PROTOTYPE OF AN ORBITAL SPACE STATION FOR SPACE COLONIZATION

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Abstract. In this particular project, I will be designing a prototype of an orbital space station. But before designing, studies must be done on space station designs to observe the requirements, the engineering and the physics needed to be taken into account when designing. Hence, Stanford Torus and O'Neill Cylinder, two famous space station designs will be studied. After knowing all the theoretical requirements, a 3D prototype of an orbital space station will be designed using NX12 Siemens PLM Software. Each component of the prototype will be explained and its measurements will be shown. Then the overall theoretical functionalities of the prototype will be described in detail, especially on how many inhabitants that it can house, how the inhabitants obtain artificial gravity, how the inhabitants obtain natural sunlight, how the prototype collects energy and the cooling of the prototype. Further in the thesis, I will show in detail the steps of the designing process of the prototype via the software. Subsequently, a simulation of the movements of the prototype will be created via the same software to get the visual representation of how the prototype moves and its steps will also be shown. Finally, comparison will be made between the prototype, Stanford Torus and O'Neill Cylinder to see the improvements made and if there's any drawbacks in the design. **Keywords:** Space colonisation, Orbital space station, Stanford Torus, O'Neill Cylinder, artificial gravity, toroidal space station, NX12 Siemens PLM, human colonies in space, non-rotating orbital station, Coriolis effect.

1. INTRODUCTION

Many scientists stated that the maximum carrying capacity of the Earth is 9 billion to 10 billion people [1]. McConeghy [2] estimates that the capacity might lies between 2 billion to 40 billion people. It depends on the way of the people's living and how they treat the Earth. In 2020, there are already a ton of problems regarding the resources and human pollutions. Due to the high population, the Earth's resources decrease because of the high consumption of the resources by the population. Plus, the high population also causes higher amount of pollutions to the Earth. As we all know, one of the biggest nature problems is global warming which is mainly human-caused. We use technologies that emit a huge amount of carbon dioxide and other greenhouse gases to the environment. Fossil fuel burning, cement production and deforestation are also human pollutions that causes this global warming. And not to forget, the current COVID-19 pandemic that we are having which has causes millions of deaths all around the world. Imagine if these problems stay untreated and keep getting worse as the years go by, how will the Earth look like 100 years from now? How will the human cope with extreme nature problems and with dying resources? Could Earth maintain the overpopulation at that time? Therefore, to ensure the survival of our species and to save the environment of Earth, we must think of solutions no matter if it is a small scale, big scale, long-term or short-term. One of the solutions is starting a human colonization in space.

Theoretical physicist and cosmologist Stephen Hawking also suggested that space colonization is needed to save humanity in the future [4]. One of the ways for space colonisation is by creating an orbital space station. There are already several designs of orbital space station made by professionals. One of them is called Stanford Torus. It is a proposed NASA design in Summer 1975 conducted at Stanford University [5]. Then the physicist named Gerard K. O'Neill proposed a design called O'Neill Cylinder. He explained the concept and the designs in his 1976 book "The High Frontier: Human Colonies in Space" [6] and in an article "The Colonization of Space" in the 1974 book, Physics Today [7]. There is also McKendree Cylinder which uses the same concept as O'Neill Cylinder. It was proposed by engineer Tom McKendree during NASA's Turning Goals into Reality conference in 2000.

2. STUDIES OF THE THEORETICAL REQUIREMENTS FOR DESIGNING THE PROTOTYPE

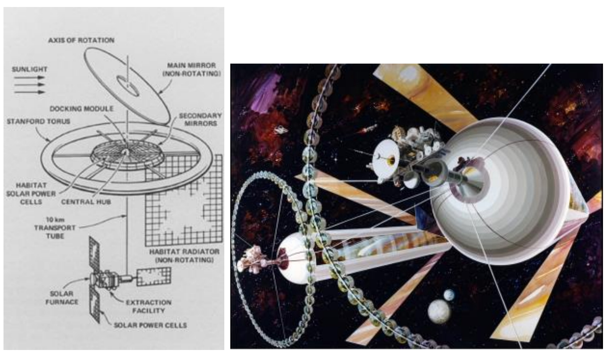

Figure 1: Stanford Torus (left) and O'Neill Cylinder (right) designs [5][6]

During the studies made on both Stanford Torus and O'Neill Cylinder designs, I have found the requirements needed to be taken into account when designing a prototype of an orbital space station. As this project is more focus on theoretical perspectives, in this section, I will state and simplify all the theoretical requirements that are needed to be focus in this project.

