Electrodynamic Gravity Generator

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Weightless environment in space is causing numerous deleterious effects on human health, complicating all human activities and material handling. For long-term stays in space it will be needed to achieve at least partial gravity conditions. It is necessary to generate artificial gravity and to design a kind of artificial gravity generators as a life support and habitation systems. Rotation is in the focus of all artificial-gravity research because centripetal acceleration generated by rotation can be substitute for gravity. A very effective way to spin an object in space is to use electrodynamic technologies based on Eddy-currents. Deep space is cold vacuum without gravity forces so it offers significant advantages. The aim is to obtain controlled rotation of habitat for generating gravity sensation by means of guidance and velocity control by a unified trajectory control system made of propulsion and steering subsystems. Employing superconducting electrodynamic technologies in space could result in development of a new critical technologies to enable human exploration missions and design of human habitats, achieving the old idea of a rotating wheel-shaped space station generating gravity sensation on its inside hull.

Nomenclature

a	=	relative acceleration
a_{cor}	=	Coriolis acceleration
a_{cp}	=	centripetal acceleration
EDGG	=	electrodynamic gravity generator
EDS	=	electrodynamic suspension
EMS	=	electromagnetic suspension
EVA	=	extra-vehicular activities
E_A	=	induced voltage in rotation generator
F_P	=	propulsion force
g	=	acceleration due to gravity
g_a	=	total artificial gravity acceleration
Fr	=	radial component of the magnetic force acting between moving SCM and null-flux coil
Fx	=	X component of the magnetic force acting between moving SCM and null-flux coil
Fy	=	Y component of the magnetic force acting between moving SCM and null-flux coil
Fz	=	Z component of the magnetic force acting between moving SCM and null-flux coil
F_P	=	propulsion force
I	=	loop current
I_A	=	armature current in rotation generator
i	=	circuit mesh current
Maglev	=	magnetic levitation
M_s	=	mutual inductance between SCM and loops of figure-eight null-flux coils pair
n	=	spin rate
P_A	=	active power
r	=	radial distance from the center of rotation
SCM	=	super conducting magnet
v	=	relative tangential velocity
ω	=	angular velocity
ψ	=	phase angle between the armature current and induced voltage

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I. Introduction

WEIGHTLESSNESS occurs when all forces applied to a person or object are uniformly distributed as in a uniform gravitational field, or when they are not acted by any force. In orbit and deep space, weightlessness occurs when an object or person is falling freely. Exposure to weightlessness conditions cause numerous deleterious effects on human health and significant health concerns: vertigo, nausea, headache, lethargy, skeletal and muscle reconditioning and atrophy, loss of bone mineral density, cardiac problems, lose of heart mass, cardiovascular changes, red blood cell loss, fluid redistribution and loss, weight loss, facial distortion, and changes of the immune system. There are physiologic problems of adaptation to microgravity conditions and of renewed adaptation to Earth-normal gravity conditions. 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. The most distinguished concept is the one of rotating torus or wheel-shaped habitat to produce artificial gravity by the centripetal force which always points toward the center of rotation causing objects to behave as if they had weight while inhabitants and objects keep moving in uniform circular motion. Effects of the centripetal force could be accepted as artificial or simulated gravity and the whole system can be seen as artificial gravity generator.

The idea of using rotation to create artificial gravity in space was introduced by Konstanin 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 a 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.

The term "Maglev" refers to magnetic suspension in use for Maglev trains, wind generators, and bearings. In trains it is used to enable suspension only with support of electromagnetic fields counteracting the gravitational force. Linear induction motors are used for propulsion. The most distinguished Maglev train technologies are servo-stabilized EMS developed in Germany and EDS systems developed in USA and Japan.

II. Superconducting Electrodynamic Technology Applied in Space

EMS is based on attraction forces using conventional electromagnets while EDS is based on repulsive forces and use powerful SCMs. Although EMS energy consumption is lower, obtained gaps in EDS are much larger enabling their use in cirular paths. EMS is unstable needing active electronic stabilization while stable EDS does not need it. 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 offering possibilities for a very effective way to spin an object in space by contolled rotation.

A. Low Temperature and Superconducting Electromagnets

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 stop moving. Although there are slight shifts of this value, it is the generally accepted temperature in space. Such a low temperature makes very interesting use of superconductor materials. Superconductivity occurs in certain materials at very low temperatures followed by zero electrical resistance and the Meissner effect, which excludes the interior magnetic field. Superconductors’ electrical resistance decreases gradually when temperature decreases and drops strongly when the material is cooled below its critical temperature. Electrodynamic systems use expensive cryogenic systems to cool SCMs, but, in the frigid space environment it will not be needed at all. The SCMs provide strong electromagnetic fields which result in stronger repulsive forces and larger and safer operating gaps between the rotating module and the rotation generator to obtain completely contactless rotation. They 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 weightlessness deep space so, the only target to achieve is to obtain controlled rotation. Electrodynamically propulsed system suited in space will need one and unified trajectory control system to achieve fully controlled rotation for deliberate acceleration for replacing natural gravity. The only clearances to be controlled are between propulsed 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 rotation and ending with designed values in rotating habitats.

