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Electrodynamic Centrifuge for Space Habitats with Artificial Gravity

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Abstract

Centripetal acceleration can be used as a substitute for gravity. An effective way to generate rotation in space is through electrodynamic technologies, which can be optimized for high efficiency in a frigid vacuum environment without gravity. The electrodynamic centrifuge is a rotation generator with rotating habitats, being a high-precision, self-aligning, contactless, and frictionless system due to a specific coil arrangement in the propulsion and guidance system. Axially oriented habitat modules provide increased comfort, without Coriolis effects or gravity gradient. Stability is achieved through a configuration with two counter-rotating centrifuges included in a larger, non-rotating space frame structure.

Abbreviations

EDC	Electrodynamic Centrifuge	Maglev	Magnetic Levitation
EDS	Electrodynamic Suspension	MGS	Mars Gravity Simulator
EVA	Extra-Vehicular Activities	NFC	Null-Flux Coils
g	Acceleration due to gravity	PGS	Propulsion and Guidance System
HTS	High Temperature Superconductors	RMS	Rotating Modular Set
LTS	Low Temperature Superconductors	SCM	Super Conducting Magnet
MAG	Modules with Artificial Gravity	SSAG	Space Structure with Artificial Gravity

1. Introduction

Artificial gravity is essential to resolve or reduce the problems caused by weightlessness. This can be achieved through artificial gravity generators as life support and habitation systems. The sensation of gravity can be generated by the inertial reaction to the centripetal acceleration acting on a body in circular motion. Rotating 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 moving in uniform circular motion, where centripetal acceleration acts as artificial or simulated gravity. For extended stays in space, at least partial gravity conditions will be necessary. It is crucial to demonstrate the ability to generate gravity through rotation and to prove that humans can live and work in an artificial gravity environment. Artificial gravity will also provide opportunities for life sciences and advanced technology research.

2. Superconductors and electrodynamic technologies applied in space

Space as cold vacuum without gravity is a very favorable environment for EDS technologies:

- Low temperature (temperature in space is -270 Cº while absolute zero temperature is -273 Cº).
- Lack of gravity: The only goal is to achieve controlled rotation. Technical factors such as lift-off speed, lift-off force, and weight sensitivity are irrelevant.
- Vacuum conditions: No medium is required for propagation of electromagnetic waves. Electromagnetic waves propagate in vacuum traveling at the speed of light.
- Abundant solar energy: Space acts as a “superconductor” for photons. Energy generation is highly efficient.

Key advantages of superconductors and EDS in space:

- Strong and stable electromagnetic fields and forces.
- Conduction losses are significantly reduced, leading to much higher power densities.
- Frictionless movements. Zero resistance. Minimal power loss.
- Energy efficiency: Power reduction coefficient is about 0.10 (about 10% of power required on Earth).
- Lightweight and compact.

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- Reduced cooling complexity.
- Durability and reduced maintenance.

3. Electrodynamic Centrifuge (EDC)

The general theory of moments for electrodynamic magnetic levitation systems, based on dynamic circuit principles and emphasizing loop-shaped coils and figure-eight-shaped null-flux coil suspension, as used in Maglev EDS trains in Japan, can be modified and fully applied to spinning objects in the space environment of a cold vacuum without gravity. This system offers very low magnetic drag at low speeds, high suspension stiffness, and favourable lift-to-drag and guidance-to-drag ratios.

The electrodynamic centrifuge is an axial-thrust rotational system designed for integration into large space structures to generate artificial gravity. By controlling magnetic forces and rotating magnetic fields between the rotating modules and the guideway, it enables stable, controllable, and contactless rotation. The system consists of a circular guideway and a rotating modular set (RMS).

The guideway provides a constant and stable trajectory and is designed to be incorporated into larger non-rotating structures. Initially, the RMS can be either inline or crossline. Although more complex, the crossline RMS is the preferred option, as it provides greater stability and increases the system's overall capacity. Desired level of artificial gravity is achieved inside the rotating habitat modules incorporated into the RMS. There are three possible orientations of the habitat modules with respect to the rotation axis: axial, tangential, and radial, as shown in Figure 1.

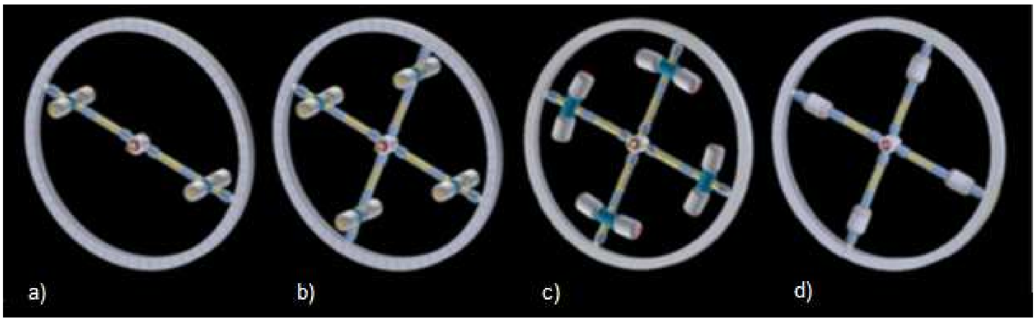

Figure 1: EDC configurations. Orientation of habitat modules

Axial orientation is the least dynamically stable, relying on the guideway and rotating modular set to maintain stability. However, it offers the greatest comfort as neither Coriolis forces nor gravity gradients occur, eliminating the need for curved flooring. The absence of Coriolis forces also permits a smaller rotation radius to achieve low artificial-gravity levels. Axially oriented modules facilitate counter-rotating cylinder configurations. A four-arm RMS configuration provides stable rotation. Figure 1a) illustrates an EDC with a two-arm RMS and axially oriented habitat modules, while Figure 1b) shows one with a four-arm RMS - adopted in this paper owing to its overall advantages.

Tangentially oriented modules provide moderate stability and comfort: Coriolis forces occur but gravity gradients do not, requiring curved flooring. This orientation demands electrodynamic centrifuges with larger radii; for smaller radii, the modules must be slightly inclined (see Figure 1c). Tangential orientation also enables rotating ring–shaped structures. Figure 1c) illustrates an EDC with a four-arm RMS and tangentially oriented habitat modules.

Radial orientation provides maximum dynamic stability but offers the lowest comfort. It produces significant gravity gradients and strong Coriolis forces, requiring ladders and making internal orientation challenging. Figure 1d) illustrates an EDC with a four-arm RMS and radially oriented habitat modules.

The inherent stability of an object rotating around its axes is determined by the ratio of the object's principal moments of inertia. The electrodynamic centrifuge is designed based on the concept of a major-axis spinner. The symmetries combined with the coaxial positions minimize the angular momentum of the rotating modules, enabling maximum maneuverability during rotation and minimizing spin-up and spin-off efforts. The electrodynamic centrifuge is a high-precision, low-speed, self-aligning, low-noise system capable of providing stable rotation. Spin rate, spin-up, and spin-off requirements can be easily met by adjusting AC frequencies. The rotation is uniform, contactless, and efficient. Vibrations, wobbling, and shaking are minimized. Electrodynamic centrifuge will have significantly improved efficiency, causing minimal environmental impact. It is necessary to apply two coaxial electrodynamic centrifuges to generate counter-rotations that cancel out angular momentum.