2.1 ARTIFICIAL GRAVITY

To obtain the artificial gravity (similar to the gravity on the Earth surface: 9,81 m/s^2), the station has to rotate at certain speed and angular velocity based on their diameter. The centripetal force due to the rotation needed to be equal to gravitational force. Therefore, the equation that needed to be taken into account are;

$$F^{centripetal} = \frac{mv^2}{r} = mr\omega^2 \quad (1)$$

$$r\omega^2 = g \quad (2)$$

Then we can know the period (T) of the rotation of the prototype by;

$$\omega = \frac{2\pi}{T} \quad (3)$$

2.2 CORIOLIS EFFECT

Coriolis effect is an effect of induced nausea felt by human due to Coriolis force. "Coriolis effect – The misperception of body orientation, commonly accompanied by nausea and vertigo on exposure to Coriolis acceleration" [9]. And this Coriolis acceleration is generated by Coriolis force. "Coriolis force – An apparent force observed on any free-moving object in rotating system" [9]. This Coriolis force and acceleration are not usually experienced by a human on Earth. So, for a human to live in a rotating space station, they have to embrace this Coriolis effect. The only way to reduce this effect is to slow down the angular velocity of the space station as it will reduce the Coriolis force. Based on the definition in [9], the slower the rotation of a system, the lower the Coriolis force experienced by any free-moving object in the system.

Therefore, the aim in designing the orbital space station prototype is to make sure the period (T) is not too quick as it will increase the Coriolis effect that would be experienced by the colonies. The mission is to make the period (T) more than 60 s.

2.3 AXIAL ROTATION

As the prototype will be rotating in an axis, it will create an angular momentum;

$$L = I * \omega \quad (4)$$

"Even in space objects have mass. And if they have mass, they have inertia. That is, an object in space resists changes in its state of motion" [10]. So, there will be an angular momentum L in the prototype when it is rotating. In space, there is no air resistance or friction as there is no air in space. "Air resistance is like friction. It is caused by the molecules in the air pushing against a craft in flight. It is what slows parachutists down and keeps them from crashing into the Earth. There is no air resistance in space because there's no air in space" [11]. This means that there will be no external force and torque (no gravity) that can slow down or disrupt the angular momentum L of the rotating station. Once in rotation the station will stay like this with the same angular velocity ω and angular momentum L.

2.4 SOLAR ENERGY

Next requirement is the amount of energy needed for powering the whole prototype including daily electricity, household appliances, interior lighting and personal mobility. As the station would be located in space, solar energy has to be fully utilised as the main energy due to the high exposure of solar. Solar panels would be installed into the prototype. To get a certain amount of electrical power, we have to make sure that the prototype has an adequate value of total solar panel area;

$$P = \frac{W}{t} \quad (5)$$

$$\eta max = \frac{Pmax}{E * Ac} * 100\% \quad (6)$$

2.5 THERMAL CONTROL

Waste heat generated by power consumption and excess sunlight must be dissipated. The plan is to install main radiators near the wheels and small radiators near the window of the habitat and the exterior wall. In this design we will only focus on the main radiators. To know how big is the main radiators, we will need to study the thermodynamics between the space temperature and the estimated temperature emitted by the prototype. We will need to apply the Stefan-Boltzmann Law of radiation;

$$P = e\sigma A(T^4 - Tc^4) \quad (7)$$

3. PROTOTYPE OF ORBITAL SPACE STATION

My main goal in designing this prototype is that I want to challenge myself in figuring out how to make a better toroidal space station that improves Stanford Torus design and can match up with O'Neill Cylinder design. My design idea for the prototype is multiple rotating rings that connected in a static centre station. My goal is to design it in moderate size, bigger that Stanford Torus but much smaller than O'Neill Cylinder. This is for making sure that this design is feasible in the future as this design would not require too much materials and cost. In this section, I will be showing the general design of the prototype, its components and its functionalities.

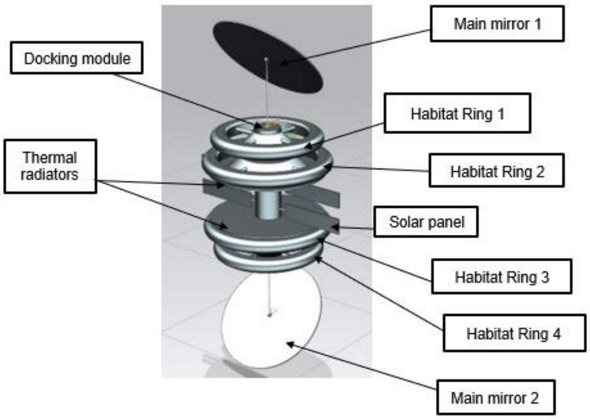

Figure 2: The prototype [Own Source]

The prototype is 16 km long and the habitat rings have a diameter of 5 km and 5,8 km. The prototype consists of 4 rings, which would rotate at a certain angular velocity to produce artificial gravity within the outer ring. And the outer ring would be the habitat for the colonies. It also consists of two main mirrors, which would be use to redirect sunlight to light up the habitat in the outer rings. 4 sets of solar panels would be installed in the centre of the design as the prototype will solely rely on sunlight as the energy. Two disc-shaped radiators would be incorporated for eliminating waste heat into the space.

