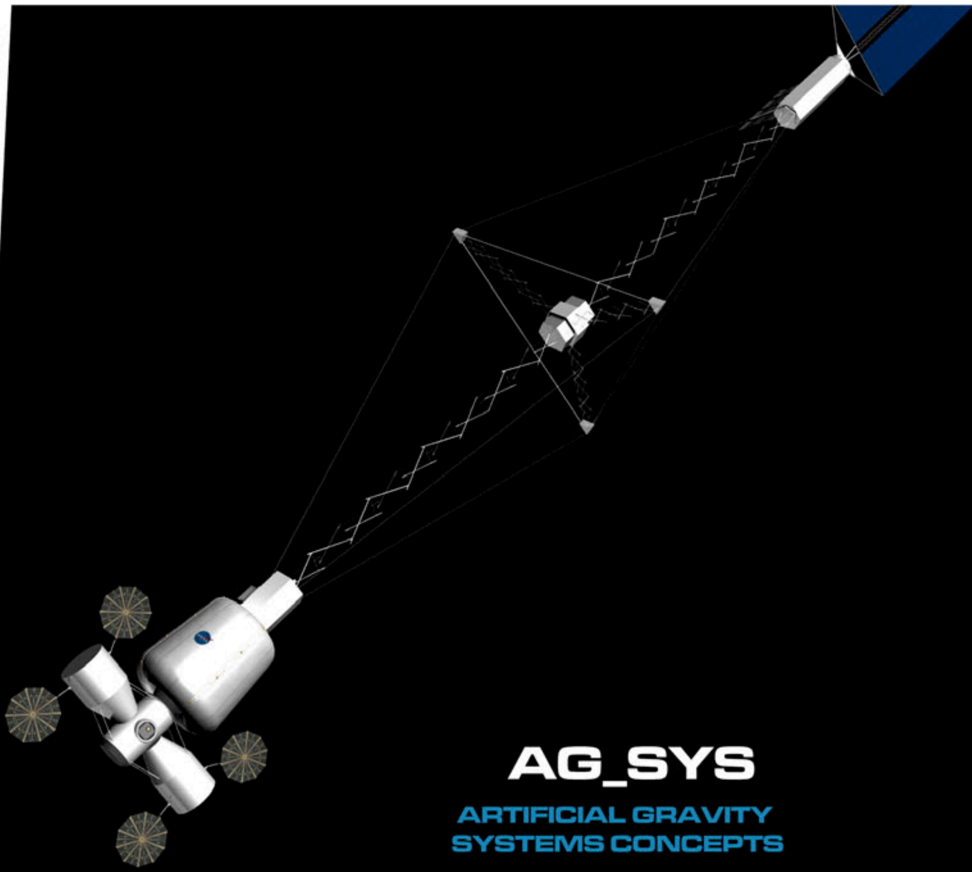

AG_SYS

ARTIFICIAL GRAVITY SYSTEMS CONCEPTS

TOMAS ROUSEK

INDIVIDUAL PROJECT REPORT SUBMITTED TO THE INTERNATIONAL SPACE UNIVERSITY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS OF THE MSc. DEGREE IN **SPACE STUDIES**

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Abstract

This report describes conceptual studies of a series of spacecraft with implemented artificial gravity. The main objective is to design solutions intended for LEO, NEO and Mars missions that study new configurations with current and near-term future NASA and ESA assets. The artificial gravity environment is generally created by spinning of the whole spacecraft. The focus of the study ranges from the level of the main structures to a scale of the interior elements from architectural and human factors point-of-view. Particular attention is paid to inflatable and deployable systems enlarging the structures beyond the limits of the payload shroud of the launch vehicle.

AG_X is a small-scale achievable project that is intended to investigate responses of human body to partial gravity levels. Centrifuge would consist of two tethered Space Exploration Vehicles or European ATV connected to a Space Exploration Vehicle.

AG_LAB is the project of variable artificial gravity research station in Low Earth Orbit. The purpose of the station is to investigate the various gravity parameters and habitability in environment influenced by Coriolis force. The first generation uses tether system and radial orientation of habitation module while AG_LAB 2G is Mars transit vehicle precursor with tensegrity truss boom and radial orientation.

AG_NEO is the conceptual proposal for the NEO mission that would Space Exploration Vehicles (SEV) AG_HAB or NODE3 module can be repurposed from ISS.
AG_CYCLER is a design of E-M semi-cycler Mars transit vehicle with solar electric propulsion and tensegrity truss boom.

AG_HAB interior is TransHab-derived solution with features specific for artificial gravity environment with Coriolis force taken into account.

The architecture design work is based on artificial gravity research of Theodore W. Hall, PhD. from University of Michigan and Prof. Gilles Clement from International Space University and Neuroscience laboratory at NASA JSC.

Acronyms

AG	Artificial Gravity
ATV	Automated Transfer Vehicle
CAM	Centrifuge Accommodation Module
CTB	Cargo Transfer Bag
ECLSS	Environmental Control and Life Support System
ECMS	European Modular Cultivation System
EDT	Electro-Dynamic Tether
ESA	European Space Agency
EVA	Extra Vehicular Activity
ISS	International Space Station
IVA	Intra-Vehicular Activities
L2L	Logistics2Living
LEO	Low Earth Orbit
LMO	Low Mars Orbit
LOX/LH2	Liquid Oxygen / Liquid Hydrogen propellant
NASA	National Aeronautics and Space Administration
NEO	Near Earth Objects
SEP	Solar Electric Propulsion
SEV	Space Exploration Vehicle
TEI	Trans Earth Injection
TMI	Trans Mars Injection

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1. Introduction

AG_SYS is a student internship project done in partial fulfillment of the Master of Space Studies degree of International Space University at NASA JPL in Pasadena, California. This report is divided into seven main chapters describing artificial gravity, spacecraft concepts, interior design study and conclusions.

The study addresses major issues of manned deep space missions - physiological deconditioning due to microgravity exposure and radiation. The presented design concepts are showing the possible path of utilization of Artificial Gravity (AG) in the subsequent alternative steps. The various gravity levels should be first investigated at smaller scale in short-term missions in the Low Earth Orbit in order to gain insight in the physiological factors, structural dynamics and attitude control. In the next steps, it is possible to focus on long-term habitability and exploration factors and create precursor missions to exploration of the Mars and beyond.

1.1. Artificial gravity

Even three centuries after Isaac Newton, mankind still doesn't fully understand the gravity. Compared with other 3 known forces, gravity is the weakest one, but it is the most strongly perceived on human level of the scale of the known universe. During the evolution of the life on our planet, it played an important role in development of structures of organisms and their physiological processes. The terrestrial organisms can adapt to microgravity quickly with except of processes depending on gravity such as reproduction, but the biggest problem remains the transition back to gravitational environment, which is especially critical in long-duration missions to other planetary bodies. These issues involve bone demineralization, muscle atrophy, cardiovascular and sensory-motor deconditioning and regulatory physiology systems malfunctioning. It is possible to treat these problems system by system, or globally by implementing the artificial gravity into the design of the habitat. While the muscle atrophy is possible to countermeasure by exercising and medication, the bone loss still isn't sufficiently solved. Also the demineralization releases Calcium from the body that can create kidney stones that can occur during the 3-year mission to Mars. In the first days of after the landing on Mars, part of the crew can have medical problems with return to gravity field and can have significantly decreased workability. This would be especially hazardous in the scenarios of separated habitat and crew landings, if crew has to move from the lander to the habitat by EVA operations and deploy necessary systems (CLEMENT, G., Bukley. A., 2007).

1.1.1. Full rotation of the spacecraft versus short-radius centrifuge

NASA's current baseline is to use microgravity environment aboard the spacecrafts and artificial gravity in the form of short-arm centrifuges. The experiments have shown a particular help of even short doses of intermittent artificial gravity, however global gravitational environment brings a lot of advantages. There exist multiple rationales for artificial gravity use from the operational point of view. It saves time of the crew needed for exercise or centrifuge treatment, eases the hygiene and other Intra-Vehicular Activities (IVA), enables convection in liquids and air for better circulation, higher plant growth, settling and easier collection of debris that can be potentially harmful when inhaled (SANDLER, H., 1995). Several Mars mission architectures propose the use of the spinning of the whole vehicle, and we would like to continue in this direction in the first phase to find new concepts and evaluate their feasibility as well as operational requirements.

The artificial gravity should have as low additional mass penalty as possible, which is for instance the advantage of tethered spinning systems. The proposed habitation modules are based on both pre-integrated CLASS I and inflatable CLASS II technologies. These habitats should provide the necessary functionality in both micro-g and gravitational conditions and enhanced radiation protection for long-duration missions out of protective Earth's magnetic field. The psychological wellbeing is also discussed and concept presents Augmented Reality interface for better orientation in the Coriolis force environment or virtual windows as psychological countermeasure.

1.1.2. Past artificial gravity experiments in space

The idea of artificial gravity is not a novelty, its roots are in 19th century in concepts of Konstantin Tsiolkovski and there appeared many paper concepts during the last century. However, very little was actually realized. In the 1966, Gemini-11 tested the tethered spinning formation flight with Agena booster, where the crew experienced acceleration of 0.0005 g. The acceleration wasn't big enough for crew to feel simulated gravity pull and to study physiological efects. Astronauts in Skylab conducted artificial gravity exercise by running in the cushioned ring in the large open space compartment. In the year 1992, the STS-42 SpaceLab Shuttle mission involved linear sled which exposed test subjects to linear accelerations in the range 0.2 - 1 g, however constant acceleration was possible only 0.05 g due to the short trajectory. In conclusion, subjects didn't feel the acceleration lower than 0.2 g in Gz direction as artificial gravity. STS-90 NeuroLab mission in 1998 then systematically tested short-radius centrifuge, where test subjects were tested in 10 minutes centrifuge runs every other day. Even smaller doses of the acceleration were increasing the resistance against vestibular system malfunctioning and its decreased performance. (CLEMENT, G., Bukley. A., 2007).

There were also experiments with animals and plants such as Cosmos-782, Cosmos-936, various experiments aboard Skylab, Salyut, Mir, SpaceLab and ISS. Currently is ISS equipped with European Modular Cultivation System (ECMS) Rotor providing artificial gravity 0.001 g to 2.0 g in 600 mm centrifuge (ESA, 2010). Centrifuge Accommodation Module (CAM) with 2.5-m centrifuge built by JAXA and NASA was unfortunately left on the parking lot in Japan after the project was cancelled.

2. AG_X

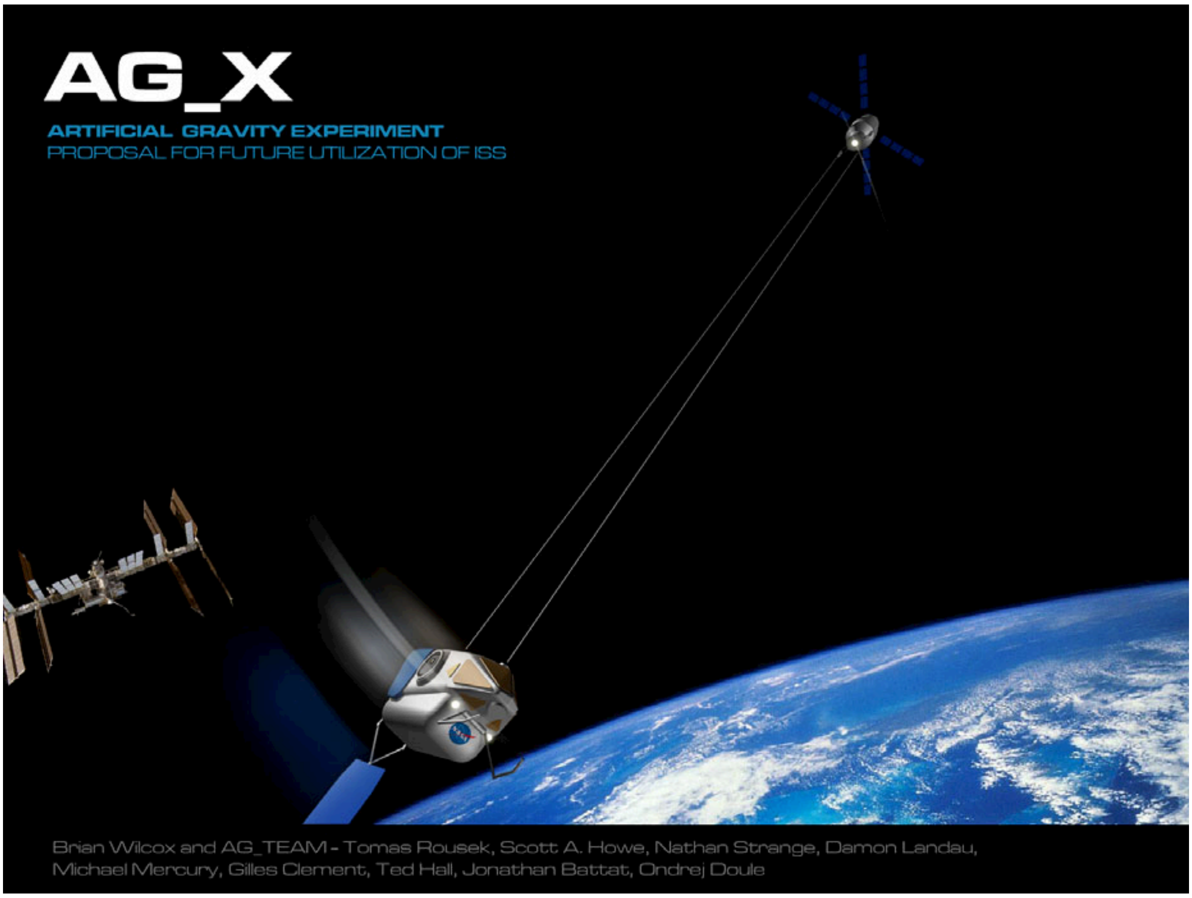

Figure 1. Multi-Mission Space Exploration Vehicle and ATV.

2.1. AG_X Mission Objectives

Artificial Gravity eXperiment (AG_X) is an achievable project for simulation of variable artificial gravity utilizing planned Space Exploration Vehicles (SEV) and European Automated Transfer Vehicle (ATV). The mission would take place in the vicinity of International Space Station as a preparation of long manned exploratory missions. The concept is based on the idea of Brian Wilcox (head of Robotic Vehicles Group, NASA JPL). It was presented during the workshop in Washington about future utilization of ISS in July 2010. The goal of the experiment is to investigate bone loss and muscle atrophy under partial gravity levels. Amount of Calcium released from the body indicates the deconditioning of the bones even in short periods of adaptation to different gravity levels, which allows multiple short-duration experiments. The threshold of the bone loss can be discovered by daily analyzing the calcium content in the urine under the AG exposure. Multiple missions allow creating continuous graphs of physiological reactions of the human body (CLÉMENT, G., Bukley, A., 2008). More astronaut crews involved in multiple experiments would help to specify the Artificial Gravity Comfort Zone.

2.2. AG_X Design Drivers

The experiment should meet requirements that are specific for an ISS mission, especially safety restrictions. It would be performed at safe distance, while keeping the possibility of rescuing the crew in case of emergency. Experiments will have durations of 1-2 weeks according to the capabilities of SEV, the cabin can accommodate crew of 2 for 14 days or crew of 4 for 7 days, which is rather for emergency purposes. SEV doesn't have re-entry capability, so ISS infrastructure will enable the spacecraft return after the experiment and the results can be analyzed directly in ISS laboratories (NASA, 2010).

2.2.1. Artificial Gravity Parameters

The generated AG will be variable in several parameters. Radius of rotation could be ranging from 30 to 200 m at various angular speeds ranging from 0.5 rpm to 6 rpm. The variable acceleration can be in interval 0.1 – 1 g. Mainly lunar and Martian gravity tests will be important, this information would have significant value for planning lunar outpost and Mars exploration mission. We could for example discover, that lunar or Martian gravity levels are not sufficient and the long-term surface habitats will need to include adequate countermeasures (CLEMENT, G., Bukley. A., 2007).