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3.1 Propulsion Guidance System (PGS)

Controlled rotation is achieved through guidance and velocity control, managed by a unified trajectory control system consisting of propulsion and guidance subsystems. Figure 2 illustrates the electrodynamic centrifuge section, with all the components of the propulsion and guidance system distributed between the guideway (1) and the rotating modular set (2). Null-flux coils (NFC, 3), resembling the number eight, are embedded in the guideway walls, while the electromagnetic chucks (6) are embedded in the inner coaxial surface of the guideway. The propelled modules (4) carry superconducting magnets (blue coloured) and clamps (5). The purpose of the rotating modular set is to generate an artificial gravity sensation in the habitat modules with artificial gravity (MAG, 7) located near its endpoints.
Propulsion and guidance are achieved through electrodynamic interactions between propulsion coils, null-flux coils, and superconducting magnets (SCMs). The guidance system consists of axial and radial centering.

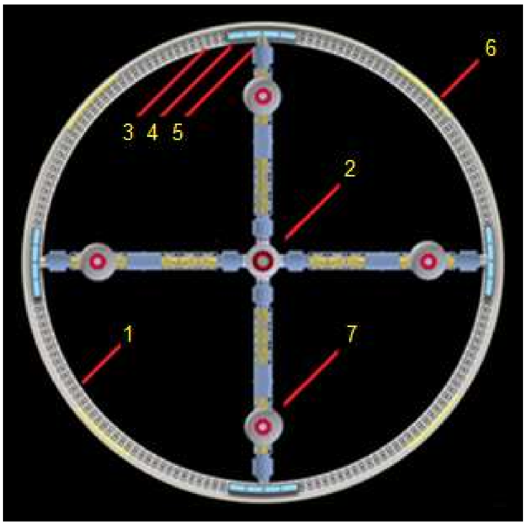

Figure 2: Electrodynamic centrifuge and coils arrangement in propulsion and guidance system

The Propulsion Guidance System (PGS) is composed of superconducting coils located on the lateral sides of the propelled modules (parallel to the guideway sidewalls), propulsion coils, and figure-eight-shaped NFCs embedded in the guideway sidewalls. The figure-eight NFCs located on the facing walls are cross-connected by additional Null-Flux cables to form a null-flux circuit, while the NFCs located along the same guideway wall are connected in series circuits for AC supply. Cross-connected pairs of facing NFCs are used for guidance, while serial-connected NFCs are used for propulsion, as shown in Figure 3.

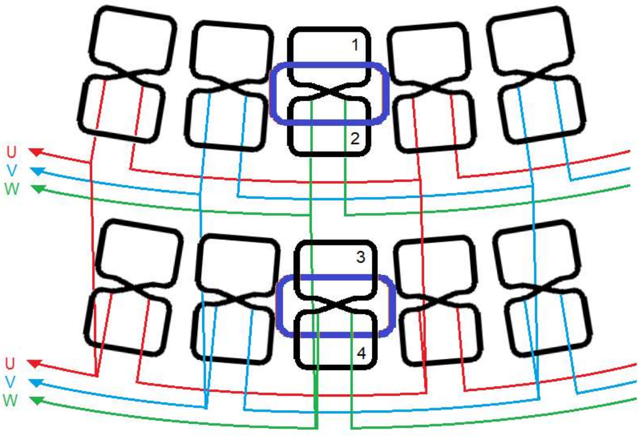

Figure 3: Arrangement of null-flux coils (NFCs) and pairs of SCMs running over their centers

NFCs for propulsion, guidance, and levitation, developed for EDS trains in Japan, can be applied in space, where the levitation forces used in Maglev trains provide radial guidance and centering for path control. Guidance and propulsion forces are generated by introducing electric current into the NFCs and by pairs of facing coils connected with a null-

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flux cable, as shown in Figure 3. By controlling the direction and intensity of the currents in the NFCs, the sign and intensity of the magnetic field also can be controlled. NFCs are to be installed on the inner surfaces of the circular guideway sidewalls, covered with aluminium panels. This design concept offers high guidance-to-drag ratios and very low magnetic drag at low speeds. The null-flux effect reduces power losses from induced currents in metal loops, resulting in smaller magnetic drag forces. NFCs enable strong and fast-acting trajectory control forces, which are inherently and passively stable. They have high mechanical strength to withstand magnetic forces. The NFCs are wound from aluminium conductors, moulded with unsaturated polyester resin reinforced with glass fibre, and electrically insulated. NFCs can be either symmetric or asymmetric. Higher speeds generate larger guidance and propulsion forces while decreasing drag forces.

SCMs are sequentially mounted on the outer surface of the lateral sides of the propelled modules. They consist of superconducting coils made from conventional superconductors. A permanent direct current (DC) flows through them, generating a strong magnetic field that enables both guidance and propulsion through interactions with the null-flux coils. The coils are closed, and the generated magnetic field remains constant. When the propelled modules move quickly and near the null-flux coils, the magnetic fields created by the superconducting coils scan the null-flux coils, inducing currents to flow through them. The induced currents generate magnetic fields that interact with the magnetic fields produced by the superconducting coils in the propelled modules. The relative motion of the magnet-coil system induces a voltage in the coils, which creates a current flow that generates a secondary magnetic field opposing the flux change caused by the relative motion.

An essential issue is the choice of superconducting material to be used, LTS (Low Temperature Superconductor) or HTS (High temperature Superconductor). LTS is great for applications where maximum superconducting performance is needed, but it requires more complex and bulky cooling systems. HTS is more practical for space due to its higher operating temperature, simpler cooling system, reduced mass, and easier handling of the heat load in space.

Considering the constraints and demands of space missions (e.g., mass, volume, cooling complexity), HTS is more recommendable for space applications. The key reasons are:

- Less complex cooling: HTS can be cooled using liquid nitrogen (LN2), which is much easier to handle compared to liquid helium, especially in a space environment. The cooling system becomes less demanding since LN2 boils at 77 K, which is still far below the critical temperature of HTS materials.
- Higher operational temperatures: HTS materials like YBCO (Yttrium Barium Copper Oxide) and BSCCO (Bismuth Strontium Calcium Copper Oxide) can remain superconducting @ liquid nitrogen temperatures (~77 K), which is easier to achieve with standard cooling systems like cryocoolers and cryogenic fluids.
- Reduced mass for cooling: Liquid nitrogen is easier to store, and handle compared to liquid helium.
- Although HTS may have slightly lower performance compared to LTS, LTS is usual choice for space missions, especially when the overall system mass and complexity are reduced.

The EDC must be a low-speed system, as it is necessary to slow down the rotation to improve comfort inside the habitat modules with artificial gravity. Unfortunately, low-speed EDS systems are unstable and pulsative at lower speeds, especially regarding the forces required for radial and axial centering. To improve motion stability, propulsion, centering, and guidance, an additional set of propulsion coils could be implemented, embedded in the guideway sidewalls, underneath and parallel to the null-flux coils (as shown in Figure 4), to generate additional propulsion and guidance forces. Controllable AC current in the propulsion coils, along with the electromagnetic fields generated by the onboard SCMs, translate into propulsion forces, generated simultaneously with additional guidance (centering) forces. The coil arrangement is shown in Figure 4, where the propulsion coils are yellow, the null-flux coils are red, Null-Flux cable is black, and the SCMs are highlighted in blue.

Figure 4: Coils arrangement in PGS

The operating gap is a design decision. Strong magnetic fields enable larger gaps between the rotating modular set and the guideway, improving safety and allowing for larger construction tolerances, which are convenient for circular trajectories and corresponding circular structures. The dynamic circuit theory can be extended to curved SCMs and coils. Slightly curved gradient coils allow for instantaneous adaptation to changes in the circular trajectory, benefiting electromagnetic field interactions and the rotation itself. SCMs are easy to construct and operate. They continue to conduct electricity even after the power supply has been shut off. Magnetic fields are strong, and their penetration into the interior of habitats must be limited with barriers made of conductive materials to serve as electromagnetic shields. Superconducting materials can expel magnetic fields through the Meissner effect.