3.1 MAIN COMPONENTS

The prototype would be formed by 17 components. Those components consist of a long non-rotating station, 4 solar panels, 2 radiator discs, 4 habitat rings, and 2 main mirrors and 4 bearings.

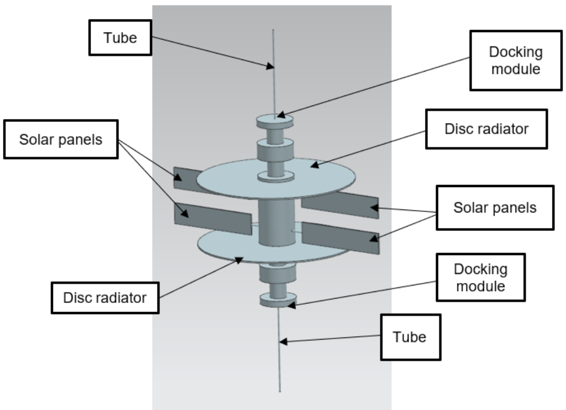

Figure 3: Non-Rotating Station [Own Source]

The Non-Rotating station would be connected by 2 radiator discs and 4 solar panels. At the end of the port on both sides, there would be ports to dock with spaceships. This configuration would make it easier for the spacecraft to dock with the port since the spacecraft pilot will not have to consider any rotational speed when docking due to the station to be non-rotating. There would also be a long tube at both end, which would be used to connect with main mirrors. The length of the station is 6,2 km and has a diameter of 1,2 km. Each tube is 3,015 km long and has a diameter of 50 m. Each solar panel has an area of:

$$A^{rectangle} = b * h \tag{8}$$

$$A = b * h = 700\ m * 3000\ m = 2{,}1 * 10^6\ m^2$$

The area of each disc radiator that will be used for eliminating waste heat is;

$$A^{disc} = \pi(R^2 - r^2) \tag{9}$$

$$9A = \pi(5200^2\ m^2 - 1200^2\ m^2)$$

$$A = 2{,}56 * 10^7 \pi\ m^2$$

Habitat Ring 1 and 4 are from the same component. They both will have the same exact size and dimension. As we can see in Figure 3, this prototype's design is symmetrical, the bottom part is mirror of the upper part. Habitat Ring 4 will be incorporated upside down as the colonies in there would receive the redirected sunlight from the Main Mirror 2.

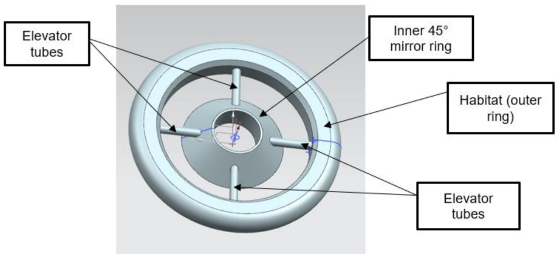

Figure 4: Habitat Ring 1 and 4 [Own Source]

This ring has 4 elevator tubes that would be used to transport passengers or cargos from the port to the habitat. There will also be an inner ring, which has a 45° mirror surfaced for sunlight reflection. This habitat ring has a diameter of 5 km and the radius between the floor of the habitat to the centre of the ring would be 2,2 km. This radius will determine the angular velocity needed for the ring to rotate at to achieve artificial gravity.

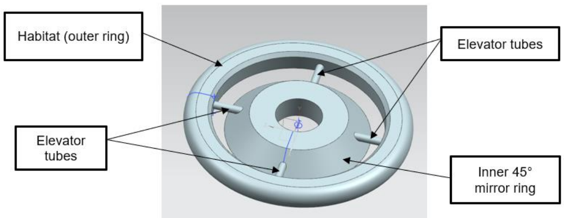

Figure 5: Habitat Ring 2 and 3 [Own Source]

Just like Habitat Ring 1 and 4, the design for Habitat Ring 2 and 3 consist of 4 elevator tubes, the inner ring will have a 45° mirror surfaced to redirect sunlight to the habitat. This ring design is slightly bigger in diameter compared to Habitat Ring 1 and 4. The diameter of the ring is 5,8 km and the radius between the floor of the habitat within the outer ring and the centre of the ring is 2,6 km.

