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Artificial Gravity Conceptual Orbiting Station Design

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Abstract

One of the key challenges of long term human presence for exploration and research in low earth orbit is the microgravity environment. This environment is a key enabler for research on today's International Space Station (ISS), but is also a major factor contributing to negative effects on the human body and mind. In order to expand the capabilities of a future orbiting station the element of artificial gravity will need to be added.

During the summer of 2016 a team of space professionals looked into the design challenges of a large orbiting facility in low Earth orbit. This design challenge was part of the Space Studies Program 2016 of the International Space University, hosted at the Technion Israel Institute of Technology in Haifa. This orbiting facility should not only support microgravity and other space-based research, but also be a place to live, work and visit for much larger numbers of people than current space stations.

The Artificial Gravity Conceptual Vehicle Design includes key engineering and design considerations for a crewed low Earth orbit space station, which uses rotation to provide artificial gravity. It will have a center section which will provide a microgravity environment for research and manufacturing, and will also serve as the docking location for the station. This vehicle will be a grand complex. It is designed to be orbited in the 2035 to 2040 timeframe, and it will make living and working in space commonplace. The station will be very large and provide an environment compatible with work and tourism. It is expected that up to 200 people may reside on the complex at any one time. Workers and their families will live onboard. A hotel to house tourists will be part of the complex. There will be schools, stores, green areas with ponds or streams, a cinema, restaurants, etc.
Keywords: (artificial gravity, space station, design)

1. Introduction

For over a century space stations have been part of the dream of space exploration, first contemplated by visionaries such as Konstantin Tsiolkovsky and Hermann Oberth [1]. This new concept offered the opportunity to establish a human presence in orbit by creating an environment in which humans could live and work. As the space age dawned, space stations were seen as a place in which astronauts could take advantage of a microgravity environment for scientific research and technology development [2].

The aim of this project was to design a commercial space station on behalf of Axiom Space LLC. The station contains an artificial gravity section and a microgravity section, both of which shall be fully operational by 2040.

By 2045, the station will allow 200 people to live in an Earth-like environment, while enabling space tourism, in-orbit manufacturing, and scientific research. This study focuses primarily on the engineering and life sciences challenges, and also takes into consideration societal, business, and legal aspects. This paper is an output from our team project; further details can be found in the project report [3]. Early in the project we chose a team and station name: Starport 1. This name will be used to refer to the station in this paper.

We begin this paper with a comprehensive overview of the mission architecture, including a timeline for its implementation (Section 2). The overall design of the Starport 1 station is provided in Section 3, including the station configuration and subsystems. Section 4 describes the procedures for launching, assembling, operating, and de-orbiting Starport 1. Human performance and the corresponding life support systems on Starport 1 are discussed in Section 5. The station's governance and social structure are discussed in Section 6. Potential business models and income streams for the station are explored in Section 7. The legal and policy aspects of the station, including ownership and government funding, are described in Section 8. Section

9 concludes the paper and summarises the key points of the Starport 1 station.

1.1 Overview of concept

Artificial gravity space stations have become prominent in public perception through their depiction in science fiction, more recently with the Hermes station in The Martian [4], and the space city portrayed in the film, Elysium [5]. However, the first proposals of artificial gravity come from the "father of astronautics", Konstantin Tsiolkovsky, who suggested how a rotating spacecraft could be used to counteract microgravity effects on humans [6]. We explored a variety of proposed artificial gravity station concepts as we sought the general concept for Starport 1.

One of the early designs for an artificial gravity concept was Dandridge Cole's 'Bubbleworld' [7]. This involved capturing and hollowing out an asteroid, and then spinning the asteroid to provide artificial gravity. The supposed advantage of this is that the materials needed to build the structure are mostly already present (the asteroid itself). One of the big roadblocks in this concept is: i) it assumes a mature industrial space mining industry with the technological capability to achieve this, and ii) a suitable near-Earth asteroid available for capture during the period the station is to be operational. This concept was rejected given the significant amount of uncertainty

In 1974, Gerard K. O'Neill proposed the O'Neill cylinder [8]. The concept consists of a huge, pressurised, cylindrical steel structure that rotates about its cross-sectional centroid to provide artificial gravity. Envisioning a space settlement that could house up to 10,000 people in the first stage of assembly, O'Neill suggested a concept that ensures a massive internal volume. In addition to huge mass and material costs that would arise from such a concept, O'Neill suggested having two counter-rotating cylinders to counteract gyroscopic precession. We decided that constructing this station would be too expensive and impractical for a 200 crewed space station by 2040.

