i_2), while Equation (6) determines a total guidance force.

The sum of all guiding forces *Fy* is to be 0 for the xyz coordinate system with the 0 in the center of the rotation.

In a stable system, any variation from its stable position will push it back to the designed optimal position. Electrodynamic system is stable and it does not need active electronic stabilization. The radial gap between the propelled SCMs module and the EDGG guideway could reach 12-20 centimeters (5-8 inches).

D. Axial Centering

When running propelled SCMs module displace laterally together with the set of superconducting magnets attached on its lateral sides, in the loop is induced an electric current. This result in repulsive force acting on the null-flux coils on the side near the module and attractive force acting on the null-flux coils on the other side. Thus, a running propelled SCMs module is always located at the center of the guideway. The repulsion force increases the closer the propelled module gets to the guide way. The farther the module moves from the centerline of travel, the stronger will be the induced repulsive force acting to bring it back, as shown in Fig. 8. The coils can be molded out of non-saturated polyester sheet molding compound and electrical insulated. They must have high mechanical strength to bear magnetic forces.

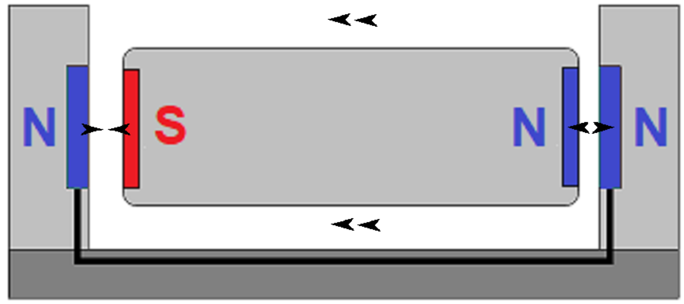


Figure 8. Axial centering. *Facing pair of null-flux coils cross-connected by null-flux cable constituting a loop. Rotating propelled SCMs module remains centered over designed path thanks to attraction and repulsion forces between null-flux coils and displaced SCMs. Electrodynamic spring.*

Current will be induced by the Lenz law to restore position of the propelled SCMs module to its midline position as the current that flows in the coil is such as to oppose or eliminate any flux change within the coil, also known as flux eliminating coil. This can be described as magnet spring constant that is equal to the slope so, the rotating module always keeps rotating over the designed path.

Electrodynamic axial centering will act as "electrodynamic spring" not only for enabling guided rotation of the propelled SCM modules, but, also to enable docking activities and all kinds of displacements and maneuvers. In other words, thanks to the features of the "electrodynamic spring" the rotating module will transmit the rotation to a hub with docking port and air lock system located in the axis of the rotation.

The sum of all null-flux centering forces that are induced in all facing sets of the SCMs and the null-flux coils is to be zero for the xyz coordinate system with the center located in the center of the rotation.

All propelled SCMs modules will rotate under the same conditions. If only one of them gets out of the projected path approaching to the guideway, all propelled SCMs modules will get under the same reaction simultaneously being pushed and pulled to bring the rotating modular set back into the designed trajectory to preserve controlled and contactless rotation of the rotating modular set inside the EDGG guideway.

E. Angular Momentum Canceling

Interactions among the EDGG guideway and the rotating propelled SCM modules will result in relative motion among them induced by the magnetic forces and traveling magnetic fields, provoking undesirable phase angles. It is necessary to avoid rotation of the EDGG in free space. This can be achieved with two coaxial EDGGs inserted in larger but hollow space frame structure with counter-rotating sets of modules propelled to spin in opposite directions to cancel angular momentums. The total angular momentum of the system must be constant in accordance with the Law of Conservation of Angular Momentum (When the net external torque acting on a system about a given axis is zero, the total angular momentum of the system about that axis remains constant).

IV. Artificial Gravity Space Habitat (AGSH)

A space habitat with artificial gravity would provide a facility for exploring the ability for humans to live and work in artificial gravity. It would enable sustainable exploration and colonization of space.

A. System Architecture and Design

Artificial Gravity Space Habitat (AGSH) consists of Space Frame Structure (SFS) and two coaxial Electrodynamic Gravity Generators (EDGG), as shown in Fig. 9.

The total angular momentum of the system must be constant in accordance with the Law of Conservation of Angular Momentum (When the net external torque acting on a system about a given axis is zero, the total angular momentum of the system about that axis remains constant). Interactions inside the EDGGs will result in relative motions caused by forces and momentums as well as undesirable phase angles induced by the magnetic forces and traveling magnetic fields, also transmitted to the Space Frame Structure. Therefore, the EDGGs are to be coaxial and to spin rotating modules in opposite directions to cancel angular momentums and make it easier to orient and move the whole structure. If counter-rotating modular sets are equal, the overall configuration is symmetrical and canceling of angular momentums is simplified. If counter-rotating modules are not equal, the configuration is asymmetrical and canceling of angular momentums will be obtained by adjusting of their rotational speeds by change of frequencies of alternating currents to harmonize rotation and counter-rotation in accordance with desired rotation rates

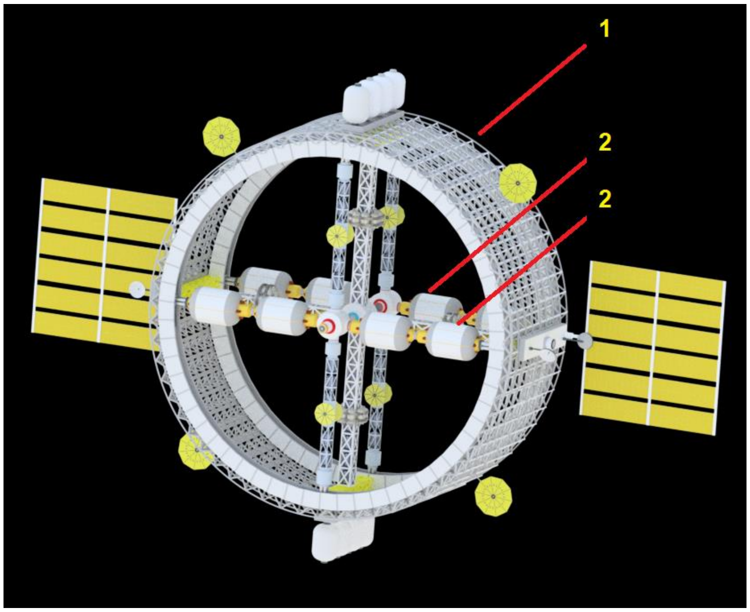


Figure 9. Artificial Gravity Space Habitat (AGSH).
1 – Space frame structure (SFS).
2 – Electrodynamic Gravity Generator (EDGG).