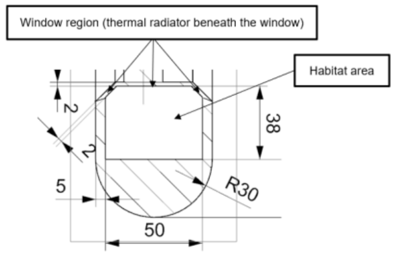

Figure 6: habitat in the outer ring (1mm:10m) [Own Source]

The top part will be a window panels which would allow the redirected sunlight to reach the habitat from the top. The vertical length of the habitat is 380 m the width of is 500 m.

There will be two main mirrors that being incorporated in the prototype. The diameter of each main mirror is 5,24 km. As the mirror would be installed in 45 degrees.

3.2 FUNCTIONALITIES

3.2.1 ARTIFICIAL GRAVITY AND ANGULAR VELOCITY

Habitat Ring 1 and 4 have the same diameter which is 5 km. And Habitat Ring 2 and 3 have a diameter of 5,8 km. But the measurement that must be taken into account is not the full diameter of those rings, it is the diameter between the habitat floor to the opposite site of habitat floor (refer Figure 7 and 8). This is because the habitat floor is where the colonies will step on in the prototype and the artificial gravity must be 9,81 m/s^2 at that exact spot. The angular velocity of Habitat Ring 1 and 4 is;

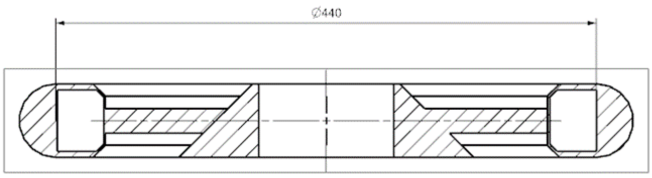

Figure 7: Dimensions of Habitat Ring 1 and 4 (1mm:10m) [Own Source]

$$r\omega^2 = g \tag{2}$$

$$\omega = \sqrt{\left(\frac{9{,}81\ ms^{-2}}{2200\ m}\right)} \approx 0{,}06678\ rads^{-1}$$

And the angular velocity Habitat Ring 2 and 3 is;

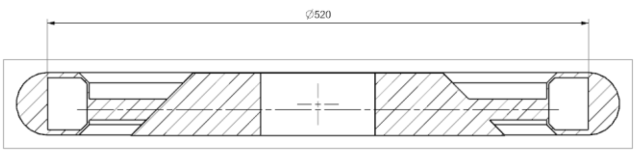

Figure 8: Habitat Ring 2 and 3 (1mm:10m) [Own Source]

$$\omega = \sqrt{\frac{9{,}81\ ms^{-2}}{2600\ m}} \approx 0{,}06143\ rads^{-1}$$

3.2.2 TIME PER ROTATION

As for the period (T), it can be calculated based on the angular velocity (ω) previously obtained.

For Habitat Ring 1 and 4;

$$\omega = \frac{2\pi}{T} \tag{3}$$

$$T = \frac{2\pi\ rad}{0{,}06678\ rads^{-1}} \approx 29{,}949\pi\ s \approx 94{,}09\ s$$

$$\frac{1\ rev}{94{,}09\ s} \approx 0{,}0106\ revs^{-1}$$

For Habitat Ring 2 and 3;

$$T = \frac{2\pi\ rad}{0{,}06143\ rads^{-1}} \approx 32{,}557\pi\ s \approx 102{,}28\ s$$

$$\frac{1\ rev}{102{,}28\ s} \approx 9{,}777 * 10^{-3}\ revs^{-1}$$

3.2.3 BEARING SYSTEM

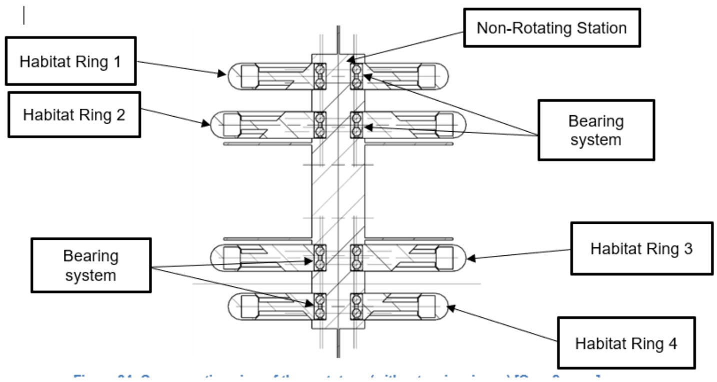

Figure 9: Cross-sectional view of the prototype [Own Source]

All the habitat rings connected to the non-rotating station via bearing system and would rotate at certain angular velocity around the station. The non-rotating station would act as an axis to the habitat rings. This system is the same system used by O'Neill Cylinder design [9]. The bearing is a sealed type-bearing with 2 ball bearing each. The reason that the bearing is sealed is to reduce the surface area exposed to the space.