There have been many examples of rotating wheel (or torus) artificial gravity space station concepts. Most notably, the Stanford torus concept that was developed by NASA in the 1975 Summer Faculty Fellowship Program. The Stanford torus is a large space habitat that can house up to 10,000 people, with a diameter of over one mile [9]. More recently, the NAUTILUS-X Multi-Mission Space Exploration Vehicle [10] was a concept developed by NASA to limit the effects of microgravity for long duration space missions for crews of up to six people. Its modular, rotating habitable torus lends itself to many of the primary design requirements of Starport 1. The modularity ensures the station can be operational from early assembly stages in 2040, and it can be easily expanded to house more people.

Attempting to strike a balance between the scale of the Stanford torus and the modularity and size of the NAUTILUS-X, we developed our own modular tube concept that consists of a wheel with a circular cross-section. The toroid is divided into inflatable, pressurized modules that can be attached and assembled in orbit into a complete habitable structure. We chose this at the final concept for Starport 1, with further details discussed in Section 3. [3]

2. Roadmap to a space city

Starport 1 will achieve the vision of a space city from 2045 onwards, with the phases of development detailed below.

2.1 Development (Up to 2030)

The legal framework in which the station would operate is laid out. The station habitat is designed and optimised for the initial residents. Launch services and various other stakeholders will be contacted, and contracts with various business partners will be finalised and signed.

2.2 Microgravity construction (2030-2033)

The station will be made up of eight microgravity modules. The personnel aboard these modules will be predominantly crew, scientists, or manufacturers. The modules will carry 24 people with a maximum capacity of 44 individuals.

2.3 Outer ring assembly (2034-2039)

An artificial gravity test will be conducted between 2035 and 2037. This will involve spinning up and spinning down the station. Twelve artificial gravity modules will be launched between 2039 and 2040. The number of residents will reach 100, comprising tourists, crew, scientific researchers, and manufacturing residents.

2.4 Commercialization (2040-2045)

An additional 20 modules will be added to the station, increasing its capacity from 100 residents in 2040 to 200 by 2045. An increase in commercial opportunities such as space hotels is projected, to accommodate the growing number of tourists onboard. Starport 1 will provide an increased proportion of the food consumed by residents, reducing resupply missions further.

2.5 Space city (2045-2060)

Starport 1 reaches full residential capacity in 2045. The station will have a maximum number of 32 artificial gravity modules. These modules will include agriculture, crew residences, medical facilities, hotel rooms, social areas, parks, manufacturing support, and storage. These modules can be repurposed according to the needs of the station.

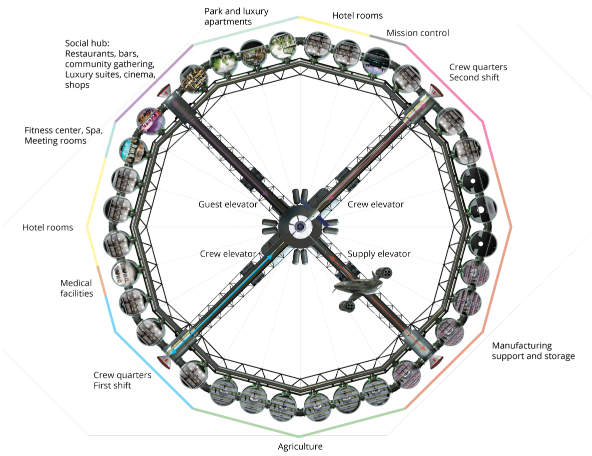

Fig. 1. Distribution of 32 artificial gravity modules [3]

2.6 Future (2060 onwards)

Increased radiation shielding should be considered at this point, as well as the efficacy of modules. Disposal plans for older station components should be considered. Station owners and operators will evaluate the commercial benefits of adding a second ring to the station. Enough data should be available to recommend whether children can live onboard the station, making the station accessible to a wider demographic. [3]

3. Station design

Starport 1's concept design was a load bearing skeleton, with various modules. Starport 1 consists of two main parts: a stationary microgravity section at the center, and an outer ring which rotates to create an artificial gravity environment.