2.2.2. Multi-Mission Space Exploration Vehicle (SEV)

Figure 2) is servicing and exploration system derived from next-generation Lunar Electric Rover cabin being developed at NASA JSC. This offers same volume as previous cabin, but has elliptic section to reduce the mass penalty of the flat walls of current LER cabin (HOWARD, R., 2010). The orbital version contains also a two suitports, two robotic arms manipulators with a small airlock and has added propulsion unit with propellant for delta-v budget 100 m/s per fill. It can dock to ISS and perform manned, teleoperated and autonomous operations (NASA, 2010). The basic configuration well usable for AG experiments, the solar arrays are also oriented according to the AG field direction.

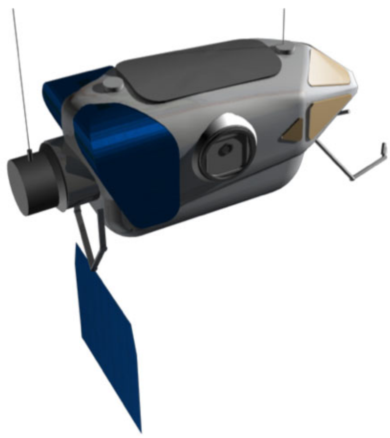

Figure 2. Multi-Mission Space Exploration Vehicle (SEV) in centrifuge with reel attached to launcher adapter interface.

The interior (Figure 3, Figure 4) is very confined, but analog simulations in DESERT RATS missions prove that astronauts can spend inside up to two weeks period during exploratory trips (NASA, 2010).

Figure 3. Mockup of LER cabin at NASA JSC (photo by Tomas Rousek).

Figure 4. Interior view of the mockup of LER cabin at NASA JSC (photo by Tomas Rousek).

2.3. AG_X Design Concepts

2.3.1. Dual SEV Configuration

Dual SEV configuration (Figure 5) offers equal balance of masses on both sides of the centrifuge and good maneuverability for testing tether dynamics. The most critical are the spinning up and down maneuvers, and stabilizing of the axial configuration that could involve special control algorithms and correction maneuvers. It is possible to test axial and tangential orientations with regards to axis of rotation as well as offset thrusting used in AG_CYCLER concept. The tether system consists of doubled lines for safety reasons. The reels are attached to the launch vehicle adapter and both SEV vehicles should have interfaces for docking together before deployment of the tether.

Figure 5. Dual SEV Centrifuge.

2.3.2. SEV and ATV Configuration

The European ATV vehicle is usable for AG experiment as well due to independent subsystems and propulsion (Figure 6, Figure 7, Figure 8). The additional module with reels and docking adapter would be attached to the hatch. Its dry mass of 10 470 kg and estimated mass of 12 000 kg with propellant is adequate to the weight of SEV (ESA, 2010). Spin maneuver requires small delta-v and there should be enough propellant left after the experiment for return to ISS and de-orbiting the spacecraft at the end of the lifetime.

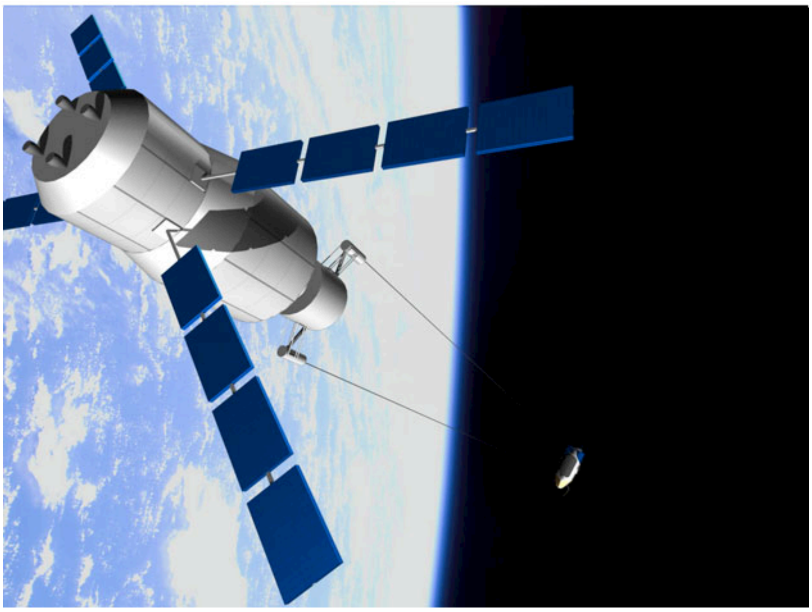

Figure 6. AG_X with ATV in LEO.

Figure 7. Artificial Gravity experiment in axial configuration

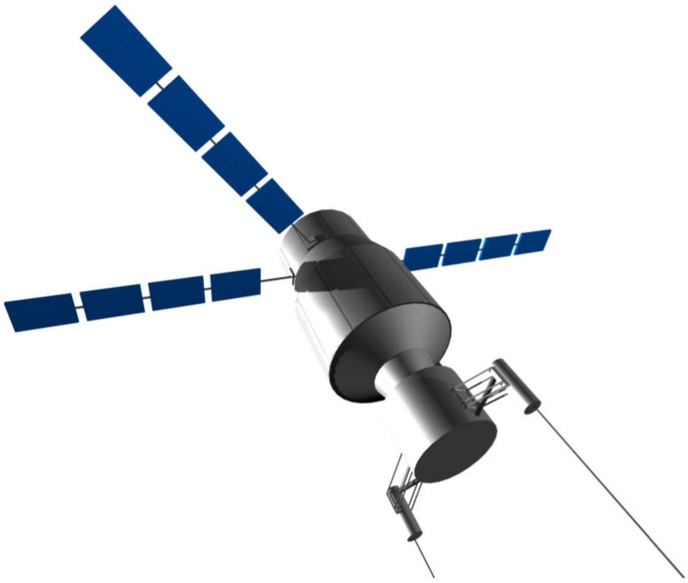

Figure 8. ATV Segment with reel and deployable interface.

2.4. AG_X Conclusion

This project would be cost-effective opportunity to investigate artificial gravity effects and parameters that are necessary for next generations of artificial gravity spacecraft.

3. AG_LAB

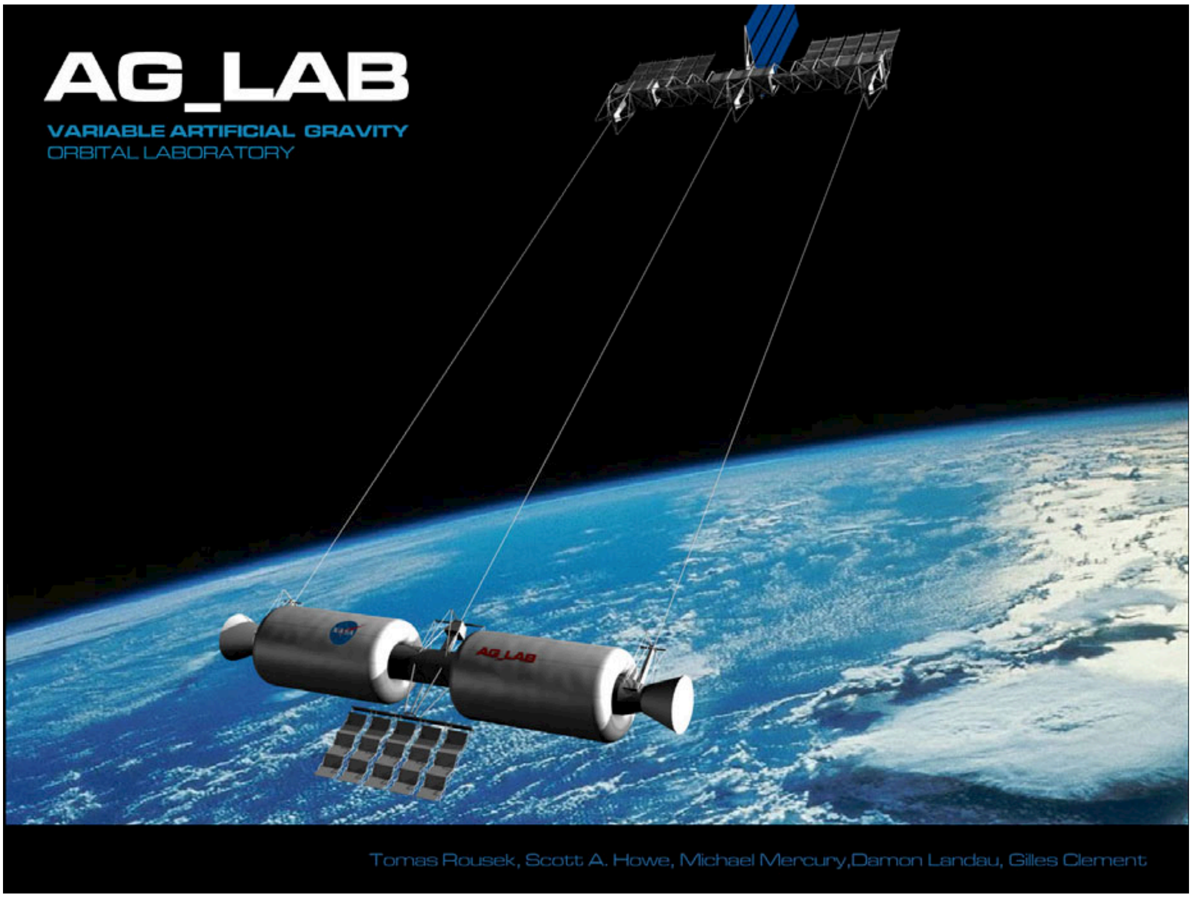

Figure 9. AG_LAB, variable artificial gravity research station.

3.1. AG_LAB Mission Objectives

AG_LAB is the project of variable artificial gravity research station in the Low Earth Orbit (LEO). This station (Figure 9) would enable long-term testing of artificial gravity environment as a preparation of missions to Phobos, Mars and beyond. This orbital facility would accommodate crew of eight people in two main modules - laboratory module and habitation module. The laboratory will offer both microgravity and variable gravity environments for experiments in life sciences, material science and space technology testing, life support systems among others.

3.2. AG_LAB Design Drivers

Spacecraft will be situated in Low Earth orbit similar to ISS, in altitudes of 300-450 km. The inclination of the orbit can be 28°, minimum inclination of Kennedy Space Center in order to increase possible payload mass to be delivered. The launch vehicle was selected Delta IV Heavy, capable of delivering more than 23 tons of the payload to LEO on this inclination (BOEING, 2010).

3.2.1. In-orbit servicing robotic spacecraft

The assembly of a structure consisting of number of modules without Space Shuttle has to rely on autonomous and teleoperated operations and use of robotics technology instead of astronaut skills. The concept could take advantage of in-orbit servicing robotic spacecraft that uses solar electric propulsion or Electro-Dynamic Tethers for boosting the modules from lower orbits to higher altitudes and increase the maximum payload mass (LORENZINI, E., Sanmartín, J., 2004). It can do rendezvous maneuvers with the station and perform assembly tasks necessary for completion of the station. Due to such technology, we would be able to launch heavier payload even with current rocket vehicles.

3.2.2. Artificial Gravity parameters

Spinning the whole vehicle generates the artificial gravity with centripetal acceleration in interval 0.1 – 1 g. The artificial gravity aboard station can have again variable parameters to test best combination for long exploratory missions. The radius of centrifuge would be ranging from 40 to 250 m at various angular speeds ranging from 0.5 rpm to 6 rpm. It is important to test the preferred Martian gravity 0.38 g for a long period comparable with the transfer to Mars and find the minimal configuration to save mass and cost of Mars transit vehicle. (CLEMENT, G., 2010).

The comfort zone estimates differ between the authors, the adaptation to Coriolis force will be crucial factor. The first generation of the station has axial orientation of a cylindrical habitat with respect to the axis of rotation (Figure 10). It has important advantages such as decreased effects of Coriolis accelerations when walking in the direction of the habitat axis, no necessary floor curvature or apparent slope and reduction of rotational illusions or dizziness. The drawback is the decreased stability of such formation; it is the least stable orientation that could need advanced attitude control (Theodor W. Hall).

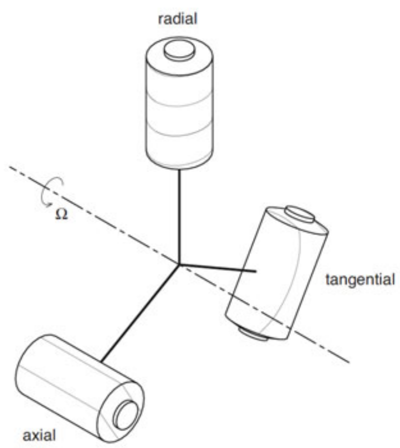

Figure 10. Orientation of the module with respect to the axis of rotation (HALL, T. W., 2002).

Such orientation could be maintained by small correction maneuvers as it was proposed already in sixties in Lockheed concept (Figure 11).

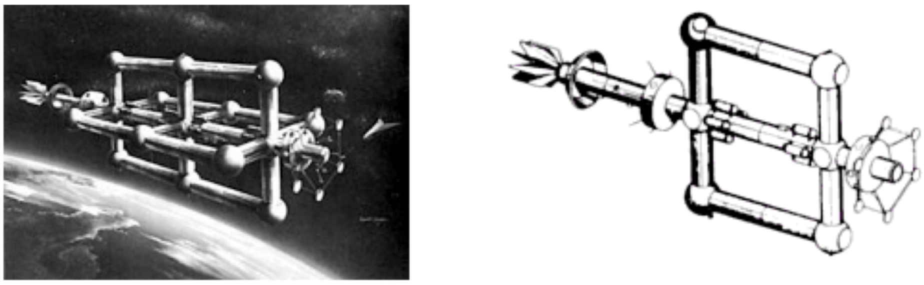

Figure 11. A Modular Concept for a Multi-Manned Space Station. (KRAMER, S. B., Byers, R. A., 1960).

3.3. AG_LAB Design Concepts

The station consists of two parts of centrifuge connected by tethers (Figure 12). Two TransHab-derived modules in horizontal configuration contain habitation and laboratories. Dragon capsules would deliver the cargo and logistics and be docked to two ports. Triple tether is used for increased safety and stabilization and is attached to reels with connecting interfaces and docking mechanism. The opposite part is on-orbit maneuvring unit with integrated power and propulsion subsystems of the station. It can also accommodate scientific experiments attached to unpressurized modules. The visualized design was originally intended for the polar sun-synchronous dawn-dusk orbit to get more solar energy at stable orientation of arrays, so there was increased radiator surface area. The station would be assembled in four to six launches of Delta IV Heavy. Assuming the price 254 million USD per launch, the launch operations of the whole station could actually cost about the similar budget as one average STS flight (WADE, M., 2009).

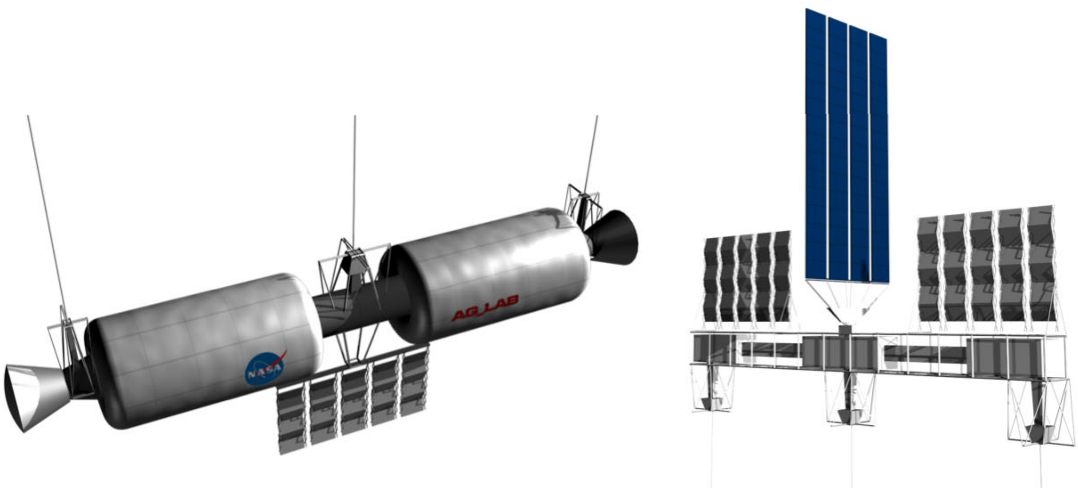

Figure 12. Elements of the AG_LAB station.