C. Vacuum Conditions

Outer space is hard vacuum being the closest natural approximation of a perfect vacuum environment. No medium is required for propagation of electromagnetic waves as they are able to propagate in vacuum travelling at the speed of light which increase the efficiency of electromagnetic and electrodynamic technologies in space. Outer space has a very low density and pressure being effectively without friction. There is no need to have in account the atmosphere drag force nor correspondent resistance, nor frictions, which are so significant in the Earth conditions. Lift-to-drag ratio does not have sense except in the case of magnetic drag. Frontal cross section does not matter. Electrodynamically propulsed completely contactless rotation without atmospheric nor any other friction would be completely loss-less and frictionless with highly improved overall power efficiency. Another advantage of vacuum conditions in space is that there is no corrosion problem.

D. Abundant Solar Energy

Space offers the most favorable conditions for use of abundant and completely accessible solar energy. Energy supply needed for an electrodynamically propulsed system could be obtained directly from the Sun using photovoltaic solar panels without obstacles in a safe, reliable, renewable and highly efficient way.

III. Electrodynamic Rotation Generator

Just as it is applied to EDS systems on the Earth, the 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 could be modified and fully applied in space. The cross-connected null-flux superconducting EDS technology applied in the Maglev trains technology in Japan is especially suitable to be modified and applied in space. 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. SCMs suited on the propelled module will spin in a field created by a ring of magnets suited on the guideway. The only clearances to be controlled are those between electrodynamically propelled rotating cylinder-shaped module and the internal cylinder-shaped sidewalls of the non-rotating guideway. Propulsion of the electrodynamic repulsive system can be described as "pull - neutral - push". The propelled module is able to remain centered thanks to a combination of attraction and repulsion forces. Rotation is totally stable without any electronics control thanks to stabilizing Eddy currents induced by permanent magnets. This effect is normally referred to as the electrodynamic repulsion principle. Null-flux and double-layered propulsion coils are suitable to be applied as they allow instantaneous adaptation to changes in the circular trajectory. Generation of controlled magnetic forces and rotating magnetic field between magnetic body (the rotating module) and magnetized body (the rotation generator) will obtain stable and contactless rotation.

E. Unified Propulsion & Guidance System

The aim of use of electrodynamic technologies is to obtain fully controlled rotation of habitat for generating gravity sensation by means of guidance and velocity control by a unified rotation and trajectory control system for uninterrupted and total control of propulsion, trajectory, and contactless rotation itself. The unified rotation and trajectory control system is electro-magnetic guideway consisting of propulsion and guidance subsystems.

The rotating module has to be in the same axis with the rotation generator being guideway at the same time. This way they can be concentric and with uniform radial

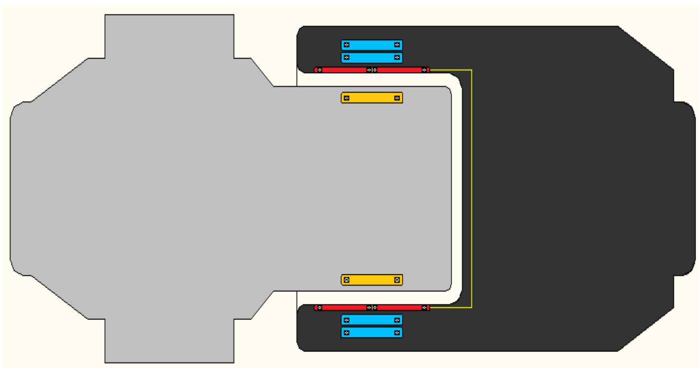

Figure 1. Electrodynamic radial thrust rotation generator. *Arrengment of the coils in the unified propulsion & guidance system.*

gap. The path is completely circular and unique and it can not be changed nor modified. Radial and axial centering can be achieved by the magnetic field generated by the radial set of null-flux figure-eight-shaped coils (red colored in Fig. 1 and Fig. 3) attached on the inside hull of the rotation generator and the radial set of SCMs (yellow colored in Fig. 1 and Fig. 3) attached on the external surface of the rotating module. Sets of the SCMs jointed in outer aluminum made vessels with incorporated electromagnetic shields, that are radially inserted in the electro-magnetically propelled rotating module, will produce permanent magnetic field. The sets are not to be continually inserted but in facing pairs as it is shown in Fig. (3), (4) and (5). The other magnetic field is induced from the changes of the field that occur as the SCMs moves relative to the radial set of conductors located in the guideway. The relative motion between the rotating module and the rotation generator creates a repulsive magnetic fields to hold the two objects apart. As the rotating module rotates, 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.

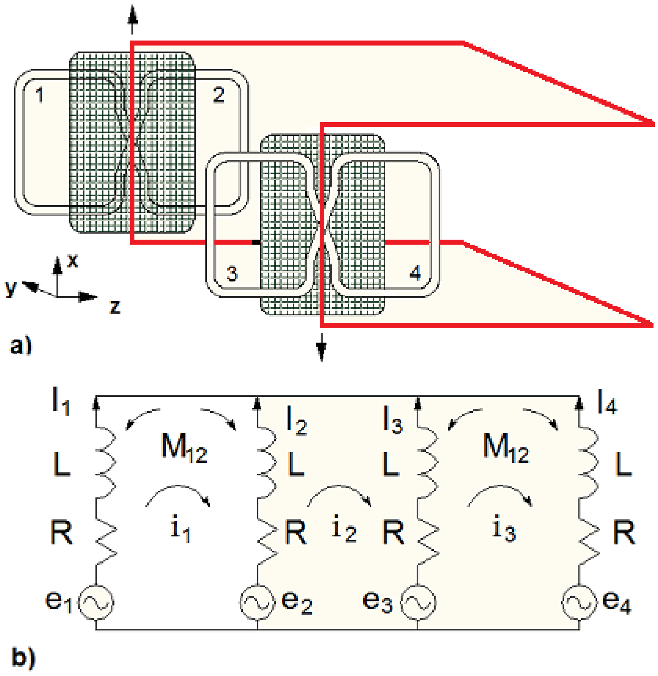

Figure 2. Cross-connected null-flux coils arrengment.
a)Facing pair of figure-eight-shaped coils cross-connected by null-flux cable constituting a loop.
b)Equivalent circuit for the cross-connected null-flux coils.