Space Frame Structure (SFS) is the main structural backbone composed of the central hub, two coaxial EDGG guideway structures, truss structure, and four columns, as shown in Fig. 10. It is practically a hollow structure suitable to be 3D printed and assembled in space by robots and robotic arms. The coaxial EDGG guideway structures are attached by truss structure (double-layer braced barrel vaults) forming a cylinder-shaped main structure. The central hub with airlock is a carrier of the columns, and a 0-gravity hub to serve as a pass through and storage space. The columns are made as lattice structures to be used for power buses and for transfer

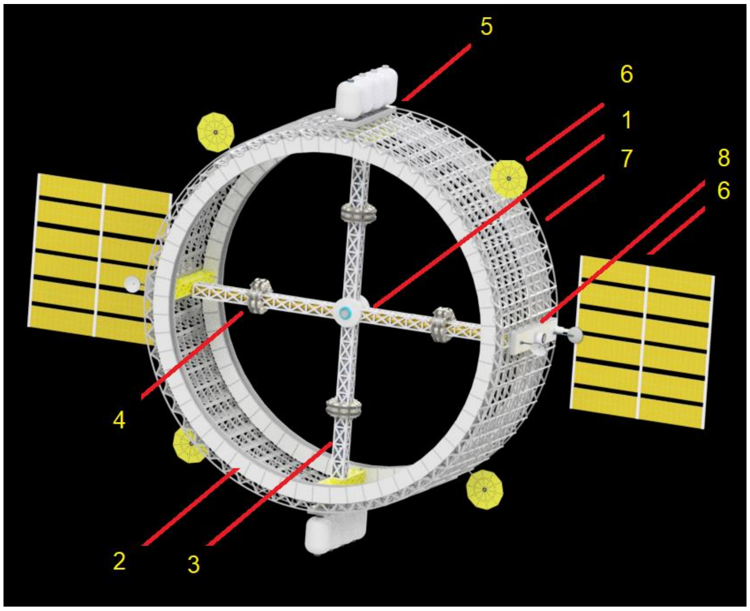


Figure 10. Space Frame Structure (SFS).

1 – Central hub.	*5 – Fuel depot.*
2 – EDGG guideway structure.	*6 – Solar array.*
3 – Column (power bus).	*7 – Truss structure.*
4 – Column (transfer tunnel).	*8 – Secondary docking port.*

tunnels between the central hub and the truss structure where are located secondary docking ports, fuel depots and solar arrays. Transfer tunnels may be inflatable or made of solid hollow structures with enough space to include a simple electrical elevator (winch). SFS is suitable to carry photovoltaic panels, batteries and communication systems.

EDGG consists of the guideway structure (including null-flux coils, null-flux cables, and electromagnetic chucks), and Rotating Modular Set (RMS), as shown in Fig. 11. EDGG is high-precision system able to provide stable rotation over its 360 degrees of movement. Spin-up and spin-off requirements for docking activities are easy to meet by simple change of AC frequencies. It is low-speed rotation, self-aligning, high precision, and noiseless system. Rotation is uniformed, completely contactless and practically loss-less while vibration, wobble, and shaking are highly reduced. Rotation is induced by traveling magnetic fields in space, being completely contactless and frictionless causing minimal impact on the environment.

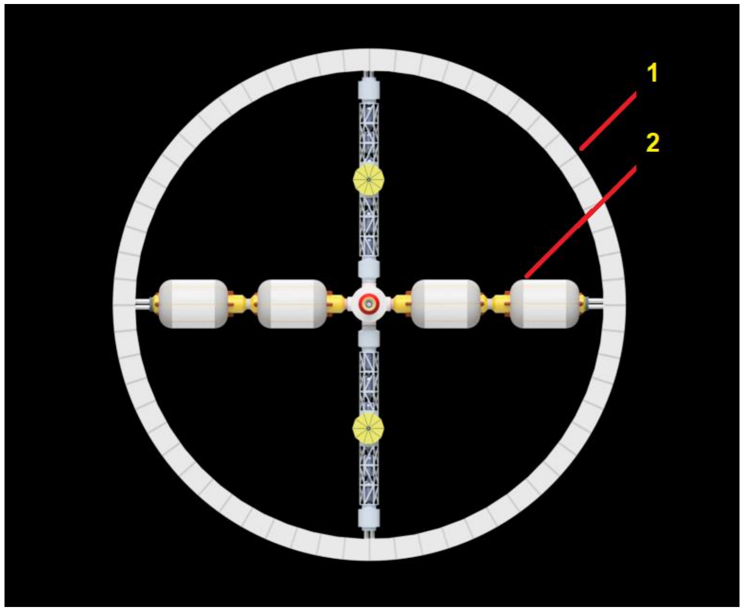


Figure 11. Electrodynamic Gravity Generator (EDGG).
1 – EDGG guideway.
2 – Rotating Modular Set (RMS).

Rotating Modular Set (RMS) consists of the hub with docking port, Artificial Gravity Modules (AGMs), two power bus modules and propelled SCMs modules., as shown in Fig. 12.

Hub with docking port and airlock is a carrier of habitat modules (AGMs) and columns with power bus modules, and a 0-gravity hub to serve as a pass through, research laboratory, and storage space.

