Escola Politècnica Superior
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FINAL DEGREE PROJECT

TITLE: PROTOTYPE OF AN ORBITAL SPACE STATION FOR THE SPACE COLONIZATION

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RESUMEN

La idea de la colonización espacial se ha sugerido desde la década de 1990 como la respuesta para mantener la supervivencia a largo plazo de la civilización humana. La estación espacial orbital es uno de los tipos de colonización espacial distintos del planeta terraformante. Muchos diseños para la estación espacial orbital habían sido realizados por profesionales de la física, ingenieros, maestros e investigadores.

En este proyecto en particular, diseñaré un prototipo de una estación espacial orbital. Pero antes de diseñar, se deben realizar estudios sobre diseños de estaciones espaciales para observar los requisitos, la ingeniería y la física deben tenerse en cuenta al diseñar. Por lo tanto, estudiaré Stanford Torus y Cilindro O'Neill, 2 diseños famosos de estaciones espaciales.

Después de conocer todos los requisitos teóricos, diseñaré un prototipo 3D de una estación espacial orbital utilizando el software NX12 Siemens PLM. Explicaré cada componente del prototipo y mostraré sus medidas. Luego, describiré en detalle las funcionalidades teóricas generales del prototipo, especialmente sobre cuántos habitantes puede albergar, cómo los habitantes obtienen gravedad artificial, cómo los habitantes obtienen luz solar natural, cómo el prototipo recolecta energía y el enfriamiento del prototipo.

Más adelante en la memoria, mostraré en detalle los pasos del proceso de diseño del prototipo a través del software. Posteriormente, crearé una simulación de los movimientos del prototipo a través del mismo software para obtener una representación visual de cómo se mueve el prototipo. También mostraré sus pasos.

Finalmente, haré una comparación entre el prototipo, Stanford Torus y Cilindro O'Neill para ver las mejoras realizadas y si hay algún inconveniente en el diseño.

Palabras clave (máximo 10):

Colonización Espacial	Estación Espacial Orbital	Stanford Torus	Cilindro O'Neill
Gravidad artificial	Estación Espacial Toroidal	NX12 Siemens PLM	Colonias humanas en el espacio
Estación orbital no giratoria	Efecto Coriolis		

ABSTRACT

The idea of space colonisation has been suggested since the 90s as the answer for the survivability of human civilization in the long-term. Orbital space station is one of the types for space colonisation other than terraforming planet. Many designs for orbital space station had been made by physics professional, engineers, professors and researchers.

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 (10 maximum):

Space Colonization	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		

Contents

FIGURE SUMMARY

TABLE SUMMARY

SIGNATURE GLOSSARY, SYMBOLS, ABBREVIATIONS, ACRONYMS AND TERMS

m	mass [kg]
g	gravitational acceleration [9,81 kgm/s^2]
v	velocity [kgm/s^2]
ω	angular velocity [rad/s]
r	radius [m]
d	diameter [m]
a	acceleration [m/s^2]
F	force [kg m/s^2] [N]
L	angular momentum [kgm^2/s]
I	moment of Inertia [kgm^2]
π	pi
T	period [s]
h	length / height [m]
≈	approximately equal to
η	solar cell efficiency [%]
P	Power [W]
E	Incident radiation flux [W/m^2]
Ac	Area of collector [m^2]
A	area [m^2]
σ	Stefan-Boltzmann constant [5,67 x 10^{-8} Wm^{-2}K^{-4}]
T	temperature [K]
b	base [m]
h	height [m]
Ho	solar radiation intensity [Wm^{-2}]
Hsun	solar radiation intensity at the Sun's surface [64 x 10^6 W/m^2]

1. INTRODUCTION

Earth was formed around 4,54 billion years ago [1]. As the years go by, the human population on Earth has been increasing exponentially. On this date, February 2020, the current world population is 7,765 billion [2].

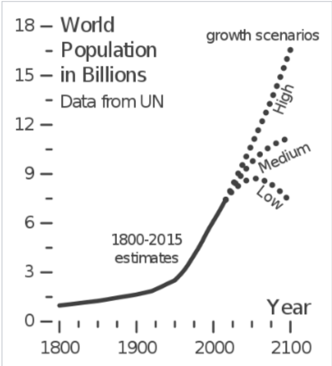


Figure 1: World population estimates from 1800 to 2100 [3]

Many scientists stated that the maximum carrying capacity of the Earth is 9 billion to 10 billion people [4] and based on the current world population, we are less than 2 billion people away to reach the maximum carrying capacity. A researcher named McConeghy [5] 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 [6]. And also not to forget, the COVID-19 pandemic that has killed millions of people 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 in the year 2050 or in 2100? Will the resources totally have gone? 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. By doing this big-scale, long-term and expensive solution, we can solve the overpopulation problem. And by solving this overpopulation problem, we can minimise human pollutions and we can use the empty spaces on Earth for forestation. Thus, repair the Earth's environment and solve the resources problem.

Theoretical physicist and cosmologist Stephen Hawking also suggested that space colonization is needed to save humanity in the future [7]. There are many ways for space colonization. One way is by creating an orbital space station that can house from hundred thousand to billions of colonists. There are already several designs of orbital space station made by physicists, researches, scientists, educators and engineers. One of them is called Stanford Torus. It is a proposed NASA design in Summer 1975 conducted at Stanford University [8]. 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*" [9] and in an article "*The Colonization of Space*" in the 1974 book, *Physics Today* [10]. 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 [11].

1.1 OBJECTIVE

There are several objectives for this project. Firstly, to study the existing theoretical designs of orbital space stations. This includes;

- Study the design of Stanford Torus, its Physics and engineering.
- Study O'Neill Cylinder design, its Physics and engineering.

Then with the knowledge and studies gained from the objectives above, I will:

- Find the theoretical requirements for building an orbital space station.
- Study on material requirements for building the prototype.
- Design a general 3D prototype of an orbital space station with adequate measurements using NX12 Siemens PLM Software.
- Simulation of the prototype by using NX12 Siemens PLM Software.
- Calculate the estimated number of inhabitants that the prototype can house based on the area in the habitat.
- Calculate the angular velocity needed for the prototype to obtain the artificial gravity same as the Earth's gravity.
- Find a suitable location in space for the space station to be located.
- Figure out how sunlight can reach in the habitat.
- Figure out type of energy that will be used and investigate the amount needed to generate electricity in the whole prototype.
- Find out about the cooling requirement for this prototype.

2. STUDIES OF THE DESIGNS OF ORBITAL SPACE STATIONS

The direct translation of space colonization is human habitation in space. It can be anywhere off the Earth. It can be at Mars, other planets or in the orbit. Orbital space station is an example of space colonization that would be located in the orbit. Right now, there is already one fully operational space station which is located in low Earth orbit. This small space station is called International Space Station (ISS). It is solely used to carry out space studies and for space craft testing. It is not used as a permanent space habitat as it can only carry 6 crews [12]. For space colonization, there are some theoretical designs for a big-scale space station. They are known as Stanford Torus and O'Neill Cylinder. The goal for this section is to study these two designs.

2.1 STANFORD TORUS

The Stanford Torus was a concept of space colony proposed to the NASA by a group of researchers, scientists and educators on the summer of 1975. The design was proposed at Stanford University. Hence, the space station is called Stanford Torus [13]. The idea is to make this space station as a solar power station. This station collects solar energy and beams it back to the Earth for the space power companies. This is a way to fully emphasize solar energy as a new form of energy. The habitat in the station will be used as a home for the solar power workers [14].

2.1.1 THE DESIGN

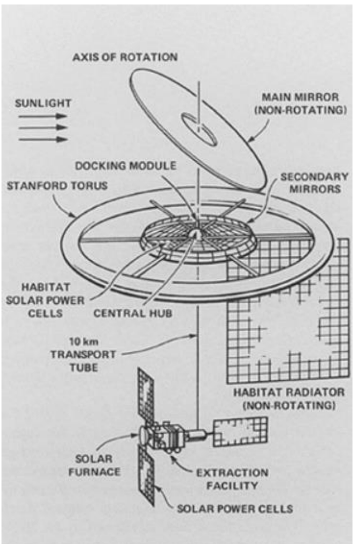


Figure 2: Colony configuration [8]

The Stanford Torus consists of a donut-shaped ring with a diameter of 1,8 km. The ring rotates once per minute to provide artificial gravity inside the habitat [15]. There is a transport tube which is 10 km long in the centre as shown in Figure 2. It also consists of a big stationary mirror at 45° at the top of the ring. Small mirrors which is also at 45° are located in the inner part of the ring. The reason of mirrors is to redirect the sunlight towards the outer ring by using light reflection method. Behind the small mirrors, there are main solar power cells shaped like a disc which is used for powering up the station and electricity in the habitat inside the outer ring via photovoltaics.

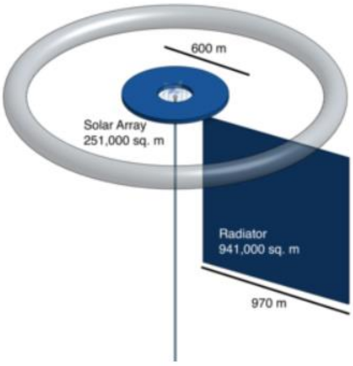


Figure 3: Stanford Torus solar array and radiator sized to scale [16]

A flat stationary radiator is located below the inner disc as shown in Figure 2 and Figure 3. It is used to dissipate heat waste released by the station. In the centre of the solar power cells, there is a docking module for the space craft to land and dock with the station [16].

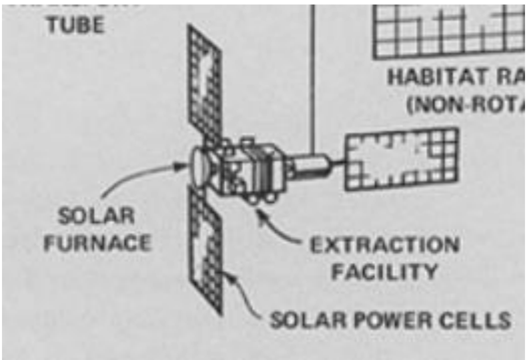


Figure 4: Zoomed picture of the solar power generation satellite [8]

At the bottom of the transport tube, there is a tethered solar power generation satellite. It collects solar energy and use it to generate the remainder of power required that is not generated by the main solar power cells [16].

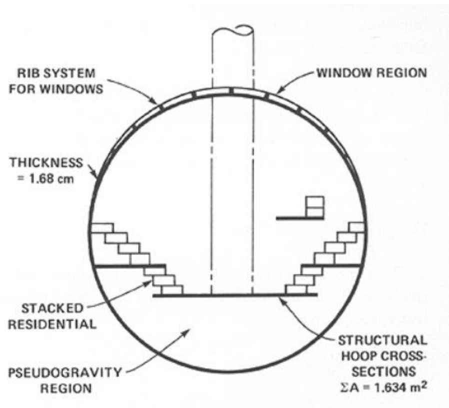


Figure 5: Outer ring structural cross section [8]

Figure 5 shows the cross-sectional view of the outer ring. This is where the colonists will stay in at the station. Its radius is 130 m and as we can see in the figure, there is a window region at the top. It is for the colonists to receive the reflected sunlight. Figure below is a painting of how the habitat would look like in the outer ring;

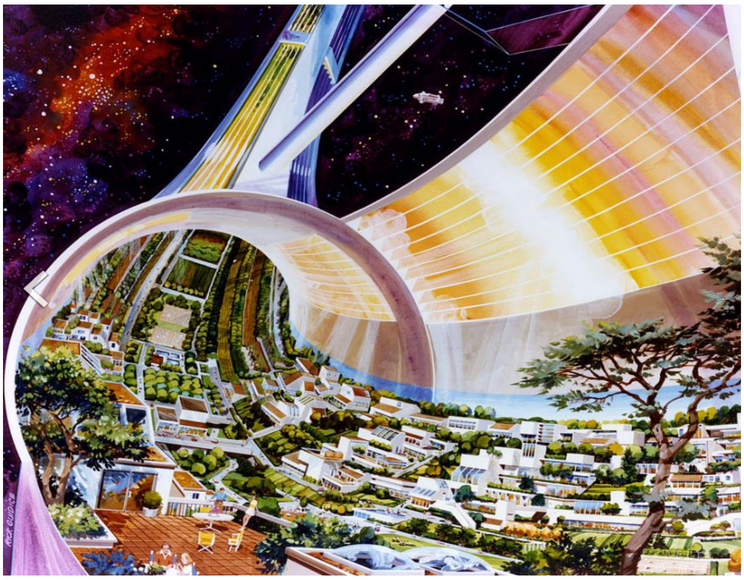


Figure 6: Painting of cutaway view of a Stanford Torus [17]

2.1.2 ARTIFICIAL GRAVITY AND ANGULAR VELOCITY

Artificial gravity in the outer ring is achieved using centrifugal force.

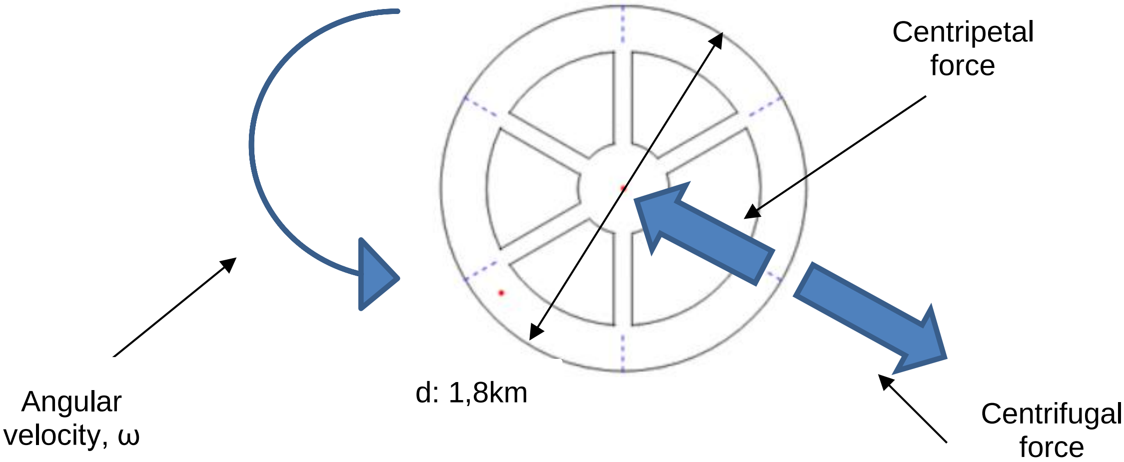


Figure 7: Torus with the forces that it experienced when rotating [Own Source]

When the outer ring is rotating, there will be a centripetal force acting towards the centre of rotation. Based on Newton 3rd Law, there will always be an opposite and equal force to a reaction. In this case, the force is centrifugal force. It has the same magnitude as centripetal force but it acts in the opposite direction. “Note that while centripetal force is an actual force, centrifugal force is defined as an apparent force. In other words, when twirling a mass on a string, the string exerts an inward centripetal force on the mass, while mass appears to exert an outward centrifugal force on the string.