3.3.1. The inflatable volumes

The habitation module is CLASS II inflatable structure with rigid core and horizontal layout (Figure 14). Inflatables offer large living volumes using existing launch shrouds. The interior in Delta IV Heavy version of the TransHab in microgravity mode (Figure 13) could be divided into five floors that wouldn't be desirable (GRIFFIN, B., 2010).

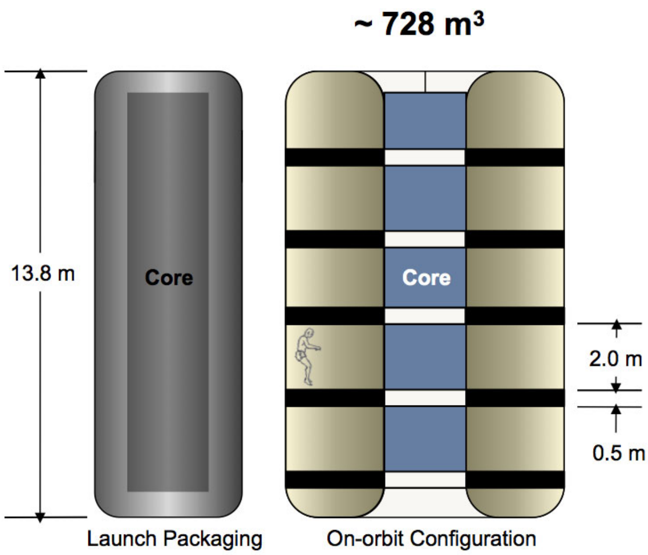

Figure 13. Vertical configuration of the TransHab module in dimensions according to Delta IV Heavy payload shroud (GRIFFIN, B., 2010).

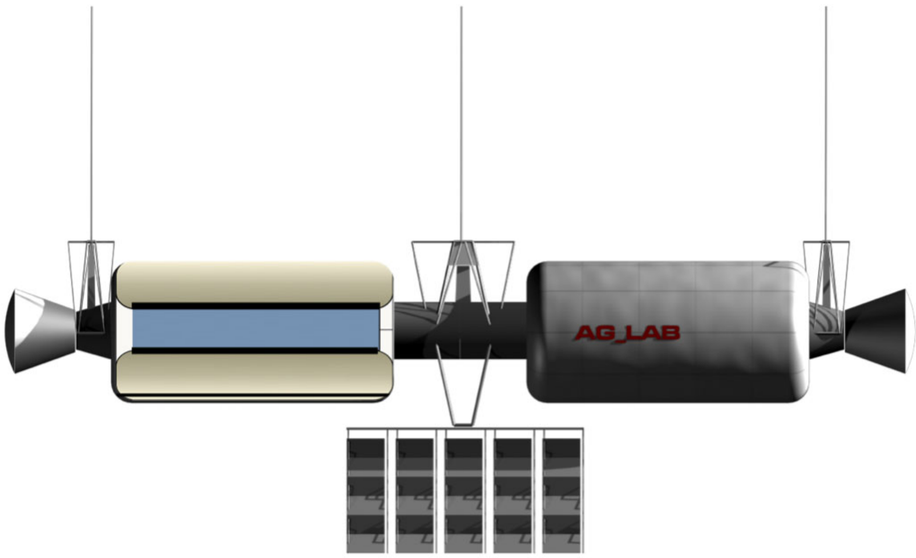

Figure 14. Horizontal configuration of the AG_LAB inflatable module.

The station should operate both in micro-g and artificial gravity modes. The rendezvous and docking has to be performed in the despun mode (Figure 15). The re-boosting of the station could be done in compact mode with stowed tether by means of the special secondary Electro-Dynamic Tether (EDT) system to save costs of imported propellant. ISS would save up to 1.2 billion USD on propellant for re-boosting in 10-year period if there would be implemented this technology using only 10% of the station power (LORENZINI, E., Sanmartín, J., 2004).

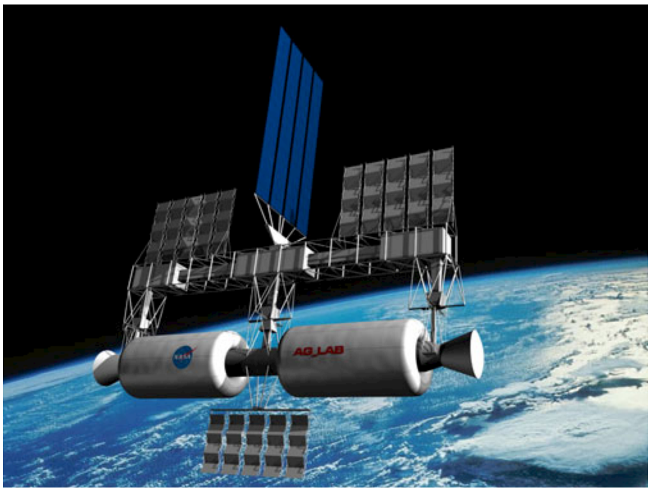

Figure 15. Despun Microgravity mode for rendez-vous and reboosting.

Figure 16. Deployment of the tether system.

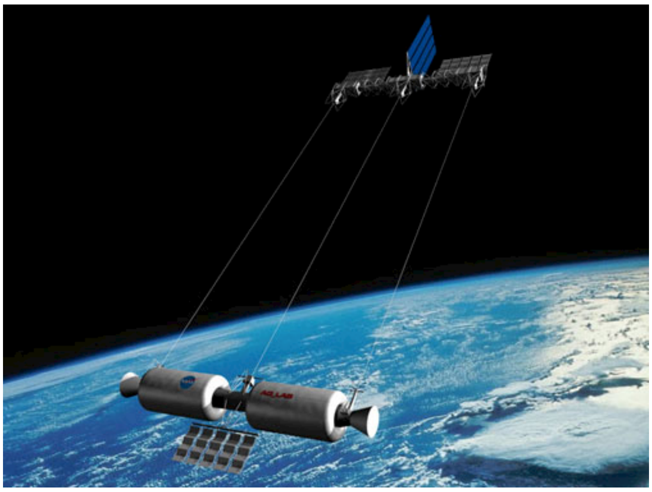

Figure 17. Spinning maneuvre.

3.4. AG_LAB 2G

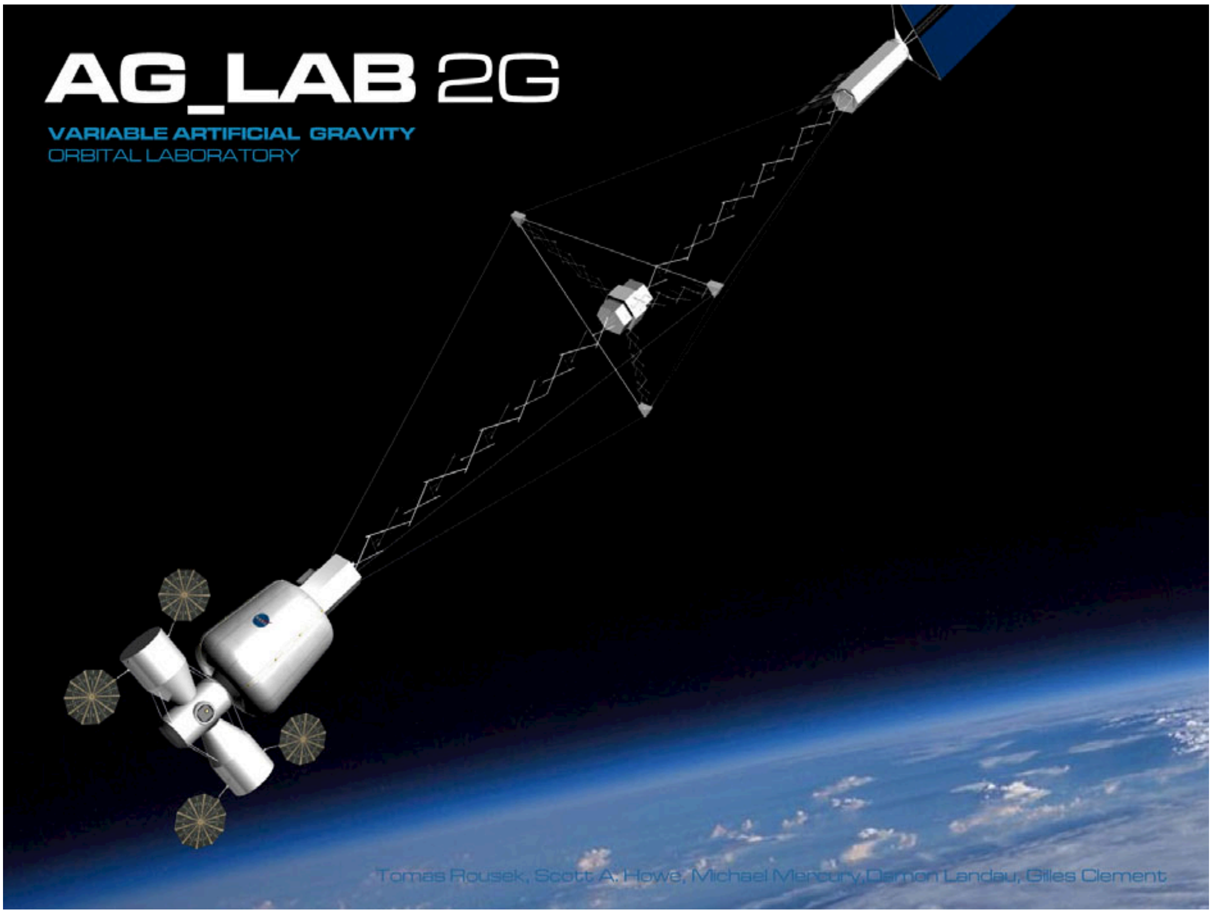

Figure 18. AG_LAB 2G, 2nd generation

Second generation of AG_LAB, AG_LAB 2G, is a precursor mission to Mars exploration mission. The structure is based on the lightweight deployable tensegrity truss boom (Figure 19) and vertically orientated modules. The prestressed tensegrity structure enables significant prolongation with variable length at very small weight. The principle of tensegrity is the ballance of tension and pressure elements in the structure that consists of carbon rods with kevlar strings. Additional tethers provide further stabilization of the truss boom against deformation to side.

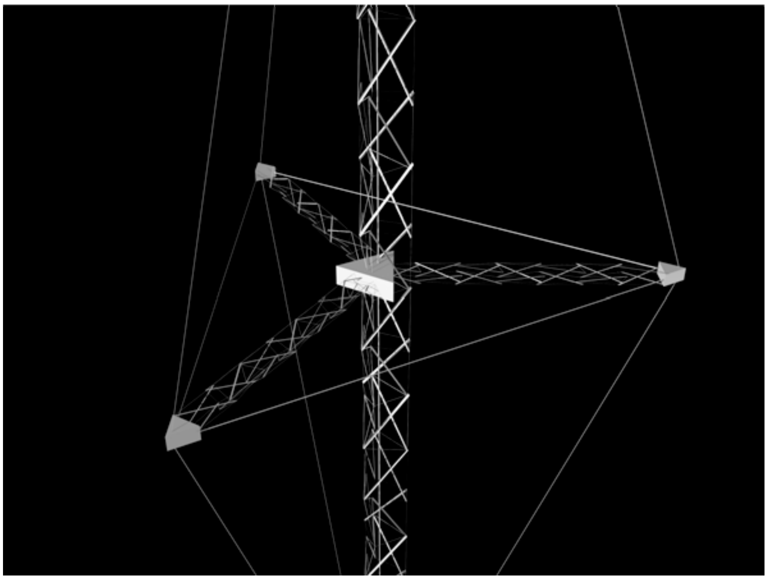

Figure 19. Tensegrity truss with tether system.

The alternative version of AG_LAB 2G uses UltraFlex solar arrays that have higher stiffness and are more suitable for AG (Figure 20). For example arrays of Orion capsule were designed for 3 g loads.

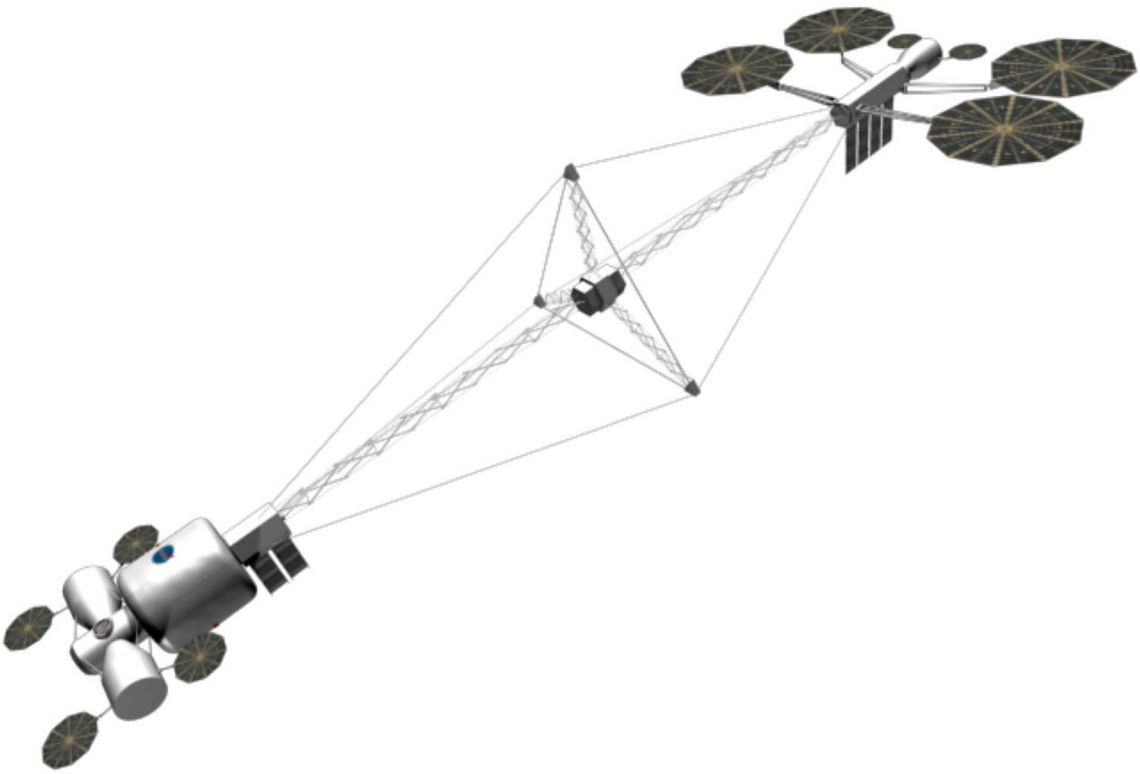

Figure 20. AG_LAB 2G with Ultraflex solar arrays.

3.5. AG_LAB Conclusion

The variable artificial gravity research station would be important contribution and test bed for development of next generations of artificial gravity vehicles for long exploratory missions. The negative factor is the cost, especially under current trend to get beyond the LEO orbit where the human space program stayed for decades. The future iterations of AG_LAB based on heavy-lift vehicle could use large inflatable volumes with rigid floor and free internal space to allow flexible interior outfitting in the similar manner to lofts; such facility would be real architectural laboratory. Then there would be possible to build interior elements with variable orientations and layouts to test them and discover best solutions for AG interiors.