So-called figure-eight-shaped null-flux coils similar to those applied in the Japanese EDS Maglev trains could be applied in space to act as trajectory and guidance control coils. They are to be installed on the inner surface of the circular rotation generator guideway and covered with aluminum curved-shaped panels. The guidance null-flux coils are placed over the propulsion coils which are arranged in one or even two overlapping layers to reduce the external electromagnetic disturbances influencing the SCMs mounted sequentially around the outer surface of the rotating module. Each pair of facing eight-shaped coils can be cross-connected by null-flux cable under the guideway constituting a loop as it is shown in Fig. 2. This concept includes high guidance-to-drag ratios and very low magnetic drag at low speed. The null flux makes the power losses in the guideway 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 aluminum conductors molded out of unsaturated polyester resin reinforced with glass fiber and electrical insulated.

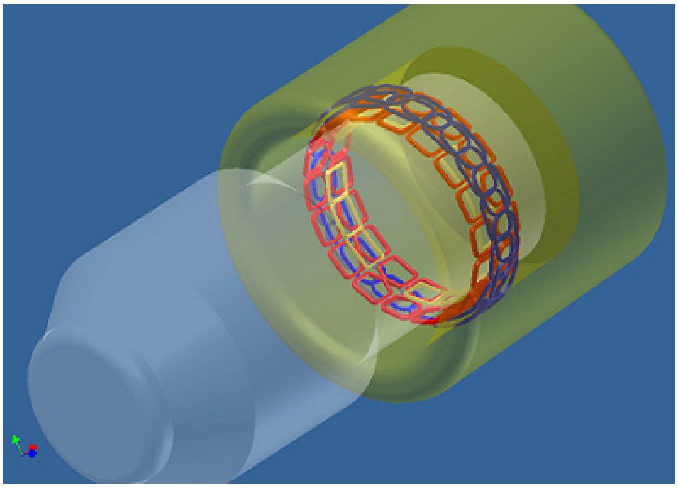

Figure 3. Arrangement of the coils and SCMs in the unified rotation & trajectory control system.

The rotating module is guided and driven by superconducting coils (blue colored in Fig. 1 and Fig. 3) mounted sequentially around the inner surface of the rotating generator characterized by a strong magnetic field which enable larger gap between the rotating module and the rotation generator. 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 the circular movement. The dynamic circuit theory could be extended for nonflat and curved SCMs and coils. Although the null-flux coils and SCMs are usually flat, taking in account the circular path, use of slightly curved gradient coils would allow instantaneous adaptation to changes in the circular trajectory to benefit the electromagnetic fields interactions and the rotation itself. SCMs are not complicated to construct nor operate. They 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 a habitat must be limited with a barrier 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 a stable system, any variation from a stable position will push it back to the designed optimal position without any active electronic stabilization

F. Propulsion

The SCMs suited on the propelled module will spin in a field created by the ring of the propulsion magnets suited on the rotation generator guideway, made of superconducting coils and energized by a three phase alternating current creating a shifting magnetic field. Alternating current is generating a traveling magnetic field which moves the rotating module without any contact. 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 the two magnetic fields are synchronized and locked among themselves. As a result, the speed of the rotation is proportional to the input frequency of the alternating current. A force that pulls the rotation forward is produced by the excitation current in the SCMs and the magnetic field induced by the propulsion magnets. The propulsion force can be controlled by changing the magnitude and the phase angle of armature. The propulsion force F_P and active power P_A are:

$$F_P = \frac{P_A}{v} \tag{1}$$

$$P_A = 3E_A I_A \cos\psi \tag{2}$$

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 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 downwards magnetic flux is followed by an upwards flux, then by downwards 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 module and the rotation generator.

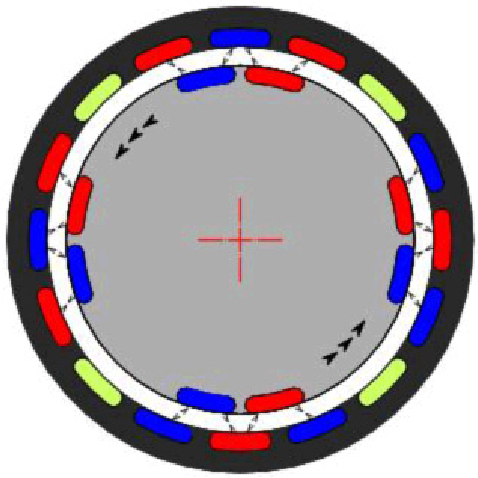

Figure 4. Propulsion. *Rotating SCMs are attracted and pushed by the shifting field, propelling the rotating module.*

The propulsion coils are wound aluminum conductors molded out of epoxy resin being electrically insulated and mechanically strong as they have to persist the reaction force of propulsion and high voltage simultaneously. Undesirable vibrations of the SCMs caused by the magnetic field's change from propulsion coils and the magnetic drag, can be reduced by implantation of high voltage double-layered propulsion coils. The front and the back coils are different because their distances from the SCMs are different and it is necessary to adjust their numbers of windings. SCMs have been very improved recently making possible adoption of single layered propulsion coil structure with shorter coil length, simpler structure and easier installation being more cost-effective. Elevated number of terminals along the rotation generator guideway and one-touch connectors can simplified the cable connecting. Although the propulsion coils are usually flat, as the path is circular, use of slightly curved gradient coils would allow instantaneous adaptation to changes in the circular trajectory to benefit the electromagnetic fields interactions and the rotation itself.