"The difference between centripetal and centrifugal force has to do with different 'frames of reference,'" [18]. Therefore, centripetal force has to be equal to gravitational force. To achieve that, the torus has to rotate at certain angular velocity to achieve the artificial gravity inside the outer ring same as the gravity of the Earth.

$$F^{centripetal} = \frac{mv^2}{r} = mr\omega^2 \tag{1}$$

$$mr\omega^2 = ma \tag{2}$$

$$a = g = 9{,}81\ ms^{-2}$$

The mass on both side of the equation can be cancelled out as they are the same mass.

$$r\omega^2 = g \tag{3}$$

$$900\ m\,.\,\omega^2 = 9{,}81\ ms^{-2}$$

$$\omega = \left(\frac{9{,}81\ ms^{-2}}{900\ m}\right)^{\frac{1}{2}} \approx 0{,}1044\ rad\ s^{-1}$$

Therefore, the torus has to rotate with angular velocity of 0,1044 rad/s to make the colonists inside the outer ring experience the same gravity as the Earth (9,81 m/s^{-2}).

2.1.3 TIME PER ROTATION

Based on the angular velocity obtained in 2.1.2, the time per rotation (period *T*) can be calculated.

$$\omega = \frac{2\pi}{T} \tag{4}$$

$$0{,}1044\ rad\ s^{-1} = \frac{2\pi}{T}$$

$$T \approx 60{,}18\ s \approx 1\ min$$

To make this design works, the torus has to rotate at 1 rev/min.

2.1.4 LIGHT REFLECTION

Sunlight would be redirected by mirrors into the interior of the outer ring. This would allow the colonists to get natural light and experience the same day and night just like the Earth.

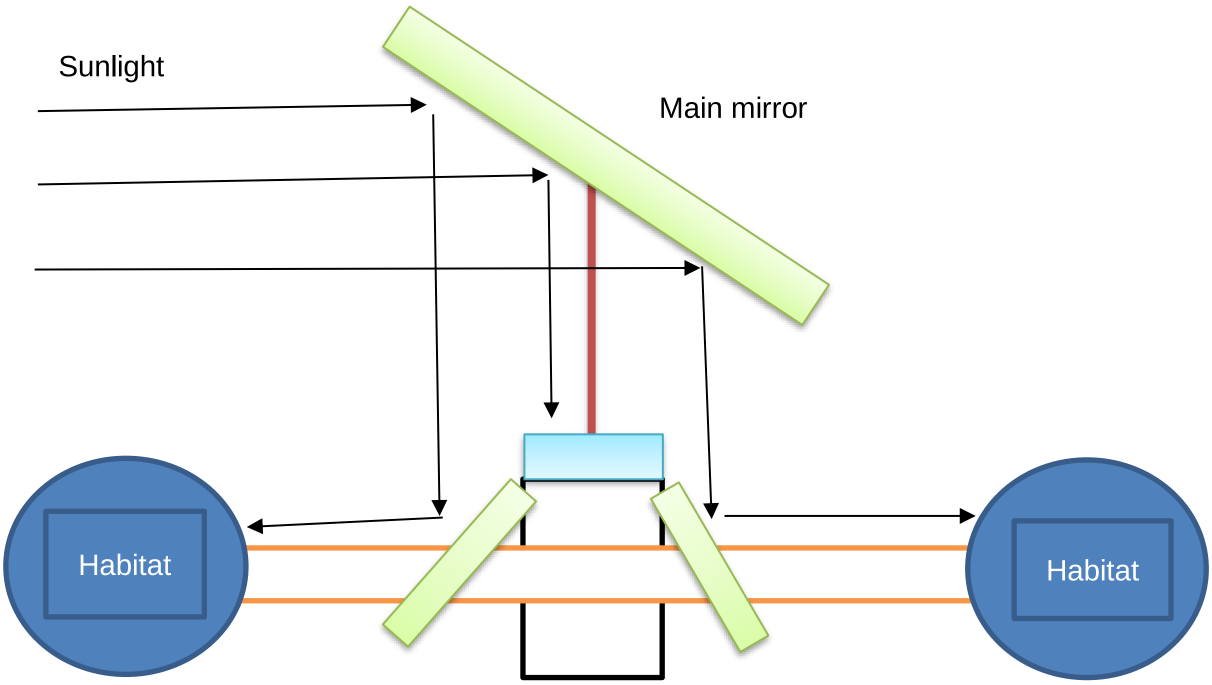


Figure 8: Simple cross-sectional view of Stanford Torus [Own Source]

The green-coloured object are mirrors, the blue-circled objects are the outer ring and the light blue object is considered as solar power cells (refer Figure 8). As we can see in Figure 8, Stanford Torus would feel the sunlight coming horizontally from the side. The big stationary mirror will reflect the sunlight vertically downwards as the mirror is at 45°. The reflected sunlight will then hit the solar power cells and thus generate power. The light will also hit the 45° small mirrors and then it will change the direction horizontally towards the inner part of the outer ring. The outer ring has window (Figure 3) so that the reflected sunlight can reach the habitat inside the outer ring. This sunlight is needed to the habitat because it would be used for agriculture, illumination and also to heat the habitat [16].

2.1.5 ENERGY REQUIREMENTS FOR THE HABITAT

This Stanford Torus is fully powered by using solar energy. Solar power generation via photovoltaics would be used to generate all the electricity in the torus [16]. In that case, a sufficient amount of solar panel area is needed to be installed has to be calculated.

Based on the article in [16], the team who proposed this Stanford Torus design estimated that there is 1390 W per square meter of solar energy available in space. The average electrical power needed for each person in the habitat is 3 kW. It is actually a double amount per capita electricity consumption of American in 1975. As the habitat can house

10.000 people, this means that the electrical power needed is 30 MW. With the solar panel efficiency of 10%, Stanford Torus will require a minimum solar panel area of 215.827 m^2.

2.1.6 COOLING REQUIREMENTS

Assuming that the power needed to generate electricity is 30 MW, for agriculture is 66 MW, for illumination and heating is 35 MW, the estimated waste heat that needs to be radiate would be 131 MW. The characteristics of the radiator are 280 K in temperature, can emit 348,5 W/m^2, and has an efficiency of 60%. This means that the radiator area needed is 628.000 m^2 [16]. But the radiator area of Stanford Torus is 941.000 m^2 (refer Figure 3) which is almost 1,5 times bigger. Therefore, the radiator used by Stanford Torus is more than enough to expel all the waste heat out into the space.

2.1.7 MATERIALS REQUIREMENTS

There is not much articles about the materials needed for the construction of Stanford Torus. The main materials that would be used are the materials that extracted from the Moon. Materials that the Moon doesn’t have will be imported from Earth. There is also an alternative source of materials which is Asteroid mining [19]. It is an exploitation of raw materials from asteroids and minor planets. A thick raw lunar soil will be located outside the Stanford Torus acting as an outer layer and as a radiation shield. The outer layer would be 1,7 meters deep [19].

2.2 O'NEILL CYLINDER

American physicist named Gerard K. O'Neill proposed a concept of space colonization in his book *The High Frontier: Human Colonies in Space* which was published in 1976 and in his article *The Colonization of Space* in a book, *Physics Today*. He later proposed three designs, which he called Island 1, Island 2 and Island 3. Island 1 and 2 are spherical in shape while Island 3 is a cylinder which later named as O'Neill Cylinder [9].

2.2.1 THE DESIGN

O'Neill Cylinder consists of two rotating cylinders which counter rotate with each other. Both cylinders would be connected by a tension cable at their front ends and by a compression tower at their back ends [9] (refer Figure 10).

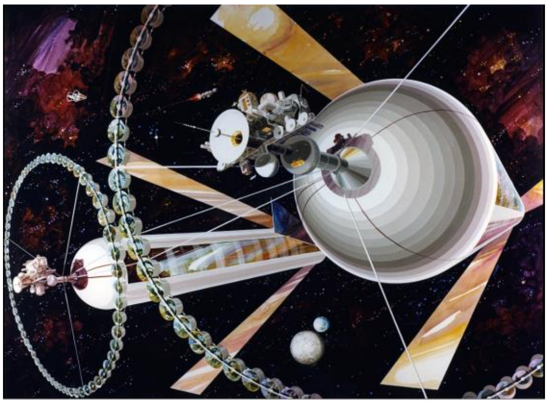


Figure 9: Artist's depiction of O'Neill Cylinder [20]

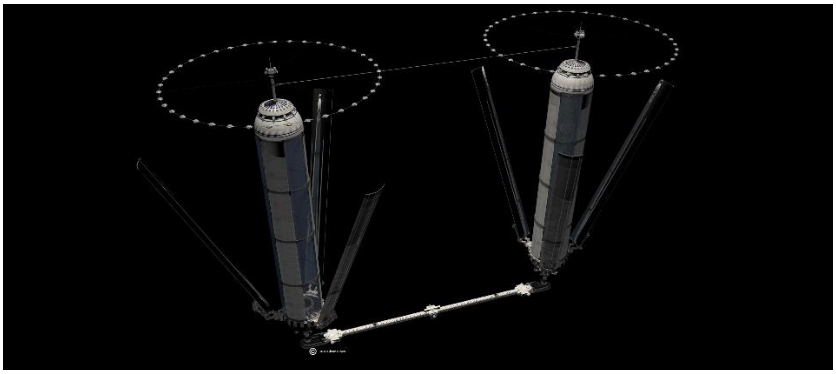


Figure 10: Top view of O'Neill Cylinder drawn by an artist [21]

Each cylinder is 32 km long and has a diameter of 8 km. Each cylinder would be hinged by a 3 long rectangle mirrors, which are 45° to the cylinder [9] (as shown in Figure 9 and 10). In the cylinders, where the colonies would live in, consist of 6 equal stripes. 3 of them are for habitable land which are called Valley 1, Valley 2 and Valley 3. The other 3 of the stripes are transparent windows (Solar 1, 2 and 3) for receiving reflected sunlight from the mirrors [10] (refer Figure 11). Each cylinder could house up to 100.000 people. So, the total people that the O'Neill Cylinder could house is 200.000 people [17].

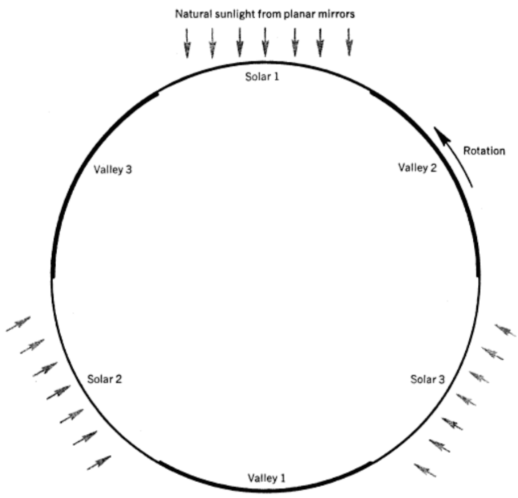


Figure 11: Cross-section sketch of the cylinder [10]

As we can see in Figure 9 and 10, there would be an outer ring connected with each cylinder. These rings are for agriculture. They are 32 km in diameter, rotating at slower speed compared to the cylinders. Every agriculture process would take place inside the outer ring. The artificial gravity inside the outer ring would be less as it would be easier to perform any agriculture process inside the ring [10].

2.2.2 ARTIFICAL GRAVITY AND ANGULAR VELOCITY

<u>CYLINDERS IN THE DESIGN</u>

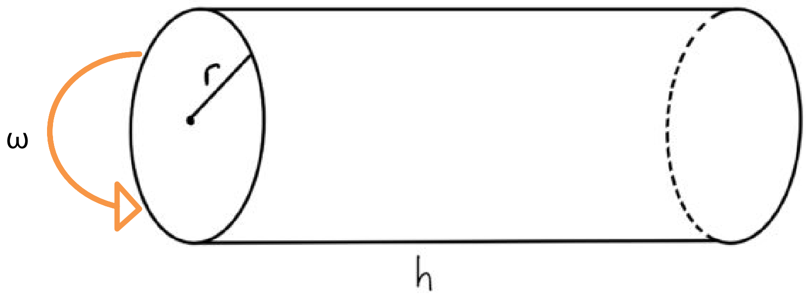


Figure 12: Simple cylinder concept of O'Neill Cylinder [Own Source]

As stated in 2.2.1, the diameter is 8 km and the length of the cylinder is 32 km. Therefore, to make sure that the artificial gravity inside the cylinder is the same as the gravity of Earth, the cylinder has to rotate at certain angular velocity.

$$r = 4000\,m \qquad h = 32000\,m$$

$$a = g = 9{,}81\,m/s^2$$

$$F^{centripetal} = F^{gravitational}$$

$$r\omega^2 = g \tag{5}$$

$$\omega^2 = \frac{9{,}81\ ms^{-2}}{4000\ m}$$

$$\omega \approx 0{,}0495\ rad\ s^{-1}$$

Hence, the cylinders would rotate at angular velocity of 0,0495 rad/s.