Electromagnetic chucks are embedded in the inner cylindrical and coaxial surfaces of the guideway (Figure 2). They are designed to hold the propelled modules during the assembly phase, for braking, and for fixing already stopped propelled modules of the rotating modular set (RMS). The number of chucks is no less than the number of propelled modules. In the example shown in Figure 2, the electromagnetic chucks are positioned in the guideway facing the propelled modules of the rotating modular set. Their role in the final assembly stage is crucial, as they hold the propelled modules until the rotation is initiated, at which point the propelled modules are released simultaneously. The electromagnetic chucks enable rotation to stop and restart.

3.2 Propulsion

NFCs are energized by three-phase AC creating a traveling magnetic field. SCMs are DC magnets, and their fields do not vary with time. Force that propels the rotation forward is produced by the excitation current in the SCMs and the magnetic field induced by the propulsion NFC serial circuits. Propulsion is achieved when two magnetic fields are synchronized and locked among them. Speed of the rotation is proportional to the input AC frequency. To counteract magnetic drag, additional propulsion coils can be employed, if necessary, as shown in Figure 5a).

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 modules with SCMs and the guideway, as shown in Figure 5.

All propelled modules will rotate under the same conditions being pushed and pulled by the rotating magnetic fields. The sums of forces acting over each SCM on each propelled module will create torques to rotate complete RMS. Repulsive and attractive forces over the propelled modules keep the RMS coaxial with the guideway.

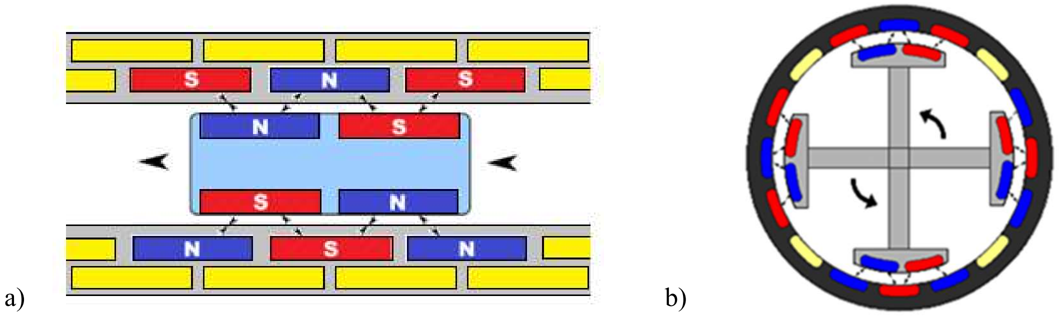

Figure 5: a) Propulsion forces generated by PGS
b) RMS rotation generated by the sum of repulsive and attractive forces (schematic illustration)

3.2 Radial centering

When propelled SCMs run over the circular path defined by the centers of NFCs, no force is induced. If displaced, the SCM will leave the projected path generating more current in the half of a NFC that stays in larger interaction with the SCM, depending on displacement direction. The change in that half of the NFC will be greater than that in the other half of the same NFC, inducing current and generating magnetic forces. The magnetic pole in that half of the NFC is the same as that of the SCM, while the other half has the exact opposite magnetic pole, so that both halves of the coil generate the same direction components of magnetic force on the SCM bringing it back into designed path over the center of the NFC. NFCs can induce a current and generate magnetism only when the SCMs are in motion.

The farther the SCM moves from the projected rotation path defined by the centers of the NFCs, the stronger will be the induced repulsive and attractive forces bringing it back, as shown in Figure 6.

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

The sum of all guiding radial forces is to be zero for the xyz coordinate system with the center located 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.

Radial centering presents a kind of “electrodynamic spring” necessary for displacements of a complete structure containing the electrodynamic centrifuge and preserving controlled and contactless rotation.

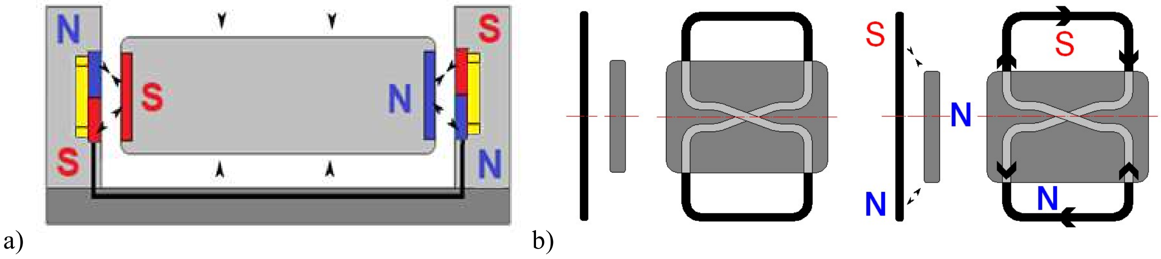

Figure 6: a) Repulsive and attractive forces keep propelled module centered over the projected path
b) Interactions between SCM and null-flux coil when SCM displace from the projected path

3.2 Axial centering

While running, the propelled module may shift laterally along with the set of superconducting magnets attached to its sides. This lateral displacement induces an electric current in the loop, generating a repulsive force on the null-flux coils located closer to the module, and an attractive force on the coils farther away. As a result, the propelled module remains centered within the guideway. The repulsive force increases as the module approaches the guideway walls. The farther it deviates from the centerline of travel, the stronger the induced force becomes to restore it to the centered position, as illustrated in Figure 7.

Each opposing pair of null-flux coils, cross-connected by a null-flux cable, constitutes a loop, as shown in Figure 7. The rotating propelled module remains centered along the designed path due to the combined attraction and repulsion forces between the null-flux coils and the displaced superconducting magnets. According to Lenz’s Law, an electric current is induced to restore the propelled module to its central position. This induced current flows in such a way as to oppose any change in magnetic flux within the coil - hence the term “flux-eliminating coil.” This behavior can be described by a magnetic spring constant, which corresponds to the slope that ensures the rotating module consistently follows the designed trajectory. Axial centering functions as an “electrodynamic spring,” enabling guided rotation during displacements, dockings, and maneuvers. The sum of all forces induced in each facing set of SCMs and null-flux coils must be zero within the xyz coordinate system, with its origin at the center of rotation. All propelled modules rotate under identical conditions. If a single module deviates from the projected path and approaches the guideway, all propelled modules simultaneously experience the same corrective forces, being pushed and pulled, to bring the entire rotating modular set back into the designed trajectory (axial centering), maintaining stable and contactless rotation inside the guideway.

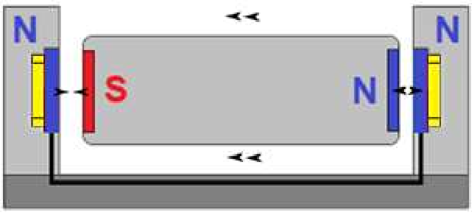

Figure 7: Axial centering of propelled module

4. Electrodynamic Centrifuge (EDC) in space structures

The electrodynamic centrifuge (EDC) is not viable as an independent space system. As shown in Figure 8, it is designed to operate in tandem with a coaxial EDC (2), both integrated into a larger structural frame (1). Interactions between each EDC’s guideway and its corresponding rotating modular set (RMS) generate relative motions due to forces and moments, as well as undesirable phase shifts induced by magnetic forces and traveling magnetic fields. These effects are transmitted to the structural frame. To mitigate these disturbances, it is essential to synchronize both electrodynamic centrifuges. This is achieved by integrating two coaxial EDCs within a common, non-rotating space frame, rotating in opposite directions to cancel out angular momenta. Maintaining the frame in a non-rotating state is crucial to preserve its orientation in space.