4. AG_NEO

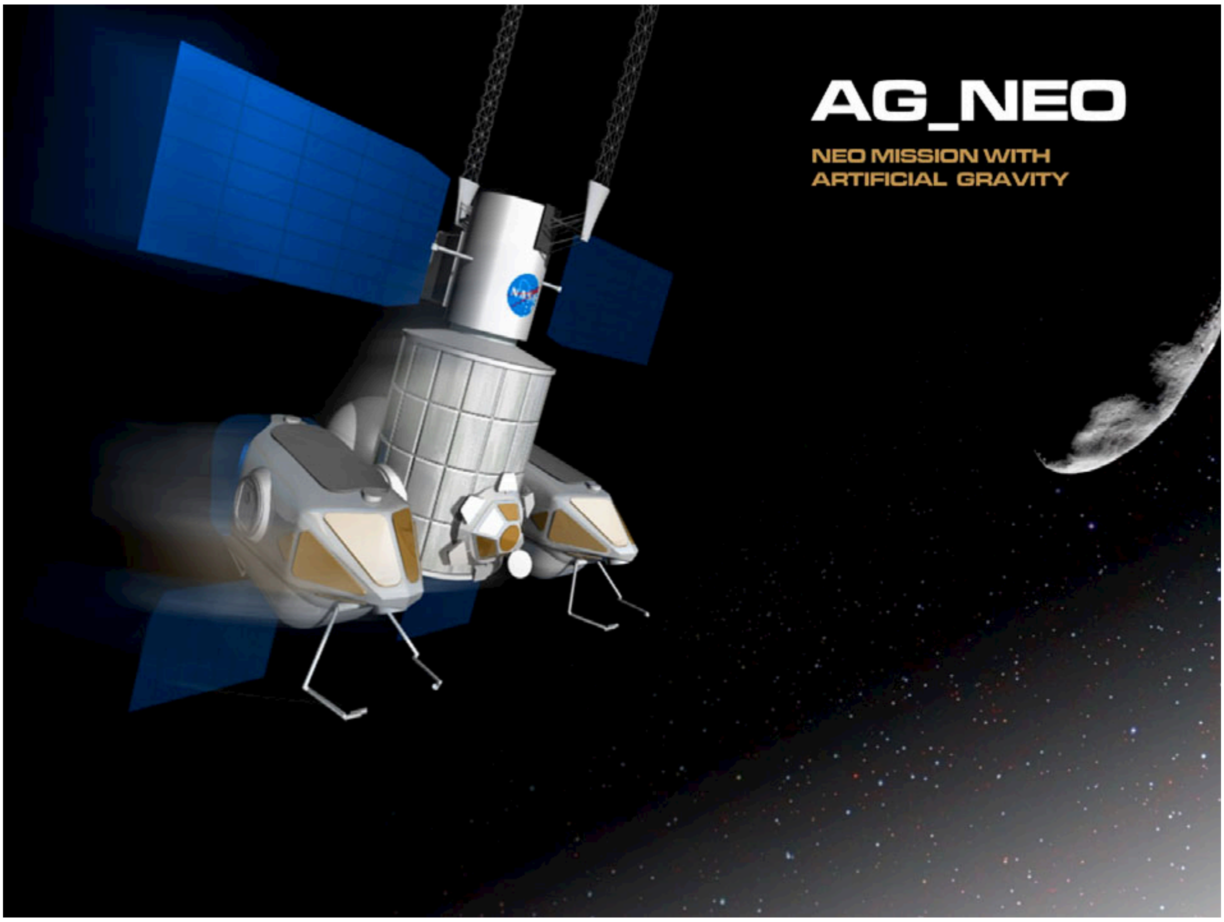

Figure 21. AG_NEO mission to asteroid with artificial gravity.

4.1. AG_NEO Mission Objectives

AG_NEO are mission concepts to Near Earth Objects (NEO) that would use artificial gravity and new Space Exploration Vehicles (SEV). The concept is based on the idea of Brian Wilcox (JPL) and it was presented Washington DC at "Explore NOW": Exploration of Near Earth Objects (NEO) Objectives Workshop on 11th August 2010. The main goal of the project was to propose feasible solutions for explorations of asteroids in the vicinity of Earth with the use of artificial gravity. Both 2 configurations of use SEV for final exploration and surface operations (Figure 21).

4.2. AG_NEO Design Drivers

The spacecraft should be capable of supporting the crew of 4 for missions in durations up to a year. The mission profile involves two spinning periods of the whole formation during the outbound and inbound trip. The assembly will be performed at ISS, booster will make insertion maneuver in the compact mode. The spacecraft will spin up to create artificial gravity after the insertion to the trajectory to asteroid and despin in advance to slow down. The main spacecraft will stow the tether in the NEO orbit before detaching SEVs. These then approach the surface to collect samples, crew will perform EVA operations with the use of the robotic arms. The trip back is performed in similar manner to ISS where the crew transfers to re-entry capsules.

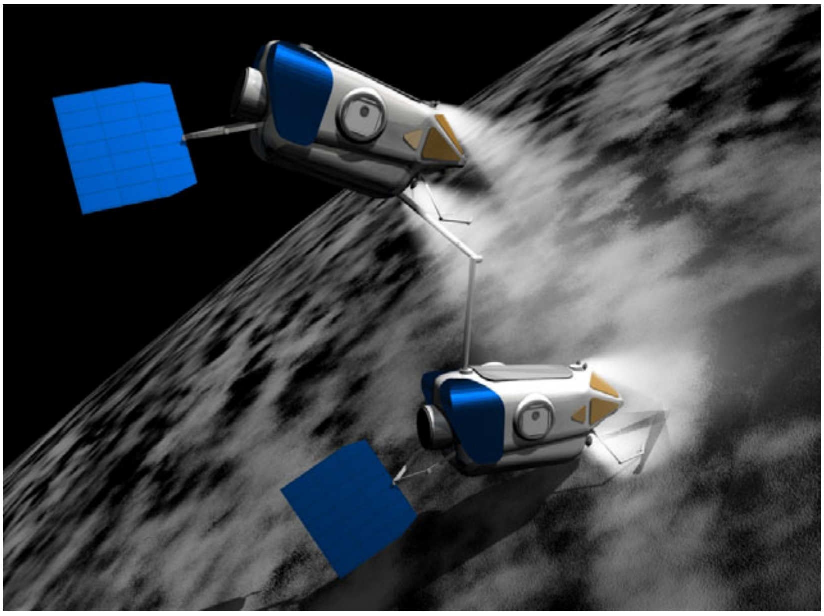

Figure 22. Surface Operations of 2 SEVs connected by robotic arm.

Two SEVs will be connected by a robotic arm, one of the SEVs approaches the surface of an asteroid and the other one is thrusting with its RCS system (Figure 22, Figure 23).

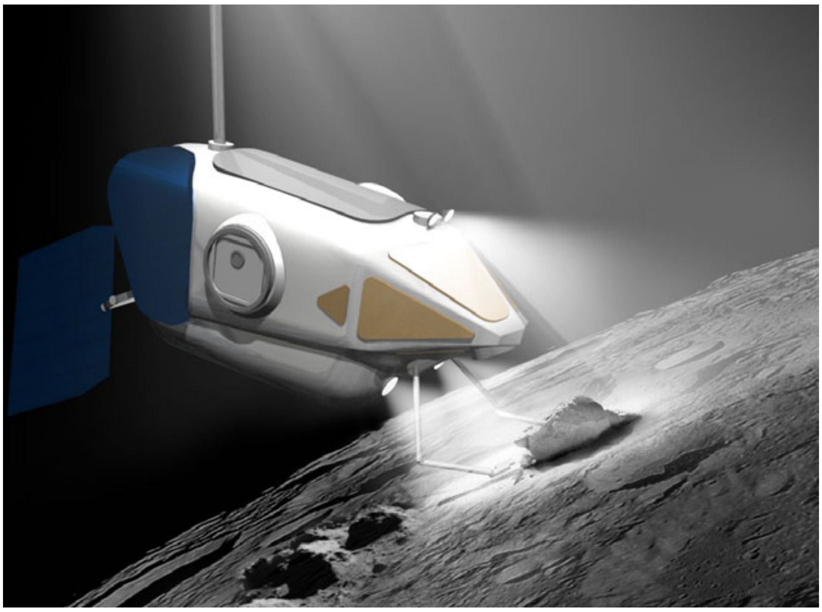

Figure 23. Collection of samples by robotic arms of SEV.

4.2.1. HoyTether

Double HoyTether (Figure 24) is implemented for increased safety, this concept uses 8 main lines and 16 secondary lines to avoid break caused by micrometeroid and debris impacts (HOYT, R. P., 2009).

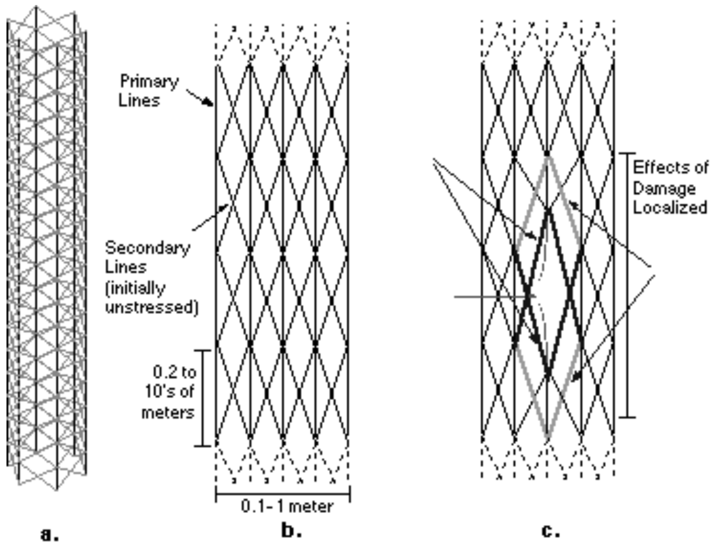

Figure 24. HoyTether multi-line system (HOYT, R. P., 2009).

4.2.2. Artificial Gravity parameters

The spacecraft will spin to generate 0.38 g centripetal acceleration equivalent to Martian gravity. The relatively lower gravity poses lower loads on the structures and mechanisms and eases the movement of the crew inside the module. Lower gravity is probably not efficient enough in stopping the bone loss and providing necessary traction for walking inside.

4.3. AG_NEO Design Concepts

Two different alternatives are based on the NODE3 of International Space Station (ISS) and inflatable AG_HAB.

4.3.1. NODE3 Version

The NODE3 module could be repurposed from ISS, attached to the reel interface with subsystems (Figure 25) and it can also have attached inflatable spherical storage compartment (Figure 26). Inflatable spherical storage compartment is necessary to provide additional storage due to limited volume of NODE 3 and SEVs can be used as crew quarters for sleeping.

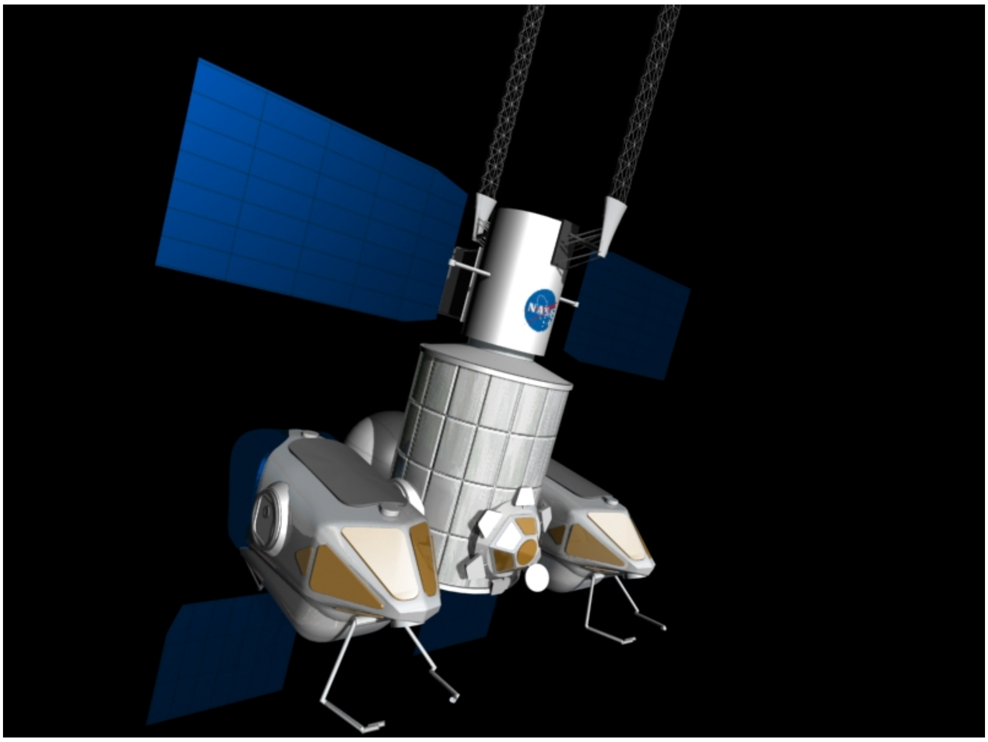

Figure 25. NODE3 Configuration.

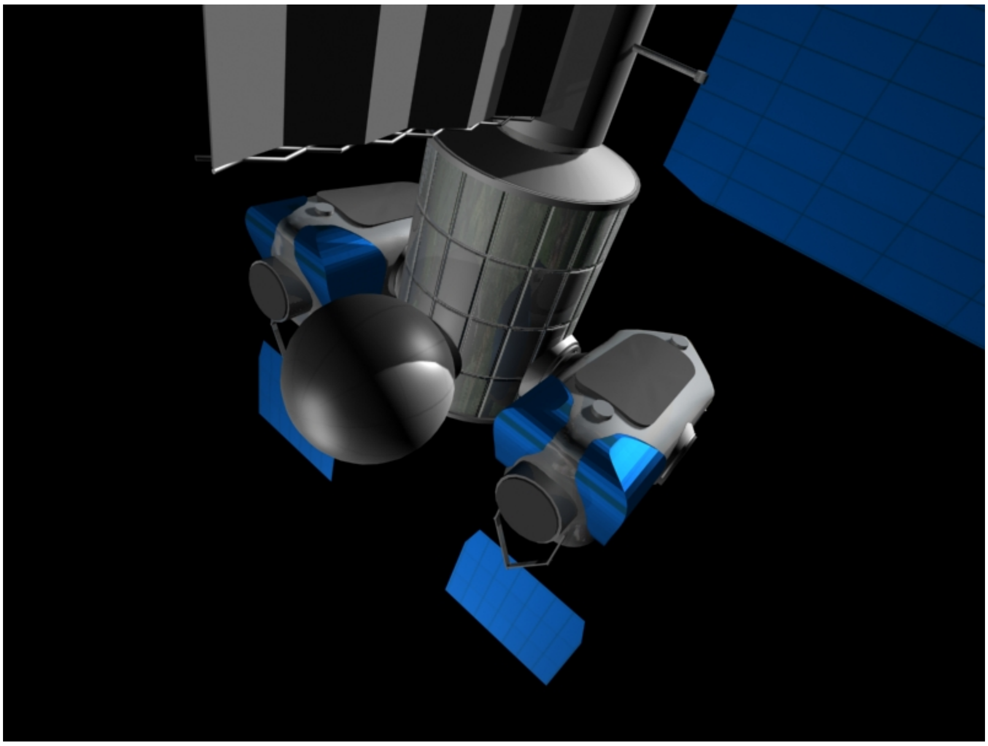

Figure 26. NODE3 Configuration with inflatable spherical storage compartment.

The counterweight of the centrifuge is a propulsion stage for insertion maneuvres (Figure 27). This has attached module with additional subsystems and reels that deploy dual multi-line HoyTether for increased safety.