AGRICULTURAL RINGS IN THE DESIGN

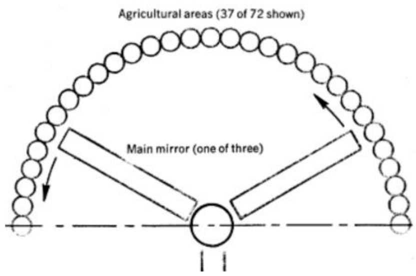


Figure 13: Agricultural ring in half [10]

In these rings (d = 32 km), the artificial gravity would be 10^{-2} times the gravity of Earth [17]. This means that the centripetal force acting on the rings would be 0,0981 m/s^2.

Therefore, the rings would rotate at angular speed of;

$$r\omega^2 = g \tag{6}$$

$$\omega^2 = \frac{0{,}0981\ ms^{-1}}{16000\ m}$$

$$\omega \approx 2{,}476 * 10^{-3}\ rads^{-1}$$

2.2.3 TIME PER ROTATION

CYLINDERS IN THE DESIGN

Angular velocity of 0,0495 rad/s means that the cylinders have to fully rotate in;

$$\omega = \frac{2\pi}{T} \tag{7}$$

$$T = \frac{2\pi\ rad}{0{,}0495\ rad\ s^{-1}}$$

$$T \approx 126{,}93\ s$$

$$\frac{1\ rev}{126{,}93\ s} = \frac{1\ rev}{126{,}93\ s} * \frac{3600\ s}{1\ hr} \approx \frac{28{,}36\ rev}{1\ hr}$$

The cylinders need to rotate at about 28 revolutions per hour so that the habitat within the cylinders experiences the same gravity as the Earth.

AGRICULTURAL RINGS IN THE DESIGN

As the angular velocity of each agricultural ring is 2,476 x 10^{-3} rad/s, the period T for one rotation of the rings is;

$$\omega = \frac{2\pi}{T} \tag{8}$$

$$T = \frac{2\pi\, rad}{2{,}476 * 10^{-3}\, rads^{-1}}$$

$$T \approx 2.537{,}64\, s \approx 42\, min$$

2.2.4 LIGHT REFLECTION

Just like Stanford Torus, this design uses mirror to redirect the light from the Sun to the habitat with the cylinders.

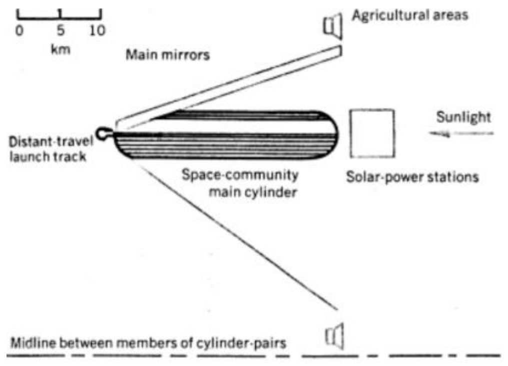


Figure 14: A view of left cylinder [10]

As described in 2.2.1, in each cylinder, there would be 3 stripes of transparent windows. These windows would be aligned with the 3 main mirrors and the mirrors would rotate at the same angular velocity as the cylinder. This is to ensure that the reflected sunlight reaches the habitat within the cylinder via the transparent windows.

As seen in Figure 14, the reflection process happens when the sunlight reaches to the 45° mirrors and the light would be reflected vertically downward, straight to the transparent windows of the cylinder.

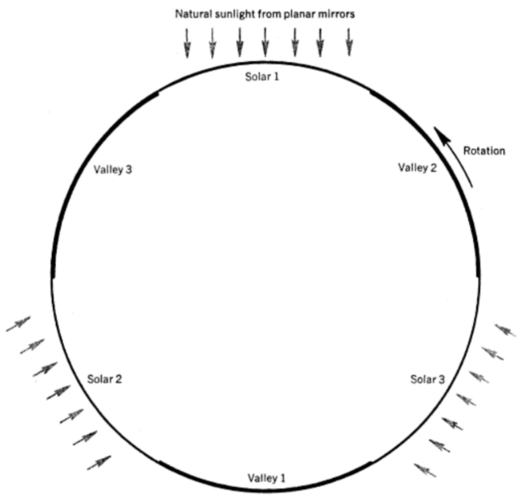


Figure 15: Cross-section sketch of the cylinder [10]

The reflected sunlight that passes through the transparent window named Solar 1 will light up the habitat at Valley 1, the light that passes through Solar 2 will light up Valley 2 and light that passes through Solar 3 will light up the habitat in Valley 3.

2.2.5 AXIAL ROTATION

The two cylinders are connected with each other at their ends. At front ends, there would be a tension cable that connects them, and at their back ends, there would be a compression tower that connects them [10] (Figure 10).

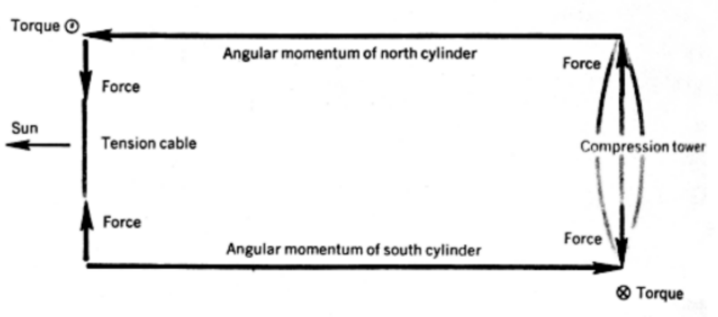


Figure 16: Force and torque diagram [10]

The tension cable and the compression tower will create forces and torques that would lock the position of O'Neill Cylinder in the space due to the zero axial angular momentum produced by the combination of these forces and torques. Therefore, the axis of O'Neill Cylinder, which is between the two cylinders, would always be pointed towards the Sun.

2.2.6 ENERGY REQUIREMENTS FOR THE HABITAT

O'Neill Cylinder fully works by using solar energy. The solar power stations, which is located at front ends of both cylinders (refer Figure 9 and 14), would be used to generate the electricity for the habitat inside the cylinders. The power stations would consist of paraboloidal mirrors, boiler tubes and conventional steam-turbine electric generators. Each person in the habitat would receive an amount of 10 kW. Therefore, as each cylinder can house 100.000 people, the total power needed per cylinder would be 1.000 MW. The solar station for each cylinder, with thermal efficiency of 33%, could generate 36.000 MW which is way more than the power needed by the community inside the cylinder [10].

1 cylinder – 100.000 people

1 person – 10 kW

1 cylinder – 10 kW/person x 100.000 persons – 1.000 MW needed

2.2.7 COOLING REQUIREMENTS

There would be infrared radiators installed at O'Neill Cylinder. They would be used to send waste heat into the space [10].

2.2.8 MATERIAL REQUIREMENTS

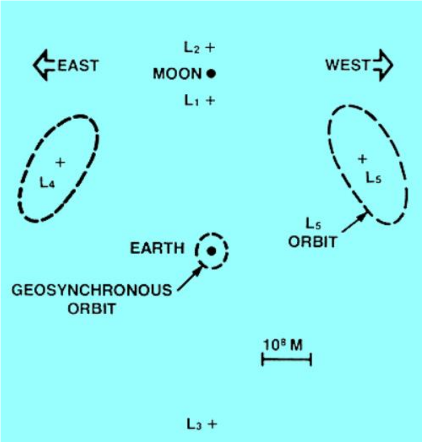


Figure 17: Earth-Moon Libration Points [22]

Some of the materials would be produced at spacecraft at L5. Earth-Moon L5 is a Lagragrian point that lies at the same position with respect to Earth and Moon (refer Figure 17). A spacecraft would be placed at this point and would be used to process and produce materials from the elements obtained from the Moon [22]. Aluminium, Titanium, Silicon and Oxygen are the elements required to build this design. Aluminium and glass would be produced at L5 from lunar material [10]. The reason that those materials need to be produced at L5 is because O'Neill Cylinder's design requires huge amount of aluminium and glass, and transporting things from the Moon would take 5% lesser energy than transporting things from Earth [10]. Aluminium would be used to build the structure of O'Neill Cylinder and the glass would be used to build the transparent windows (Solar 1, 2 and 3) and the main mirrors. Lunar soil would also be needed [10]. It would be used for agriculture.

2.3 SUMMARY OF THE ADVANTAGES AND INCONVENIENCES

Both Stanford Torus and O'Neill Cylinder have their own advantages and inconveniences. As O'Neill Cylinder is the latest and updated design compared to Stanford Torus, it might be the most relevant for Space Colonization.

2.3.1 STANFORD TORUS – ADVANTAGES AND INCONVENIENCES

As this design was proposed in 1975, it still has several inconveniences as the technology used in the design is not as advanced as current technology.

ADVANTAGES	INCONVENIENCES
Easier to build on Earth and send it to space as the design is not big.	Can only house 10.000 to 140.000 inhabitants.
Less cost compared to O'Neill Cylinder as the cylinder is bigger.	The design is complex and requires a lot of different materials.
Lesser volume of materials needed	High Coriolis effect would be experienced by the colonies as the period of the rotation of the torus is high (1 rev/min).
	Not as efficient as O'Neill Cylinder as the motor needs to generate higher angular velocity for housing 10.000 colonies.

Table 1:The advantages and the inconveniences of Stanford Torus

As the design is not big (refer section 2.1.1), we can say that this design requires less volume of materials than O'Neill cylinder, thus the total cost for the materials is lesser too. This design is also easier to build on Earth as the torus is only 1,8 km in diameter. The inconveniences are that this design cannot house many colonists, which would be inconvenient. Plus, as the torus rotates, it produces high Coriolis effect as it rotates at fast speed (for details about Coriolis effect, refer section 3.2).

2.3.2 O'NEILL CYLINDER – ADVANTAGES AND INCONVENIENCES

ADVANTAGES	INCONVENIENCES
Can house a total of 200.000 inhabitants.	The design has to be built in Lagrange Point L5 of Earth-Moon (refer section 2.2.8) as it is too big to be built on Earth.
Most of the design requires the same material which is Aluminium and glass.	It is highly expensive compared to Stanford Torus.
Low Coriolis effect experience by the colonies as the period of rotation of cylinder is low (28 rev/hr).	Requires a lot of space engineers as it has to be built in space.

Table 2: The advantages and the inconveniences of O'Neill Cylinder

As each cylinder can house 100.000 inhabitants, the total colonies that this whole design can house is 200.000 which is efficient. Even though this design is big, most of the part of the design requires the same materials which are only Aluminium and glass. But as the design is big, the amount of Aluminium and glass needed is a lot, this will be highly expensive compared to Stanford Torus. And O'Neill Cylinder cannot be built on Earth as this design is too big (refer section 2.2.1).

This design has lower Coriolis effect as it rotates at 28 rev/hr which is a good thing for the colonies.

2.3.3 CONCLUSION ON THE SUMMARY

Both designs have their own advantages and inconveniences. But O'Neill Cylinder is more ideal and efficient compared to Stanford Torus as its advantages weight out its inconveniences. Even though it is harder to be built and it is more expensive design, the number of colonies that the O'Neill Cylinder can carry is what makes this design better than Stanford Torus.

3. REQUIREMENTS NEEDED IN DESIGNING THE PROTOTYPE

There are important requirements that 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.

My design idea for the prototype is multiple rotating rings that connected in a static space station. Hence, the first requirement that needed to be focused is how the colonies would experience the same gravity as Earth. In this case, we have to create an artificial gravity.

3.1 ARTIFICIAL GRAVITY

To obtain the artificial gravity (similar to the gravity on the Earth surface: 9,81 m/s^2), the wheels have to rotate at certain speed and angular velocity based on their diameter. If each wheel has different diameter, each wheel has to rotate at different angular velocity to achieve the same artificial gravity. The outward force, centrifugal force (experienced by the observers living inside the torus) needed to be equal to gravitational force. Therefore, the equation that needed to be taken into account are;

$$F^{centripetal} = \frac{mv^2}{r} = mr\omega^2 \tag{9}$$

$$F^{centripetal} = F^{gravitational}$$

$$r\omega^2 = g \tag{10}$$

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

$$\omega = \frac{2\pi}{T} \tag{11}$$

3.2 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” [23]. And this Coriolis acceleration is generated by Coriolis force. “Coriolis force – An apparent force observed on any free-moving object in rotating system” [23].

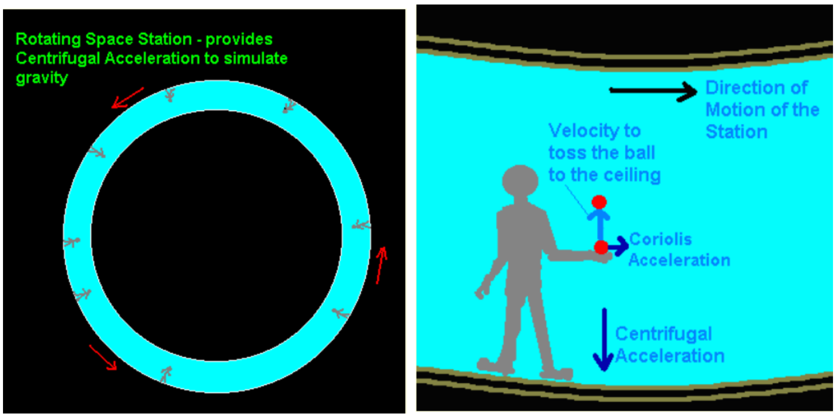


Figure 18: Coriolis effect [24]

As the colonies experienced artificial gravity (centrifugal acceleration: 9,81 m/s^2) in a rotating space station, they will also experience Coriolis acceleration based on figure above. Now imagine, if they throw a tennis ball upward, there will be both artificial gravity (centrifugal acceleration) and Coriolis acceleration act on the tennis ball. The Coriolis force and Coriolis acceleration are always perpendicular to the direction of the ball and the axis of the rotation of the station [24]. 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 [23], 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.

3.3 AXIAL ROTATION

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

$$L = I * \omega \tag{5}$$

Where L = angular momentum [kgm^{2}s^{-1}]

I = Moment of Inertia [kgm^2]

ω = angular velocity [rad/s]

"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" [25]. 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" [26]. 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.