The final Starport 1 specifications are shown in Figure 2:

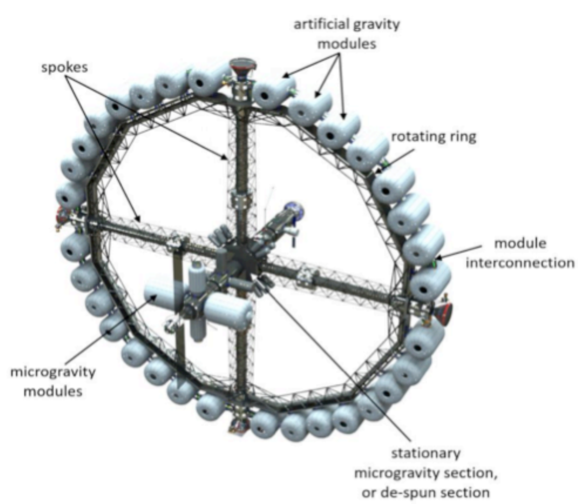

Fig. 2. Starport 1 general design

Table 1. Starport 1 Specifications

Parameter	Value
Diameter (Excluding the AG section)	150 m
Diameter central section	20 m
Angular velocity	2.9 rpm
Artificial gravity	0.7 - 0.8 g
Mass estimate	10e6 kg
Max. number of AG modules	32

In order to produce the 0.8 g artificial gravity required for comfortable human habitation, a trade-off study between the station radius and angular velocity was carried out. According to [11], humans can readily adapt to up to 4 rpm, so 2.9 rpm was selected to keep the size of the station low with a margin in the angular velocity. The gravity gradients and Coriolis effects were taken into account in this analysis.

3.1 Central section

The microgravity section is composed of a central hub, where spacecraft dock, and where the manufacturing and scientific modules are located. A cupola section, separate from the manufacturing module, will be used by tourists to view the Earth. In this hub, a 20 m diameter bearing system is located, where the four spokes of the rotating section are connected. The bearing includes a seal and drive system. Each spoke has a pressurized elevator shaft with a pressurized elevator, which minimizes the Coriolis Effect on elevator users.

3.2 Outer ring

The outer ring is the artificial gravity section of the station. It is composed of up to 32 inflatable modules that have been selected due to their high volume-to-mass ratio. The modules are attached to a structural ring, which contains a pressurized corridor with a diameter of 3 m. This corridor is to be used in case of emergency or maintenance that prevents passage through a module. The main way to move through the artificial gravity section is through interconnections between neighbouring modules. These interconnecting tunnels are 3 m in diameter. The modules are oriented parallel to the rotating axis in order to decrease Coriolis Effect and accommodate more modules. The station's structural components are designed to withstand the centrifugal force due to the rotation of the ring. Before the ring is constructed, an artificial gravity test is performed with three modules attached to each spoke. The truss of the spoke is designed for this load case. The structure is mainly composed of carbon fiber tube trusses and Twaron tethers. Three methods are proposed to add and remove modules while the station is rotating: a crane with the base located in the central hub, a small shuttle, or a rail system. The modules will be assembled before the spin-up if possible.

3.3 Orbital control system

The station will have an attitude and orbit control system (AOCS) to maintain a stable orientation and orbit, as full control is needed over the six rotational and translational degrees of freedom. Starport 1's unique challenge compared to other space stations is that it is a spinning station and therefore a gyroscope. Future research will need to account for mitigating these effects and stabilising the station orbit. Starport 1's orientation must be such that the rotating ring is in the orbital plane, with the minimum cross-section being exposed to reduce drag. This orientation reduces the need for stationkeeping.