AGMs are radially oriented with respect to the rotation. Radial orientation is dynamically stable. Although it is less comfortable than axial and tangential orientations, radial orientation of habitats is chosen for AGSH as it is more feasible using innovative high-TRL expandable habitat modules**.** Inflatable structures are preferable because of their reduced packaging volume, low weight, good strength in terms of pressure, significant ability to resist impact, and better radiation shielding. Radiation shielding against solar flare serves as radiation shielding against strong magnetic fields. Radiation shields are to be incorporated in the walls of all modules and habitats with the crew presence.

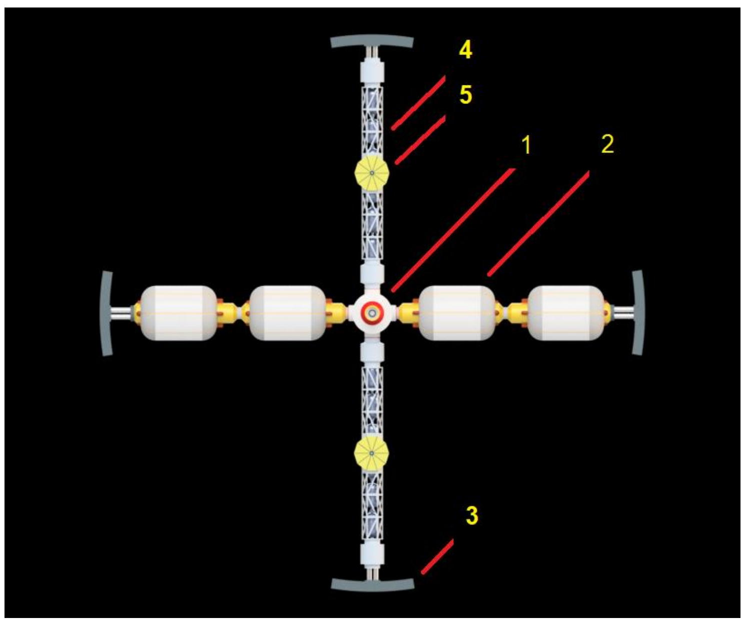


Figure 12. Rotating Modular Set (RMS).
1 – Hub with docking port.
2 – Artificial Gravity Module (AGM).
3 – Propelled SCMs module.
4 – Power bus module.
5 – Solar array.

Gravity generation is gradual, starting from zero in the hub with docking port and raising towards AGMs and propelled SCMs modules. Desired gravity levels are achieved in AGMs as they are main habitats. Gravity sensation level is adjustable by changing of rotation rate obtainable by change of AC frequency in EDGG guideways.

Spin-up and spin-off requirements for docking activities are also easy to meet by change of AC frequencies. Electrodynamic axial centering will act as “electrodynamic spring” during docking and relocation activities.

Principal modules are to be equipped with propulsion units for maneuvering activities, especially important in the assembly phase during which will be needed high-precision maneuvers. Also, they could be used to move the whole structure to other orbits, even to transform it to spaceship.

SFS and both RSMs are coaxial so their hubs are also coaxial. They are not in contact but distances are reduced. Displacements from one hub to another are EVA.

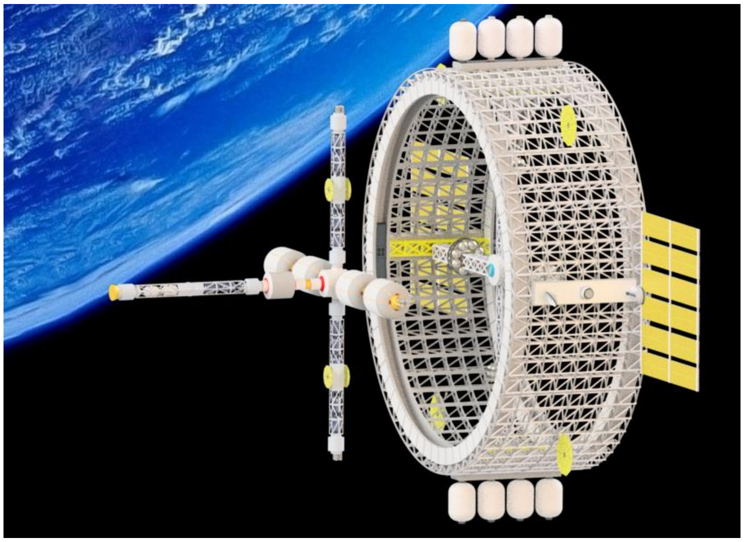


Figure 13. Assembly of RMS into already assembled SFS.

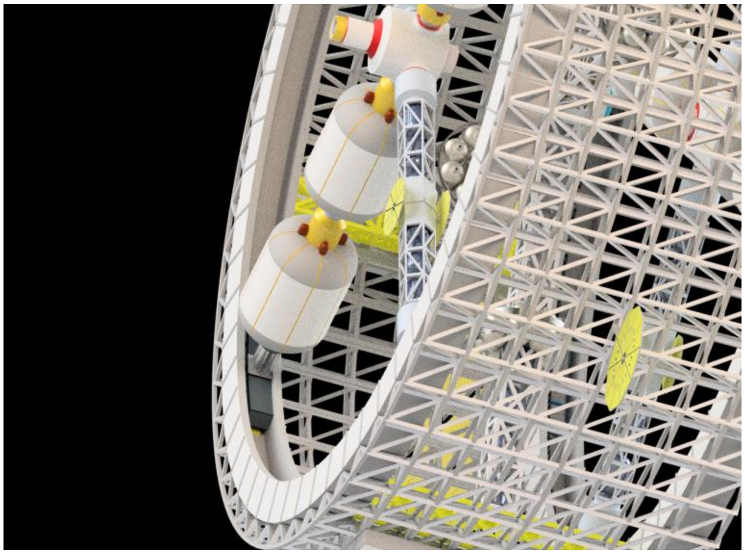


Figure 14. Assembly of RMS into EDGG and SFS.