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The EDC is a high-precision system capable of stable rotation throughout its full 360-degree range of motion. It operates at low speed, is self-aligning, highly precise, frictionless, and virtually noiseless. As an electrodynamic system, the EDC is inherently stable and does not require active electronic stabilization. Its rotation is uniform, entirely contactless, and nearly lossless, with minimal vibration, wobble, and oscillation.

Artificial gravity is generated gradually, starting from zero at the RMS hub and increasing outward toward the modules with artificial gravity (MAGs) and propelled modules. The desired gravity levels are achieved in the MAGs, which serve as the primary habitat areas. Gravity intensity can be adjusted to the desired level by varying the rotation speed, which is controlled by modifying the AC frequency supplied to the EDC guideways to accelerate or decelerate rotation. Electrodynamic axial centering functions as an "electrodynamic spring" during eventual docking and relocation operations. The rotation can be stopped and restarted as needed. The system is electrically powered, with solar energy as its primary energy source.

Space structures equipped with artificial gravity will enable exploration of human adaptability to such environments - an essential factor for long-term space missions and colonization. Their modular design allows flexibility and supports a wide range of configurations.

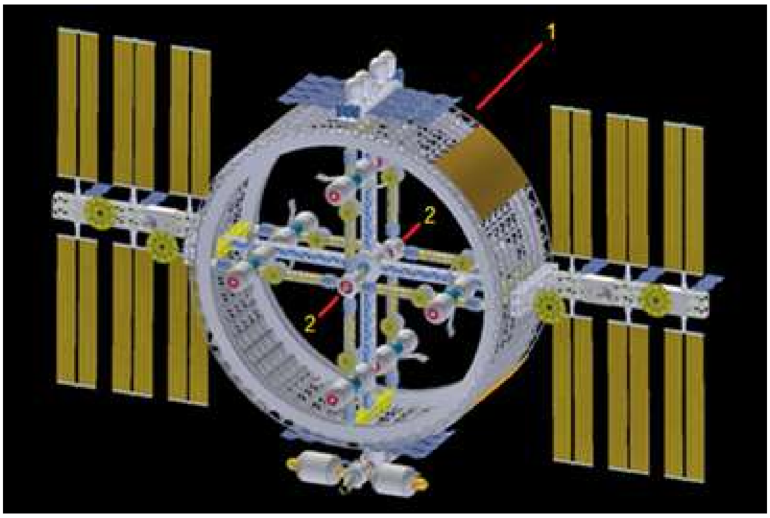

Figure 8: Space structure with artificial gravity (SSAG)

4.1 System architecture and design

The main objective of the space structures with artificial gravity (SSAG) presented in this paper is to design a feasible, stable, and modular architecture incorporating electrodynamic centrifuges, intended for space stations and spacecraft required for long-duration exploration and colonization missions.

SSAG features a modular design composed of highly integrated, lightweight modules. This architecture enables the construction of large space systems in low Earth orbit (LEO) and offers flexibility for upgrades and reconfiguration.

The SSAG comprises a coaxial frame structure and two electrodynamic centrifuges, as illustrated in Figure 9. These centrifuges rotate in opposite directions to cancel angular momentum. Rotational stability is ensured by the compact configuration of the centrifuges and the main frame. The guideways of both EDCs are integrated into the frame structure, while the rotating modular sets move within the guideways.

As shown in Figure 9a), the rotating modular set (RMS) includes a cylindrical hub module with a docking port and airlock (1), a central transfer node serving as a solid carrier for the columns with transfer tunnels inside (2), habitat modules with artificial gravity (3), and propelled modules equipped with superconducting magnets (5) and corresponding clampers (4).

Figure 9b) illustrates the main components of the non-rotating frame structure: the circular truss structure (1), central hub (2), two electrodynamic centrifuge guideways (3), columns with transfer tunnels (4), up to three docking ports, central control and non-gravity habitat modules (5), lateral truss carriers (6), solar arrays and panels (7), fuel depots and power bus (8), radiators (9), and airlocks for EVAs (10).

The frame structure is the primary structural unit of the SSAG architecture. It is built using linearly and radially expandable truss elements. The zero-gravity central hub is the frame's and SSAG's core node, communicated with whole the structure through the columns, and serves as a pass-through and power transfer center, providing access to every part of the SSAG. It includes two airlocks for short EVAs, enabling crew transfer between the frame and the counter-rotating EDCs.

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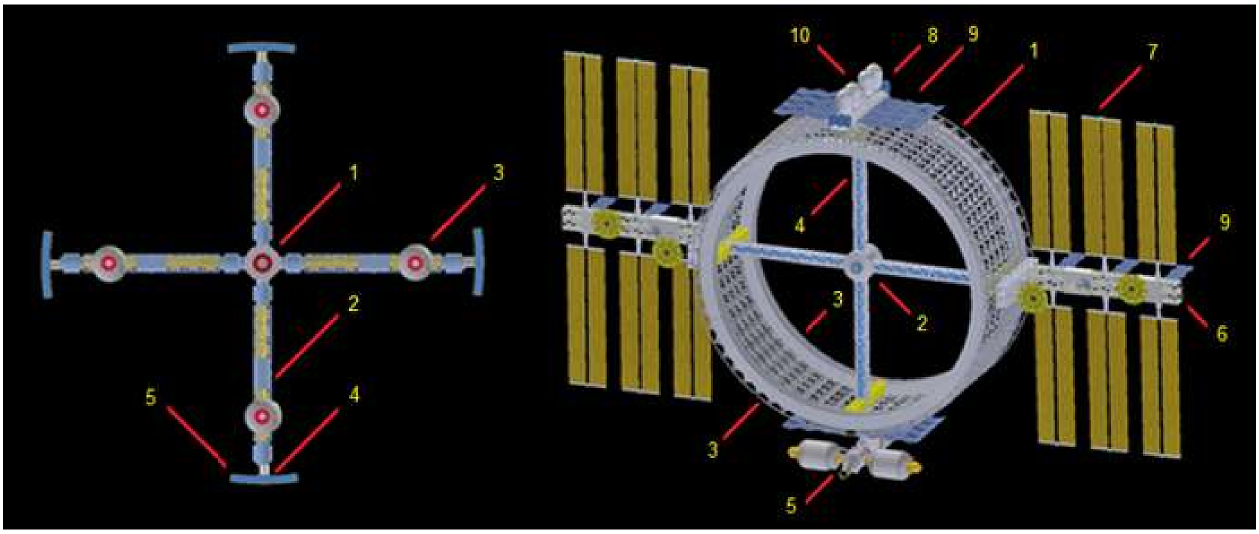
Interactions within the electrodynamic centrifuges (EDCs) induce relative motions resulting from internal forces, moments, and undesired phase shifts. These perturbations are transmitted to the lateral walls of both EDC guideways and subsequently to the structural frame. The resulting dynamic loads are directed primarily along the axial direction rather than radially. Consequently, the use of radially tensioned cables between the central hub and the circular truss structure is not strictly required, although their implementation remains optional for additional structural reinforcement. The circular truss is further stabilized through the integration of concentric beam structures.

The coaxial guideway compact structures are integrated into the cylindrical frame truss structure, which is made of double-layer braced barrel vaults. The frame structure is designed to support the power supply system, thermal control system, communication systems, docking ports, control modules, and other components in microgravity environments.



a) b)

Figure 9: a) EDC's rotating modular set (RMS, 2 units), b) Frame structure with two EDC's guideways

If the counter-rotating modular sets are identical, the overall configuration is symmetrical, simplifying the cancellation of angular momentum. If the rotating modular sets are not identical, the configuration becomes asymmetrical, and angular momentum cancellation must be achieved by adjusting their rotational speeds. This can be accomplished by varying the frequencies of the alternating currents to harmonize the rotation and counter-rotation according to the desired angular velocities.