The rotating module has no contact with the rotation generator and the rotation is completely contactless. The power for its SCMs can be obtained from solar panels attached to the rotating module or to another structures mounted on it. Also, it can be wireless powered by power transmission through magnetic resonance between transmitter located in the rotation generator and receiver located in the rotating module. Generated current can be converted into a direct current for superconductors by AC/DC converter.

G. Radial Centering

When the rotating module is displaced from the designed rotation axis and position, the SCMs on the side that gets closer to the rotation generator guideway will have the same polarity as those on the top of the guideway. The repulsive forces between the two magnetic fields will push the rotating module from the guideway toward the designed position. At the same time, the opposite set of the SCMs on the opposite side of the rotating module where the gap has increased, will have the opposite polarity then the facing ones on the top of the guideway. The attractive forces between the two fields will pull the rotating module toward the designed position.

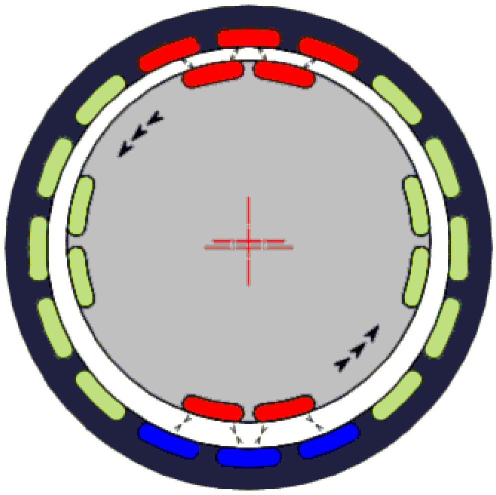

Figure 5. Radial centering. *The repulsive and atractive forces between two magnetic fields keep the rotating module centered.*

As the rotating module moves over the coils, its SCMs create a repulsive force forcing the module to float above the guideway. In other words, electrodynamics employs magnets on the rotating module to induce currents in the guideway. 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 axis, the stronger will be the induced repulsive and attractive forces bringing it back, as it is shown in Fig. 5.

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

$$F_x = \sum_{j=1}^{4} I_s I_j \frac{\partial M_{sj}}{\partial x} = I_s \left\{ i_1 \left(\frac{\partial M_{s1}}{\partial x} - \frac{\partial M_{s2}}{\partial x} \right) + i_2 \left(\frac{\partial M_{s2}}{\partial x} - \frac{\partial M_{s3}}{\partial x} \right) + i_3 \left(\frac{\partial M_{s3}}{\partial x} - \frac{\partial M_{s4}}{\partial x} \right) \right\} \quad (3)$$

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

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

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. 2. I_s is SCM current while I_j (j=1,4) are currents in the loops. Equation (4) represents total 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 same as the radial component of the magnetic force acting between moving SCM and null-flux coil. All induced total magnetic forces over the rotating SCMs are directed toward the center of the rotation tending to be completely equilibrated. The final result is the radial centering of the rotating module keeping it in the same axis with the rotation generator. As mutual inductances between the null-flux coils and rotating SCMs are time-dependent and space-dependent, these equations can be further developed on the basis of harmonic approximation to obtain simplified analytical expressions.

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 rotating module and the rotation generator could easily reach 9-12 inches, much bigger then the maximum gaps on the Earth that are 6-7 inches big.

H. Axial Centering

Electro-magnetically propelled rotating module is able to remain centered over designed trajectory on the electro-magnetic guideway thanks to a combination of attraction and repulsion forces. Guidance or steering is possible thanks to the sideward forces that guide the rotating module to follow the guideway. When the rotating module is in the straight position no current flows, but, if it leaves the straight position it creates a changing flux that generates a field that pushes it back into the line as it is shown in Fig. 6.

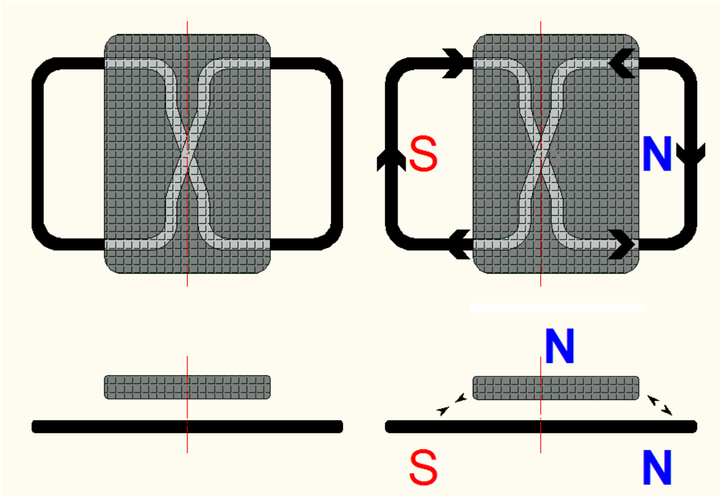

Figure 6. Axial centering. *Rotating module remains centered over designed path thanks to attraction and repulsion forces between the eight-shaped null-flux coils and displaced SCM.*