The last phase of assembly is incorporation of both RMS into already assembled SFS. They are to be assembled in orbit independently and then pushed or dragged by other space module towards the EDGG guideway in the SFS till reaching desired position with respect to the propelled SCMs modules already assembled and fixed over electromagnetic chucks located in the EDGG guideways, as shown in Fig. 13 and in Fig. 14. Fundamental role in complex positioning process will have the central hub of the SFS as it is to be in-line with the hubs of both RMS. AGMs that are at the endpoints of the RMS are equipped with clampers. Once the positioning phase is completed, four clampers are pulled out to plug into correspondent slots in the propelled SCMs modules with radial electromagnetic chucks inside, as shown in Fig. 14. Once the assembly is completed, DC radial electromagnetic chucks in the propelled SCMs modules will fix the clampers. Assembly is over and the next phase is to generate initial rotation. AC null-flux coils will start to interact with DC SCMs in the propelled SCMs modules. Once reached desired AC frequency in EDGG guideway, power supply in the electromagnetic chucks will cut-off and liberate propelled SCMs modules. Propulsion is achieved when the magnetic fields are synchronized and locked among them. Two pairs of induced opposite direction forces create torques. Their sum generates controlled rotation of RMS that creates artificial gravity sensation inside AGMs. Final assembly is viable by use of high precision positioning sensors.

Electromagnetic chucks in the guideways also serve to fix the propelled SCMs modules for the rotation abort.

It is necessary to design an emergency system for a hypothetical situation of total power cut off, to prevent separation of the rotating module and the rotation generator. It can be managed by a set of swing or linear arms delimiters made of permanent magnets, radially suited in the entrance of the rotation generator module and moved by power packs with autonomous batteries. This system will be possible to use in a hypothetical case of a deliberate rotation abort.

Electrodynamically propelled rotating system architectures such as EDGG are stable and there is no need for active electronic stabilization. Magnetic drag is very low at low speed rotation and propulsion forces will easily overcome it. It will not produce oscillations in flexible components of the non-rotating part of the system nor there will be internal frictions provoking energy dissipations and causing increase of the wobbling amplitude. Active and passive control systems will be reduced and shock absorbers are not going to be needed. The system will not require absolute mass equilibrium (although it is desirable) and there is no need that every component must have a counter balance. The Rotating Modular Sets are to be well connected to disable unpredictable changes in distribution of weights.

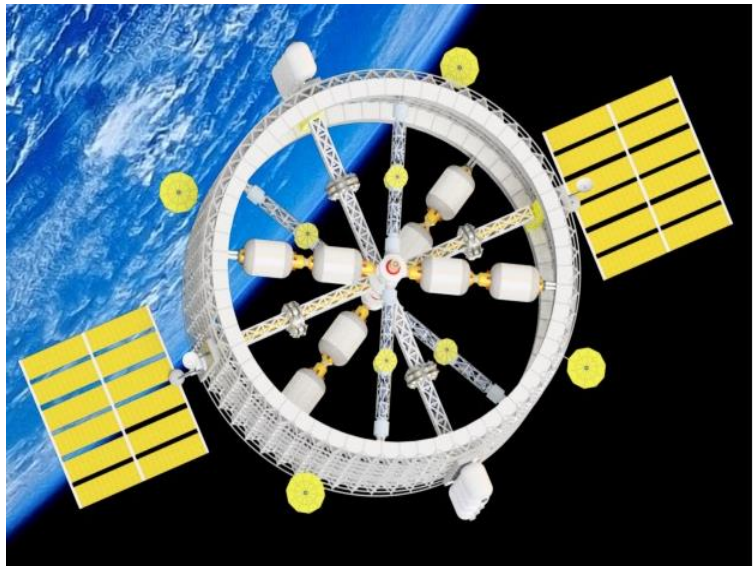


Figure 15. AGSH in LEO.

The inherent stability of an object rotating axes is determined by the ratio of the object's principle moments of inertia. EDGG and AGSH design concepts are of a major axis spinner. Their symmetries combined with their coaxial positions minimize angular momentums of the rotating modules and enable maximum maneuverability during rotation, and minimum spin-up and spin-off efforts. Conditions for stable spinning are $I_{xx}/I_{yy} > 1$ and $I_{xx}/I_{zz} > 1$, where x is spin axis.

Being complex and massive, whole AGSH is to be built on-site. The only way to do it is to make it completely modular, made of lightweight modules, highly integrated systems, and simplifying the structure without jeopardizing its safety and functionality. Modular architecture enables construction of larger space systems in LEO and brings flexibility to upgrade or reconfigure the architecture. Being a large structure, SFS is to be assembled first.

Some structures and equipment destined for AGSH are to be folded up as cargo in a traditional way. Innovative and rule-breaking zero-gravity 3D printers and 3D printing autonomous robots would liberate missions from the launch constraints and enable additive manufacturing, aggregation, and assembly of large and complex systems and structures in space without astronaut EVA. Instead of sending up complete structures, it would be enough to launch raw materials with electronics, electromagnet components, sensors, fuel cells, and batteries. Zero-gravity 3D printers will print parts from a digital design that will be assembled with other pre-fabricated parts into a larger structure by use of robotic arms. This technology is the most suitable for the backbone SFS and EDGG structures. Materials needed for structures are to be advanced, lightweight, high strength, reliable, computationally designed structural materials for extreme environments, with termal protection and radiation resistance: polymer matrix composites (PMCs), metal matrix composites (MMCs), metal matrix nano-composites (MMnCs), aluminum-lithium alloys, titanium-vanadium-aluminum alloys, nickel-base alloys, etc. Smart materials can be used for deployable structures at reduced weight. New materials with repair (self-healing) functions would highly reduce needs for EVA. Advanced radiation shielding materials are necessary to protect the astronauts.

B. Power Supply

Hybrid power supply system consists of solar panels, fuel cells, and rechargeable DC batteries. Generated electricity will be used for propulsion, acceleration, guidance, and stabilization of complete space structure, as well as for: heat system, communication and telemetry systems, air condition system, sensors, light system, and other systems.