3.2.4 AXIAL ROTATION

All 4 habitat rings rotate around an axis aligned with Non-Rotating Station. They rotate via bearing system. The direction of rotation of the rings will counter rotate with each other to provide a balance in the overall system of the prototype. There will be no external force from the space or torque that can disrupt the angular momentum and angular velocity of the system. But as the rotation is via bearing system, there will be slight friction within the bearings. Lubrication in the ball bearing will minimise this friction. So, I consider the friction is quite negligible.

Habitat Ring 1 rotates in clockwise direction, Habitat Ring 2 would rotate anti-clockwise which is opposed to the direction of Habitat Ring 1. Habitat Ring 3 then would rotate in clockwise direction meanwhile Habitat Ring 4 rotates in anti-clockwise direction. All these opposing directions of rotation of the rings would balance out the system in the prototype and would keep it locked to its position in space. The prototype needs to stay in the position to ensure that the maximum amount of sunlight hit the main mirrors in the prototype.

The angular momentum of Habitat Ring 1 will balance out with angular momentum of Habitat ring 4 as they both rotate in opposing direction. And same goes between Habitat Ring 2 and 3. To simplify the calculations, we assume that the moment of inertia I of each ring is:

$$L = I * \omega \tag{4}$$

With respect to an axis that passes through its centre, the equation of moment of inertia I for the habitat rings is:

$$I = \frac{1}{2} * mr^2 \tag{10}$$

$$I1 = I4 \text{ and } I2 = I3$$

$$L^{whole\ prototype} = I1 * \omega 1 + I2 * \omega 2 + I3 * \omega 3 + I3 * \omega 4$$

$$L^{whole\ prototype} = 0$$

3.2.5 CORIOLIS EFFECT

As mentioned in section 2.2, the goal is to make sure that the period for 1 rotation to be more than 60 s. The diameters of the habitat rings are not too big, so this range of period would be decent to minimise the Coriolis effect.

The period for Habitat Ring 1 and 4 is 94,09 s meanwhile the period for Habitat Ring 2 and 3 would be 102,28 s. Both periods are more than 60 s. Hence, the Coriolis effect that would be experienced by the colonies would not be high.

3.2.6 HABITAT AREA AND ESTIMATED POPULATION

To calculate the land area, the surface area equation for cylinder (only the area of the curve) have to be applied.

$$A^{cylinder} = 2\pi r * h \tag{11}$$

Habitat Ring 1:

$$A = 2\pi * 2200\ m * 500\ m = 2{,}2 * 10^6 \pi\ m^2 \approx 6{,}91 * 10^6\ m^2$$

Habitat Ring 2:

$$A = 2\pi \,.\, 2600\ m \,.\, 500\ m = 2{,}6 * 10^6 \pi\ m^2 \approx 8{,}168 * 10^6\ m^2$$

Hence, the total land area of habitat in all the rings is;

$$Total\ A = A^{habitat\ ring\ 1} + A^{habitat\ ring\ 2} + A^{habitat\ ring\ 3} + A^{habitat\ ring\ 4}$$

$$Total\ A = 9{,}6 * 10^6 \pi\ m^2 \approx 3{,}0159 * 10^6\ m^2$$

To find the estimated population of the inhabitants, there is no right way to calculate the population as this prototype design is just a broad concept, not a full-detailed design. It has to be based on land area and compression strength of materials used.

For this section, I decided to use the basic suburban population density as a reference. Based on [12], suburban areas normally have population densities between 100 to 10.000 people/km2.

Taking the maximum suburban population density as the average habitat's population density, we can calculate the estimated population of the inhabitants;

$$\frac{10.000\ people}{km^2} * \frac{1km^2}{1.000.000\ m^2} * 9{,}6 * 10^6 \pi\ m^2 = 96.000\pi\ people \approx 300.000\ people$$

So, the estimated population of inhabitants that the prototype can house is 300.000 people.