If the moment of inertia I of the station set varies (for example, due to significant mass displacements) the angular velocity would vary (Principle of conservation of angular momentum).

3.4 SUNLIGHT

In this design, the colonists would receive natural light from the Sun. This can be accomplished by using the mirror reflection method. My aim is to make sure that the redirected sunlight comes from the roof of the habitat. This will cause the colonies to experience sunlight from the top just like when they live on Earth.

3.5 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;

$$P = \frac{W}{t} \tag{6}$$

$$\eta max = \frac{Pmax}{E * Ac} * 100\% \tag{7}$$

Based on the currently available solar panels, we can find a suitable solar panel with good solar cell efficiency (η) and investigate the estimated energy needed to power up the station. With both values, plus the estimated radiation flux (E) in space, we can find the solar panel area (Ac) needed to be incorporated in the prototype.

3.6 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;

$$P = e\sigma A(T^4 - Tc^4) \tag{8}$$

In this equation, we can calculate the estimated radiator area (A) based on the waste heat (P), the estimated temperature of the prototype (Tc) and the temperature of space (T).

4. IN-DEPTH STUDIES ON MATERIALS FOR ORBITAL SPACE STATION

The condition in space is far different compared with Earth. “Space puts all materials under severe stresses, allowing only the most robust products to survive” [27]. Currently, we have figured out the materials that can be put in low Earth orbit only. We are still lacking resources, knowledge about materials that can be put in Lagrange Point L5 of Sun-Earth (Lagrange Point L5 of Sun-Earth is the position where the prototype will be located at, this part will be explained in section 5.3.7).

To find the suitable materials, we must first study the conditions of space.

4.1 TEMPERATURE

“Most of the gas in space is too thin to warm anything up. Essentially, there are not enough gas particles to "bump" into and transfer heat to an object. So, if you were in space, but shielded from the sun, you would radiate away nearly all your heat pretty quickly and cool to the cosmic background temperature. Step (or float) into the sun, and you’d be warmed. Either way you'd need lots of protection!” [28]. The cosmic background temperature is known to be about -454,81 degrees Fahrenheit which is about -270,45 degrees Celsius or at an average of 2,7 K. “This is mostly due to a lack of atmosphere and the vacuum-like nature of space — with very few molecules to energetically bounce around, there can be no heat” [29].

There is no accurate temperature for Lagrange Point L5 of Sun-Earth but we can take average temperature of space which is 2,7 K. But I would say that it might be slight hotter as the L5 is way closer to the Sun. Therefore, I would take 4 K as the temperature at L5 so that I won’t be under measure in my calculation. The materials for the orbital space station must have **strong thermal ability** that can hold up extreme low temperatures.

4.2 RADIATION

As an object leaves Earth’s atmosphere layer, radiation levels increase. The further the object from the Earth, the higher the radiation levels [27]. “Space radiation is made up of three kinds of radiation: particles trapped in the Earth’s magnetic field; particles shot into space during solar flares (solar particle events); and galactic cosmic rays, which are high-energy protons and heavy ions from outside our solar system” [30].

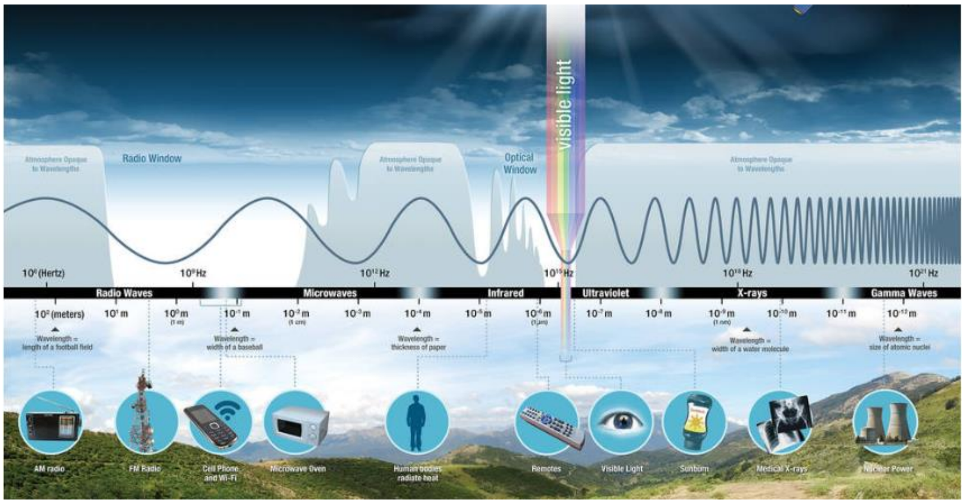


Figure 19: Electromagnetic Spectrum [30]

As Lagrange Point L5 of Sun-Earth, the source of radiation is from the Sun. Sun emits all wavelengths in the electromagnetic spectrum (EM) (refer figure above). Majority of the radiation are visible, infrared and ultraviolet radiation (UV). But, “Occasionally, giant explosions, called solar flares, occur on the surface of the Sun and release massive amounts of energy out into space in the form of x-rays, gamma rays, and streams of protons and electrons. This is called a solar particle event (SPE).” [30].

Galactic Cosmic Ray is the other type of radiation that exists in space. It comes primarily from within Milky Way galaxy [30].

Therefore, we need to find suitable materials that **can block these strong radiations** in space.

4.3 PRESSURE

There are internal and external forces that a space craft will experience. Internal pressure in a spacecraft is mainly from oxygen. “The internal pressure from oxygen inside the International Space Station is 15 pounds per inch” [27]. Meanwhile the pressure in outer space is too low that it is as non-existent. Its average pressure is 1,322 x 10^{-11} Pa [31].

Hence, we must make sure that the structure and the materials of the prototype can stand up to the force from the inside and also to retain its shape from exterior pressures on it. The materials need to have a strong **compression strength**.

4.4 OTHER CHARACTERISTICS REQUIRED FOR THE MATERIALS

There are several characteristics that are also required for the prototype building other than can withstand pressure, radiation and temperature in space.

The material firstly must be able to withstand **impacts** as in space, there are many man-made and natural objects floating. The materials need to be able to withstand intense hit.

As the prototype will be for space colonization, the materials used need to have a long lifespan before the materials broke down. The materials need to withstand **corrosion** for a long lifespan.

Finally, **flexure**. As orbital space station is for colonising thousands of people, we must find materials that can handle ton of loads without bending.

There are further experiments and studies need to be made to find the most suitable materials for the prototype. To completely find materials that can withstand all the requirements mentioned, extensive thermal testing, radiation testing, compression testing, impacts testing, corrosion testing and flexure testing need to be done [27].

4.5 CURRENT SUITABLE MATERIALS

After deep studying, I found several materials that might be useful for the prototype building. These materials don't have sufficient properties and not all can take harsh conditions in space, but they have proven to excel in space environment.

Kevlar

Figure 20: Kevlar [27]

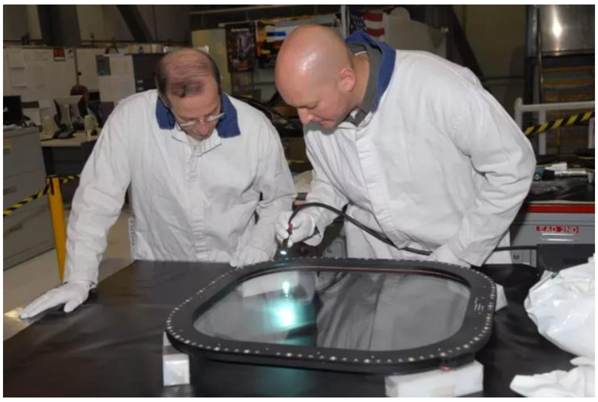
Kevlar is a lightweight fibre that has a high heat-resistant and high tensile strength. It is commonly used as bulletproof vests and armour. "In addition to its high strength, Kevlar also is incredibly resistant to temperature changes making it ideal for the orbiting structures that move in and out of the sun's direct heat as they orbit the Earth. Kevlar's toughness and durability also makes it ideal for protecting artificial satellites from dangerous orbital debris" [32].

Aluminium Alloy

Aluminium is often used for spacecraft building as it is lightweight. It also has a good corrosion resistance and good strength at low temperatures [33]. But it is not strong enough for space use unless it is combines with other metals forming a strong Aluminium alloy.

“Aluminium is used for the shutters on the windows of the International Space Station in order to protect the windows from impacts. These windows already are made with glass thicker than panes of glass on earth and often with twice as many panes. However, the additional aluminium shutters guarantee the safety of the astronauts within.” [32].

Thermal Glass



The orbital space station prototype would need suitable glass for building mirrors and windows in it. Thermal glass would be suitable as it has a good heat resistant and pressure resistant. Space shuttles use thermal glass for their windows without allowing heat to pass through the material [27].

“Thermal glass proved the solution to protect the astronauts from both high and low temperatures around the windows and the pressures of space travel” [27]. The thermal glass was made of Aluminium Silicate glass and fused Silica glass [34].

5. THE PROTOTYPE OF ORBITAL SPACE STATION

Even though rotating cylinder space station like O'Neill Cylinder is the most convenient design out there, I am more interested in designing toroidal space station like Stanford Torus. 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.

5.1 THE DESIGN OF THE PROTOTYPE

Below is the design for the prototype. The prototype is 12,23 km long and the habitat rings have a diameter of 5 km and 5,8 km (for more details, refer Annex). To see the designing process of the prototype, refer section 6.

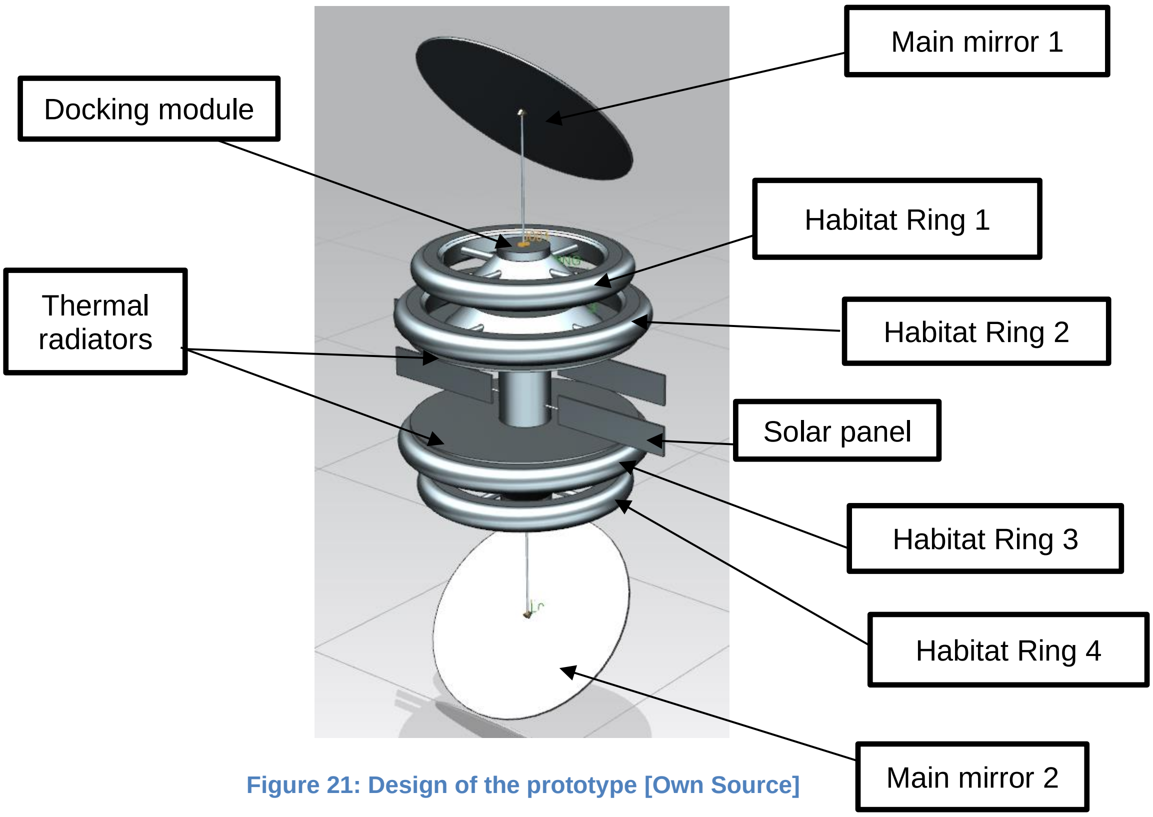


Figure 21: Design of the prototype [Own Source]

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 circular-shaped radiators would be incorporated for eliminating waste heat into the space.

5.2 THE COMPONENTS

The prototype would be formed by 17 main 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.