3.4 Ring bearings

The main bearings will be hydrostatic bearings, able to handle various types of loads and operate in an environment where the bearing fluid is depressurized. It will also cope with different axial and radial loads coming from the two areas of the station. Starport 1 seals will have five separate ferrofluid rings combined with magnets that will successively lower pressure by 0.2 bar per ring. The station will have double redundant pressure seals that activate on air flow, in case the ferrofluid seal fails. The drive system will maintain the angular velocity difference between the central section and the artificial gravity ring. It will counteract the friction in both the bearing and the seal, thus keep the central section stationary.

3.5 Power requirement

An approximate power requirement of 6 MW is expected for Starport 1. Various sources of power generation were evaluated, focusing on Helium-Xenon fission reactors available for future space power generation. This type of reactor will provide 3 MW and weigh roughly 30 metric tons. [12] Three of these reactors will be used, one of which is for redundancy.

3.5 Future work

For future work we recommend research on the effects of gyroscopic effects and its interaction with the AOCS. The use of nuclear power on a space station should be examined from both safety and legal aspects. We may have to collaborate with Bigelow to adapt their modules to work in 0.8 g, especially the cases of internal support and airlocks on the module sides. Further analysis is required for the drive system, evaluating the friction caused in the bearing and the seals.

4. Assembly, launch, and orbit

To determine Starport 1 orbit, several options were considered. Autonomous operations, stationkeeping, debris avoidance, launch and assembly and de-orbiting are the main trade-offs.

4.1 Orbit and inclination selection

A 600 km altitude orbit was chosen as a compromise between minimising atmospheric drag, limiting orbital debris encounters, and a low-radiation environment.

The selection of inclination was influenced by the choice of launch sites. NASA Space Launch System (SLS) Block 2B and SpaceX Falcon Heavy were selected as launch vehicles because of cargo needs to build Starport 1 [3]. It is assumed they will launch from Cape Canaveral, USA. We chose to place Starport 1 on a 33 degree inclination orbit to avoid travelling over the polar regions, an area of high radiation levels. The negative aspect of a 33 degree orbit is that launch sites for resupply missions have to perform inclination-changing maneuvers.

After end of operations, the station can de-orbit within nine years by stopping stationkeeping. To guarantee the station will de-orbit into the southern Pacific Ocean, some fuel must be saved for active maneuvers.

4.2. Assembly and launch

Starport 1 assembly must start in 2030. The expected mass is 10,000 metric tons and the payload capability of the launcher to low Earth orbit (LEO) should be about 100 metric tons. SLS Block 2B can lift 130 metric tons to LEO [13]. Though still in development, we assume it will be available for use by 2030, and will be used to launch the main sections of the station. The SpaceX Falcon Heavy launch vehicle will be used to carry smaller modules and the station supply.

The microgravity section will be the first part of the assembly of Starport 1. In 2037, two of the four girder structures built with four artificial gravity modules on it, will be tested. Following testing and qualification in-orbit the section will be de-spun. The artificial gravity section will be built and eight modules will be mounted. By 2045, 32 artificial gravity modules will be functional. A module arm will be used for the assembly of the station and mounting the modules. The modules from launch will be brought and be docked to the station by a servicing satellite. In total, 94 launches are planned between 2030 and 2041. 82 launches will be carried out using SLS rockets and 12 with Falcon Heavy.

4.3. Orbital debris mitigation

Orbital debris is categorized into three sections: small (diameter below 1 cm), medium (1 to 10 cm), large (bigger than 10 cm). Specific shielding will protect Starport 1 from small debris. Medium sized debris will be observed on the ground [14] and in orbit with a tracking telescope and onboard debris detection

[15], [16], [17]. From 2020, active debris removal (ADR) like the deorbit program [18] is expected. One of the ADR satellites will be used as a companion of Starport 1 to remove large debris in front of the station.

4.4. Emergency procedures

An important advantage of having Starport 1 in LEO is that the crew and inhabitants can be able to return to Earth quickly. The space station will be equipped with a variety of monitoring sensors. In the event of a fire alarm, nonessential personnel will be evacuated, while the crew attempt to extinguish the fire. The affected module will be isolated, and the ventilation system will be shutdown to avoid spreading toxic gas products to other modules. Evacuation procedures will be performed using the pressurized maintenance corridor in the structure ring that connects all the modules. In the unlikely event of an emergency such as a rapid depressurization, the crew will evacuate the station. Starport 1 will have four major docking points for evacuation spacecraft, each with a capacity of 25 people. Additional spacecraft will be added as the population increases.