3.2.7 POSITION IN SPACE

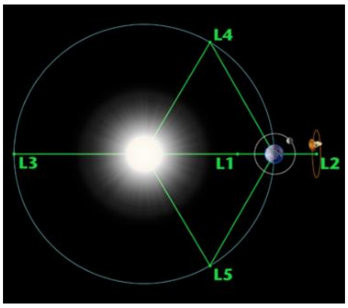

Figure 10: Lagrange Points of Sun-Earth system [13]

This prototype will be located at a Lagrange Point L5 of the Sun-Earth system. Lagrange Points are positions in space where the gravitational forces between two bodies produce enhanced regions of attraction and repulsion [13]. Figure 13 shows the Lagrange Points between the Sun and Earth. Out of the 5 points, 3 of them are unstable and 2 points are stable, which are L4 and L5. Therefore, L5, which is 240.000 miles from Earth would be a good location for the prototype to stay there and obtain a steady supply of solar energy [14].

3.2.8 LIGHT REFLECTION

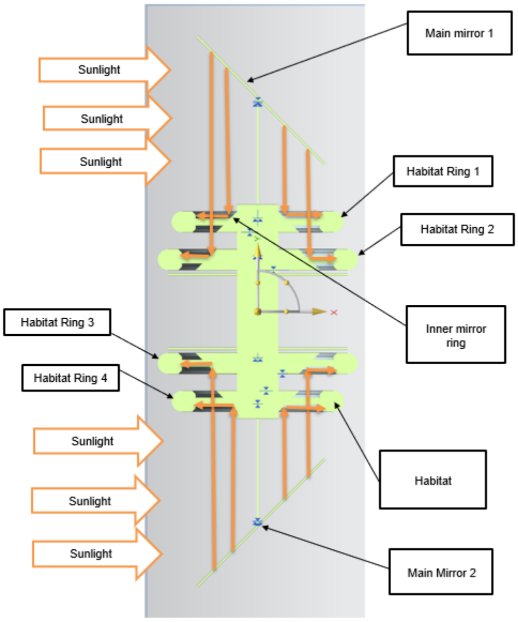

Figure 11: Reflection of sunlight on the prototype [Own Source]

This sunlight reflection method used by this prototype is better explained using image.

As the sunlight strikes the Main Mirror 1, the sunlight will be redirected downward as the main mirror is at a 45 ° angle. The redirected sunlight then hit the inner mirror ring (which also has a 45 ° angle) of Habitat Ring 1 and 2 and will be reflected horizontally into the habitat in the outer rings (refer figure above).

The bottom part of the habitat will undergo the same patterns as the top part. The sunlight coming from the left will hit the Main Mirror 2 and will be reflected upwards. After that, the light will hit the inner mirror ring of both Habitat Ring 3 and 4. And then the light will be reflected horizontally towards the habitat of the outer rings.

3.2.9 ENERGY REQUIREMENTS

The 4 photovoltaic solar panels generate electricity for daily living, household appliances and industrial processes. For agriculture and heating of the habitat, there is no electrical energy that will be used, only pure sunlight. With 300.000 inhabitants in the habitat, we can calculate the amount of energy needed based on the power per capita. The average power per capita in the current world is about 1,5kW per capita [15]. To be safe, we'll take 10kW per capita as the average for the habitat so that the extra power can be used for emergency purposes.

$$Pmin = 10\ kW\ per\ capita * 300.000\ capita$$
$$= 3 * 10^9\ W$$

To know the radiation flux, we must refer to the distance between L5 and the Sun which would be 240.000 miles [14]. 240.000 miles is equivalent to 386.242,56 km.

To know the solar radiation intensity (Ho), this equation will be applied [16];

$$Ho = \frac{R^2 sun}{(D^2)} * Hsun \tag{12}$$

Hsun is the power density at the Sun's surface, Rsun is the radius of the Sun and D is the distance from the Sun to the prototype. The radiant solar intensity at the Sun's surface is 64 x 106 W/m^2. Therefore,

$$Ho = \frac{(696.340.000\ m)^2}{(386.242.560\ m)^2} * 64 * 10^6\ Wm^{-2}$$

$$\approx 208,0187 * 10^6\ Wm^{-2}$$

The radiant solar intensity (Ho) will be the incident radiation flux (E) in the solar cell efficiency equation which is equation below;

$$\eta max = \frac{Pmax}{E * Ac} * 100\% \tag{6}$$

High-quality solar panels currently have an efficiency around 22 %. SunPower solar cells has an efficiency of 22,8 % [17]. For this prototype, we will incorporate the SunPower solar cells.

There are 4 solar panels incorporated in the prototype. Each panel has an area of 2,1 x 106 m^2. Therefore,

$$22,8\% = \frac{Pmax}{208,0187 * 10^6\ Wm^{-2} * 4 * 2,1 * 10^6\ m^2}$$
$$* 100\%$$

$$Pmax \approx 3,98 * 10^{14}\ W$$

$$3,98 * 10^{14}\ W >> Pmin = 3 * 10^9\ W$$

This power would be more than sufficient to power up the whole prototype.