5.2.1 NON-ROTATING STATION WITH CONNECTED SOLAR PANELS AND RADIATORS

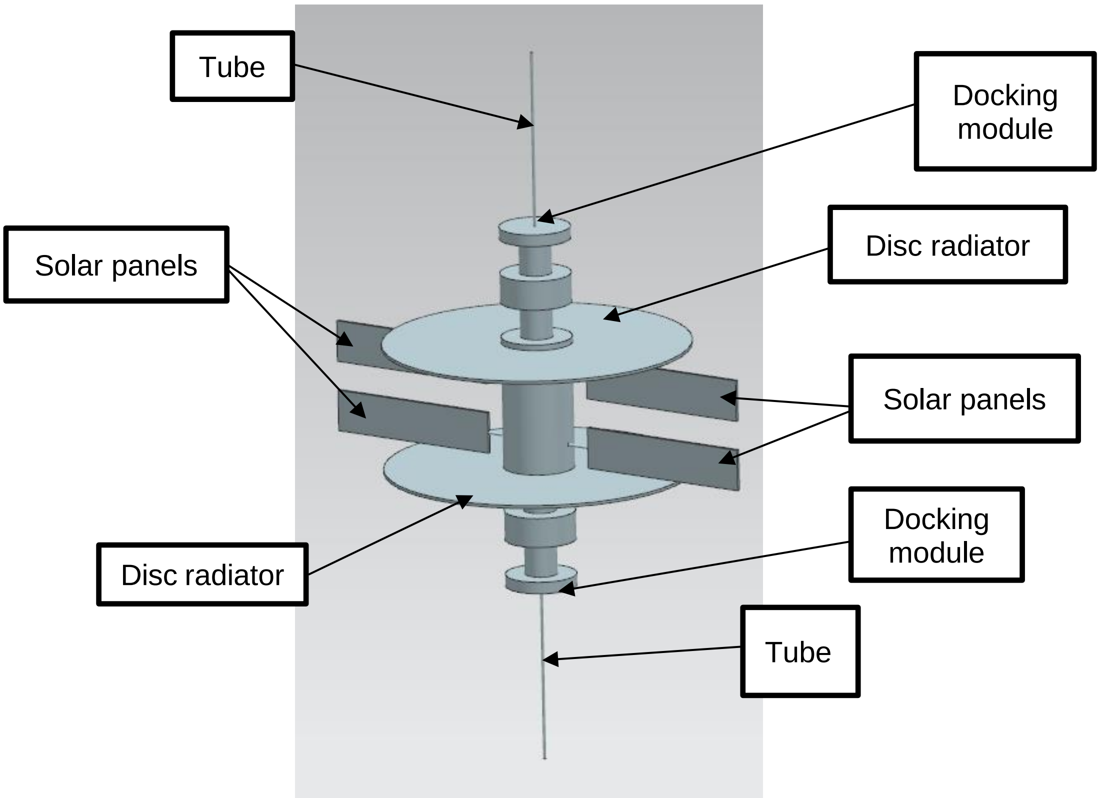


Figure 22: Non-Rotating Station [Own Source]

The Non-Rotating station would be connected by 2 disc-shaped radiators 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.

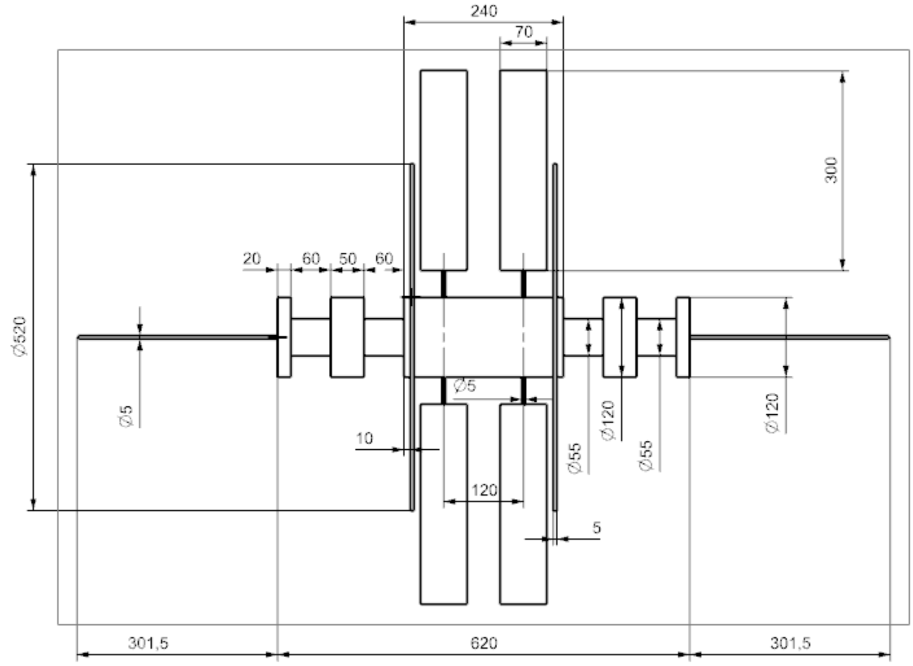


Figure 23: Non-Rotating Station's dimensions from the side (ratio 1 mm : 10 m) [Annex 5]

Based on Figure 20 above, we can see the ratio measurements of the port component. 1 mm of the dimension is equal to 10 m. As we can see, the length of the port 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;

$$A^{rectangle} = b * h \tag{9}$$

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

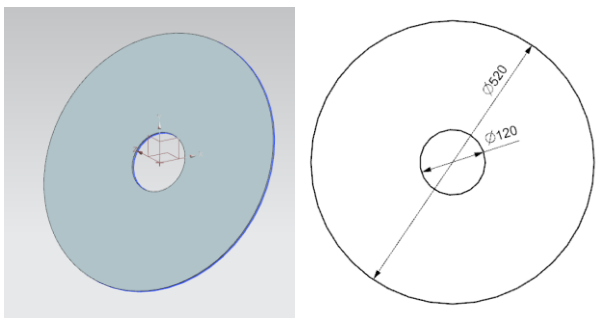


Figure 24: A radiator disc in the Non-Rotating Station (ratio 1 mm:10 m) [Own Source]

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

$$A^{circle} = \pi r^2 \tag{10}$$

$$A^{disc} = \pi R^2 - \pi r^2 \tag{11}$$

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

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

5.2.2 HABITAT RINGS

Habitat Ring 1 and 4

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 18, 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 (refer Figure 19).

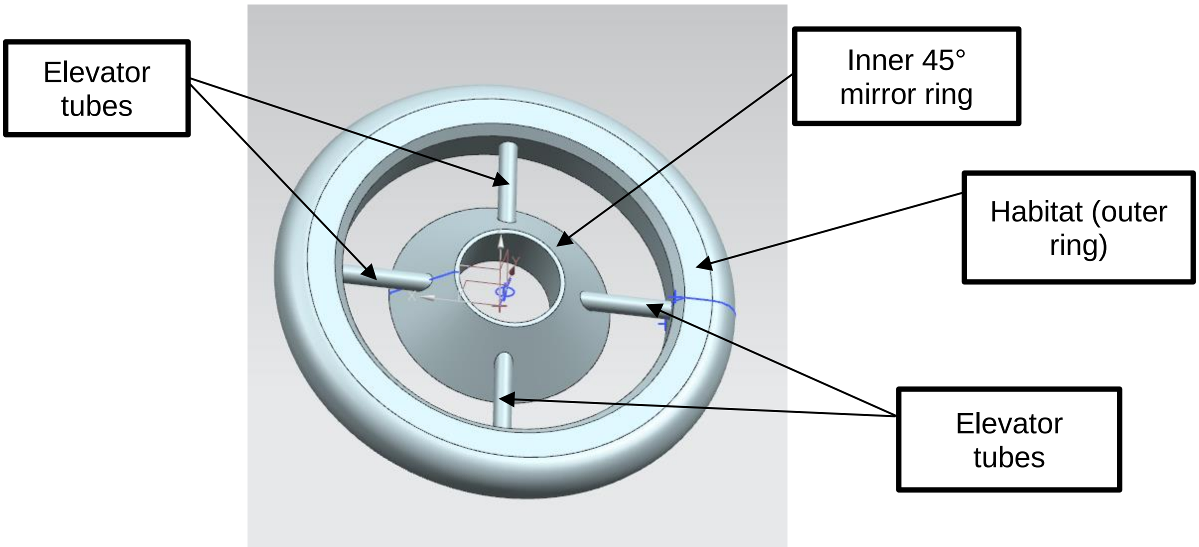


Figure 25: Habitat Ring 1 and 4 [Own Source]

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.

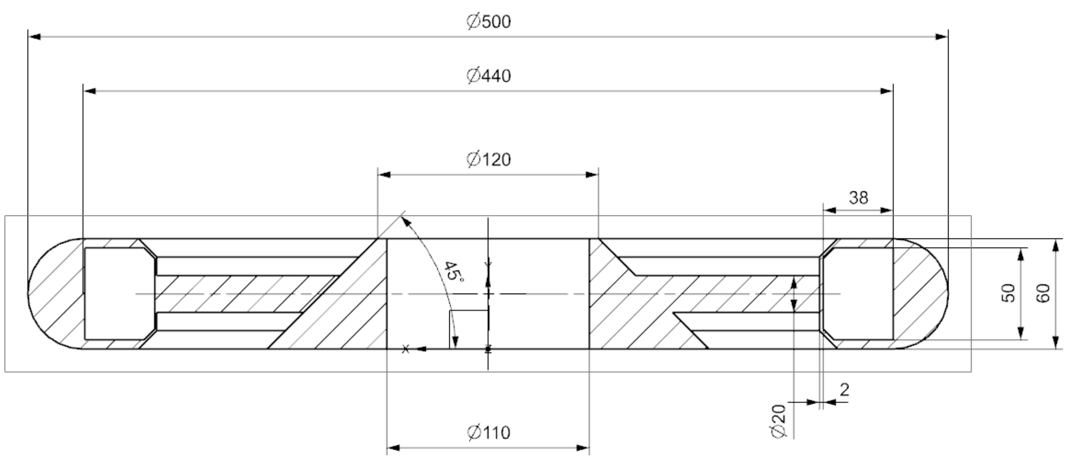


Figure 26: Cross-section view of Habitat Ring 1 and 4 (ratio 1 mm : 10m) [Annex 6]

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.

Habitat Ring 2 and 3

Both Habitat Ring 2 and Habitat Ring 3 will also have the same design and measurements.

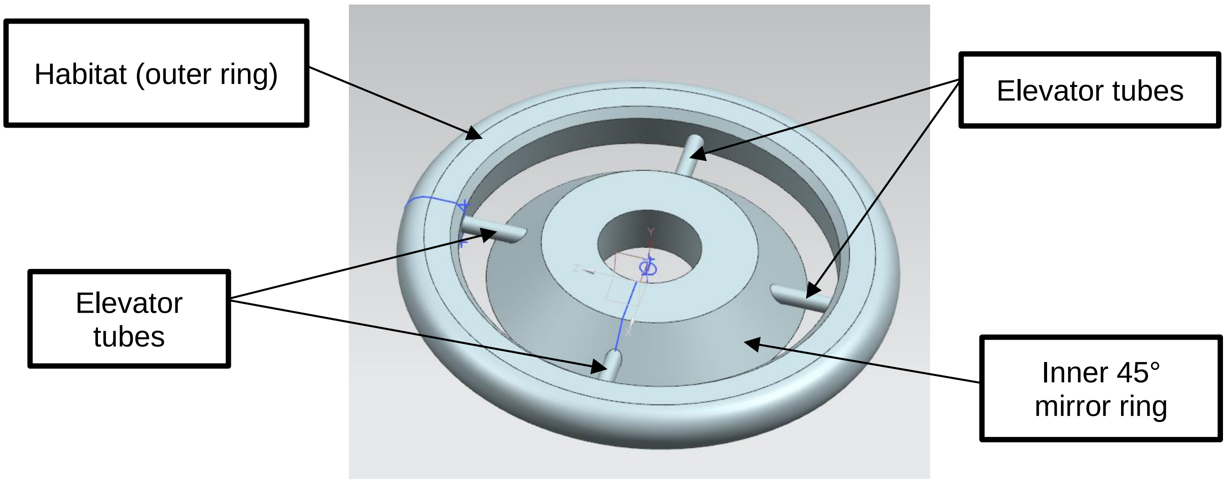


Figure 27: Habitat Ring 2 and 3 [Own Source]

Just like Habitat Ring 1 and 4, the design for Habitat Ring 2 and 3 consist of 4 elevator tubes for transportation between port and habitat. The inner ring will have a 45° mirror surfaced to redirect sunlight to the habitat.

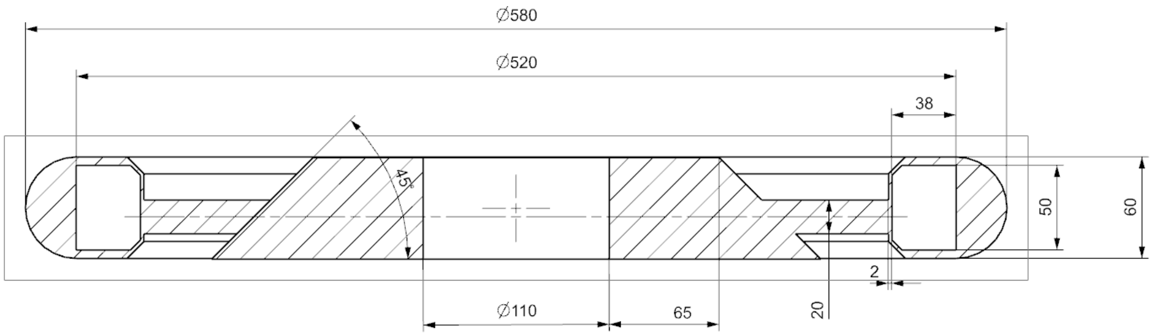


Figure 28: Cross-section view and dimensions for Habitat Ring 2 and 3 [Annex 7]

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.

Habitat in the outer ring

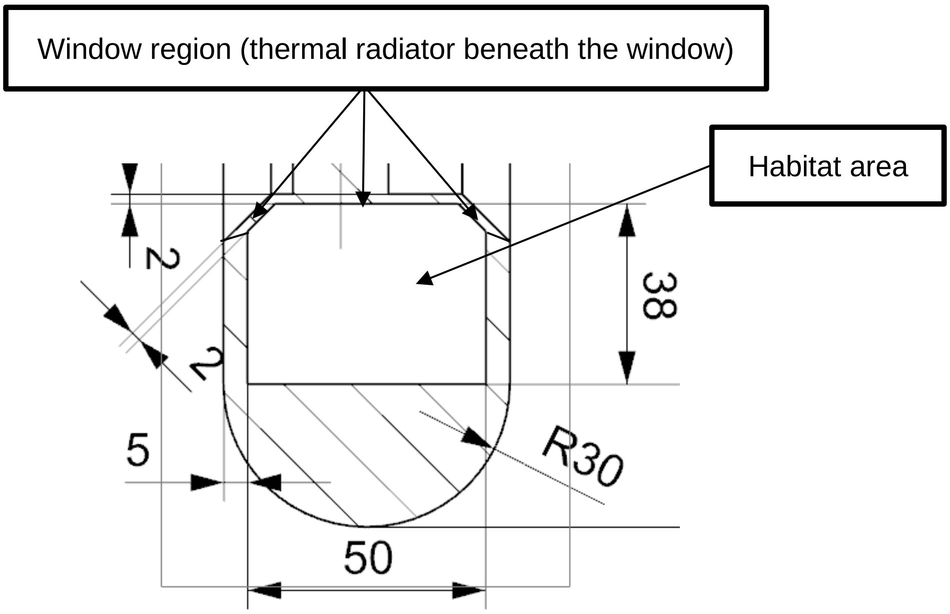


Figure 29: Habitat within the outer ring [Annex 6 and 7]

Figure 27 shows the cross-sectional view of the outer ring, but the figure is rotated to make the view vertical with respect to the position of the colonies in the habitat. 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.