5. Station habitat

The artificial gravity section of the space station is designed for long-term habitation, and as such has many challenges in keeping the passengers happy and healthy, both physically and psychologically.

5.1. Rotation effects on humans

The creation of artificial gravity through rotation is key as a countermeasure against many of the physiological effects associated with prolonged exposure to weightlessness. However, the Coriolis forces and cross-coupled acceleration that may be created in a rotating station need special consideration when looking at the design elements of the station. This is particularly relevant when placing ladders and other module transfer devices, as well as in the decision whether the floor should be flat or curved. Cross-coupled acceleration can be limited by designing workstations to promote vertical (vs horizontal) head motions [19]. With regards to rotation of the station itself, research suggests that humans can readily adapt to 3-4 rpm rotation [11], meaning Starport 1 inhabitants should adjust to the 2.9 rpm rotation . However, little research has been done to investigate human adaptation to daily transfers between a microgravity and gravity environment, as would be expected on this station, and their effect on spatial disorientation and motion sickness. [20]

5.2. Radiation exposure

Radiation exposure represents another key area of concern. With current shielding technology, radiation is the limiting factor for inhabitants to remain aboard Starport 1. For instance, individuals under 21 and pregnant women are not allowed on the station per our radiation guidelines. The use of superconducting wires to provide magnetic shielding represents a critical technological development that will allow for prolonged stay and will be crucial to elevate Starport 1 to true city status. [3]

5.3. Environmental control systems

Environmental control and life support systems (ECLSS) will be integral to keep passengers alive and to help bring the station closer to a self-sustaining system. Starport 1 will make use of innovative and disruptive technologies such as: electric swing adsorption system for air revitalization, plasma pyrolysis to recover further hydrogen from CO2 removal, electrostatic precipitator with the addition of soft x-rays to remove smoke and dust particles from gas streams, supercritical water oxidation for solid waste processing, and non-thermal plasmas for surface disinfection. For further discussion on these technologies and their specific impact on the station, please see the Starport 1 report [3].

5.4. Food

In the initial stage Starport 1 will rely on food supplies delivered from Earth. However, it is hoped that advances in 3D food printing [21], and aeroponic farming [22] will enable increased self-sustainability of the station. Closed loop life support systems is assumed to be a viable option in 2060 [3].

5.5. Passenger well-being

Passenger well-being will be promoted through strategic use of community areas, including communal dining, garden areas, and the promotion of organized activities to maintain a sense of community. Art and music will be encouraged as a means of self-expression and preventative measures against the stressors of orbital life. The artificial gravity section will have e-windows, allowing passengers to personalize their surroundings, while also limiting further radiation and circadian rhythm disruptions from the station orbiting Earth every 96.5 minutes. Mirrors and screens will be used to promote open space. Seasonal affective disorder lighting will be utilized throughout the station, with light tone and intensity being varied to support the opposing diurnal cycles recommended to maximize manufacturing efficiency. Crew modules are split to ensure crew working in opposing diurnal cycle shifts can adjust to their schedule and activities. Initial psychological training will be offered to all future inhabitants to support cohesion and cooperation between them [3].

6. Station society

Starport 1 will bring diverse traditions and values into orbit, housing people from different nations and cultures. This paper addresses various technical issues, but we also need to ask ourselves why we should embark on this project of creating the largest space station ever made. The ISS has provided a model for how cooperation on international space projects can propel development, diplomacy, and human progress [23]. Careful ethical considerations is necessary when designing and planning this expanded human presence in the universe, and we must ask ourselves: What values should we bring with us? What kind of opportunities and lifestyles should be offered in space? Who gets to decide these questions? The countries jointly operating the ISS share common values and worldviews. Will this continue to be the case for Starport 1, even with a larger and potentially more diverse pool of space actors interested to participate?