3.2.10 COOLING REQUIREMENTS

In average, a person releases 100 to 120 W of heat energy to the surrounding [18]. As there will 300.000 inhabitants in the prototype, the heat releases by them would be 3 x 10^7 W to 3,6 x 10^7 W.

Area radiators = 2,56 x 107 π m^2

σ= Stefan-Boltzmann constant = 5,67 x 10-8 Wm^{-2}K^{-4}

e= 1 (assuming black body)

T= space temperature = 4 K (refer section 4.1)

Tc= radiator temperature = 27 ° C = 300 K

$$P = e\sigma A(T^4 - Tc^4) \tag{7}$$

$$P \approx -3,69 * 10^{10}\ W$$

The sign is negative as the radiator is cooling down the station to the temperature of the space by releases off heat waste.

$$3{,}69 * 10^{10}\ W \gg waste\ heat\ by\ the\ colonies$$
$$= 3{,}6 * 10^{7}\ W$$

These 2 radiators will also be sufficient for eliminating waste heat from electrical appliances, lighting and from the excess sunlight.

3.2.11 MATERIALS

The materials need to have a really strong thermal ability, good radiation resistance, good pressure resistance, high compression and tensile strength.

But if we want to refer to materials that currently known for space use, we can build the prototype by Aluminium Alloy, Kevlar and Thermal Glass. Most of the prototype will be made of Aluminium Alloy, the habitat windows and the main mirrors will be made of Thermal Glass. Kevlar will be used to cover and protect the habitat rings as it has strong durability, tensile strength and heat resistant. The Kevlar can give extra support and hold the Aluminium Alloy structure of the habitat ring as the weight/load of the colonies (due to artificial gravity) pushes the structure outward.

In my opinion, these materials aren't the most suitable as to hold 300.000 inhabitants requires stronger material properties. Further extensive testing and experiments on wide variety of materials, metals and alloy needed to be made to ensure that we find the most suitable materials for this orbital space station.

4. DESIGNS COMPARISON

4.1 IMPROVEMENTS

STANFORD TORUS	O'NEILL CYLINDER	THE PROTOTYPE
Can house 10.000 to 140.000 inhabitants only.	Can house 200.000 inhabitants.	Can house 300.000 inhabitants.
10 km in length and the torus' diameter is 1,8 km.	Each cylinder is 32 km long and has a diameter of 8 km.	16 km long and the habitat rings have a diameter of 5 km and 5,8 km.
Earth-like environment in the habitat.	Non-Earth-like environment in the habitat	Earth-like environment in the habitat.
Less materials.	Huge volume of materials needed	Less materials
Low cost.	High cost.	Even though the right materials haven't been figured out, the cost will still be lesser than O'Neill Cylinder as the prototype's size is way smaller than O'Neill Cylinder.

Table 1: Designs comparison

As the prototype is smaller in scale, in is much more efficient as based on its size, it can still house a maximum of 300.000 inhabitants maximum. This amount is 1,5 times more than the number of colonies that O'Neill Cylinder can house. Plus, it has lower-cost as this design is way smaller. In the prototype's habitat, the colonies will feel the same environment as Earth as the sunlight coming from the top meanwhile in O'Neill Cylinder, the colonies will have a different environment and feel (refer [7]).

4.2 INCONVENIENCES

Designing a toroidal space station that can fully outmatch O'Neill's Cylinder design is really challenging as O'Neill Cylinder is the most convenient and efficient space station design that had been made, and its design was planned in extensive details. There are several parts of my prototype that cannot match with O'Neill Cylinder and the parts require deeper studies.

The Prototype	O'Neill Cylinder
Period per rotation, $T = 126{,}93\ s$	Period per rotation; Habitat Ring 1 and 4, $T = 94{,}09\ s$ Habitat Ring 2 and 3, $T = 102{,}28\ s$
Lower overall surface area for its size (Only 2 big cylinders in the design)	High overall surface area for its size

Table 2: Inconveniences in the prototype

Even though the Coriolis effect for the prototype had been lowered, it still not lower than Coriolis effect in O'Neill Cylinder as its period is slightly longer than the prototype. But this prototype can slower the rotation speed by making the radius of the habitat rings. But this will increase the materials and cost needed.

O'Neill Cylinder design is efficient as for its size, it has low overall surface area compared to my prototype. The surface area of the prototype needs to be minimised to lower the radiation contact with the surface of the prototype.