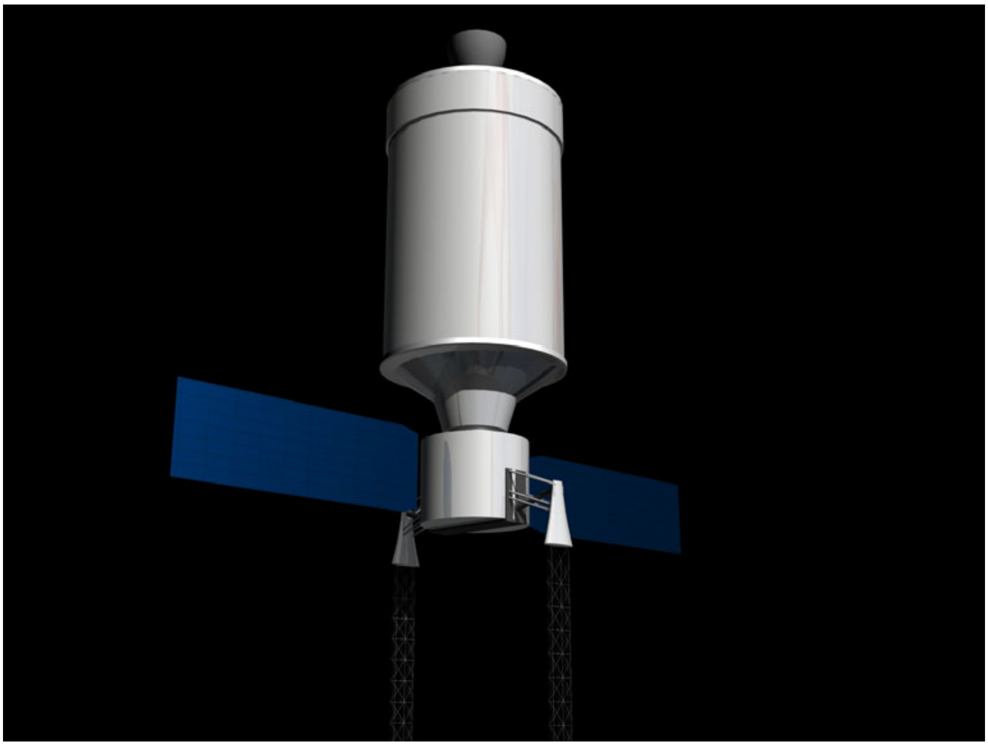

Figure 27. Propulsion segment of the centrifuge.

4.3.2. AG_HAB Version

AG_HAB is TransHab-based solution adapted to artificial gravity environment (Figure 28). These enhancements involve deployable sloping rigid floor structure, interior layout directing the prevailing and critical movements in the axial direction to avoid Coriolis effects, use of Logistics2Living (L2L) approach and lightweight furniture that is inflated or assembled from L2L parts. One third of the core is pressurized to allow store critical systems and storage in pressurized environment before inflation of the membrane. Dimensions of AG_HAB are according to the Delta IV Heavy payload shroud, conical shape enables to increase the inflated volume.

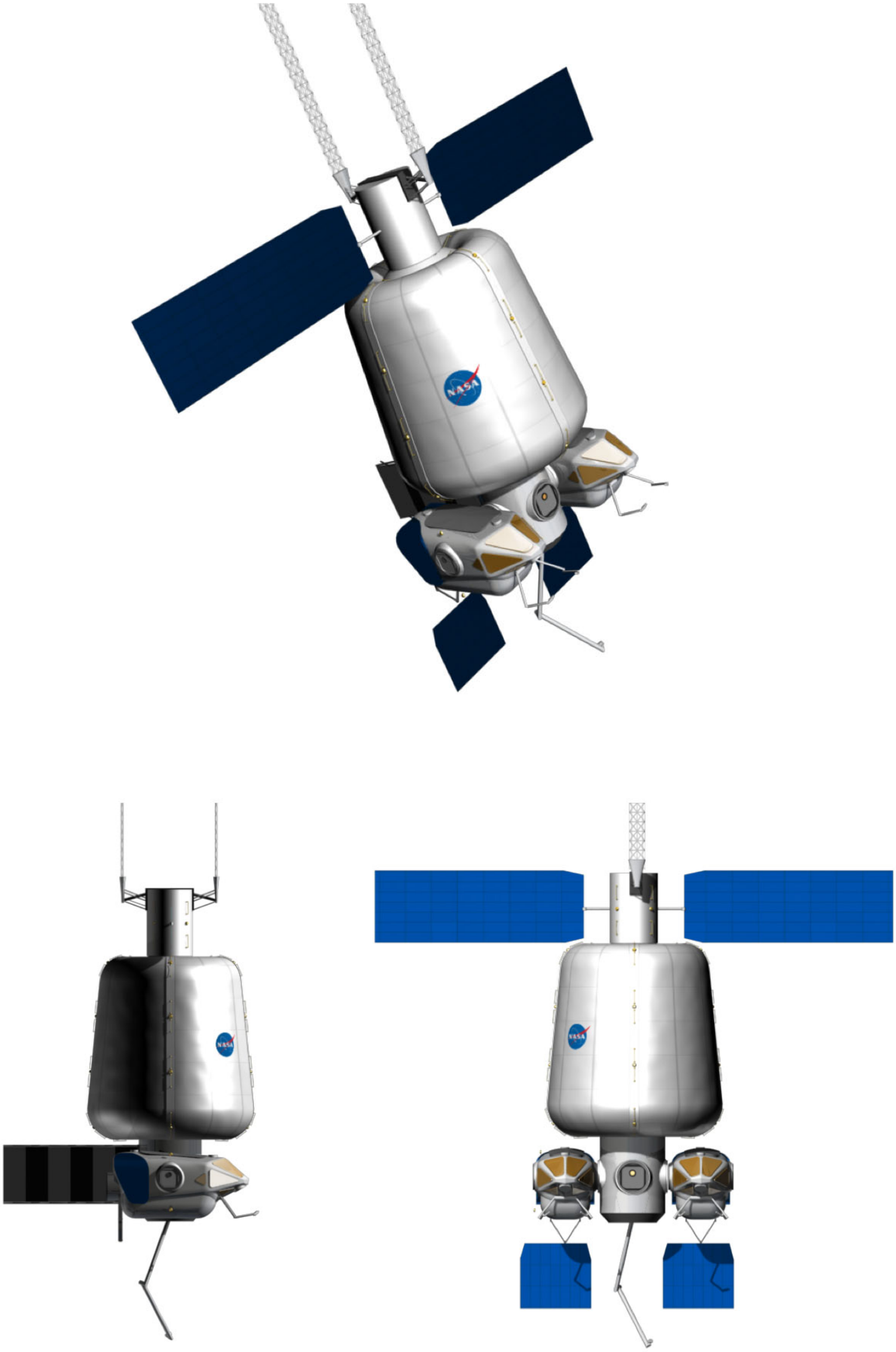

Figure 28. AG_NEO Concept with inflatable habitation module AG_HAB.

AG_HAB has attached node module with hatches and second module with subsystems and reels. Two SEV vehicles are connected to the node module and can serve as alternative accommodation for crew (Figure 29). Robotic manipulator arm can move around the whole structure like Canadarm in the inch-worm style and connect to interfaces distributed on the surface of the spacecraft. The membrane is covered by stripes with handles and attachment point from protective reasons (Figure 30).

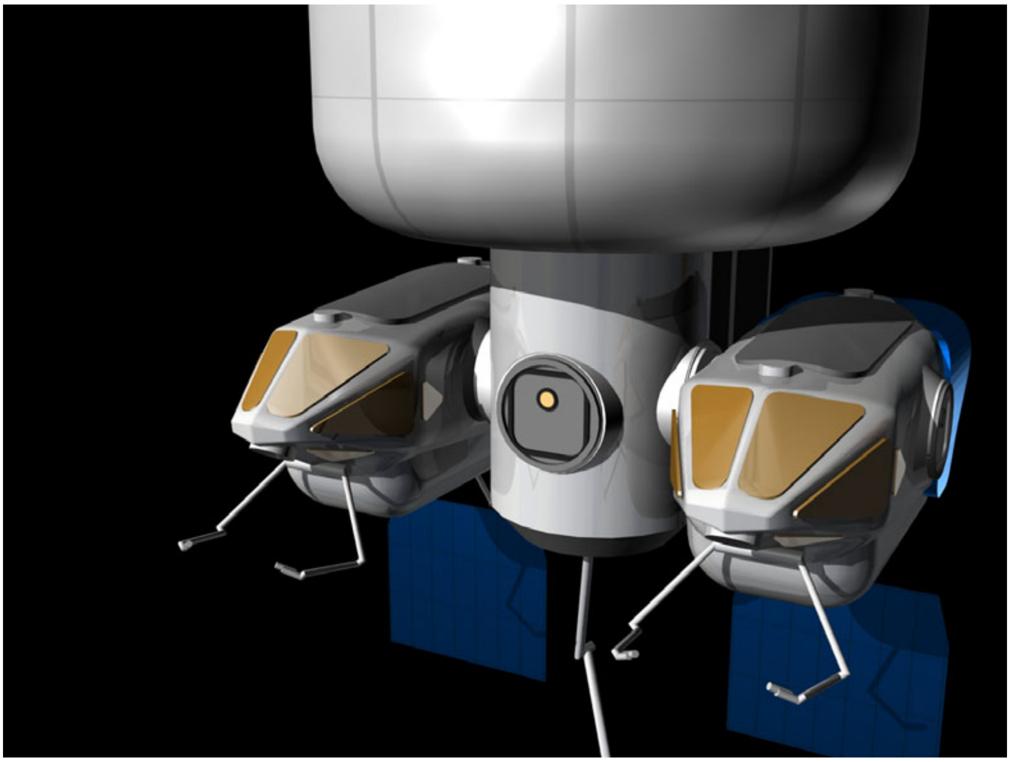

Figure 29. Inflatable AG_HAB Concept

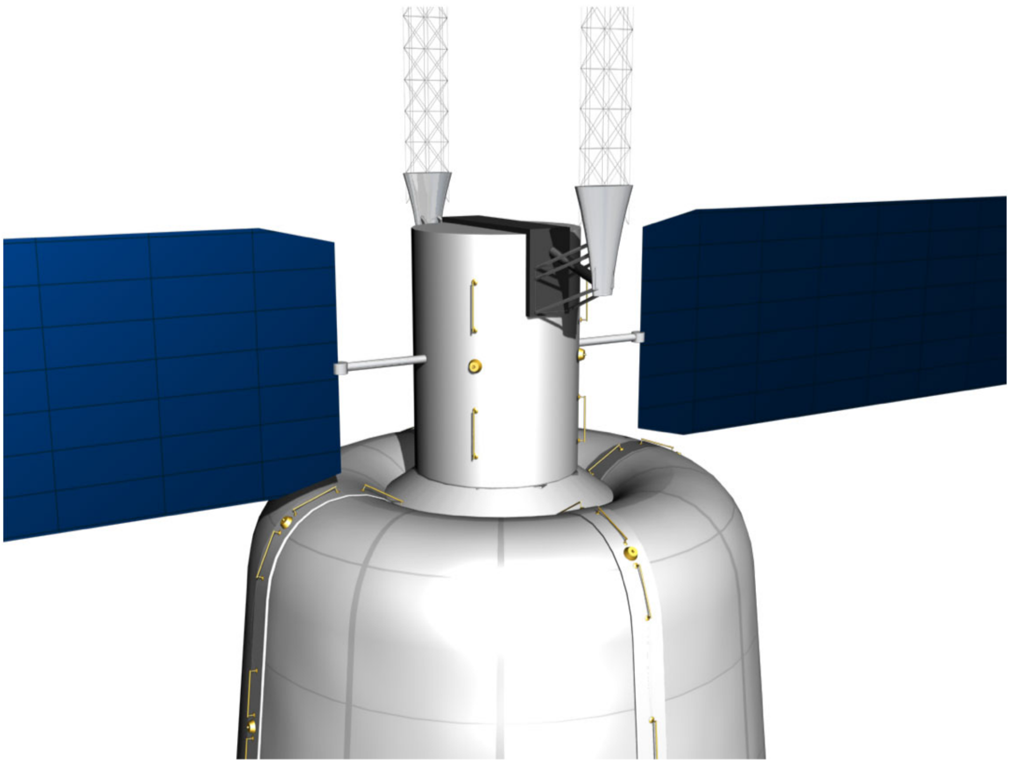

Figure 30. Inflatable AG_HAB Concept, subsystems module with tether reel.

4.4. AG_NEO Conclusion

The mission to NEO is compromise direction of NASA that currently doesn't want to return to Moon and is not ready to go to Mars in near-term. The strategy shifted from destination driven architecture to operations driven approach, to be able to go anywhere. It may appear as a more cost effective approach, but it may bring many technical challenges due to different and specific requirements of the various destinations in solar system. Such NEO mission would be the first step towards longer deep space missions. Our approach is precursor mission to test new hardware such as inflatable habitats and also to bring inspiration for the future utilization of ISS hardware in the end of its lifetime, which is an idea resonating with current recycling trends. AG_NEO project was presented on the workshop "Explore NOW": Exploration of Near Earth Objects (NEO) in Washington, D.C. on 10th August 2010 and got global media feedback for example in NewScientist, MSNBC or Russian RIA NOVOSTI.

5. AG_CYCLER

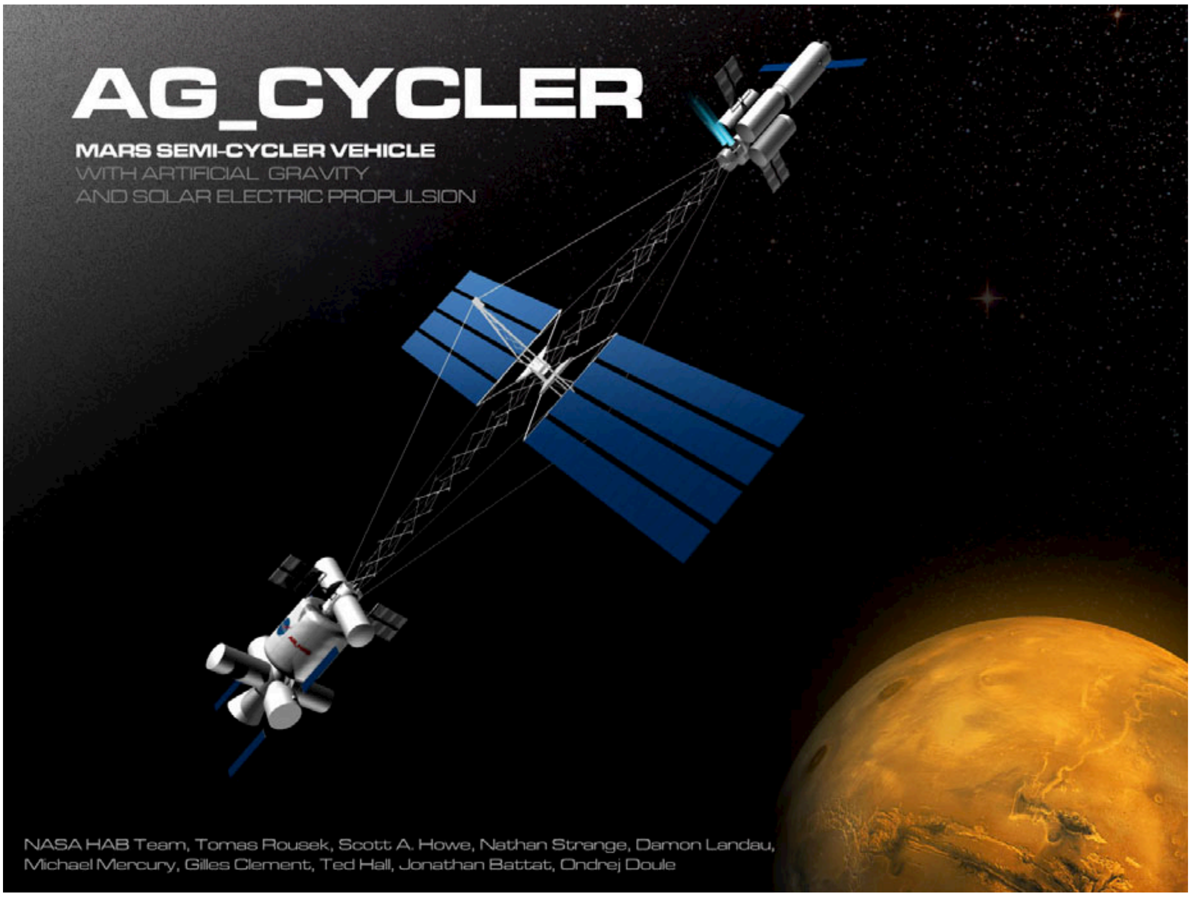

Figure 31. AG_CYCLER, semi-cycler spacecraft on mission to Mars.