6.1. Station governance

We recommend a governance structure based on a legal foundation similar to the Code of Conduct for ISS crew adopted by ISS partners on 15 September 2000 [24], having due regard for applicable national and international legislation. The crew, reporting to the Officer in Chief onboard, shall be responsible for the management of the station on a daily basis under the authority of the flight director on ground.

6.2. Crew selection and relations

While personal qualifications and background should continue to play the major role during crew selections, we encourage a broader focus including gender-sensitive selections and culture-oriented trainings. According to Kring and Kaminski [25], the most important factor affecting interpersonal relations onboard is the crew composition. Gender seems to be the predominant variable, and thus we recommend a mix of genders represented onboard Starport 1. A social hub will be a central component for the well-being of the people onboard, with facilities aiming to reduce isolation. This social center, including a sports center and dining facilities, will be located between tourist modules, providing easy access for both guests and crew.

6.3. Station personnel ratios

We project an increased number of tourists on the station as time progress, to a potential of 60 individuals when Starport 1 is fully assembled in 2040. Further crew-guest ratios are illustrated in Figure 3.

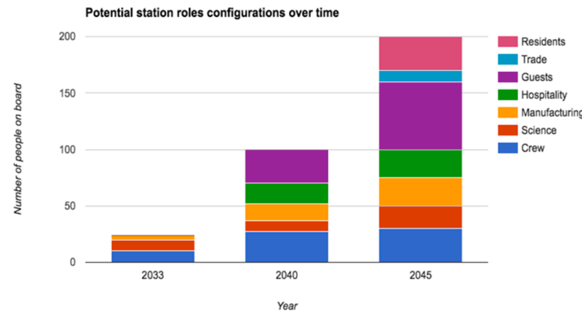

Fig. 3: Crew-guest ratios

7. Business and funding

We describe key current established terrestrial markets that would benefit from having their products manufactured in microgravity. In addition to this, we looked at future industry sectors that may emerge in the coming decades and how these could be either enhanced or only made possible by microgravity manufacturing.

7.1. Current established markets

ZBLAN fiber optics were by far the most promising market, with a current annual market value of $7.56 billion [26]. Previous studies [27] have indicated a clear optical performance increase in ZBLAN fiber produced in microgravity. In 2017 Made In Space will be sending the first ZBLAN optical fiber demonstration manufacturing facility to ISS. The current value of ZBLAN optical fiber per kilogram is much greater than present launch costs, making it attractive at a time when launch costs per kilogram remain very high [28].

7.2. Pharmaceutical R&D

This is a very established market with companies such as Procter & Gamble spending over $2 billion per annum on this area [29]. With the ability to incorporate manufacturing processes such as microencapsulation into pharmaceutical research, manufacturing in microgravity could be of large benefit to such companies. A second example is the manufacturing of protein crystals. There has been additional interest from the pharmaceutical industry into the growth of high purity protein crystals for studying x-ray diffractometry. This could have a large number of applications in drug design and manufacturing. [30]

7.3. Future potential markets

In our proposal Starport 1 [3] provides the opportunity to produce structural components in orbit, reducing launch mass and costs. Structures can also be designed and optimized for the space environment, instead of being mainly designed to survive the launch.

7.4. Leasing of facilities for science

The microgravity environment of Starport 1 can be used to conduct research experiments, similar to the

ISS. While the microgravity section of Starport 1 would prove useful for scientific purposes, its artificial gravity section would facilitate the life and help maintain the health of the scientists running the experiments. The crew of ISS need to perform all the tasks on the station; Starport 1 offers the possibility to have dedicated scientists, specialised in their field and whose only task would be to run the experiments. All of this would contribute to increase the quality of the research.

7.5. Space real estate

The different modules of the station offer the possibility to generate revenues in a similar way to real estate markets on Earth. Modules could be leased or sold, and utilities such as power, water, thermal control, or data provided to each module could be a source of income for the owners of the station. In addition, naming rights could be used as a source of income: individuals or corporations could pay to lend their name to a specific module or part of the station.