Photovoltaic energy in solar panels is converted to DC electricity. Fuel cells' output is also DC. Generated electricity can be converted from one voltage level to another by DC/DC converters. Inverters transform DC electricity to AC electricity that can be transformed to high voltage AC electricity by means of electrical transformers. AC from inverters can operate AC equipment or be rectified to DC at any voltage.

Innovative high-TRL and high-power flexible round panel array with circular deployment, unfurling mechanism, made of cutting-edge materials, is suitable to be applied as it provides high specific power, lightweight, high stiffness and strength, and small stowed volume. Another favourable option are thin-film or flexible rollout array, and concentrating arrays.

Electrochemical cells that convert stored chemical energy into electrical energy could be used to store energy and generate power on-board and independently in all the modules of the SFS and both RMS, even in the rotating habitats. Systems that bring high-energy batteries together with a high-power cell, or potentially a combination with fuel cells, are also envisioned to be key enablers of electric propulsion. Extremely low temperatures may help electric technologies reach new heights. This configuration represents an initial starting point for future optimisation, with research based on assumptions for expected long-term developments of superconducting and energy storage capabilities as key enablers.

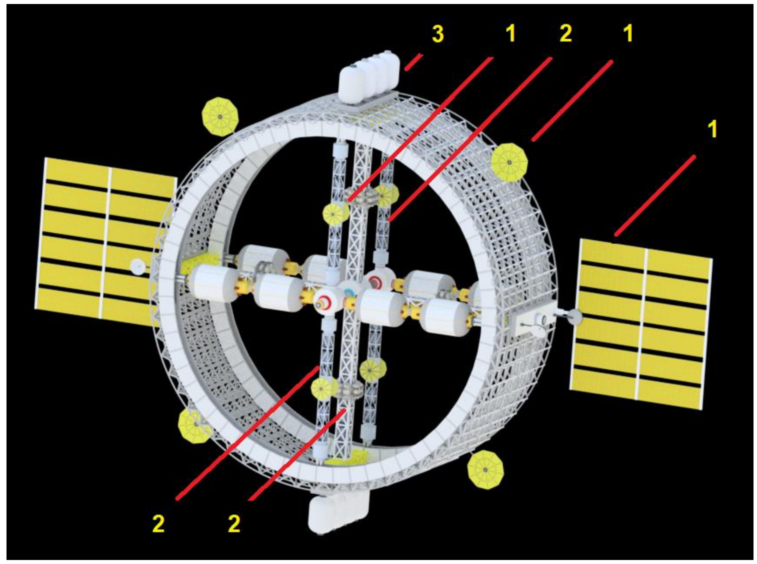


Figure 16. Power supply. *Solar panels, fuel cells, LOX storage.*
1 – Solar array.
2 – Power bus module.
3 – LOX storage.

Energy can storage in nickel-hydrogen or lithium-ion rechargeable DC batteries to provide a continuous power source. Batteries and fuel cells ensure that EDGGs are never without power. Power systems for human habitats in space will benefit significantly from batteries with large storage capability and high specific energy. Regenerative fuel systems are suitable for large-scale energy storage applications such as space habitats, requiring 10' of kW of electrical power and enhanced by high specific energy, high charge/discharge efficiency (up to 70%), high reliability, and long-life capability (approximately 10,000 hours). Regenerative fuel cell systems consist of: fuel cell, electrolyser, reactant storage, thermal management, and control.

Electric power system is to be designed for operation with oxygen and to be optimised for multi-gravity environment operations, and for thermal and water management. Liquid hydrogen and liquid oxygen (LOX) storage in space does not require cryogenic storage but only pressurized conditions. In addition, liquid hydrogen and liquid oxygen as oxidizer are commonly used as liquid rocket fuel in H2/02 rocket engines that could be used for propulsion of the whole structure.

AGSH structure offers plenty of space available for storage of electrochemical and regenerative fuel systems, and for power management and distribution system as well as for their efficient control and maintenance, even for radioisotope thermoelectric generators (RTG) in the central hub of non-rotating SFS. Storage space is approachable through docking ports and transfer tunnels for supervising and maintenance.

Magnetic fields and changes and disturbances in their presence, electrical currents, direction, angle, and rotation, are to be detected and monitored by vector magnetic sensors without physical contact.

Power consumption will be reduced and system efficiency will be increased in frigid vacuum without gravity. Artificial gravity can be generated at low speed levels compared with EDS on Earth, rotation is mostly uniform, and superconductors can conduct electricity even after the power supply has been shut off. Strong magnetic fields generated by superconductors in space vacuum conditions will permit reduction of overall size and weight of SCMs.

C. Spin Rate and Geometry Design

The total artificial gravity acceleration inside a rotating space habitat can be expressed as the vector sum of the centripetal acceleration, the relative acceleration and the Coriolis acceleration:

$$\vec{g}_a = \vec{a}_{cp} + \vec{a} + \vec{a}_{cor} = (\vec{\omega} \times \vec{r}) \times \vec{\omega} + d\vec{v}/dt + 2\vec{\omega} \times \vec{v} \tag{11}$$

where g_a is total artificial gravity acceleration, a_{cp} is centripetal acceleration, a is relative acceleration and a_{cor} is Coriolis acceleration.

Centripetal acceleration is independent of the relative motion of objects inside the rotating habitat. It is radial and directed toward the rotation axis:

$$\vec{a}_{cp} = (\vec{\omega} \times \vec{r}) \times \vec{\omega} \tag{12}$$

where ω is angular velocity and r is radial distance from the center of rotation. Relative acceleration is the first derivative of the velocity as a function of time and the second derivative of the position as a function of time:

$$\vec{a} = d\vec{v} / dt \tag{13}$$

Coriolis acceleration is proportional to the vector product of the rotating habitat angular velocity and the object's relative velocity and it is perpendicular to them:

$$\vec{a}_{cor} = 2\vec{\omega} \times \vec{v} \tag{14}$$

where ω is angular velocity and v is relative tangential velocity.