The columns are expandable lattice structures containing transfer tunnels that connect the central hub to the circular truss structure. These transfer tunnels may be inflatable or constructed from hollow structures made of solid materials and can optionally include an electric elevator or winch. At the end of one tunnel are docking modules and central control and habitat modules without artificial gravity. At the ends of the other three tunnels are secondary airlocks for extravehicular activities (EVAs), as well as access points to fuel depots, the power bus, solar arrays, communication systems, and other facilities.

Crew transfer between the non-rotating frame and the rotating habitats is a crucial and vital operation. The main docking modules are attached to the frame structure, and crew transfer to the central hub occurs through transfer tunnels located within the columns, as shown in Figure 9. The frame structure and both rotating modular sets are coaxial, meaning their hubs are also coaxial and positioned close to each other. Any displacement between them requires a very short EVA. The comfort and safety of these EVAs can be improved by using electrically powered sliding cylindrical shells coaxial with the hubs. When extended toward the neighbouring hub, the sliding cylindrical shell forms a non-pressurized, partially enclosed cylindrical passage for crew transfer. Once the transfer is complete, the sliding shell is retracted.

Inflatable structures are preferable due to their reduced packaging volume, low weight, good pressure resistance, significant impact resistance, and enhanced radiation shielding against solar flares and strong magnetic fields. Radiation shields should be incorporated into the walls of all modules and habitats occupied by crew. Although all three principal orientations of cylindrical habitat modules relative to the axis of rotation are applicable in electrodynamic centrifuges, axially oriented habitat modules are preferred because this orientation increases comfort by eliminating Coriolis effects and gravity gradients within the rotating habitats.

The rotating habitat modules with artificial gravity, the docking modules, and the control and habitat modules externally attached to the frame structure, are to be pressurized. The hubs and transfer tunnels within the main frame structure, as well as those in the rotating modular sets, could be pressurized although it is not necessary.

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4.2 Power supply system. Thermal control system.

The power supply system is a critical resource, enabling the crew to live comfortably in both artificial gravity and microgravity conditions, as well as to safely operate the SSAG and perform its functions. It comprises subsystems for power generation, energy storage, power management, conversion, and distribution.

The hybrid power generation system includes solar arrays and panels, fuel cells, liquid hydrogen and oxygen, and, if required, radioisotope power generators. The primary energy source is solar energy.

The electricity generated is used for propulsion, guidance, stabilization, heating, air conditioning, communications and telemetry, lighting, and other onboard systems. The primary source of electricity comes from large roll-out solar arrays mounted on lateral truss carriers. These arrays are divided into two photovoltaic blankets, with a deployment mast positioned between them. Other types and forms of solar panels are optional choices.

High-power flexible round panel arrays with a circular deployment and unfurling mechanism, made from advanced materials, are ideal to be used, attached on the frame structure and on RMS. Round panel arrays offer high specific power, low weight, excellent stiffness and strength, and a compact stowed volume.

To ensure a continuous power supply, the photovoltaic system is designed for both low Earth orbit (with essential energy storage capabilities) and deep space scenarios (e.g., Lagrange points).

Figure 10 illustrates the power supply and thermal control systems, including: solar arrays and panels (1), power bus modules (2), fuel depots (3), and radiators (4). The design incorporates twelve large deployable arrays, like those used on the ISS, along with auxiliary circular solar panels to provide operational margin and redundancy.

Storage of liquid hydrogen and liquid oxygen in space does not require cryogenic temperatures but only pressurized conditions. Additionally, liquid hydrogen and liquid oxygen, used as propellants in H_2/O_2 rocket engines, could be utilized to propel the entire structure equipped with manoeuvring thrusters. The SSAG uses gyros for primary attitude control.

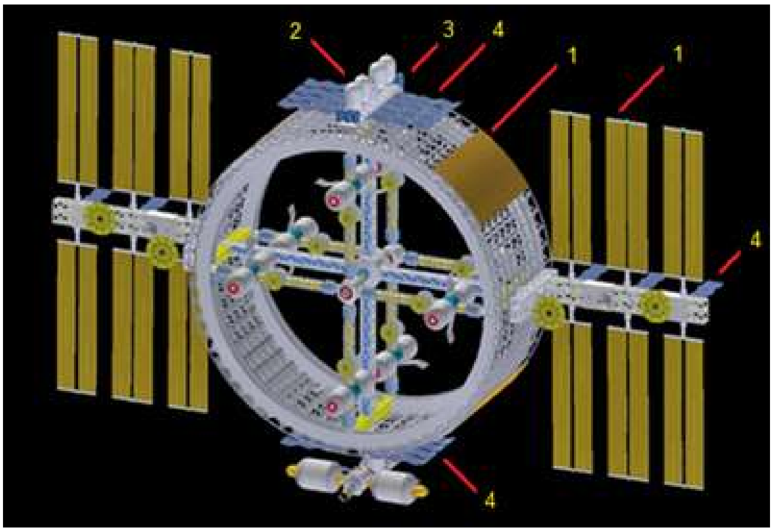

Figure 10: Power supply and thermal control systems

An especially important aspect is the transfer of power from the frame-based generation system to the counter-rotating electrodynamic centrifuges. This transfer is achieved using rotary electrical interfaces, also known as slip rings or rotary joints, which are electromechanical devices capable of reliably and contactless transmitting power and electrical signals from a stationary structure to a rotating one. These high-quality, long-life components can also be used to transmit fluid media such as hydraulic or pneumatic flows. Slip rings are installed in the hub of each rotating modular set to enable power transfer from the "stationary" central hub and the main frame structure.

Magnetic fields, induced disturbances, electrical currents, and rotational motion will be monitored using vector magnetic sensors without physical contact. Strong magnetic fields will enable a reduction in component size and weight, resulting in lower power consumption and improved system efficiency.

The energy storage subsystem consists of batteries, regenerative fuel cells, and storage units for liquid hydrogen and liquid oxygen. Most of the batteries are housed on and within the main frame truss structures.

Electrochemical cells, which convert stored chemical energy into electrical energy, can be used to store energy and generate power independently throughout the structure. Systems combining high-energy batteries with high-power cells or fuel cells are envisioned to ensure stable EDCs rotating and continuous power supply for life-support and all the other systems.

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The power management system includes control algorithms, models, and sensors. The power distribution subsystem comprises switchgear, wiring, and other passive components. The conversion subsystem consists of converters, inverters, and transformers. Photovoltaic energy from solar cells is converted into DC electricity, as is the output from fuel cells. Electricity can be converted between voltage levels using DC/DC converters. Inverters transform DC into AC, which can then be stepped up to high-voltage AC using transformers. AC power from inverters can operate AC equipment or be rectified back into DC at any voltage. One of the main challenges in using electrodynamic systems in space is generating high-voltage AC to achieve the required propulsion current levels to spin EDCs.

The power supply system is designed to operate with oxygen and is optimized for multi-gravity environments, as well as for thermal and water management.

The frame structure, including both lateral truss structures, provides ample space for power bus modules, depots, solar arrays, and other components of the power generation and supply system. Some system elements are located within the rotating modular sets, as well as in the rotating and non-rotating habitat modules, columns, and hubs. The use of radioisotope thermoelectric generator (RTG) is optional. Storage areas on the non-rotating main structure frame are accessible via the hubs, docking ports, and transfer tunnels for supervision and maintenance. Both rotating modular sets house power bus modules containing batteries and chemical cells.