5.1. AG_CYCLER Mission Objectives

The Mars mission is currently the primary rationale for artificial gravity research. If we consider conjunction-class mission to Mars in the length approximately 900 days including flights approximately 180 days long, some kind of artificial gravity solution would help preventing the undesirable physiology effects. (CLEMENT, G., Bukley. A., 2007).

Idea of the Aldrin's cycler, Mars cycler trajectory and vehicle invented by former Apollo astronaut Buzz Aldrin, proposes to use spacecraft that stays in the trajectory between Earth and Mars. (BYRNES, D.V., Longuski, J.M., Aldrin B., 1993) Taxis that accelerate to necessary speed would deliver the astronauts, cargo and propellant to the flyby transit spacecraft (Figure 31). This would help decreasing the necessary mass delivered from Earth by heavy habitation and propulsion modules that can be used for multiple missions. Such spacecraft would be usable for crew rotation and support of sustainable exploration of Mars with permanent base such as MB 10 (Figure 32) to lower the costs and decrease the trip length.

Figure 32. Permanent Mars Base 10 (DOULE, O., 2009).

The AG_CYCLER is conceptual design of Mars transit vehicle that would implement Earth-Mars (E-M) semi-cycler strategy. The spacecraft would park in the Martian orbit where it would wait for the return of the crew from surface. Then it would be accelerated for Trans-Earth Injection by chemical booster stage delivered to Mars orbit separately (BYRNES, D.V., Longuski, J.M., Aldrin B., 1993).

The concept of AG_CYCLER was developed in the design sessions at JPL together with Nathan Strange, Damon Landau, Jonathan Battat and Scott A. Howe and with consultancy of Theodore W. Hall, Gilles Clement and other members of AG_TEAM.

5.2. AG_ CYCLER Design Drivers

The major design drivers of the spacecraft are Solar Electric Propulsion (SEP) and artificial gravity generated by spinning of the whole vehicle. In the gravitational environment, many current elements developed for microgravity need to be redesigned, such as the interfaces between modules or support structures of solar arrays.

5.2.1. Solar Electric Propulsion (SEP)

AG_CYCLER would be using the Solar Electric Propulsion (SEP) during the journey in the interplanetary space. According to the estimates of Nathan Strange and Damon Landau, Boeing FAST solar arrays should produce 400 kW of power. The SEP engines should be two HAL thrusters with diameter 1m, using 50-60 tons of Xenon propellant. The aerobraking in the compact mode would decrease the speed when arriving to orbit. For the insertion maneuvers would be used LOX/LH2 booster. The SEP engines would use Offset Thrusting method (Figure 33) to maintain artificial gravity during transfer maneuvers for tethered spacecraft. (LANDAU, D.F., 2008). This method was developed for short correction maneuvres with chemical propulsion, but it could be applicable to SEP as well according to the author. The alternative configuration would be axis of rotation pointing to the Sun and gambling thrusters located on the both sides of centrifuge.

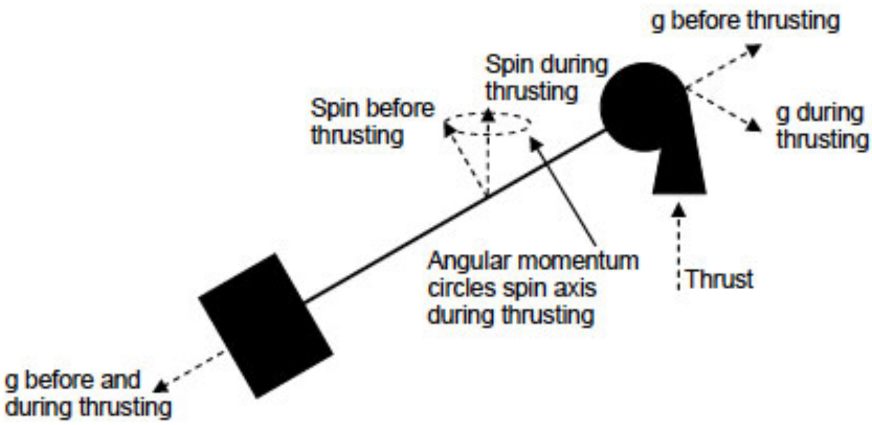

Figure 33. Offset Thrusting during the spinning (LANDAU, D.F., 2008).

5.2.2. Artificial Gravity Parameters

The Martian gravity 0.38 g could be used as nominal gravity level aboard spacecraft, enabling the crew to pre-adapt to Mars environment and investigate the response of the body to upcoming surface stay (CLEMENT, G., 2010). According to SpinCalc, online artificial-gravity calculator developed by Theodore W. Hall, the radius of the rotation should be 84 m while spinning at Angular Velocity 2 rpm generating 0.38 g acceleration. The "optimum" Comfort Limits recommendation by Robert R. Gilruth is 67 m radius at Angular Velocity 2 rpm generating 0.3 g acceleration (GILRUTH, R. R., 1969) (HALL, T. W., 2000).

Since we are proposing the rigid truss and the center of gravity will move towards the habitat while spending the propellant, thus shortening the radius, we would use the shorter recommended 67 m radius measured to the center of habitat. On the inbound trip, the rotation speed could be increased to 2.5 rpm, slightly above the estimated comfort zone limits, generating 0.3 g with shorter radius of 42 m. These limits should be experimentally tested prior to Mars mission in variable gravity orbital station or other experiments. If the Coriolis force caused discomfort, the crew could slow down the rotation speed on demand, the spinning speed change requires relatively small Delta-v budget.

5.3. AG_ CYCLER Design Concepts

The spacecraft consists of three main parts, HAB segment, propulsion segment and deployable tensegrity truss boom with solar arrays (Figure 34). The masses should be balanced in order to achieve better dynamic behavior of the whole structure. The vehicle will operate in two modes, microgravity as well as artificial gravity modes. The truss should be shortened for the TMI and TEI maneuvers. Solar arrays are attached to the central part where they have smaller weight in artificial gravity field and therefore smaller load on the gambling mechanisms, which increases their lifetime and reliability. Three perpendicular trusses in the middle of tensegrity truss are also deployable, so they can be shortened in the breaking mode or during insertion maneuver.

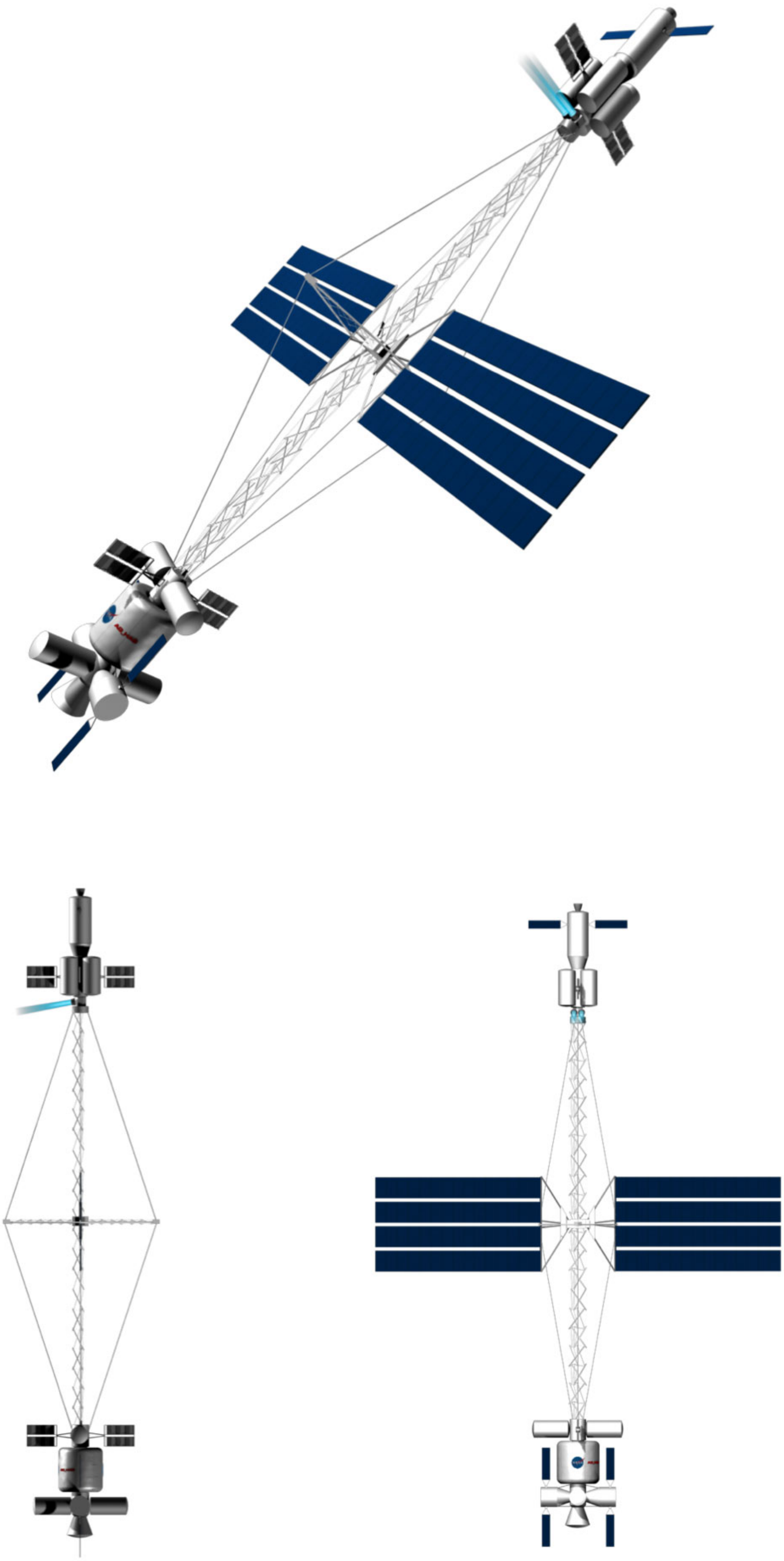

Figure 34. Elements of the AG_CYCLER.

5.3.1. HAB segment

Habitation module (HAB) is derived from TransHab inflatable solution and will be designed according the AG_HAB proposal. To this module will be attached two nodes that will connect crew and cargo taxi capsules, Multi-Purpose Logistics Modules (MPLMs) and Mars lander capsule (Figure 35). The upper node will accommodate truss interface and radiators.

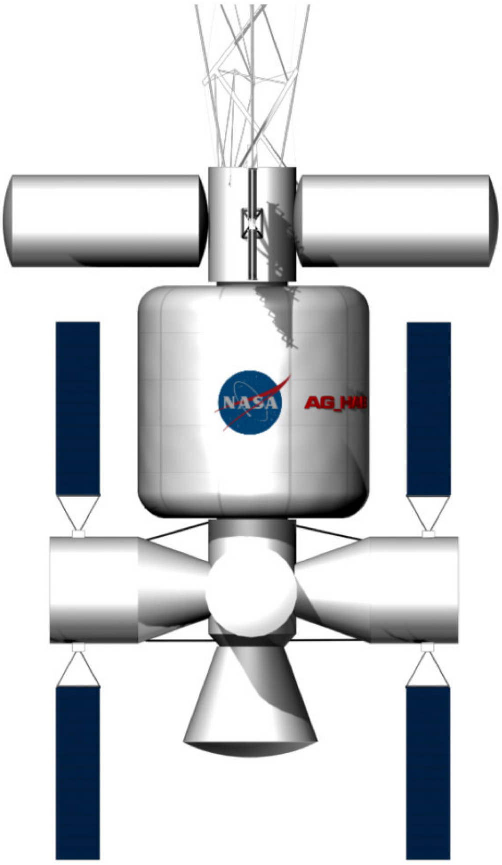

Figure 35. HAB Segment

5.3.2. Propulsion segment

The spacecraft uses dual propulsion and the main parts of propulsion segment is chemical LOX/LH2 booster and HAL thrusters with Xenon propellant tanks (Figure 36). The radiators should provide adequate cooling capacity to keep the propellant at nominal temperature. The second booster for Trans-Earth Injection will be delivered to Mars parking orbit separately to achieve linear increase of the mass budget instead of exponential. In the propulsion segment will be also placed reel mechanisms for tethers.

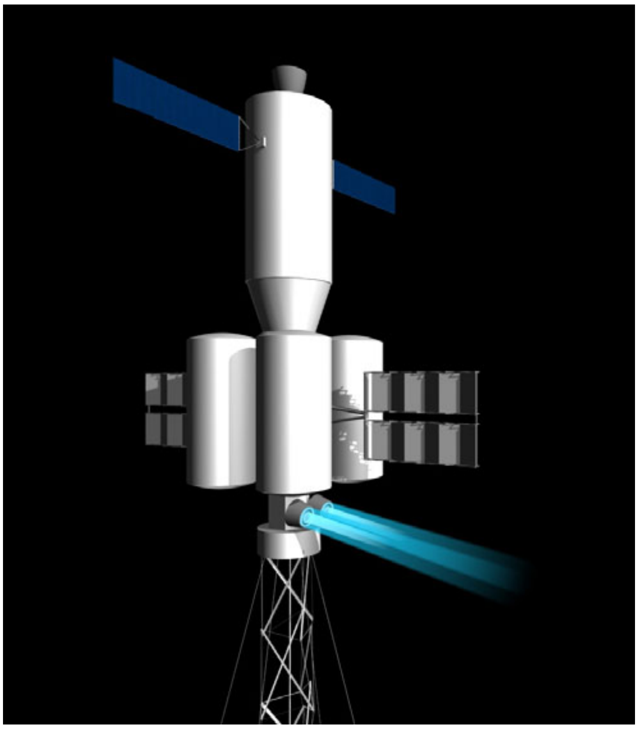

Figure 36. Propulsion Segment

5.4. AG_CYCLER Conclusion

This spacecraft is an alternative to nuclear powered Mars transfer vehicle concepts. The utilization of solar energy brings many operational challenges; it has to maintain attitude to Sun and the structure has more difficult dynamics. The alternative configuration in next iterations will be orienting the axis of rotation pointing to the Sun and gambling thrusters on the both sides of centrifuge.