8. Law, policy, and economics

For any project as large and complex as Starport 1, observing the applicable legal frameworks will be key to the station's success. While Starport 1 is designed to be a commercial entity, it is highly likely that public funding will play a key role in early station design, construction, and operation. The geopolitical environment will dictate what kind of national space policies are formed and, as a result, the funds that are devoted towards a project of this nature. As governments have historically been the drivers for projects that are beneficial to humanity, though not initially profitable, they will be key drivers of Starport 1's initial launch. It is hoped that during its beginning, Starport 1 will attract involvement from many nations, both spacefaring and otherwise, in addition to private investors. One important model of this is the public-private partnership (PPP).

8.1. Legal regimes

Once funding is achieved, it will be crucial to identify the legal regimes that might apply to Starport 1, both from the standpoint of international and domestic laws. Due to its founding company's incorporation in the United States, the US will likely serve as the Launching State of Starport 1. As a result, the US will liable due to its adoption of four of the five major outer space treaties drafted by the United Nations Committee on Peaceful Uses of Outer Space. It might also take into consideration language found in the Moon Treaty, even though the US was not a signatory of that treaty. United Nations principles, declarations, and guidelines should also be considered, including Principles Relevant to the Use of Nuclear Power in Outer Space and the IADC Space Debris Mitigation Guidelines.

On a domestic level, Starport 1 might apply the same scheme found onboard ISS, giving States control over components they register pursuant to the Registration Convention. Additionally, should the US retain jurisdiction, Starport 1 may be subject to certain licensing requirements dictated by the classification of each passenger. Under the law of the Federal Aviation Administration (FAA), passengers are divided into spaceflight participants, government astronauts, and crew, all of which have varying duties regarding legal issues such as informed consent.

8.2. Future legal frameworks

An important factor to take into consideration is the ever-evolving nature of the law. Legal frameworks currently in place may have changed drastically by 2040, and perhaps that change is an evolution that Starport 1 would like to be involved in. It will be important to follow the changes in law and policy aspects that develop over the years of Starport 1's construction.

9. Conclusions

Starport 1 is a conceptual design of a commercial space station that makes life and work on LEO available to a wider population. An international and multi-professional team focused on questions relating to station design, assembly and orbit choice, habitat, society, business, and law. The design is based on current available research, on the assumption of new and upcoming technologies, and on novel and creative approaches. There is a clear, progressive path for the construction and operation of Starport 1, which will culminate in a station capable of housing tourists and crew, and providing facilities for manufacturing and research in both microgravity and artificial gravity.

Orbit and inclination were chosen following careful consideration of station requirements, practical solutions, and safety. The pathway of station assembly is proposed and incorporates current launch capabilities. The design drivers for the station were simplicity, robustness, and efficiency. Starport 1 consists of a central microgravity section (which is key for commercial opportunities), and a spinning outer ring with habitable modules. The presented concept allows for adding and removing modules, maintenance, and modifications to the station. The angular velocity of the rotating ring is 2.9 rpm which creates artificial gravity of 0.7 - 0.8 g. Such gravitational levels are deemed sufficient for sustaining human physical health, and should allow prolonged stay in outer space. Further research looking into effects of artificial gravity on humans will be necessary to create a complete star city. Inhabitant well-being is one of the highest priorities in the design, and proposed ways of maintaining it include biological, psychological, and societal factors.

The paper proposed societal structure and governance, likely revenue sources, and possible legal framework for Starport 1. Due to the novel arrangements and probable multinational cooperation on Starport 1, legal aspects will need to be regularly updated and reviewed.

Final construction and operation of Starport 1 will depend on technological developments and increase of human knowledge, which we expect to happen in the next two decades. Research into areas highlighted in this paper can speed up the process of turning the theoretical concept into a reality.