The magnitude of the nominal artificial gravity sensation in a rotating space habitat can be expressed by its centripetal acceleration where the artificial gravity force is equal to the centripetal force. Centripetal acceleration depends only of the angular velocity of the rotating habitat and its radial distance from the rotation axis, becoming larger for greater speed and smaller radius. Less radius means less system's total weight and implies less launching and material costs. Effects of the centripetal force could be accepted as artificial or simulated gravity and the whole system can be accepted as artificial gravity generator.

Artificial gravity environments can be determined in terms of four parameters: artificial gravity acceleration equal to the centripetal acceleration, radial distance from the center of rotation, rotation rate, and tangential velocity. Equations (15) and (16) are showing relations among these parameters:

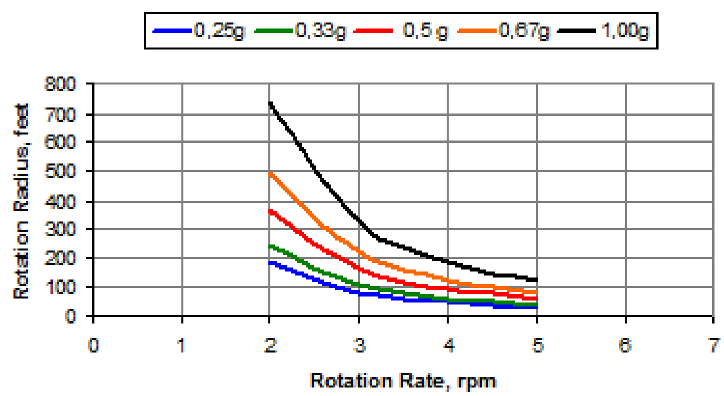


Figure 17. Rotation radius as a function of rotation rate.

$$a_{cp} = v^2 / r \tag{15}$$

$$r = g_a / (0.01097\, n^2) \tag{16}$$

where a_{cp} is centripetal acceleration, v is relative tangential velocity, r is radial distance from the center of rotation, g_a is total artificial gravity acceleration, and n is spin rate. Fig. 17 and Fig. 18 are showing tangential velocity of the rotating habitat and the rotation radius as functions of the rotation rate, for desired values of artificial gravity sensation.

Rotation can cause important problems including the Coriolis forces provoked by any movement unparallel to the rotation axis. If a head is moved into a plane different then the plane of rotation, the inner-ear fluid movement keeps in the previous plane giving a disorienting and nauseating sense of rotation in the new plane. This sensation becomes worse with higher rotation rates and shorter radius of rotation.

Angle and magnitude of the centripetal acceleration change is in accordance with changes of the inhabitant's position. Point of convergence of the total acceleration is offset from the center of rotation by the Coriolis acceleration component. To obtain healthiest gravity it is needed to reduce the Coriolis forces to acceptable levels corresponded to the spin rate between 1 and 2 rpm and to increase the habitat's tangential velocity. Taking in account the effects of the Coriolis forces and referring to Eq. (16), it results that to produce the Earth normal gravity sensation (1g) with 2 rpm rate of spin, the radius of rotation should be at least 224 meters (734 feet) with the tangential velocity of approximately 168 kilometers/hour (105 miles/hour). It is too ambitious in the short-term period, but some steps could be made in the years to come making some smaller and cost-effective artificial gravity generators. Centripetal acceleration must have some minimum value to guarantee practical advantages of the artificial gravity.

Research should determine the acceptable combination of gravity level and duration of the artificial gravity stimulus, and the effects of transition to a different gravity levels. Inferior levels of gravity sensation could be acceptable being more cost-effective to be achieved. Rotation rates over 2 rpm will reduce needed radius still provoking acceptable levels of Coriolis forces.

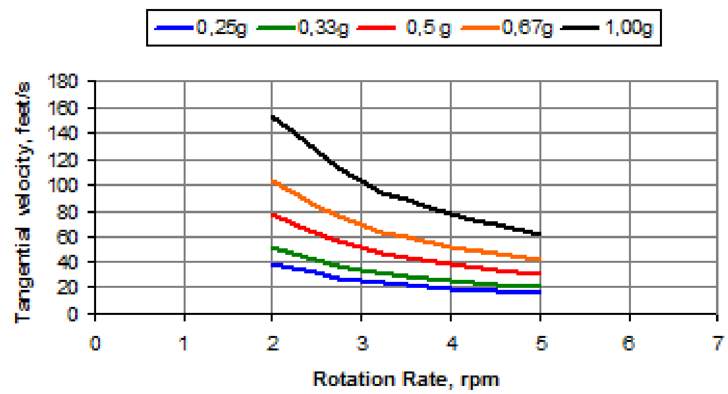


Figure 18. Tangential velocity as a function of rotation rate.

Estimates of the four main parameters of the comfort zone limits proposed by several authors are:

- Min. radius: 12 meters (39.37 feet).
- Maximum rotation rate: 3 - 6 rpm.
- Comfortable centripetal acceleration: 0.3•g – 1.05•g.
- Min. tangential velocity: 10 meters/second (32.80 feet/second).

These parameters are to be combined with the main parameters of electrodynamic and electromagnetic interactions in EDGGs, especially with tangential velocity of the propelled SCMs modules as it is the most important parameter. It is not possible to determine exact minimum tangential velocity needed to activate electromagnetic fields needed for the guidance in cold space vacuum without gravity, but, it should be at least 85% of 15 meters/second (49.21 feet/second) valid in Earth conditions that makes 12.75 meters/second (41.83 feet/second).

D. Artificial Gravity Space Habitat with Earth gravity and partial gravity. Mars Gravity Simulator (MGS)

Generated gravity in EDGGs is gradual, starting from zero in the hub with docking port and raising towards AGMs and propelled modules. Desired gravity levels are to be achieved in AGMs. Gravity levels are adjustable by changing of rotation rate by change of AC frequency in EDGG guideway.