6. AG_HAB

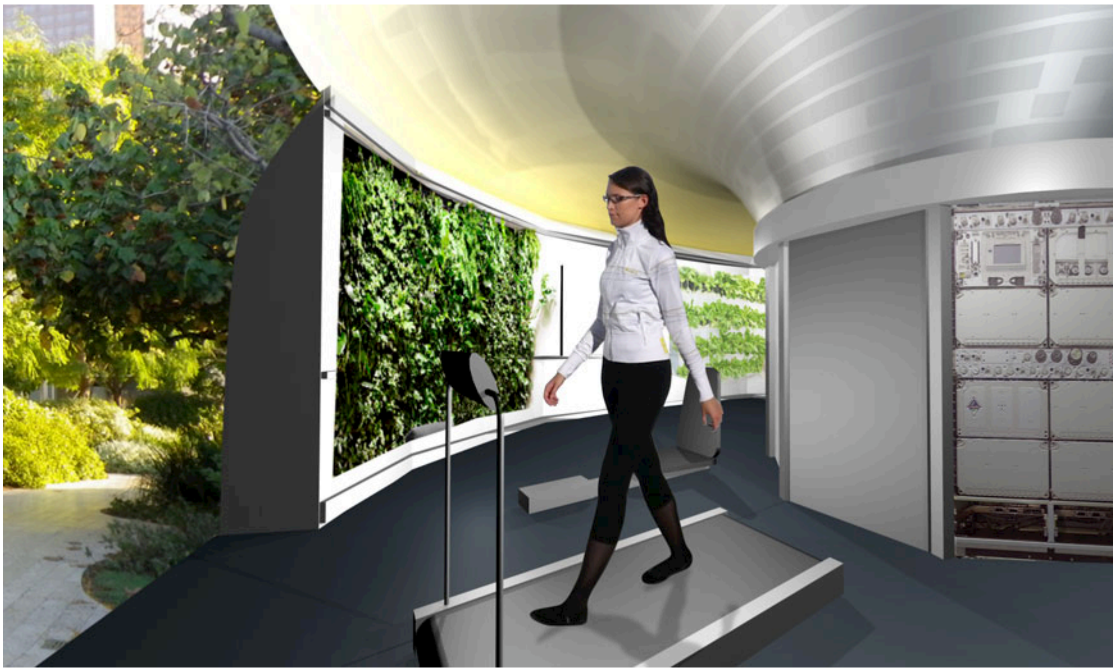

Figure 37. Interior visualization of the 3rd floor of AG_HAB.

6.1. AG_HAB Objectives

The goal of the AG_HAB interior study (Figure 37) is to integrate new features specific for artificial gravity environment into inflatable TransHab-derived module. This module would be used in AG_LAB 2G, AG_NEO, and in bigger version also in AG_CYCLER spacecraft. The theoretical platform of the interior design is the research of Theodore W. Hall on habitability factors in artificial gravity environment.

6.2. AG_HAB Design Drivers

The design addresses major issues of the manned deep space missions - radiation and physiological problems of bone loss and muscle atrophy. The AG_HAB module can accommodate up to 6 people and laboratories for life-science experiments in both microgravity and artificial gravity. Such facilities can become a test bed for development of new long duration exploration technologies directly in the environment where they will be used. The inflatable habitat provides increased volume for partially bio-regenerative life support system that could be tested before the Mars mission.

The membrane structure should be protected as much as possible. Therefore it has decreased number of interfaces, openings and attachments; large virtual windows replace small physical windows in order to protect membrane, decrease complexity, increase reliability and reduce the release of the gases (HOWE, S. A., 2010).

6.2.1. Artificial Gravity interior

The vertical orientation of the module is not ideal compared to axial or tangential and is determined by the attachment to the truss boom and other structures. Coriolis force heavily influences the movement in vertical direction (Figure 38) and in many previous published spacecraft proposals have wrong orientation of ladders that could be actually dangerous (HALL, T. W., 2002). Therefore AG_HAB has two ladders for movements upwards and downwards.

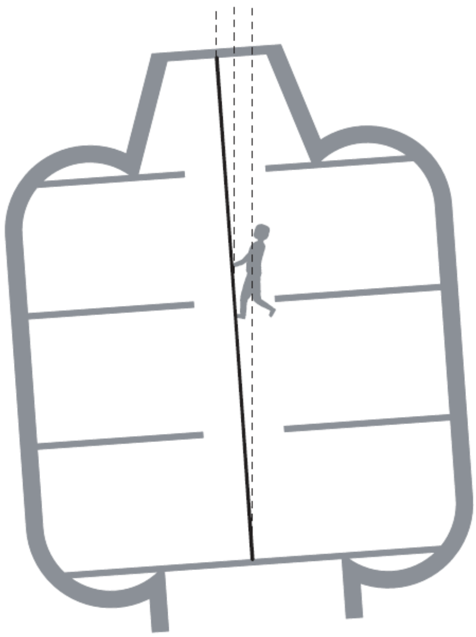

Figure 38. Vertical descending movement on ladder creates apparent inclination that can cause hanging of person if used from opposite side (HALL, T. W., 2002).

The interior design can offer visual clues that help astronauts to orient in the environment with Coriolis force. These should inform about the direction of the rotation and can be formally created by special design of the lighting, colors of light, arrow shapes and other means (Figure 39). The augmented reality interface can enhance the visual perception by virtual objects and overlay graphics that can show virtual windows, navigation and control elements and 3D video communications (Figure 40).

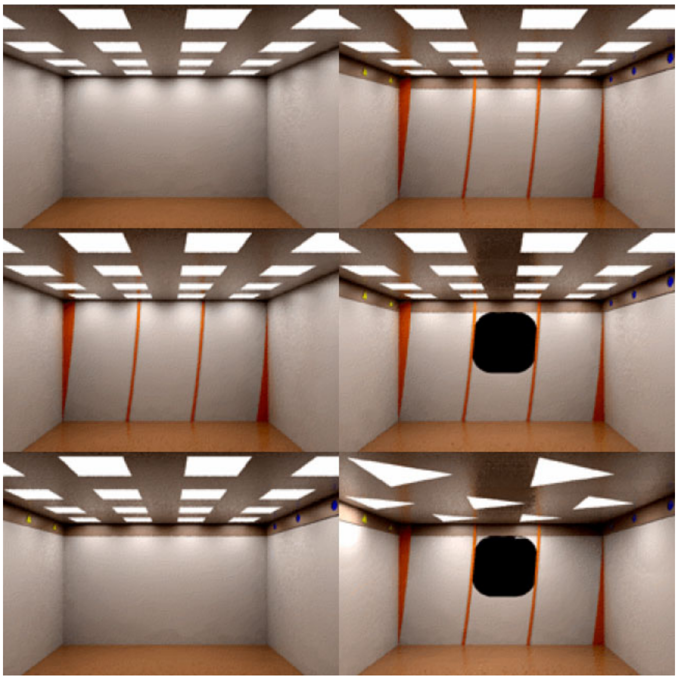

Figure 39. Indication of the rotation in AG interior (HALL, T. W., 1997).

Figure 40. Interior visualization of the "NASA Eyes on the Earth interface".

6.2.2. Radiation and micrometeorite protection

The radiation protection comprises of multiple layers of different materials. The complex TransHab membrane comprises of more than 10 layers of webbing, pressure bladder, insulating and protective layers made of Nextel, Kevlar, Mylar and Polyethylene among others. Protective properties were tested by impact of 1.8 cm particle at 7 km/s and provided higher micrometeorite and debris protection than traditional aluminum structures of ISS (CADOGAN, D. et al., 1999). Also low atomic weight materials shield high-energetic particles better than high atomic weight metals (BADHWAR, G. D. et al., 2002).

6.3. AG_HAB Design Concept

The shape of volume is conical according to the gravity field geometry in the section perpendicular to the axis of rotation. The habitat is designed for Delta IV Heavy payload shroud, where the conical shape allows achieving bigger floor radius and volume in lower floors while keeping the upper floor radius smaller for stowing the floor segments.

6.3.1. Logistics-2-Living and radiation protection

Logistics2Living approach is innovative way of dual utilization of packaging used in logistics. The covers and structures of the packages can be turned into furniture, walls, radiation protection (Figure 42) and many other purposes. CTB packages (Figure 41) can supply habitat with packaging material with double membrane that will be filled and turned into water walls for increased protection in critical regions (HOWE, S. A., Howard, R., 2010). Polyethylene and the hydrogen-impregnated materials can be layered hanging on the walls. The stowed packages full of consumables and equipment create thick layers along the outer membrane walls while the crew activities are concentrated around the rigid metal core away from walls.

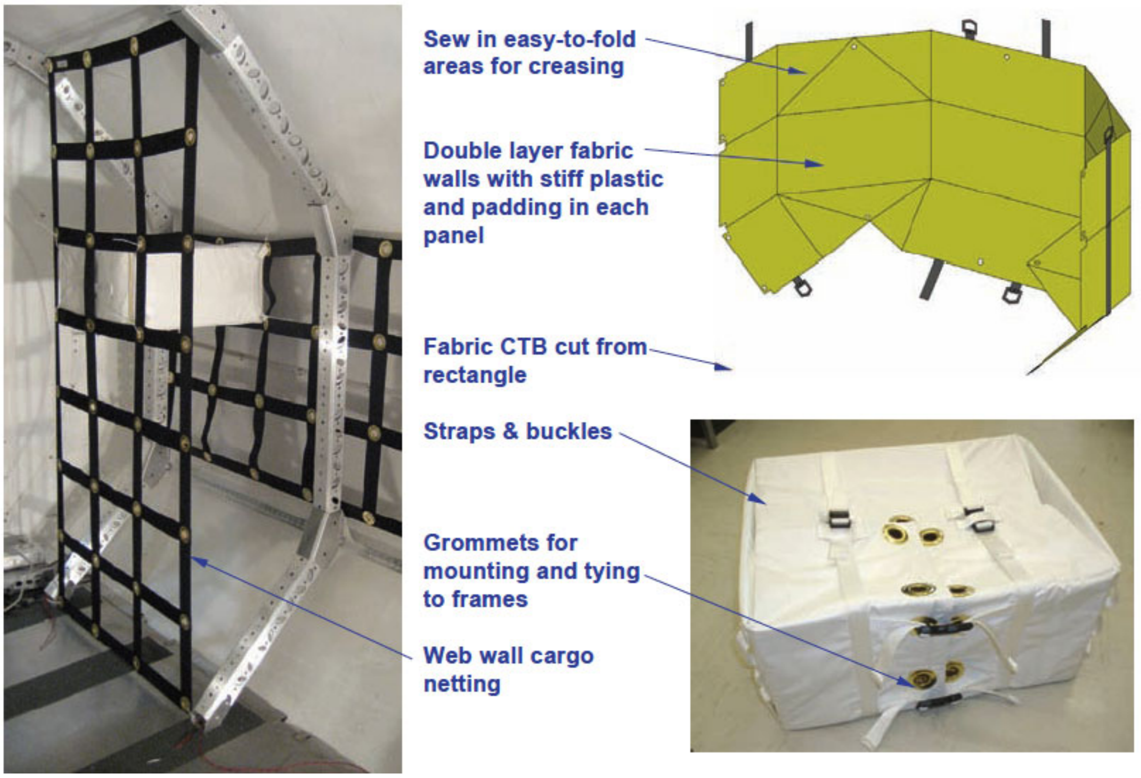

Figure 41. CTB logistics packages can be used for multiple purposes (HOWE, S. A., Howard, R., 2010).

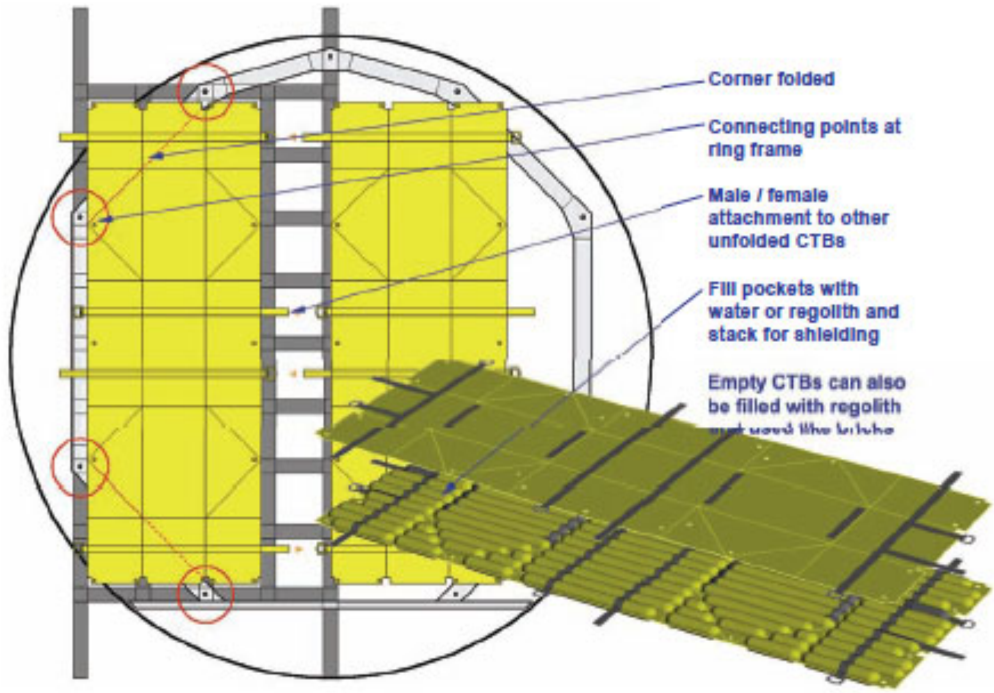

Figure 42. L2L waterwalls for radiation shielding or partitions (HOWE, S. A., Howard, R., 2010).

6.3.2. The Section of AG_HAB

The vertical communications are combination of stairs and a ladder (Figure 43), while the stairs are more suitable than ladder because the both hands are not occupied and can hold objects (HALL, T. W., 2002).

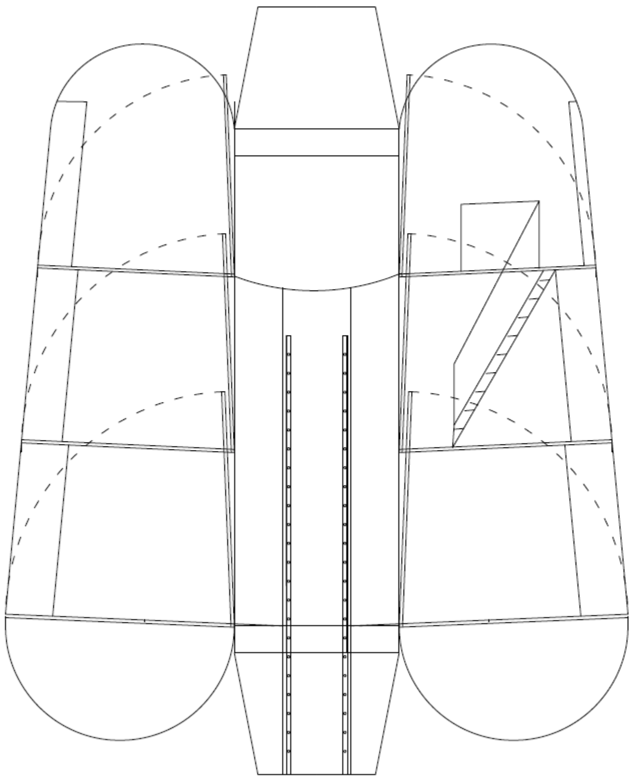

Figure 43. Section plan.

6.3.3. The layouts of AG_HAB

In gravitational environment, the floor area is more important factor for utilization than the volume. The floor is divided into 3 segments (Figure 45) that are sloping according to radial AG field (Figure 44). This enables to use rigid deployable floor system originally developed by HAB team for lunar surface systems toroidal inflatable modules. The maximum deviation from ideal curved floor is 1.5 cm, which creates slope tolerable for habitability and movement of the crew.

The floor deploys from the rigid core as eight basic rectangles that are then deployed to sides to cover the whole surface area (Figure 46). The deployment would be performed in microgravity mode.