When running SCM slightly displace laterally from the center of the eight-shaped null-flux coil, within the coil is induced electric current temporarily acting as electromagnet. Electric current induced in the loop results in repulsive forces acting on the coils on the nearer side and attractive forces acting on the coils on the side farther apart. The repulsive forces are pushing the SCM toward the straight position and the rotating module toward the desired path while attractive forces are pulling it toward at the same time. Current is induced by Lenz law to restore position of the moving SCM to nearly its midline position, because the current that flows in that 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 determined by the centers of the null-flux coils.

I. Design Varieties

It is possible to develop three different designs of the electrodynamic rotation generator:

- Radial thrust rotation generator has been previously described and shown in Fig. 1 and Fig. 3.
- Axial thrust rotation generator is including the cross-connected figure-eight-shaped null-flux coils and the propulsion coils suited on the both circular walls of the rotation generator and SCMs suited on the both faces of the cylindrical-shaped rotating module as it is shown in Fig. 7.
- Combined axial/radial thrust rotation generator that combines the first two concepts.

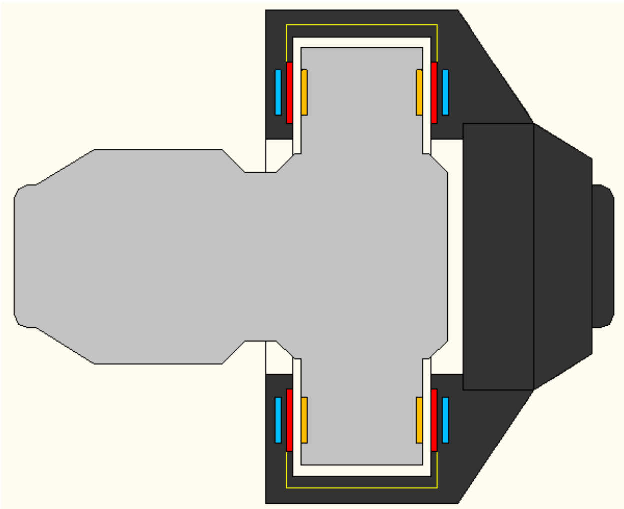

Figure 7. Electrodynamic axial thrust rotation generator. *Arrengment of the coils in the unified propulsion & guidance system.*

In all these cases, all basic principles are equal and unchanged except there are three different arrangements of the SCMs, null-flux coils and propulsion coils.

IV. Electrodynamic Gravity Generator (EDGG)

The EDGG system consist of the rotation generator, rotating module, docking module, rotating habitats, columns, energy supply system, and command & control system, as shown in Fig. 8. The main part of the EDGG is the electrodynamic rotation generator made of the unified propulsion & guidance subsystem that consists of the rotation generator and the rotating module. The non-rotating rotation generator and the rotating module generate travelling electromagnetic fields which spin the rotating module that transmits generated rotation to a rotating habitats on which inside hulls is to be generated general gravity sensation.

J. Design Considerations

Gravity generation in a wheel-shaped artificial gravity generator is gradual, starting from zero and ending with designed gravity levels which can be easily adjustable by changing of rotation speed by simple change of frequency of the alternating current. The centripetal acceleration depends only on the angular velocity of the rotating object and the radial distance between the rotation axis and the rotating habitat.

The EDGG is low speed and very light version of EDS system. Rotating movement of the EDGG induced by traveling magnetic fields in space will be completely contactless and frictionless without axles, wheels, and transmissions. Magnetic drag is very low at low speed rotation. 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 mass equilibrium and there is no need that every component must have a counter balance. There are not going to occur unpreviewed changes of weight distribution. Completely contactless rotation will make whole the system simpler, easier for maintenance and control, and more cost-effective. The EDGG will be high-precision system able to provide stable rotation over its 360 degrees of movement.

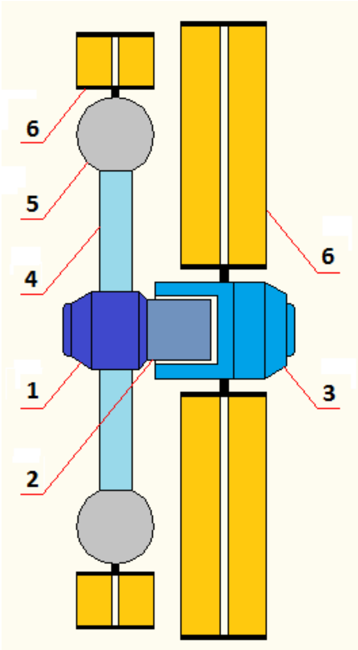

Figure 8. Basic structure of radial thrust EDGG.
1 – Docking module. 4 – Column.
2 – Rotating module. 5 – Rotating habitat.
3 – Rotation generator (section). 6 – Solar panels.