AGSH and EDGGs are designed to generate various artificial gravity levels, including the Earth gravity level and the Mars gravity level at different spin rates. This way, AGSH will have double function. It can be used not only as space habitat with Earth and partial Earth gravity but, also, as Mars Gravity Simulator (MGS) for Mars simulation science and missions for experiments in preparation for future missions to Mars. The surface gravity on Mars is about 38% of the surface gravity on Earth being considered acceptable gravity level from medicine standpoint.

In order to achieve Earth's gravity or at least partial gravity levels in habitats, and taking in account the limits of the comfort zone for artificial gravity and main technical parameters of electromagnetic and electrodynamic circuits and interactions among the traveling electromagnetic fields, min. outer diameter of EDGG is to be of 77.5 meters (254.27 feet), AGSH outer diameter is to be 80 meters (262.47 feet), and main diameter of electrodynamic propulsion defined by the centers of the null-flux coils in EDGG's guideway is to be 75 meters (246.06 feet). Accepted rotation rate of 5.8 rpm is slightly lower than the max. rotation rate of 6 rpm, to increase comfort sensation. Minimum tangential velocity in AGMs is 10 meters/second (32.8 feet/second). Min. tangential velocity at main diameter of electrodynamic propulsion is 22.5 meters/second (73.82 feet/second), 50% higher than 15 meters/second (49.21 feet/second) valid on Earth. Under these conditions Earth and partial Earth gravity radial comfort zone will spread between 16.46 meters (54 feet) and 27,38 meters (89.83 feet) offering comfortable pseudo gravity levels between corresponding 0.62•g and 1.03•g. The width of the comfort gravity zone is 10.92 meters (35.83 feet), as shown in Fig. 18. Tangential velocity of the propelled SCM module at the main diameter of electrodynamic propulsion is 22.78 meters/second (74.74 feet/second). Larger radius of rotation and lower spin rate will amplify the comfort zone and increase the overall costs.

To achieve Mars gravity levels in habitats, and taking in account the limits of the comfort zone for artificial gravity and main technical parameters of electromagnetic and electrodynamic circuits and interactions among the traveling electromagnetic fields, accepted spin rate is to be 3.5 rpm. This value has been obtained by correspondent calculations. Min. tangential velocity in AGMs is 10 meters/second (32.8 feet/second). Minimum tangential velocity at the main diameter of electrodynamic propulsion is 85% of 15 meters/second (49.21 feet/second) valid in Earth conditions that makes 12.75 meters/second (41.83 feet/second). Under these conditions Mars-like gravity radial comfort zone will be between 27.28 meters (89.50 feet) and 29.93 meters (98.20 feet) offering comfortable pseudo gravity levels between corresponding 0.374•g and 0.41•g. The width of the Martian gravity comfort zone is 2.65 meters (8.69 feet), tiny but useful space of Martian – like gravity, as shown in Fig. 19. Tangential velocity of the propelled SCM module at the main diameter of electrodynamic propulsion is 13.74 meters/second (45.08 feet/second).

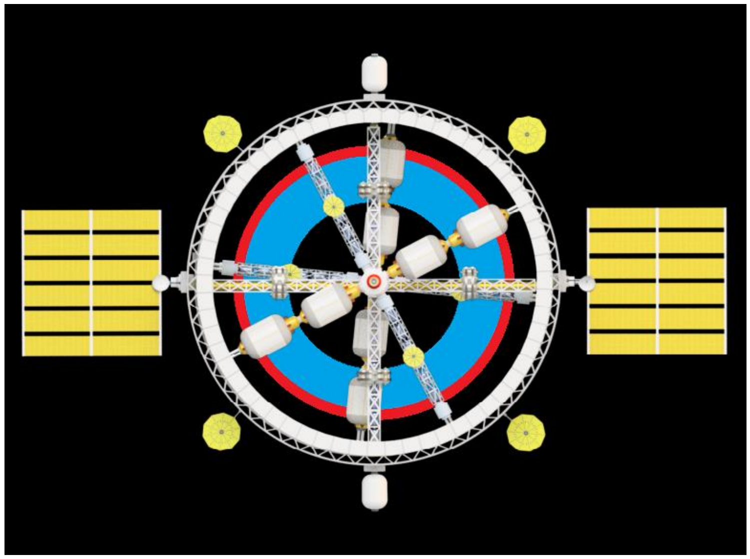


Figure 19. Comfort gravity zones in AGSH.
EDGG outer diameter: 77.5 meters (254.27 feet).
Main diameter of electrodynamic propulsion: 75 meters (246.1 feet).
Earth – like gravity comfort zone at 5,8 rpm (blue colored zone).
Mars – like gravity comfort zone at 3,5 rpm (red colored zone).

The space in radially oriented AGMs inside the comfort gravity zones can serve as main human habitats while the space in those AGMs that are out of the comfort zones can be used as storage space or for greenhouse for space agriculture applying hydroponics for stable and high yields. Rotation will enable continuous-flow hydroponics culture where nutrient solution constantly flows passing the roots of the plants. The hubs can serve as manufacture zones of the AGSH to take advantage of the zero gravity and micro gravity conditions inside them, as a research laboratory, and even as an entertainment zone.

AGSH with 3,300 cubic meters (116,538 cubic feet) of pressurized volume of which 40%, or 1320 cubic meters (46,615 cubic feet), is inside the Earth – like and partial gravity comfort zone will reach overall mass of about 240,000 kilograms (529,109 pounds), will require, with a 20% of margin, power generation of about 220kW. MGS structure is completely modular to enable it to be built in LEO. SFS width is 28 meters (91.86 feet) while the distance between the docking modules of the counter-rotating rotation modules is 33 meters (108.27 feet). There is living space for 24 persons splitted in four identical inflatable habitation modules inside the comfort zone. Inflatable modules' outer diameter is 6.1 meters (20 feet). The wall thickness is 0.46 meters (18 inches). Null-flux coils and SCMs, as well as the power supply, are described in the Chapter III. There are 240 null-flux coils in each of the guideway's walls and 4 units of SCMs per each side of the each propelled SCMs module. They generate 13.5 KN propulsion force per each propelled SCMs module. Radial clearance between the RMS and the EDGG's guideway is 0.30 meters (12 inches). Gap between SCMs and null-flux coils is 0.15 – 0.20 meters (6-8 inches). Interactions among electromagnetic forces and fields will be highly efficient in outer space. These results represent the minimum size of the AGSH configuration that offers Earth and Martian gravity levels.