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References

[1] J. A. Angelo, Space Technology, Greenwood Press, Westport, Connecticut, 2003.
[2] NASA, Microgravity Research Program fact sheet, 1998 http://www.nasa.gov/centers/marshall/news/background/facts/microgravity.html [accessed 27.08.2016].
[3] C. Al-Ekabi et al., Starport 1 — Final Report, International Space University, Illkirch-Graffenstaden, 2016.
[4] A. Weir, The Martian, 2011.
[5] N. Blomkamp (Director), Elysium [Motion Picture], 2013.
[6] K.E. Tsiolkovsky, Beyond the Planet Earth (Вне Земли). Kaluga Society for Natural History and Local Studies, 1920.
[7] D. M. Cole and D. W. Cox, Islands in space: The challenge of planetoids, 1964.
[8] G.K. O'Neill, The Colonization of Space. Physics Today, 1974, 32-40.
[9] NASA. National Space Society, 1975, http://www.nss.org/settlement/nasa/75SummerStudy/Chapt.1.html#Overall, [accessed 05.09.2016].
[10] NASA. NAUTILUS-X, 2011. https://www.scribd.com/doc/51592987/Nautilus-X-Holderman-1-26-11, [accessed 05.09.2016].
[11] J.C. Buckey, Space physiology, Oxford University Press, Oxford, 2006.
[12] Cliquet, E., 2012. Future Space Propulsion. CVA Summer school Salon de Provence.
[13] B. Boen, SLS Block 2 (130-Metric-Ton) Cargo Expanded View, http://www.nasa.gov/exploration/systems/sls/multimedia/gallery/sls_config_130t.html, 2015 [accessed 15.08.2016].
[14] C. Phipps, Clearing Space Debris with Lasers http://spie.org/newsroom/4076-clearing-space-debris-with-lasers, 2015, [accessed 20.08.2016].
[15] T. Ebisuzaki et al., 2015. Demonstration designs for the remediation of space debris from the International Space Station, Acta Astronautica, 112 (2015), 102-103.
[16] JEM-EUSO Program, 2016. Mini-EUSO. http://jemeuso.roma2.infn.it/?page_id=818 [accessed 25.08.2016].
[17] J. Utzmann and A. Wagner, SBSS Demonstrator: A Space-Based Telescope for Space Surveillance and Tracking, https://drive.google.com/open?id=0B_EjlSqz_P6fbEhsWmlhZGpJdmc, 2014, [accessed 25.08.2016].
[18] ESA, e.Deorbit, http://www.esa.int/Our_Activities/Space_Engineering_Technology/Clean_Space/e.Deorbit, 2016 [accessed 25.08.2016].
[19] T. Hall, Discussion on Space Architecture and optimising habitats for human performance, 20.08.2016.
[20] A. Diaz Artiles, Discussion on human performance in microgravity and artificial gravity environment, 18.08.2016.
[21] NASA, 3D Printing: Food in Space, 2013, https://www.nasa.gov/directorates/spacetech/home/feature_3d_food.html#.V7he1lcaq1s [accessed 18.08.2016].
[22] NASA, Progressive Plant Growing is a Blooming Business, 2007,

http://www.nasa.gov/vision/earth/technologies/aeroponic_plants.html [accessed 18.08.2016].
[23] L. L. Manzione, Multinational Investment in the Space Station: An Outer Space Model for International Cooperation, American University International Law Review, 18(2002), 507-536.
[24] A. Farand, The Code of Conduct for International Space Station Crews, ESA bulletin, 105(2001), 64-68.
[25] J. P. Kring and M. A. Kaminski, Gender Composition and Crew Cohesion During Long-Term Space Missions, in D. A. Vakoch, Psychology of Space Exploration: Contemporary Research in Historical Perspective, 2011.
[26] NASA, ZBLAN Fiber Market Prediction, NASA Science, 2011, http://science.nasa.gov/science-news/science-at-nasa/zblan_prediction/ [accessed 21.08.2016].
[27] NASA, ZBLAN continues to show promise, NASA Science, 1998, http://science.nasa.gov/science-news/science-at-nasa/1998/msad05feb98_1 [accessed 07.09.2016].
[28] Made In Space, Made in Space Fibre, 2016, http://www.madeinspace.us/projects/fiber/ [accessed 07.09.2016].
[29] Procter and Gamble, P&G2014 income statement, 2014, http://www.pginvestor.com/interactive/lookandfeel/4004124/PG_Annual_Report_2014.pdf [accessed 21.08.2016].
[30] NASA High-Quality Protein Crystal Growth Experiment Onboard, 2012. http:www.nasa.gov/mission_pages/station/research/benefits/Protein_Crystal.html [accessed 07.09.2016].