The thermal control system comprises an external active thermal control subsystem and an internal passive thermal control subsystem. The active subsystem manages heat collection, transport, and rejection, maintaining thermal equilibrium when the passive subsystem’s heat load is exceeded. The process of converting sunlight into electricity and its subsequent management generates excess heat that must be dissipated. Radiators are employed to remove this heat from the spacecraft. Due to their size, deployable and retractable two-loop radiator systems are attached to both the main frame structure and the rotating modular sets.

Regarding superconductors, a special modification of the cooling system is required to adapt it to space conditions. The main challenges involve efficiently radiating heat and maintaining cryogenic temperatures for the superconducting magnets due to the absence of a medium for heat transfer, unlike on Earth. Essential solutions include advanced, highly efficient thermal radiators made from materials with high emissivity, as well as highly efficient cryogenic systems using liquid nitrogen. Additionally, the use of high-temperature superconductors (HTS), high-quality multilayer thermal insulation, thermal shields, and passive thermal control devices such as low-emissivity coatings are crucial.

4.3 System assembly

Being complex and massive, space structures with artificial gravity must be assembled on-site in Low Earth Orbit (LEO). The architecture is modular, composed of lightweight materials and highly integrated systems. These structures must be simplified while remaining safe and functional. Modular design provides flexibility for upgrades and reconfiguration. Base components, such as trusses, can be assembled in orbit, while mission-specific instruments are launched separately, allowing infrastructure costs to be spread across multiple missions. The frame structure serves as the main structural backbone of the system and is designed using linearly and radially expandable truss elements.

Double-layer braced barrel vault is a preferred structure type to be used for the main frame structure.

Double-ring truss self-locking deployable structures are suitable for deployable carriers (musts) with transfer tunnels in the frame structure and in both RMS, as they maximize space efficiency during launch by folding compactly and then deploy to provide strong structural capacity once in orbit.

Curved deployable truss structures offer more efficient load distribution and are suitable for use in large, lightweight components and structures. Unlike straight bars, curved trusses follow a continuous arc, improving structural efficiency. The use of deployable curved truss or cylindrical structures would be essential.

The EDC guideways will be constructed from modular radial shaped blocks.

All structures will be assembled in space using robotic arms and 3D printing technologies. The coaxial guideway compact structures will be integrated into the cylindrical frame truss structure, which is composed of double-layer braced barrel vaults. The frame structure is designed to support the power supply system, thermal control system, communication systems, docking ports, and related subsystems. All these components will be assembled prior to the integration of the rotating modular sets. Some structures and equipment will be folded for traditional cargo transport.

The critical assembly phase entails integrating the two rotating modular sets into the pre-assembled frame structure, which includes the EDC guideways. These modular sets will be independently assembled in orbit and subsequently manoeuvred, via propulsion modules, toward the guideways within the frame. Positioning is performed relative to the pre-installed, fixed propelled modules seated on radial electromagnetic chucks inside the guideways, as illustrated in Figure 11b. Precise coaxial alignment of the central hub of the frame structure with the hubs of both rotating modular sets is mandatory. Each rotating modular set is equipped with clampers at its termini. Upon final positioning, four clampers extend to engage designated slots in the propelled modules contained by inner electromagnetic chucks, thereby securing mechanical and electromagnetic coupling.

The final step of the assembly process is to initiate the initial rotation in both electrodynamic centrifuges. AC null-flux coils begin interacting with DC superconducting magnets (SCMs) in the propelled modules as shown in Figure11b).

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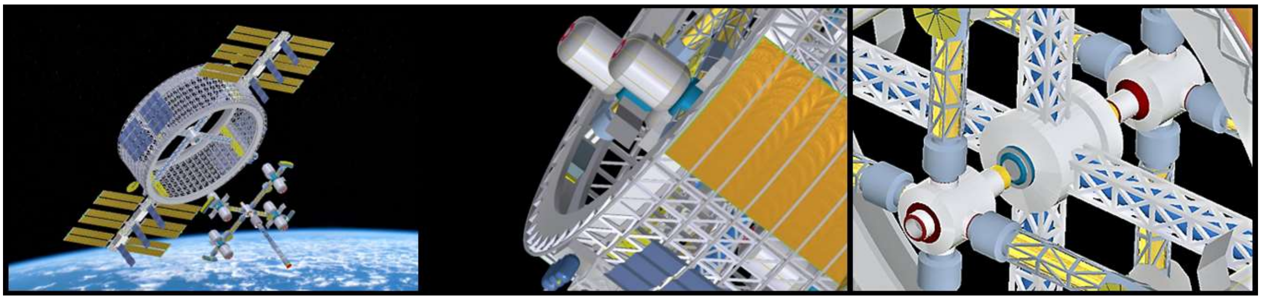
Once the desired AC frequency in the guideway is reached, power to the electromagnetic chucks is cut off, releasing the propelled modules. Propulsion occurs when the magnetic fields synchronize and lock among them. Induced forces in opposite directions create torques, whose sum generates the controlled rotation of the rotating modular set (RMS), producing artificial gravity within the modules with artificial gravity (MAGs).

Main structures are to be equipped with propulsion thrusters for manoeuvrings, which are crucial during the assembly phase when high-precision movements are required. Propulsors may also be used to relocate the entire structure to different orbits or even to transform it into a spacecraft. High-precision positioning sensors enable accurate alignment throughout each assembly phase.



a) b) c)

Figure 11: a) Assembly of an RMS into the frame structure
b) EDC assembled and ready to start rotating
c) Coaxial hubs for crew transfers

4.4 Applied technologies and materials

Assembly is a complex mission involving the launch of multiple payloads into Low Earth Orbit (LEO), where autonomous robots will assemble the structure more quickly and cost-effectively than human crews. Autonomous space assembly is an emerging technology for constructing robust space structures in a flexible, scalable manner. Robots can precisely position components, with robotic arms capable of grasping, holding, and moving large elements, and placing them in their exact orientation. The construction toolset will be reusable, repositionable, and partially expendable. Robots will operate on stacked platforms equipped with actuators that allow six degrees of freedom between two bases, along with sensors providing real-time feedback on component positioning. These modular platforms can stack to any size, supporting various configurations for component assembly. Task management software will coordinate robots of different designs and capabilities, enabling cooperative operation. An error detection system will also be integrated into the process.

Innovative, rule-breaking zero-gravity 3D printers and autonomous 3D printing robots will liberate missions from many of launch constraints, enabling the additive manufacturing, aggregation, and assembly of large and complex systems directly in space, eliminating the need for astronaut EVAs. Rather than launching complete structures, missions would only need to deliver raw material for 3D printing, along with essential elements such as electronic parts, electromagnetic coils, sensors, fuel cells, and batteries. Zero-gravity 3D and 4D printers will fabricate parts from digital designs, which will then be assembled, alongside other prefabricated elements, into larger structures using robotic arms.

Structural materials must be advanced, lightweight, high-strength, and highly reliable, computationally engineered to withstand extreme environments, while providing thermal protection and radiation resistance. Representative materials include polymer matrix composites, metal matrix composites and nanocomposites, titanium-vanadium-aluminium alloys, aluminium-lithium alloys, and nickel-based alloys. Smart materials may enable deployable structures with reduced mass, while emerging self-healing materials could significantly reduce the need for astronaut EVAs. In addition, advanced radiation shielding materials will be critical to ensure crew safety.

To reduce overall size, weight, and cost, inflatable habitat modules are a preferred solution. These pressurized structures expand upon deployment, offering increased internal volume while supporting life in outer space. They provide greater habitable space per unit mass and feature enhanced impact resistance and radiation shielding.