It is necessary to generate artificial gravity sensation to resolve or reduce numerous human health problems in weightless conditions in Earth orbit and deep space. Artificial gravity in space habitat will provide opportunities for life sciences and advanced technology research. For long-term stays in space it will be needed to achieve at least partial gravity conditions. Habitats with Earth-like gravity levels will enable not only exploration but also colonization of deep space. The AGSH concept is cost-effective as it can be used for generating of Earth-like and partial gravity levels including Mars gravity levels to is as Mars Gravity Simulator (MGS). MGS as artificial gravity research facility with the science instruments aboard that will enable scientists and engineers to study long-term exposure to Mars gravity, development and functioning of equipment to be used on Mars surface including life support equipment, Mars suit and Mars robots, structure building including 3D and 4D printers technologies, and plants grow ability. MGS as orbital laboratory can be used for research of optimal artificial gravity level for manned interplanetary travel. It is vital to deploy, test, and utilize it in LEO, shortening development time and reducing the costs. MGS as artificial gravity space station suited in LEO is a feasible project that can return valuable information about the ability of humans to travel and live in space contributing to develop manned missions to Mars.

E. EDGG Superstructures

EDGG structures could be completely independent or fully incorporated into a space station or a spaceship. Orbital and deep space hotels, laboratories, factories, solar power stations, and depots with incorporated EDGGs could be built in LEO, and moved to different orbits, or to be transformed into spaceships for human exploration missions.

Previously described AGSH structure can be upgraded by amplifying it with the identical EDGG with parallel axis of rotation and amplified by multiplying of the pairs of basic EDGG structures along parallel axes of rotation, to obtain synchronized rotation of larger and more complex counter-rotating cylinder-shaped habitat structures with highly increased over-all capacities for human settlements in Earth orbit and in deep space.

EDGG superstructures could be movable by propulsion packs attached to the non-rotating space frame structures transforming a space station for long-term human stay in deep space into a spaceship for long-term space trips with humans on board. Propulsion packs will move complete structures without interruptions of centrifuges, continuously generating artificial gravity in modules with artificial gravity. Electrodynamic radial and axial centering, and electrodynamic spring will be continuously active.

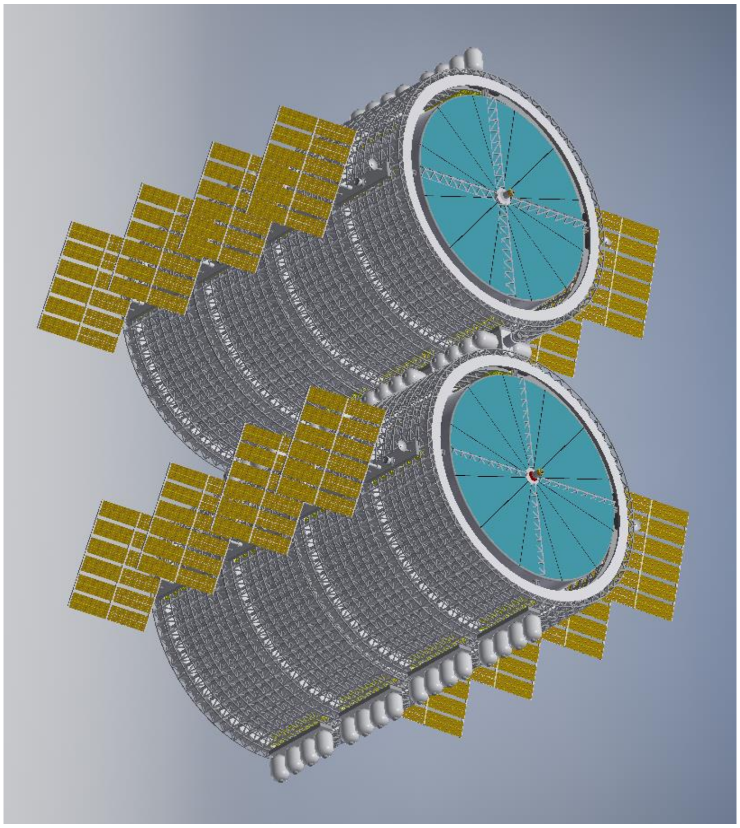


Figure 20. Space settlement concept.
Two counter-rotating cylinders with artificial gravity.

V. Conclusion

Use of electrodynamic technologies in deep space favorable conditions of cold vacuum without gravity would enable development of critical life-support artificial gravity technologies. Spinning space habitats will realize the old idea of a rotating space station generating gravity sensation on its inside hull induced by deliberate acceleration for replacing natural gravity. Artificial gravity will enable human exploration missions in deep space. Much work remains to be done and many questions are to be answered before artificial gravity becomes reality. The emergence of space tourism could impulse realization of an orbital space settlement. Well equipped with scientific and life support equipment, artificial gravity generators could be flexible exploration systems capable to proportionate a lot of knowledge important for all future steps in space, offering conditions for a big variety of possible experiments over behavior of objects, liquids, humans, animals, and plants. Artificial gravity could enable food production in space. Human habitats with a variable gravity would determine the effects of living in lunar or Martian conditions. Orbital facilities such as laboratories, factories, hotels, and depots will impulse scientific research, manufacturing, space tourism, space solar power infrastructure, refueling and repair operations, and the like. Space station with gravity generator could be built in situ, and moved to a variety of orbits, even to be transformed into space craft for human exploration missions to the moon, Lagrange points, NEOs, and Mars and its moons. The final goal is to establish human settlements in deep space and an off-Earth back-up of human civilization. Electrodynamic artificial gravity generators as life support systems will make possible exploration and colonization of space.

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