5.2.3 MAIN MIRRORS

There will be two main mirrors that being incorporated in the prototype.

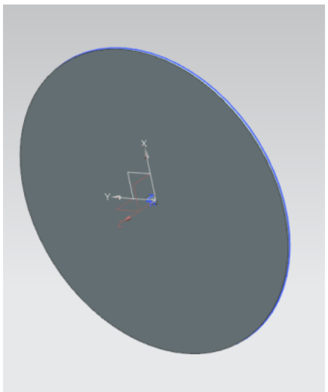


Figure 30: Main mirror [Own Source]

The diameter of each main mirror is 5,24 km. As the mirror would be installed in 45 degrees;

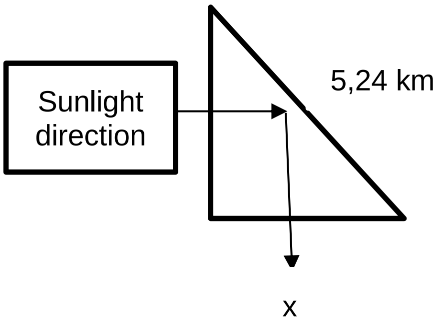


Figure 31: Simple drawing of sunlight reflection direction [Own Source]

The area of sunlight that being redirected towards the ring is;

$$\frac{adjacent}{hypothenuse} = cos\theta \tag{12}$$

$$x = 5{,}24\,km\,.\,cos45 = 3{,}705\,km$$

$$A^{circle} = \pi r^2 \tag{10}$$

$$A = \pi\,.\,(3{,}705\,km)^2 = 13{,}727\,\pi\,km^2 \approx 43{,}125\,km^2$$

5.2.4 BEARINGS

All the habitat rings would rotate via bearing system. 4 big-sized and sealed bearings would be incorporated in the prototype. Each bearing would be installed in between the inner rings and the non-rotating station.

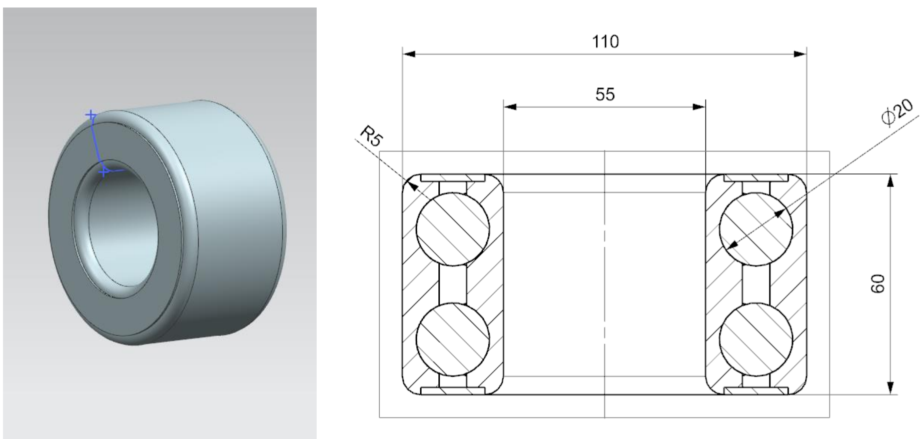


Figure 32: Bearings and its dimensions (1 mm : 10m) [Own Source] [Annex 9]

The bearings have to be sealed to reduce the surface area exposed to the space. Each bearing will use 2 ball bearings as the habitat rings have a height of 600 m.

5.3 FUNCTIONALITIES

5.3.1 ARTIFICIAL GRAVITY AND ANGULAR VELOCITY

Based on Figure 31, there are 2 smaller habitat rings and 2 big habitat rings incorporated in this prototype. Theoretically, to find out the angular velocity needed for the rings to rotate to obtain the artificial gravity in the habitats, we have to take into account the diameter of all those rings.

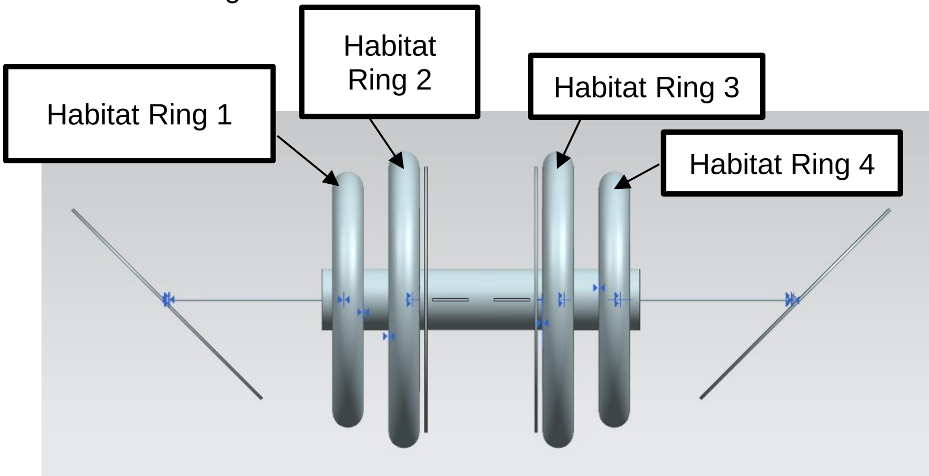


Figure 33: Side view of the prototype [Own Source]

Habitat Ring 1 and 4 have the same diameter which is 5 km (refer Figure 22). And Habitat Ring 2 and 3 have a diameter of 5,8 km(refer figure 26). But the measurement that must be taken into account is not the full diameter of those rings, it is the radius between the habitat floor and the center of the ring. 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. Therefore, based on Figure 22 and 26, the radius is 2,2 km for Habitat Ring 1 and 4, and 2,6 km for Habitat Ring 2 and 3.

For Habitat Ring 1 and 4;

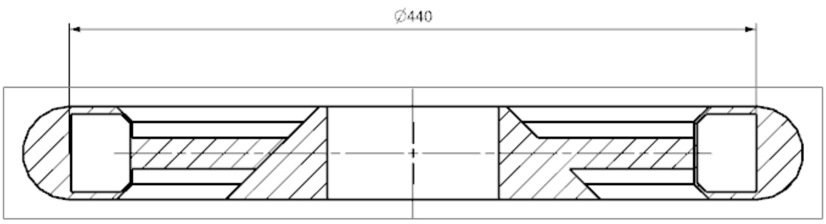


Figure 34: Diameter Habitat Ring 1 and 4 needed to be taken into centripetal force equation (1 mm : 10m) [Annex 6]

In making the habitat floor experiences a artificial gravity equal to 9,81 m/s^2, the angular velocity (ω) must be;

$$r = \frac{d}{2} = \frac{4400\ m}{2} = 2200\ m \qquad\qquad a = g = 9{,}81\ ms^{-2}$$

$$F^{centripetal} = F^{gravitational}$$

$$r\omega^2 = g \quad (12)$$

$$\omega^2 = \frac{9{,}81\, ms^{-2}}{2200\, m}$$

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

For Habitat Ring 2 and 3;

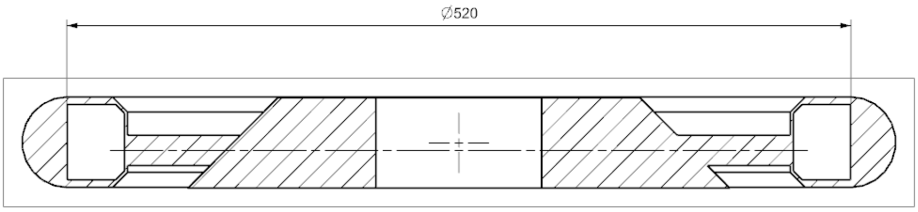


Figure 35: Diameter Habitat Ring 2 and 3 needed for centripetal force equation application (1 mm : 10 m) [Annex 7]

$$r = \frac{d}{2} = \frac{5200\, m}{2} = 2600\, m \qquad a = g = 9{,}81\, ms^{-1}$$

$$r\omega^2 = g \quad (13)$$

$$\omega^2 = \frac{9{,}81\, ms^{-2}}{2600\, m}$$

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

Hence, Habitat Ring 1 and 3 would rotate at 0,06678 rad/s meanwhile Habitat Ring 2 and 3 would rotate at a slower angular velocity which is 0,06143 rad/s.

5.3.2 TIME PER ROTATION

As for the period (T), it can be calculated based on the angular velocity (ω) obtained from 4.3.1.

For Habitat Ring 1 and 4;

$$\omega = \frac{2\pi}{T} \tag{14}$$

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

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

For Habitat Ring 2 and 3;

$$\omega = \frac{2\pi}{T} \tag{15}$$

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

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

Thus, Habitat Ring 1 and 4 have a period (T) of 94,09 s per rotation (0,0106 rev/s) and Habitat Ring 2 and 3 have a period, T of 102,28 s per rotation (9,777 x 10^{-3}).

5.3.3 BEARING SYSTEM

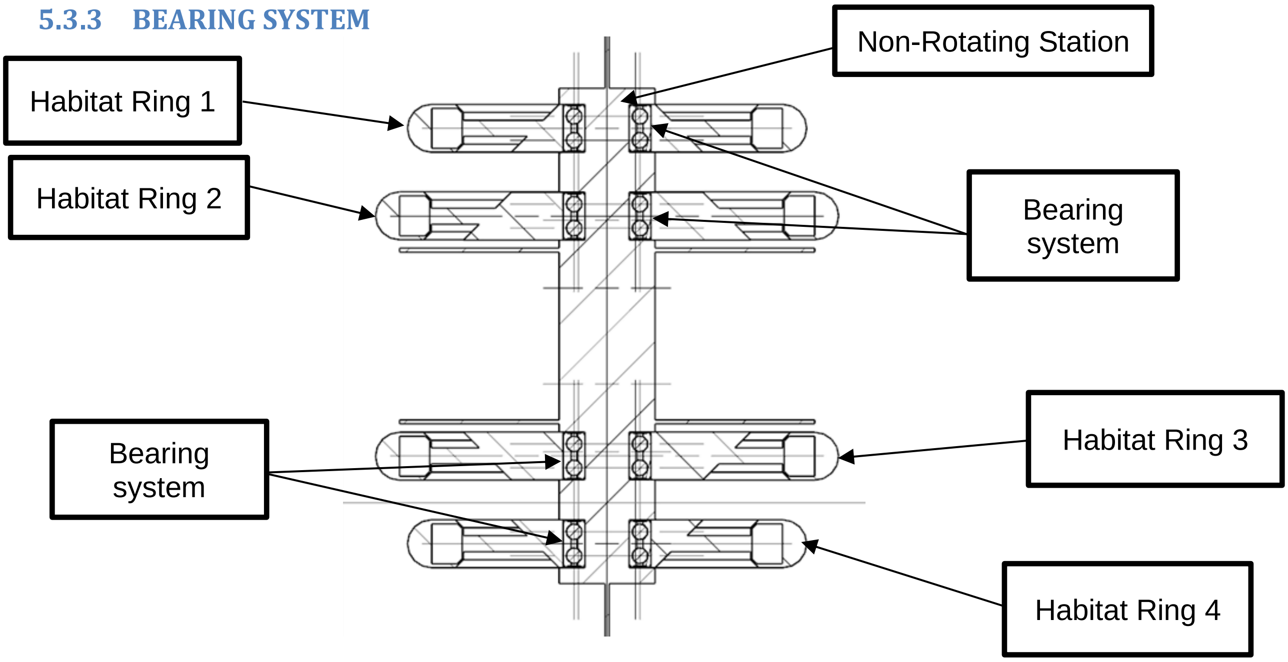


Figure 36: Cross-section view of the prototype (without main mirrors) [Own Source]

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 (refer section 5.2.4).

5.3.4 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. As explained in section 3.3, there will be no external force 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.

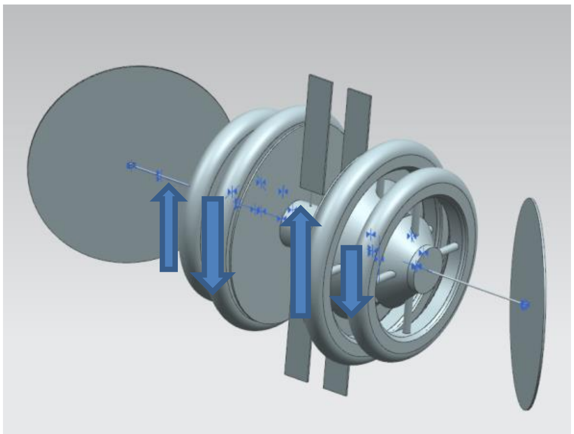


Figure 37: The direction of rotation of the habitat rings in the prototype [Own Source]

As we can see in Figure 35, 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. This part will be explained in section 5.3.8.

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:

$$L = I * \omega \tag{16}$$

With respect to an axis that passes through its centre, the equation of moment of inertia

I for the habitat rings is:

$$I = \frac{1}{2} * mr^2 \tag{17}$$

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

$$I1 = I4\ and\ I2 = I3$$

Based on section 4.3.1, ω1 is 0,06678 rad/s and ω4 is -0,06678 rad/s (opposite direction), meanwhile ω3 is 0,06143 rad/s and ω2 is -0,06143 rad/s (opposite direction).

$$L^{whole\ prototype} = \frac{1}{2} * m1 * r1^2 * 0{,}06678\, rads^{-1} + \frac{1}{2} * m2 * r2^2 * -0{,}06143\, rads^{-1} + \frac{1}{2} * m2 * r2^2 * 0{,}06143\, rads^{-1} + \frac{1}{2} * m1 * r1^2 * -0{,}06678\, rads^{-1}$$

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

5.3.5 CORIOLIS EFFECT

As mentioned in section 3.2, 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.