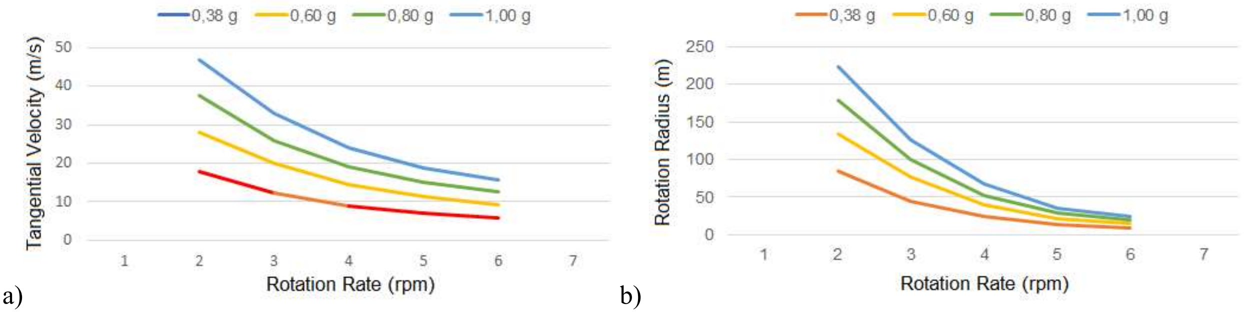
Crew transfers between the central hub within the frame structure and the hubs in the RMSs will involve a very brief EVA. To enhance crew safety, the hubs could be equipped with electrically powered sliding cylindrical shells.

A critical challenge is the power transfer between the non-rotating main frame structure and the counter-rotating modular sets, since the power generation capacity on the counter-rotating sets is significantly lower than the total capacity of all power generation subsystems installed on the main frame. This transfer can be accomplished using slip ring technology. A slip ring (rotary electrical joint) is a device that enables continuous transfer of electrical signals and

power during rotation. Low-speed rotation enhances transmission quality. Slip rings can transmit electric power (AC, DC, low and high voltage) as well as various types of signals, including analogue, digital, RF, data, control, sensor, video, and audio. They can also be customized to transfer air or liquids, supporting hydraulic or pneumatic power.
Artificial intelligence can facilitate new materials design as well as complex assembly processes control. Additionally, it can efficiently manage the counter-rotation of modular rotating sets and their docking manoeuvrers.

4.5 Rotation rate and geometry design

Artificial gravity acceleration inside a rotating space habitat can be expressed as the vector sum of centripetal acceleration, relative acceleration, and Coriolis acceleration.
Centripetal acceleration is independent of the relative motion of objects inside the rotating habitat. It is radial and directed toward the axis of rotation. Coriolis acceleration is proportional to the vector product of the habitat's angular velocity and the object's relative velocity and is perpendicular to both.
The magnitude of nominal artificial gravity in a rotating space habitat can be described by its centripetal acceleration, where the artificial gravity force is equivalent to the centripetal force. Centripetal acceleration depends only on the angular velocity of the habitat and its radial distance from the axis of rotation, increasing with greater angular speed and decreasing with larger radius. A smaller radius results in a lower total system mass, leading to reduced launch and material costs. The effects of centripetal force can be considered as artificial, or simulated gravity, and the entire system can be regarded as an artificial gravity generator.
Figure 12a) and Figure 12b) show tangential velocity of the rotating habitat and the rotation radius as functions of the rotation rate for desired values of artificial gravity sensation.



a) b)

Figure 12: a) Tangential velocity related to rotation rate
b) Rotation radius related to rotation rate

Rotation can introduce significant challenges, including Coriolis forces induced by any motion not parallel to the axis of rotation. These effects become more pronounced with higher rotation rates and smaller rotation radii.
The angle and magnitude of centripetal acceleration change according to the inhabitant's position. The point of convergence of the total acceleration is offset from the center of rotation due to the Coriolis acceleration component. To achieve optimal artificial gravity, Coriolis forces must be reduced to acceptable levels, corresponding to a rotation rate between 1 and 2 rpm, while increasing the habitat's tangential velocity. Considering the effects of Coriolis forces, producing Earth-normal gravity (1g) at a 2-rpm rotation rate requires a rotation radius of at least 224 meters and a tangential velocity of approximately 168 km/h. Some initial steps could be taken in the coming decades to develop less ambitious and more cost-effective artificial gravity generators.
Centripetal acceleration must exceed a minimum threshold to ensure practical benefits of artificial gravity. Research is needed to determine the acceptable combination of gravity level and duration of the artificial gravity stimulus, as well as the effects of transitioning between different gravity levels. Lower gravity levels may be acceptable, as they are easier to achieve. Rotation rates above 2 rpm reduce the required radius while still producing acceptable levels of Coriolis forces.
Artificial gravity environments can be characterized by four parameters: artificial gravity acceleration (equal to centripetal acceleration), radial distance from the center of rotation, rotation rate, and tangential velocity.
A comfortable artificial gravity environment is defined by the following parameter values: a minimum radius of 12 m; a maximum rotation rate between 3 and 6 rpm; centripetal acceleration ranging from 0.3g to 1.05g; and a minimum tangential velocity of 10 m/s. In the case of SSAG, these parameters must be considered alongside the main parameters of electrodynamic and electromagnetic interactions in the electrodynamic centrifuge, particularly the tangential velocity of the propelled modules. Both sets of parameters, established to achieve artificial gravity and accommodate it, will increase the design complexity, dimensions, and weight of all structures with artificial gravity.

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4.6 Example: Space structures with artificial gravity & Mars Gravity Simulator (MGS)

The gravity sensation generated by rotation increases gradually, starting from zero at the hubs and rising toward the habitat and propelled modules. Desired gravity levels are achieved within the habitat modules and can be adjusted by varying the rotation rate, enabling both Earth-like and partial gravity conditions. This capability allows the creation of a Mars Gravity Simulator (MGS) for scientific simulations and experiments in preparation for future Mars missions, where surface gravity is approximately 38% of Earth's.
It is essential to consider the four key parameters that define a comfortable artificial gravity environment, along with the main parameter governing electromagnetic and electrodynamic circuits - namely, the tangential velocity at the main diameter of electrodynamic propulsion. A tangential velocity of 20 m/s is sufficient to generate controlled rotation in the space environment. The main diameter for generating electrodynamic propulsion is defined by the centers of the null-flux coils located along the guideway of the electrodynamic centrifuges. A larger rotation radius combined with a lower rotation rate enhances comfort but increases the overall dimensions and costs of the system.
This chapter includes two cases for space structures with artificial gravity (SSAG):
Case 1: Requirements for the minimum-size SSAG with an Earth-like gravity zone (Figure 13a).
Case 2: Requirements for the minimum-size SSAG and Mars Gravity Simulator (MGS) with Earth-like and Mars-like gravity zones (Figure 13b).
In Figure 13, Earth-like gravity zones are highlighted in blue, while the Mars-like gravity zone is shown in red.