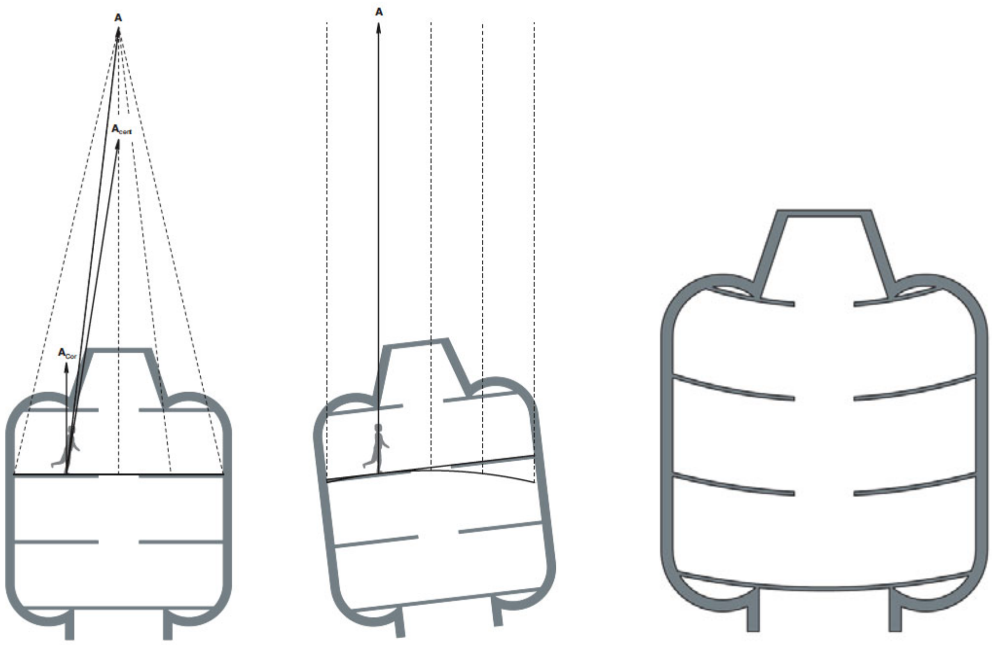

Figure 44. TransHab interior in AG - apparent slope of the flat floor and curved floor (HALL, T. W., 2002).

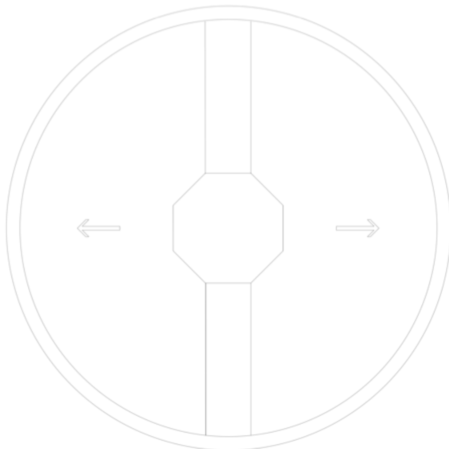

Figure 45. Three segments of the floor with 5 degree slopes.

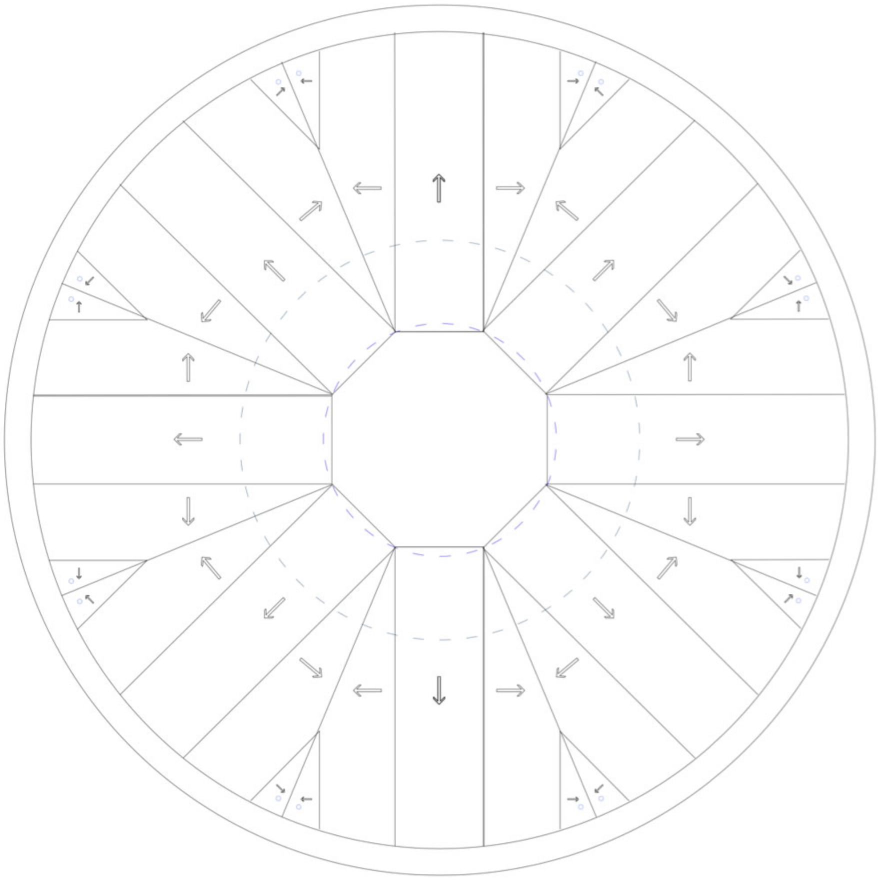

Figure 46. Deployable Floor System

The layouts in the beginning implemented the recommended circulation of people in axial direction, but the crew sitting at the outer walls is more expose to the radiation than in the middle and also the integration of deployable tables, electronics and other equipment into the rigid core is better due to multiple gravity modes.

The first floor (Figure 47) is divided into three zones - working, dining and relaxing. The walls are covered by CTBs and racks with experiments that are integrated into metal structure, not connected directly to membrane.

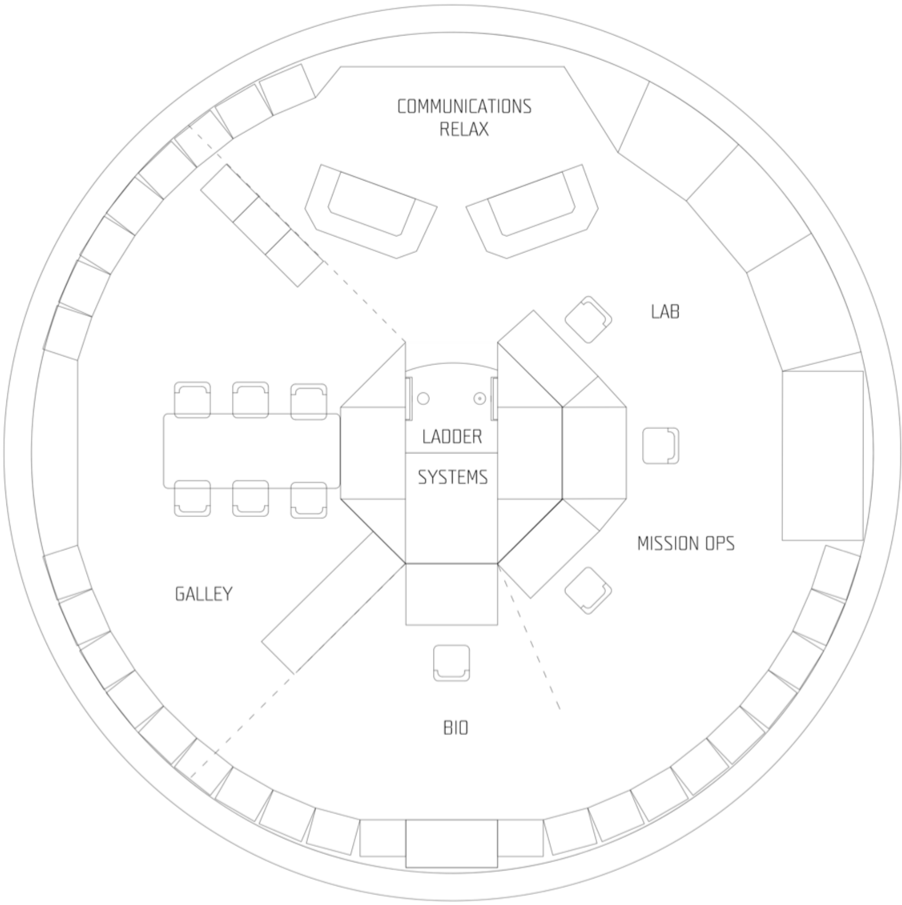

Figure 47. Layout of the 1st Floor.

The crew quarters (Figure 48) accommodate 6 crewmembers and are constructed with the use of Logistics2Living elements. The CTB packages constitute the walls, are used for creating water walls around the beds for increased radiation protection, and also are used for assembling furniture beds (Figure 49) and other furniture. The beds are oriented to avoid cross-coupling of the head pitch and body when standing up in prograde ("east") or antigrade ("west") directions. This is also ideal orientation of the workstation places (HALL, T. W., 2010).

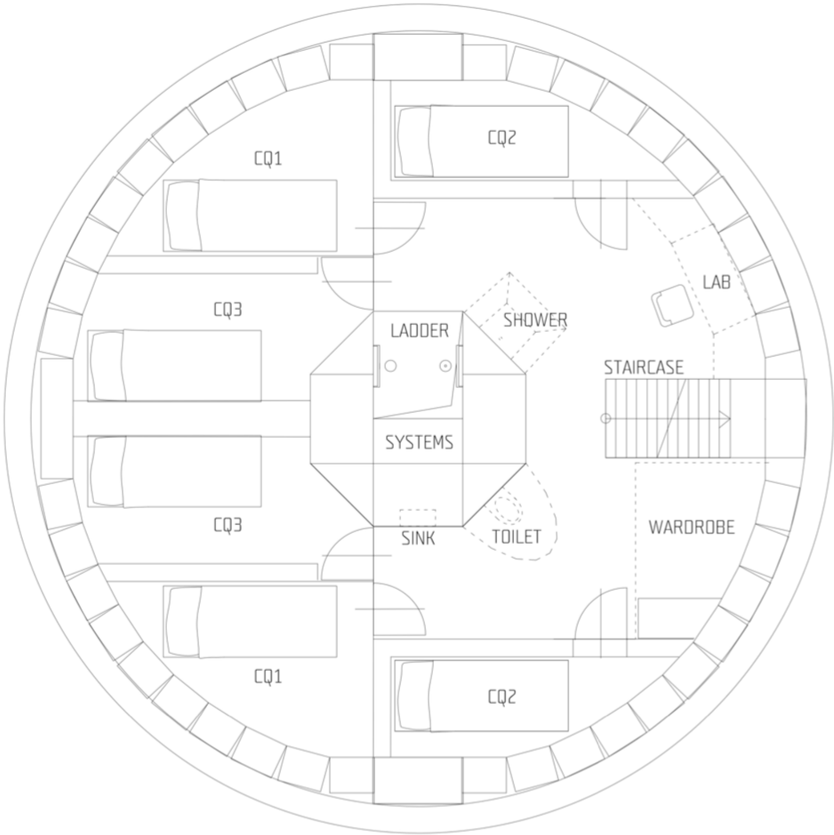

Figure 48. Layout of the 2nd Floor.

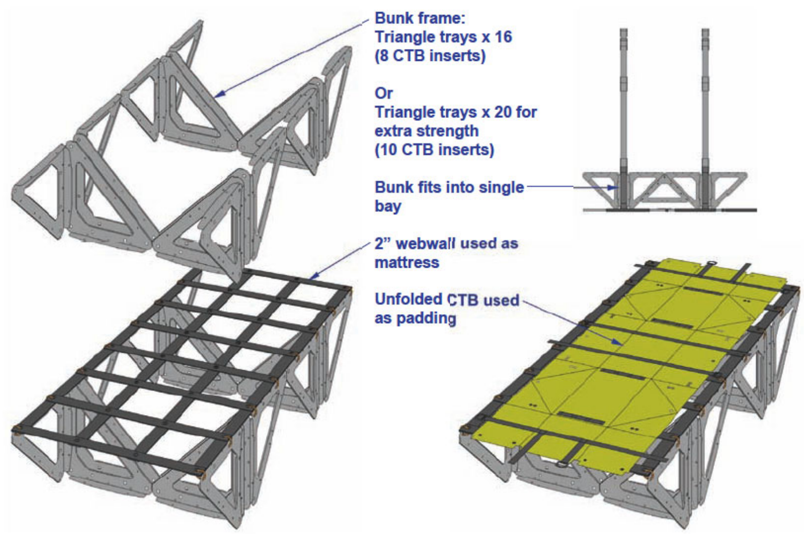

Figure 49. The design of the L2L bed (HOWE, S. A., Howard, R., 2010).

The main activities on the third floor involve exercise, laboratory work and medical ops. The pressurized part of the core is accessible through the hatch. The garden for food production and as a part of life support system has spatial vertical configuration for efficient use of the volume.

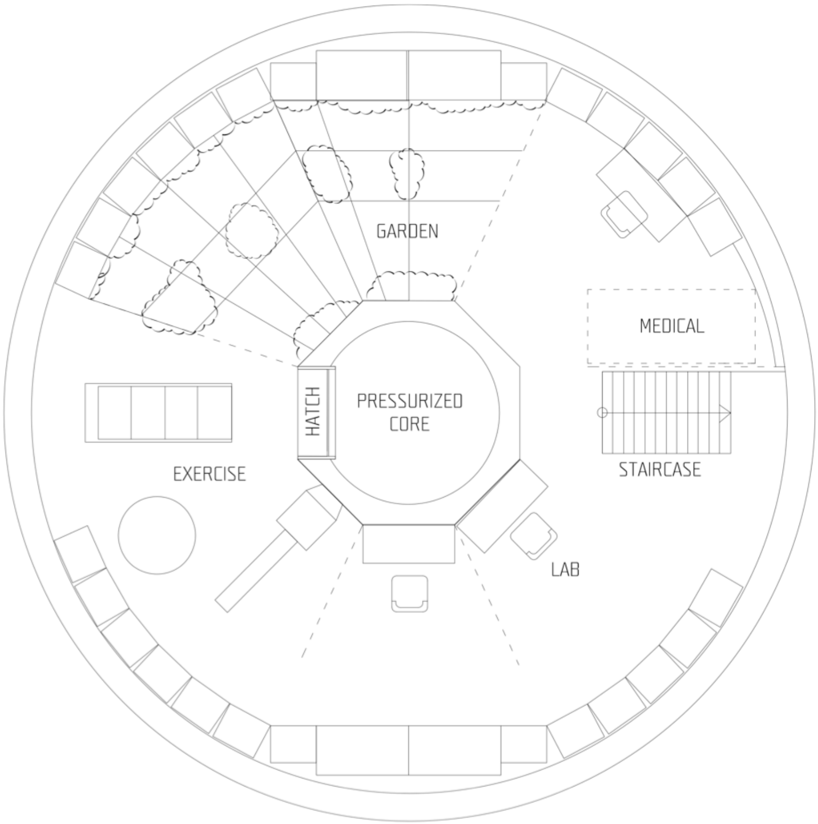

Figure 50. Layout of the 3rd Floor.

6.3.4. The process of deployment and outfitting

The module would be ideally launched and connected to ISS, where it could use its infrastructure and astronaut skills for outfitting the interior. The inflatable membrane is stowed and launch without containing the air in the beginning, then slowly inflated and the floor deployed. The core has pressurized compartment for necessary systems and storage and has hatch for access from third floor.

6.4. AG_HAB Conclusions

Artificial gravity environment introduces different approach to designing the interiors. To assure maximum comfort and workability, we would need several generations of vehicles to find optimal configurations and variable gravity in LEO could be valuable experiment. AG_HAB also includes an experimental garden for testing of new bio-regenerative life support system elements and other systems for future deep space missions.

7. Conclusions

This project is still in the beginning of the longer process and could serve as inspiration for new exploration systems. AG_X and AG_NEO were already presented on two workshops in Washington, D.C. about future utilization of International Space Station and "Explore NOW": Exploration of Near Earth Objects (NEO) and were considered for being used in Human Exploration Destination Systems technology roadmap work at NASA JSC.

We propose the missions with cost as one of key considerations that lead to smaller scale experiments in the beginning such as repurposing the ISS module, using existing launch vehicles on the market and other solutions. Any artificial gravity experiment would be very valuable and the scientific community would get real data about artificial gravity utilization, since majority of current research is based on terrestrial analog research and few experiments.

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