Based on 5.3.2, 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.

5.3.6 HABITAT AREA AND ESTIMATED POPULATION

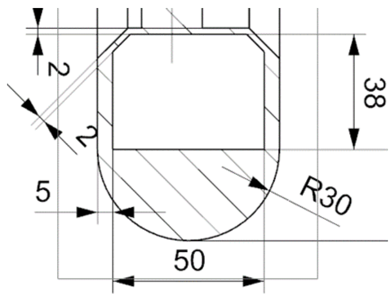


Figure 38: Cross-section view and measurements of the habitat (ratio 1 mm : 10 m) [Annex 6 and 7]

Figure 36 shows that the width of the habitat in all rings is 500 m.

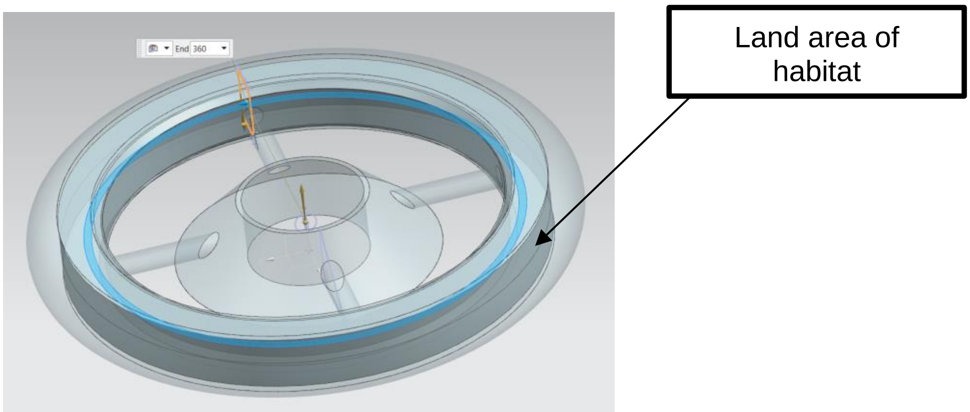


Figure 39: Land area of the habitat within the outer ring [Own Source]

The dark shade in Figure 37 shows the land area of the habitat in the Habitat Ring 1. Therefore, to calculate the land area, the surface area equation for cylinder (take side area only) have to be applied.

$$A^{cylinder} = 2\pi r * h \tag{14}$$

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

For 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;

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

$$Total\ A = 2{,}2 * 10^6 \pi\, m^2 + 2{,}6 * 10^6 \pi\, m^2 + 2{,}6 * 10^6 \pi\, m^2 + 2{,}2 * 10^6 \pi\, m^2$$

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

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 [35], suburban areas normally have population densities between 100 to 10.000 people/km^2.

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.

5.3.7 POSITION IN SPACE

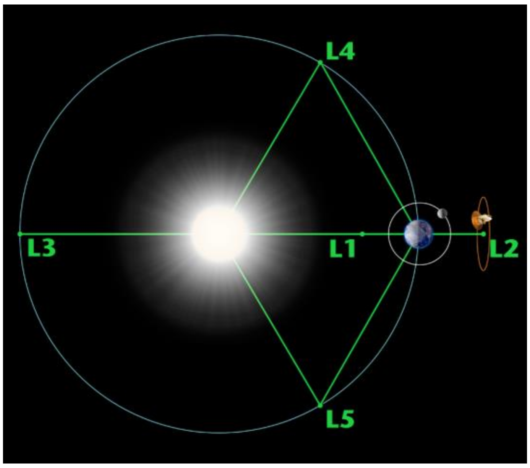


Figure 40: Lagrange Points [36]

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 [36]. Figure 38 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 [37].

5.3.8 LIGHT REFLECTION

As the prototype stays in L5, its position will be locked just like the figure below so that the maximum amount of sunlight can be reflected to the habitat of the colonies.

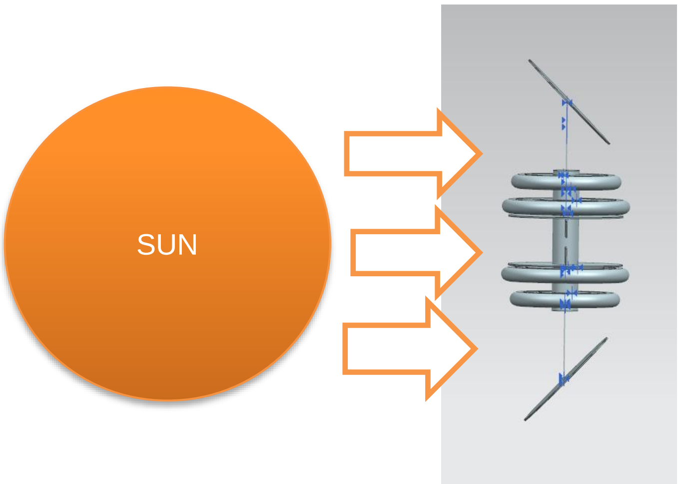


Figure 41: Side view of the prototype facing sun [Own Source]

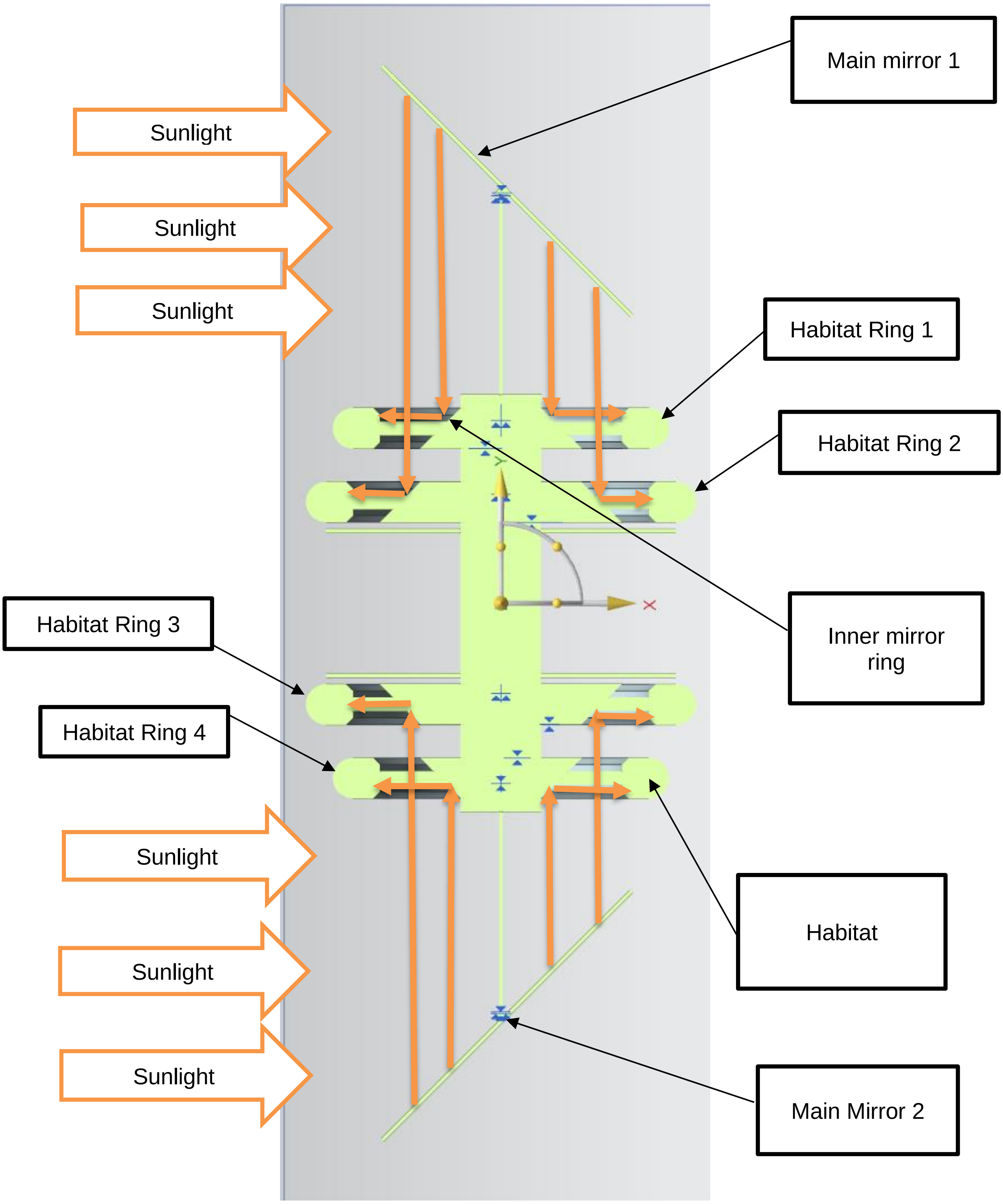


Figure 42: Sunlight direction [Own Source]

This sunlight reflection method used by this prototype is better explained using image. Figure 40 shows an image on how the sunlight will be redirected by the mirrors in the prototype.

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 40).

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.

5.3.9 ENERGY REQUIREMENTS

The prototype will fully utilised solar energy as the main energy. Four photovoltaic solar panels will be incorporated at the middle part of the design (refer Figure 41) and the plane of the panels will face the Sun so that it can get the maximum amount of solar energy.

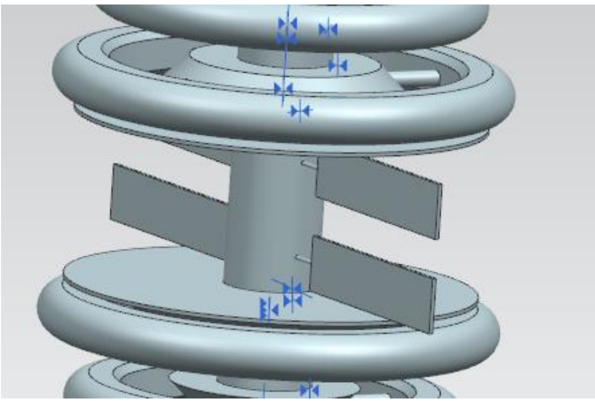


Figure 43: Photovoltaic solar panels in the design [Own Source]

The photovoltaic solar panels only 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 colonies 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 [38]. 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 (refer section 5.3.7). 240.000 miles is equivalent to 386.242,56 km.

To know the solar radiation intensity (Ho), this equation will be applied [39];

$$Ho = \frac{R^2 sun}{(D^2)} * Hsun \qquad (15)$$

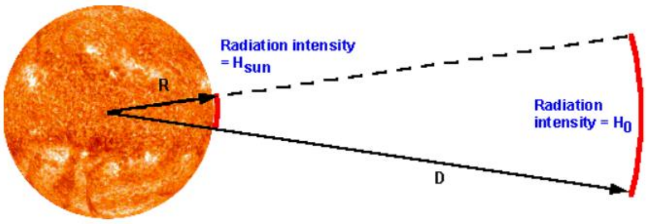


Figure 44: Radiation Intensity of the Sun [39]

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 10^6 W/m^2. Based on Eq. (15);

$$Ho = \frac{(696.340.000\ m)^2}{(386.242.560\ m)^2} * 64 * 10^6\ Wm^{-2} \approx 208{,}0187 * 10^6\ Wm^{-2}$$

The radiant solar intensity (Ho) will be the incident radiation flux (E) in the solar cell efficiency equation which is Eq (7);

$$\eta max = \frac{Pmax}{E * Ac} * 100\% \qquad (7)$$

High-quality solar panels currently have an efficiency around 22 percent. SunPower solar cells has an efficiency of 22,8 percent [40]. For this prototype, we will incorporate the SunPower solar cells.

Figure 45: SunPower solar panels [41]

There are 4 solar panels incorporated in the prototype. Each panel has an area of 2,1 x 10^6 m^2 (refer 5.2.1). Therefore, based on Eq. (7);

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

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

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

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

5.3.10 COOLING REQUIREMENTS

Two disc-shaped thermal radiators would be incorporated below Habitat Ring 2 and above Habitat Ring 3 (refer Figure 22 and Figure 44).

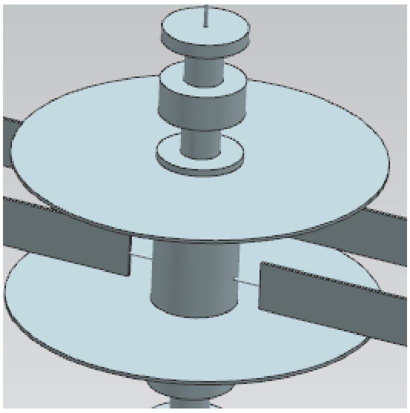


Figure 46: Thermal radiators [Own Source]

In average, a person releases 100 to 120 W of heat energy to the surrounding [42]. As there will 300.000 colonies 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 10^7 π m^2 (refer section 5.2.1)

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

$$P = e\sigma A(T^4 - Tc^4) \tag{8}$$

$$P = 1 * 5{,}67 * 10^{-8}\, Wm^{-2}K^{-4} * 2{,}56 * 10^{7}\pi\, m^2((4\,K)^4 - (300\,K)^4)$$

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

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.

5.3.11 MATERIALS

As for materials, extensive training on materials needed to be made to find the most suitable materials.

The materials need to have a really strong thermal ability, good radiation resistance, good pressure resistance, high compression and tensile strength (mentioned in section 4).

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 (refer section 4.5). 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 colonies 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.

6 PROCESS OF DESIGNING THE PROTOTYPE

The design of this prototype was made via NX12 Siemens PLM Software. NX10 Siemens PLM Software is a fully associative CAD/CAM/CAE application. It touches a full range of development processes in product design, manufacturing and simulation. There are 5 components drawn which are Non-Rotating Station (connected with solar panels and radiator discs), Habitat Ring 1 and 4, Habitat Ring 2 and 3, Main Mirror and bearing. The dimension ratio used is 1 mm : 10 m.