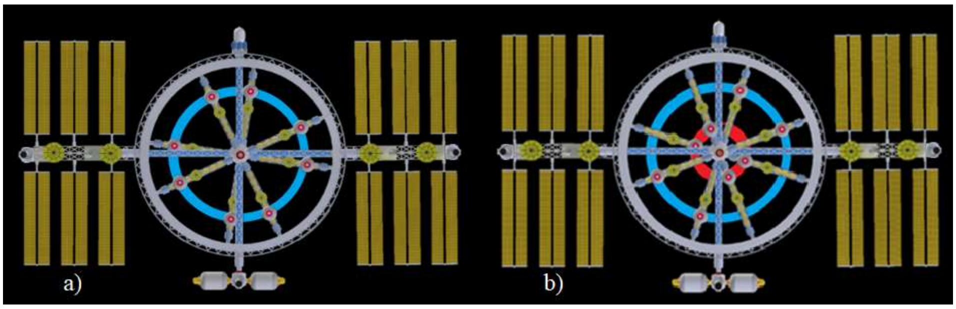

Figure 13: a) Case 1: SSAG with Eart-like gravity zone
b) Case 2: SSAG with Earth-like and Mars-like gravity zones

Table 1: Main dimensional parameters

	Case 1 (0.9g)	Case 2 (0.38g)	Case 2 (0.9g)
Rotation rate (rpm)	5.7	5.2	5.2
Tangential velocity at main diameter of electrodynamic propulsion (m/s)	20	20	20
Main electrodynamic propulsion diameter (m)	67	73.5	73.5
Outer diameter of electrodynamic centrifuge (m)	69	75.5	75.5
Frame outer diameter (m)	72	78.5	78.5
Main radius in the Earth-like gravity comfort zone (m)	24.8	12.6	29.8
Tangential velocity @ Main radius in the Earth-like gravity zone (m/s)	14.8	6.8	16.2

The SSAG includes living space within the comfort gravity zones for 16 standard crew members, with a maximum capacity of up to 20 crew members. Each habitat consists of two inflatable modules and a corresponding transfer node

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in a column. The overall SSAG dimensions depend on the desired gravity comfort levels. With inflatable habitat modules measuring 5 m in length, 4 m in diameter, and 0.5 m wall thickness, the pressurized volume inside the gravity comfort zones is about 520 m³. With two 2-meter-wide guideways, the frame width would be 23 m, and the overall width (distance between the outer MAGs) would be 35 m. This results in overall SSAG dimensions (without solar panels): Ø 72 m x 35 m (Case 1), Ø 78.5 m x 35 m (Case 2). Depending on the power supply system configuration (solar panels, hydrogen depots), docking ports, and external modules, the minimum size for the SSAG in the Case 1 could reach 135 m x 88 m x 35 m, while the SSAG in the Case 2 would measure 142 m x 95 m x 35 m. The estimated total weight for fully assembled and equipped SSAG is 635 000 kg (Case 1) and 730 000 kg (Case 2).

Case 1: Power consumption for the crew to live safely is up to 150 kW (where between 40 kW and 50 kW is needed for rotating). The hybrid power supply system could generate up to 250 kW (up to 190 kW from solar panels, the necessary collection area: ~560 m² in LEO and ~330 m² in deep space).

Case 2: Power consumption for the crew to live safely is up to 170 kW (where between 50 kW and 60 kW is needed for rotating). The hybrid power supply system could generate up to 270 kW (up to 210 kW from solar panels, the necessary collection area: ~620 m² in LEO and ~370 m² in deep space).

Triple-junction GaAs photovoltaic panels with ~30% efficiency were considered for all solar energy estimates.

Each side wall contains 420 coils in Case 1 and 460 in Case 2. Radial clearance ranges from 0.25 to 0.30 m, and the SCM-to-coil gap is between 0.15 and 0.20 m.

Each SCM includes magnetic and coil components: null-flux coils (0.60 × 0.40 m, pitch 0.9 m), SCMs (1.6 × 0.5 m, 2.1 m pole pitch, 700 kA MMF), and propulsion coils (2.1 × 0.7 m, wall thickness 0.5 m).

To counteract magnetic drag (~ –1.0 kN), additional propulsion coils can be employed (see Figure 4).

When rotation inside the EDC reaches null-flux equilibrium at 20 m/s tangential velocity, the SCMs exert axial and radial centering forces of 12 kN and 6.5 kN respectively.

MAGs within the comfort gravity zones serve as the primary habitats, while modules outside these zones can be used for storage or space agriculture (e.g., hydroponics with continuous-flow cultures). Hubs and modules without artificial gravity may function as equipment areas, manufacturing zones, research laboratories, or even entertainment areas.

The MGS, functioning as an artificial gravity research facility, would enable studies on prolonged exposure to Mars-level gravity and support the development of technologies for use on the Martian surface such as life support systems, Mars suits, robotics, structural assembly, and 3D/4D printing.

Space structures offering comfortable artificial gravity could also serve as orbital laboratories to investigate the optimal gravity conditions for human interplanetary travel.

4.7 Electrodynamic centrifuges for space super structures with artificial gravity

Main frame structure with EDC guideways can be scaled by duplicating it on a parallel rotation axis and extending both structures along both axes. Instead of the rotating modular sets, this approach yields large, counter-rotating cylindrical habitats with artificial gravity and greatly increased capacity for human settlements in Earth orbit and deep space, as shown in Figure 14. The habitats are axially oriented in terms of length and spatial distribution.

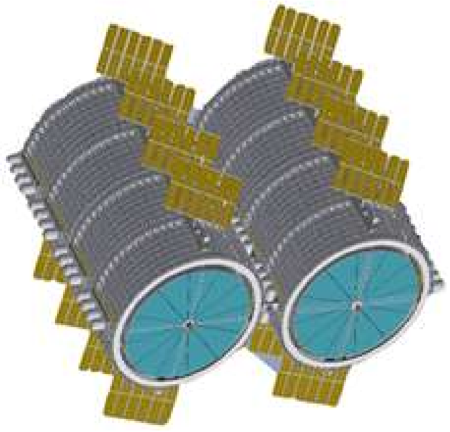

Figure 14: Space settlement with artificial gravity.

Drawing on O'Neill's cylinder concept, counter-rotating cylinders mitigate gyroscopic torques. These habitats would incorporate residential, agricultural, and industrial modules under Earth-equivalent gravity, controlled atmosphere, and radiation shielding. Sections with windows and adjustable mirrors would simulate a day–night cycle. A high-capacity

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energy system, mounted on the main frame, would exploit abundant solar flux and employ radiators for heat rejection. Artificial gravity would support diverse agricultural and manufacturing activities.
Moreover, integrating propulsion packs into the non-rotating frame would make the superstructure mobile. Thus, a deep-space colony could also function as a spacecraft, whose thrusters would propel it without altering the rotation or gravity levels of the habitats, and would relocate it to lunar orbit, the Lagrange points, Martian orbit, etc.

5. Conclusions

The use of electrodynamic technologies in space could enable the development of critical life-support systems. Well-equipped with scientific and life-support equipment, rotating artificial gravity generators could become flexible systems capable of providing valuable knowledge for future space exploration. These systems would offer the ideal environment for a wide range of experiments. Artificial gravity could facilitate food production in space. Orbital facilities, such as laboratories, factories, hotels, and depots, would foster scientific research, manufacturing, space tourism, and solar power infrastructure, as well as refuelling and repair operations. A space station with artificial gravity could be built in situ and moved to various orbits, even transformed into a spacecraft for human exploration missions. Electrodynamic centrifuges as life-support systems could enable the establishment of human settlements in deep space, acting as an off-Earth backup for human civilization.

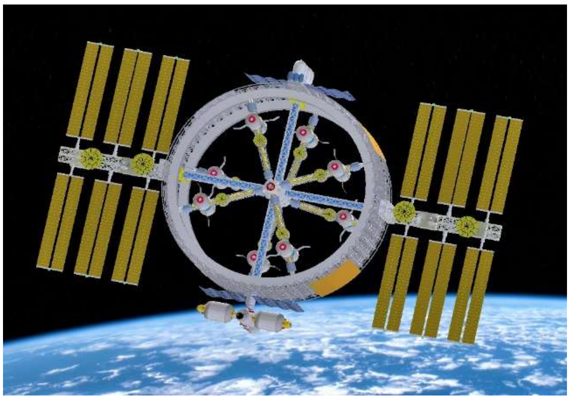

Figure 15: Space Structure with Artificial Gravity

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