Rotation itself will complicate EVA and docking with another spacecraft requiring de-spinning and provoking lost of generated gravitation. The only way to avoid this is to have a docking module attached to the propulsed rotating module or integrated with it, being in the same axis of the rotation. The docking module would serve as a carrier of the columns with habitat modules on their ends. For communication among habitats and the docking module could be also used electrical elevator as a mini-shuttle, taking advantage of inner space of the columns made as lattice structures or some hollow compact structure. Longer columns provide bigger rotation radius and improved gravity sensation at the same rotation rate, removing the habitats away from the superconductor radiation and the electromagnetic field of the rotation generator itself. Longer columns imply higher material and launching costs.

Being complex, massive, and expensive, whole the system must be built on-situ. 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. Lightweight materials like: aluminum, fiber reinforced plastics, titanium, and titanium alloyed with aluminum, vanadium, and other elements, are very appropriate and suitable to be applied.

The rotating habitats could be made as independent single modules fixed on the end of the columns or communicated or jointed to form the wheel-shaped habitat structure. They can be aluminium-can type as well as inflatable space habitats. The modular concept brings flexibility enabling construction of larger space systems capable to be amplified and reconfigured.

The rotating habitats should be on a safe distance from the electrodynamic rotation generator and protected by electromagnetic shields because magnetic fields generated by the SCMs are very strong causing serious effects on humans and problems to use magnetic data storage. Superconducting materials can expel magnetic fields by the Meissner effect.

Both, the central rotating module and the rotation generator are to be equipped with propulsion units for maneuvering activities, especially important in the assembly phase during which will be needed high-precision maneuvers.

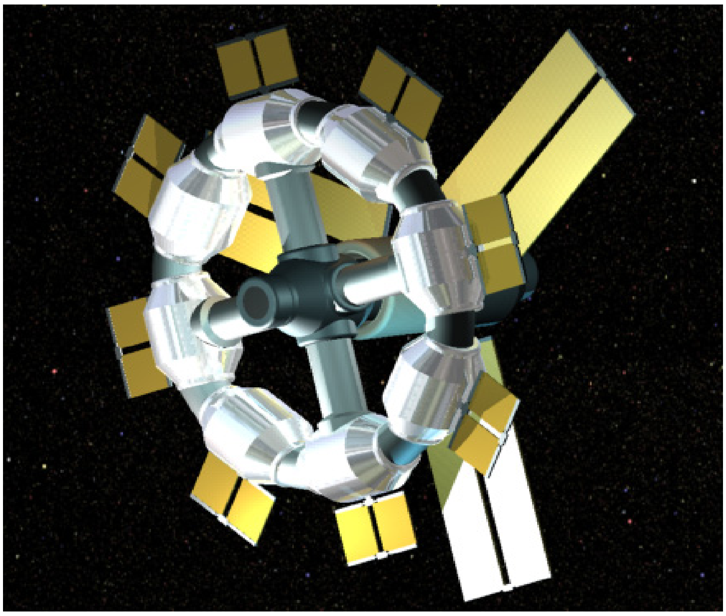

Figure 9. Basic concept of EDGG. *Wheel-shaped configuration.*

It is necessary to design an emergency system for a hypothetical situation of total power cut off, in order 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.

The EDGG structure will be suitable to carry photovoltaic panels, batteries and communication systems. As there is no contact between the rotation generator and rotating module, both of them need to be supplied with independent photovoltaic panels and rechargeable batteries.

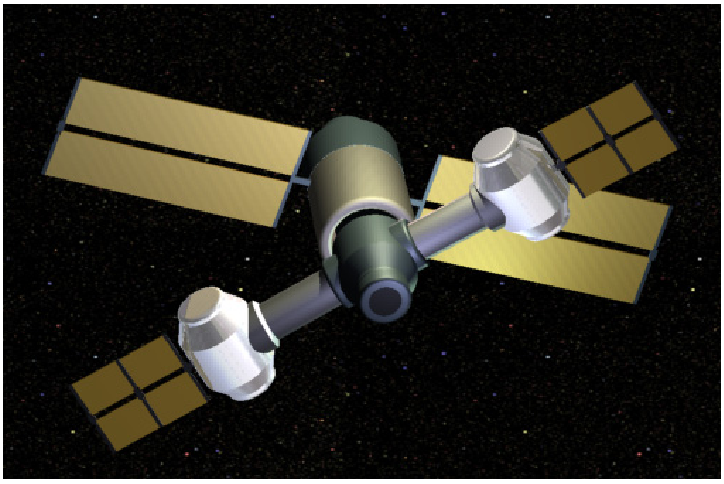

Figure 10. Basic concept of EDGG. *Simplified configuration.*

As there is no way to fix the non-rotating rotation generator (the guideway) in free space, there are going to occur phase angles between it and the rotating module caused by relative motion among them induced by the magnetic forces and traveling magnetic fields. This issue could be controlled by a kind of compensator of induced phase angle or by simple adjustment of frequency of alternating current to recuperate and harmonize the rotation in accordance with desired rotation rate of the rotating module and the rotating habitats.

The EDGG concept ensures minimal environmental impacts in space.