5. CONCLUSIONS

In this project, Stanford Torus and O'Neil Cylinder designs have been studied. Then a toroidal space station prototype has been designed via NX12 Siemens PLM Software. The design planning took a really long time as to design a toroidal space station that can match up with O'Neill Cylinder is really challenging and required extensive brainstorming and studies. Now that the project is done, we can see that the objectives and aim for the prototype is achieved but there are still some parts lacking. The conclusions are summarized as follows:

1. The prototype design is a toroidal-typed space station that has a vertical length of 16 km and a width of 8 km.
2. It consists of 4 rings, 2 of them have a diameter of 5 km and another 2 with a diameter of 5,8 km.
3. The inhabitants will stay in the habitat area, which would be in the outer rings of those 4 rings.
4. The total inhabitants that the prototype can house is 300.000 people.
5. The prototype will be located at Lagrange Point L5 of Earth-Sun in space.
6. This toroidal space station prototype can match up with O'Neill Cylinder design but requires materials that haven't been found.
7. Even with its moderate size, the prototype can house more inhabitants than the big O'Neill Cylinder design, which proves that the prototype is more efficient in terms of number of inhabitants.
8. The inhabitants in the prototype will experience a normal Earth-like environment meanwhile the inhabitants in O'Neill Cylinder would feel a really different environment unlike Earth.
9. The Coriolis effect experienced by the inhabitants in the prototype would be moderate as it revolves at slow speed but O'Neill Cylinder is slightly slower.

As this design is not fully perfect, further studies and research need be made to perfect this design. There are few recommendations that I can suggest, there are:

1. Further studies on the design of docking module.
2. Further studies on the transportation of human from the docking module to the habitat in the outer ring.
3. Further studies on the materials for space use.

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7. BIBLIOGRAPHY

[1] **N. Wolchover,** How Many People Can Earth Support?, 11 August 2011. Available: https://www.livescience.com/16493-people-planet-earth-support.html. [Last access: 20 March 2020].

[2] **J. Layton**, Has Earth reached its carrying capacity?, 11 December 2008. Available: https://science.howstuffworks.com/environmental/green-science/earth-carrying-capacity1.htm. [Last access: 20 March 2020].

[3] **R. Highfield,** Colonies in space may be only hope, says Hawking, The Telegraph, 16 October 2011.

[4] **R. D. Johnson i C. H. Holbrow,** Space Settlements: A Design Study, Washington: Scientific and Technical Information Office, National Aeronautics and Space Administration, 1977.

[5] **G. K. O'Neill,** The High Frontier: Human Colonies in Space, New York: William Morrow & Company, 1977.

[6] **G. K. O'Neill,** The Colonization of Space, de Physics Today, 1974, pp. 27(9):32-40.

[7] **J. W. Vincoli,** Lewis' Dictionary of Occupational and Environmental Safety and Health, CRC Press, 1999, p. 245

[8] Mass as a Measure of the Amount of Inertia, Available: https://www.physicsclassroom.com/class/newtlaws/Lesson-1/Inertia-and-Mass#:~:text=Absolutely%20yes!,in%20its%20state%20of%20motion. [Last access: 2 June 2020].

[9] Is there any resistance to movement in space for DS1?. Available: http://www.qrg.northwestern.edu/projects/vss/docs/propulsion/2-resisting-movement-in-space.html#:~:text=AIR%20RESISTANCE%3A%20Air%20resistance%20is,there's%20no%20air%20in%20space.. [Last access: 13 June 2020].

[10] **F Pozzi i C. Small,** Vegetation and Population Density in Urban and Suburban Areas in The USA, Columbia University, June 2002, pg 4. Available: https://sedac.ciesin.columbia.edu/urban_rs/PozziSmall2002.pdf [Last Access: 24 June 2020].

[11] **N. i W. S. T. ,** What is a Lagrange Point?, 27 March 2018. Available: https://solarsystem.nasa.gov/resources/754/what-is-a-lagrange-point/. [Last access: 20 April 2020].

[12] **W. P. McCray,** The Visioneers: How a Group of Elite Scientists Pursued Space Colonies, Nanotechnologies, and a Limitless Future, 2012, p. 56.

[13] Country Comparison: Electricity-Consumption. Available: https://www.cia.gov/library/publications/the-world-factbook/rankorder/2233rank.html. [Last access: 21 May 2020].

[14] Measuring the Universe, de Astronomic Union, 2012

[15] **V. Aggarwal**, What are the most efficient solar panels on the market? Solar panel cell efficiency explained, 22 January 2020. Available: https://news.energysage.com/what-are-the-most-efficient-solar-panels-on-the-market/. [Last access: 20 April 2020].

[16] **M. Stevens,** Human Body Heat as a Source for Thermoelectric Energy Generation, de Introduction to the Physics of Energy, PH240 - Stanford University - Fall 2016, 2016.