K. 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:

$$\vec{g}_A = \vec{a}_{cp} + \vec{a} + \vec{a}_{cor} = (\vec{\omega} \times \vec{r}) \times \vec{\omega} + d\vec{v}/dt + 2\vec{\omega} \times \vec{v} \qquad (6)$$

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:

$$\vec{a}_{cp} = (\vec{\omega} \times \vec{r}) \times \vec{\omega} \tag{7}$$

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:

$$\vec{a} = d\vec{v} / dt \tag{8}$$

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:

$$\vec{a}_{cor} = 2\vec{\omega} \times \vec{v} \tag{9}$$

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

The magnitude of the nominal artificial gravity sensation in a rotating space station 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 object and its radial distance from the rotation axis, becoming larger for greater speed and smaller radius. Less radius means less 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 (10) and (11) are showing relations among these parameters:

$$a_{cp} = v^2 / r \tag{10}$$

$$r = g_a / (0.01097 n^2) \tag{11}$$

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. The relative radial velocity of the rotating habitat is higher then the relative radial velocity of the rotating module. Figures (11) and (12) are showing tangential velocity of the rotating habitat and the rotation radius as functions of the rotation rate, for desired values of artificial gravity acceleration sensation.

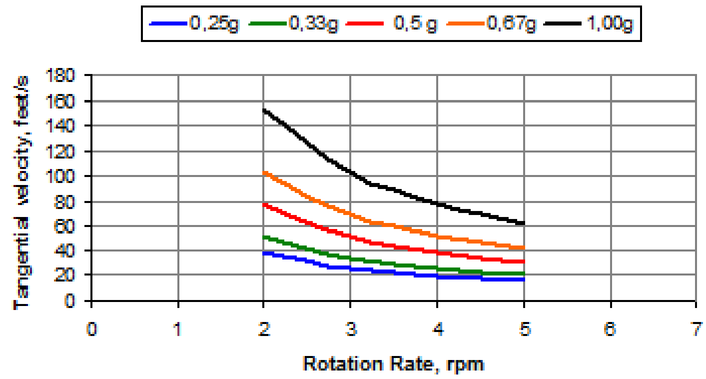

Figure 11. Tangential velocity as a function of rotation rate.

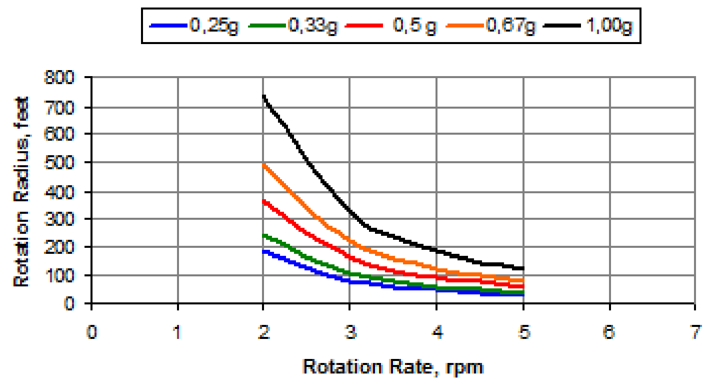

Figure 12. Rotation radius as a function of rotation rate.

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. 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. (11) it results that to produce the Earth normal gravity sensation (1g) with 2 rpm rate of spin, the radius of rotation have to be at least 735 feet with the tangential velocity of about 105 miles/hour. It is too ambitious in the short-term. Anyway, some steps could be made in the years to come making a smaller and cost-effective artificial gravity generators. The centripetal acceleration must have some minimum value to guarantee practical advantages of the artificial gravity. How much of artificial gravity is needed for long and healthy stays in space? Which is the optimal gravity? Inferior levels of gravity sensation could be also acceptable being more cost-effective to achieve them. Higher rotation rates then 2 rpm will reduce the ideal 735 feet radius still producing acceptable levels of the Coriolis forces.

A variety of experiments performed on people shown the following results:

- Min. radius: 39.4 feet.
- Maximum rotation rate: 3 - 6 rpm.
- Comfortable centripetal acceleration: 0,3•g - 1,0•g.
- Min. tangential velocity: 32.8 feet/second or 22.4 miles/hour.

As the artificial gravity acceleration equal to one third of the Earth gravity (approximately twice Moon gravity) is considered acceptable gravity level from medicine standpoint, a simplified, cost-effective and achievable EDGG similar to the one shown in Fig. 10 could be designed in accordance with the following values of the four determining parameters:

g_a = artificial gravity acceleration = g/3 = 10.62 feet/s^2

r = radial distance from the center of the rotation = 62 feet

n = rotation rate = 3.95 rpm

v = tangential velocity of the rotating habitat = 25.66 feet/s = 17.49 miles/h

L. Energy Requirements and Supply

Energy needed to make functional the EDGG can be obtained from solar energy abundant in space using photovoltaic solar panels, already verified technology in use on spacecrafts and satellites. Photovoltaic solar panels and arrays can generate electricity for propulsion, acceleration, and stabilization of EDGG as well as for: communication and telemetry systems, air condition system, sensors, heat system, light system, and others systems. The EDGG in space will have reduced power consumption and increased system efficiency because:

- Propelled modules have no weight in space.
- There is no atmosphere resistance.
- Artificial gravity sensation can be generated at low speed levels.
- There are no left-right turns and the movement of a rotating wheel-shaped space habitat should be uniform.
- Superconductors can conduct electricity even after the power supply has been shut off.

Electrical energy for the EDGG system and all its subsystems will be abundant and solar cells power efficiency is going to be highly improved thanks to favorable conditions in space. Atmospheric gases do not affect the energy of Sun. There are no energy losses through the atmosphere because of reflection and absorption. Sun energy is not affected by the day & night cycle. There are no energy losses caused by weather nor seasons changes. Solar panels can be attached on the EDGG structure or/and being located independently but connected with DC power cables and correspondent mounting. Solar panels could remain in sunlight 24 hours a day, producing a constant source of electrical power. Solar energy generation per unit area is much more effective in space then on the Earth.

Solar power supply system consists of solar panels and arrays, battery and charge controller, DC/AC inverter, mounting, solar tracker and wiring. Photovoltaic energy in solar panels is converted to direct current (DC) electricity. Addition of a micro-inverter that is built into the panel themselves could increase the solar power system efficiency allowing a more incremental approach to building it up. DC 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. The electricity from inverters can operate AC equipment or it can be rectified to produce DC at any desired voltage.

The rotating module has no contact with the rotation generator guideway and the rotation is completely contactless. The power for its SCMs can be obtained from solar panels attached to the rotating module or to another structures mounted on it, on the columns, and on the habitats. Also, rotating module can be wireless powered by power transmission through magnetic resonance between primary resonator of transmitter located in the rotation generator and secondary resonator of receiver located in the rotating module. Generated current can be converted into DC for superconductors by AC/DC converter. The power for SCMs can not be obtained by inducing AC in a kind of power collecting coils transforming it into DC because the rotation speed is very low.

The most efficient solar cells are multi-junction cells made of a several gallium arsenide based layers combined with silicon-based layers which increase efficiency significantly. While the current average efficiency of solar panels on Earth is 12-18%, the newest gallium arsenide multi-junction cells already offer efficiencies of 38-42%, already reaching 476 W/m^2 of power output per square meter. Carefully managed multi-junction cells used in space easily can obtain twice bigger energy output then solar panels of a same size on the Earth. On the other side, there are negative factors like: mechanical "aging" of the semi-conductor surfaces and electrical junctions of the photovoltaic devices, surface contamination of the transparent upper surface, surface reflections from the protective coating, absorption of solar radiation and its conversion into heat and internal heat produced by electrical resistance within the photosensitive semiconductor surfaces. So, the efficiency wouldn't be higher then 30%. The solar constant that is the total power received from the Sun above the Earth's atmosphere is about 1.5 kW/m^2.

In addition, everything indicates that there is possibility to use microwaves and laser beams for power wireless transmission from the Earth in the near future, although it is preferable to have it in the inverted direction.

Uninterruptible power supply can be achieved with rechargeable DC batteries and an inverter to supply AC power in the case the main power is not available. During the shadow phase, the EDGG will rely on nickel-hydrogen or lithium-ion rechargeable batteries to provide a continuous power source. Once the main power supply is restored, solar panels and optionally AC/DC rectifier will supply DC power to recharge the batteries. The batteries ensure that the station is never without power. Human powered electrical generators can be used as a complementary energy source, especially for power failures emergencies and off-grid applications. Just as in the ISS, primary voltage will be transformed from 160 to 120 V DC and distributed to all systems, outlets, and devices.

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

Electrochemical process of generating electricity by means of hydrogen fuel cells without combustion can be used as a complementary energy source. Liquid hydrogen (LH2) can be used for fuel cell. To exist as a liquid, H2 must be pressurized and cooled to a very low temperature of 20.28 K (-252.87°C). Storing hydrogen gas as liquid occupies less space. Liquid hydrogen and liquid oxygen (LOX) storage in space does not require cryogenic storage technology but only pressurized conditions. Liquid hydrogen with liquid oxygen as the oxidizer is commonly used as liquid rocket fuel in H2/02 rocket engines also could be used for the EDGG propulsion.

M. Electrodynamic Gravity Generator Superstructures

The electrodynamic rotation generator structure can be upgraded not only by applying more powerful electrodynamic configuration but also by multiplying of the basic electrodynamic configuration along the rotation axis to obtain synchronized rotation. Increased energy requirements can be fulfilled by using larger and more efficient photovoltaic solar panels. This way upgraded electrodynamic rotation generator can spin wider and more complex habitat structures forming larger EDGG superstructures with increased capacity.

Described EDGG can be completely autonomous structure. Also, its concept enable incorporation of whole the structure to other space stations or spaceships by direct attaching of the rotation generator to their structures, leaving the docking module free for docking and for the EVA.

EDGG structures and superstructures could be movable by a propulsion pack suited in the non-rotating central module. Rocket or some other kind of propulsion could be located along the rotation axis normal to the circle-path plane, transforming a space station for long-term human stay in deep space to a spaceship for long-term space trips with humans on board. As electrodynamic system is highly effective in space, propulsion pack could move complete structure without interrupting the rotation and continuously generating the artificial gravity sensation.

V. Conclusion

Employing superconducting electrodynamic technologies in deep space favorable conditions of cold vacuum without gravity forces, could result in development of new critical technologies for design of a new habitation systems to enable human exploration missions in deep space. Generating rotation of a space habitat will realize the old idea of a rotating wheel-shaped space station generating gravity sensation on its inside hull induced by deliberate acceleration for replacing natural gravity. Much work remains to be done and many questions are to be answered before artificial gravity becomes reality. There is no doubt that it has to be a very expensive and complex project, but, first although small steps could be made in the years to come making smaller and cost-effective artificial gravity generators, at least to get therapeutic dose of gravity for a certain period of time daily or a few times per week. 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 lots of new information and 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, taking advantage of extraordinary conditions for increasing the yield and vitality of growing live plants in space. Electrodynamic artificial gravity generators as life support systems could make possible exploration and colonization of deep space.

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