6.1 DESIGNING PROCESS OF THE NON-ROTATING STATION

The reason for making the centre station to be non-rotating is for the docking system between the spacecraft and the station to be easier. If the station is rotating, the pilot of the spacecraft will have to rotate at the same angular velocity as the station when docking it. The pilot will have high difficulty as docking is not an easy process too. Therefore, it's better to design the centre station to be non-rotating.

As the solar panels and radiator discs are connected with the Non-Rotating Station and will not rotate, they will be designed with the station as one body.

1) Firstly, start a new sketch on NX12 Siemens PLM Software as we opened it.

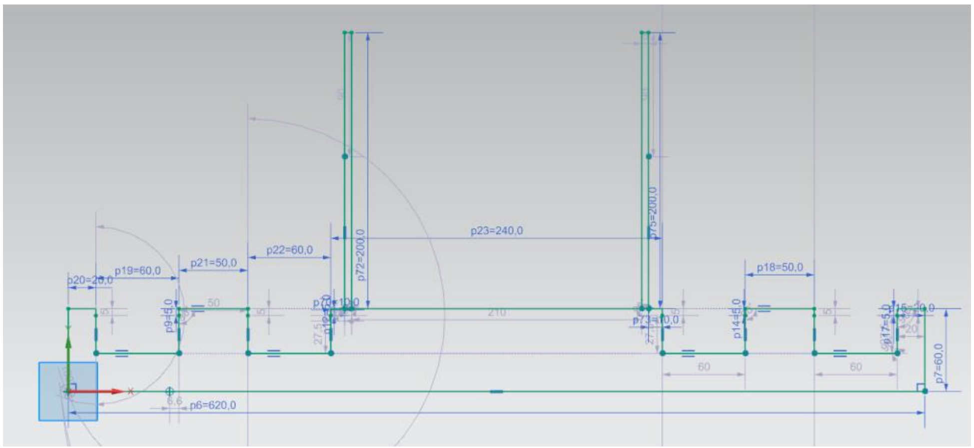


Figure 47: 2D sketch of Non-Rotating Station [Own Source]

2) As the planned design is symmetrical, the revolve method will be applied. Draw a 2D sketch with the measurements as above and make sure the centre point (blue square) lies within the lowest horizontal line as seen in figure above. This 2D sketch will include 2 radiator discs with the station.

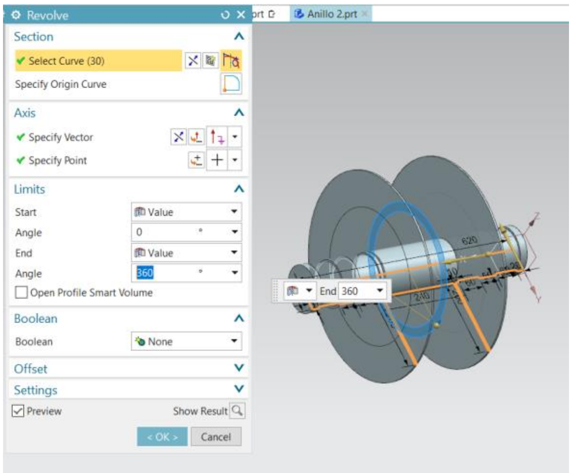


Figure 48: The revolve of the Non-Rotating Station sketch [Own Source]

3) Revolve the sketch by setting the x-axis as the revolve axis and the previous centre point as the revolve point.

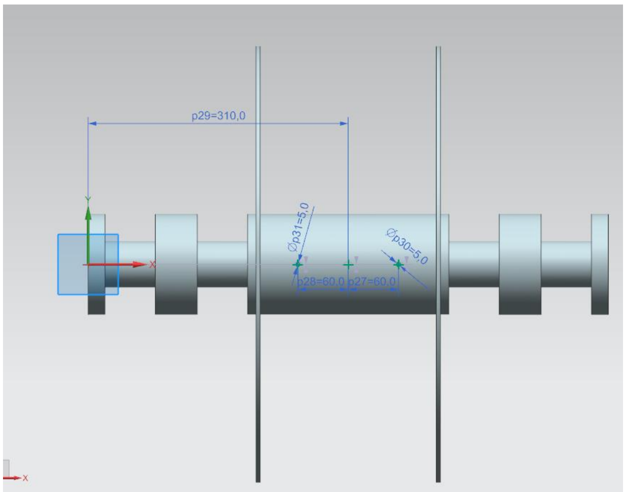


Figure 49: Points for putting the solar panels [Own Source]

4) Next, as we find the middle point of the design, put a point 60 mm to the left and 60 mm to the right (refer figure above). These 2 points will be used to create the solar panel bars.

5) At those 2 points, sketch a circle with diameter of 5 mm.

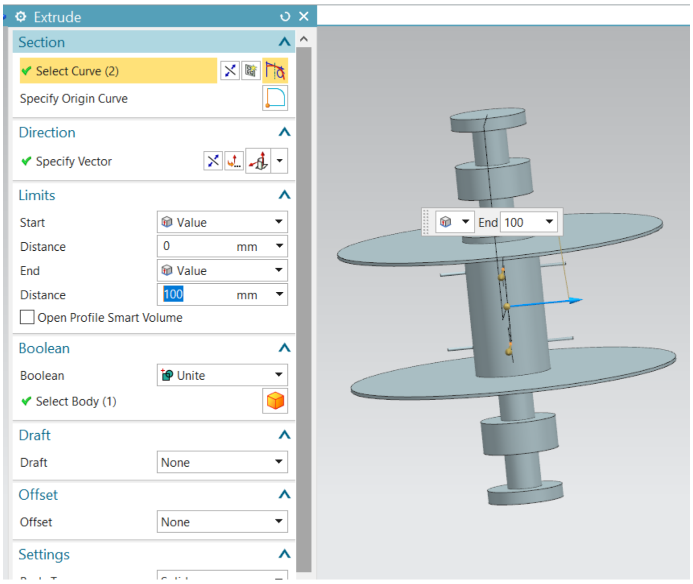


Figure 50: Extrusion of the circle sketch [Own Source]

6) Extrude the previous circle sketches outward with a distance of 100 mm. Then extrude the circles again on opposite side with the same distance.

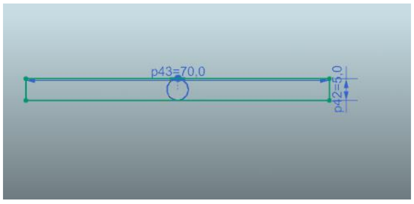


Figure 51: Base dimension of solar panels[Own Source]

7) On top of the extruded circle (solar panel bar), draw a 2D rectangle of 70 mm x 5 mm while referring the top of solar panel bar as its plane.

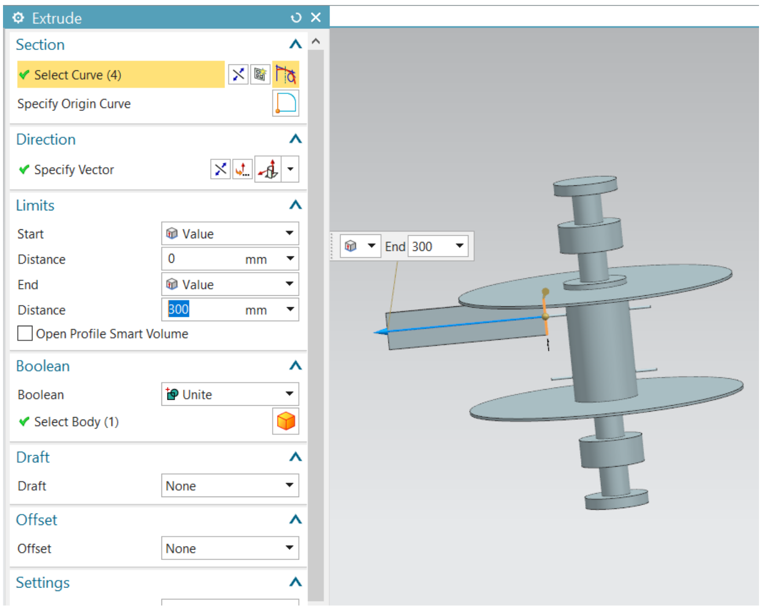


Figure 52: Extrusion of the previous 2D rectangle [Own Source]

8) As each solar panel incorporated in the prototype has an area of 2,1 x 10^6 the area has to be 3000 m x 700 m. Therefore, the previous 2D sketch has to be extruded with a distance of 300 mm.

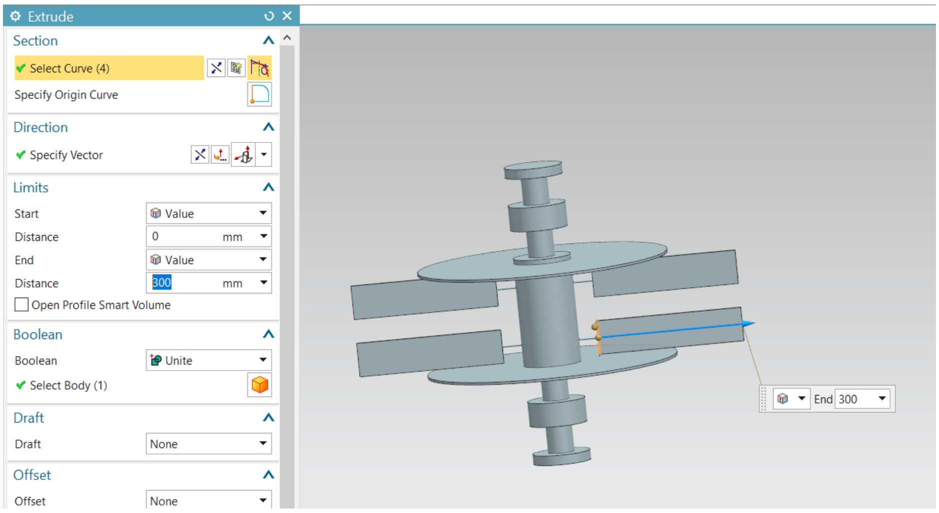


Figure 53: Non-rotating station with completed solar panels [Own Source]

9) Repeat the 2D rectangle sketch with the same measurements on top of the other 3 solar panel bars and extrude all of them with the same extrusion distance as the previous one. As we can see in the figure above, all 4 solar panels design in the Non-Rotating Station are completed.

10) Next step is to create tubes for installing the main mirrors. First step is to choose the top plane where the docking will take place as the main plane.

11) Sketch a circle with a diameter of 5 mm on the centre of the plane.

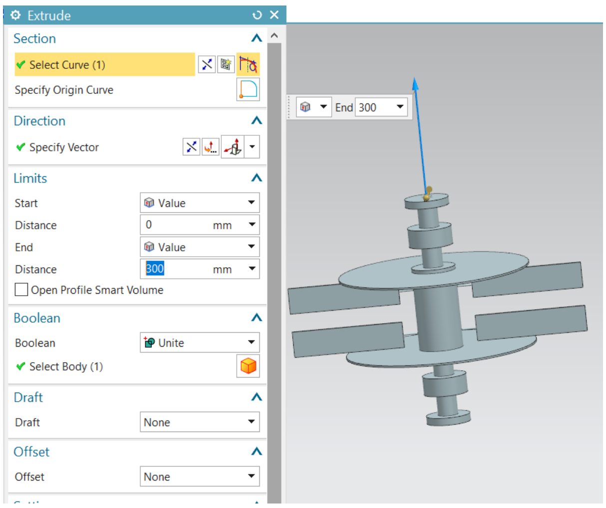


Figure 54: Extrusion of the circle creating a tube for main mirror [Own Source]

12) Extrude the circle with a distance of 300 mm. One tube is done.

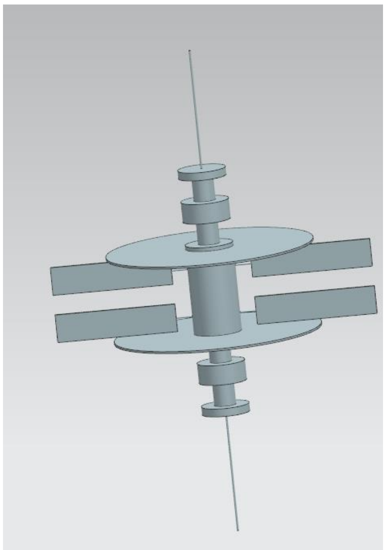


Figure 55: The completed tubes in the Non-Rotating Station [Own Source]

13) Repeat the circle sketch and the extrusion with the same exact measurements on the bottom docking plane. The 2 tubes for main mirrors are now done (refer figure above).

6.2 DESIGNING HABITAT RING 1 AND 4

To design this habitat ring, we will start with designing the inner mirror ring.

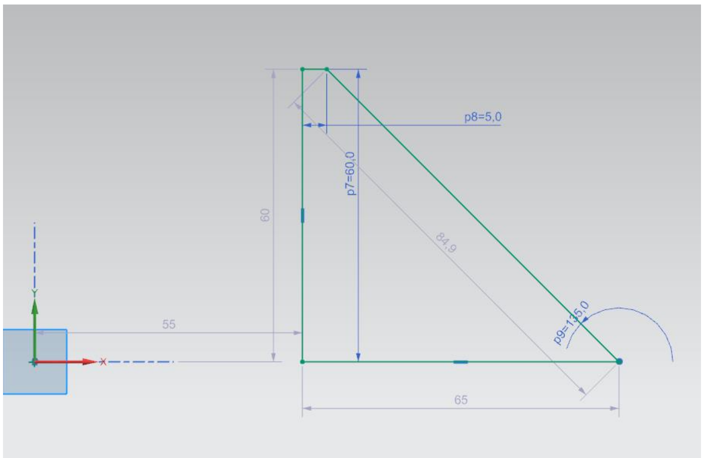


Figure 56: 2D sketch of inner mirror ring of Habitat Ring 1 and 3 [Own Source]

1) Start a new sketch on XY plane and draw a right-angled triangle with the measurements as figure above. Make sure the angle is 45 degrees as the hypotenuse part is where the mirror will be located at. Make sure the centre point of the sketch plane (blue square in the figure above) to be 55 mm to the left from the vertical line of the triangle as the point will be a reference when revolving step takes place.

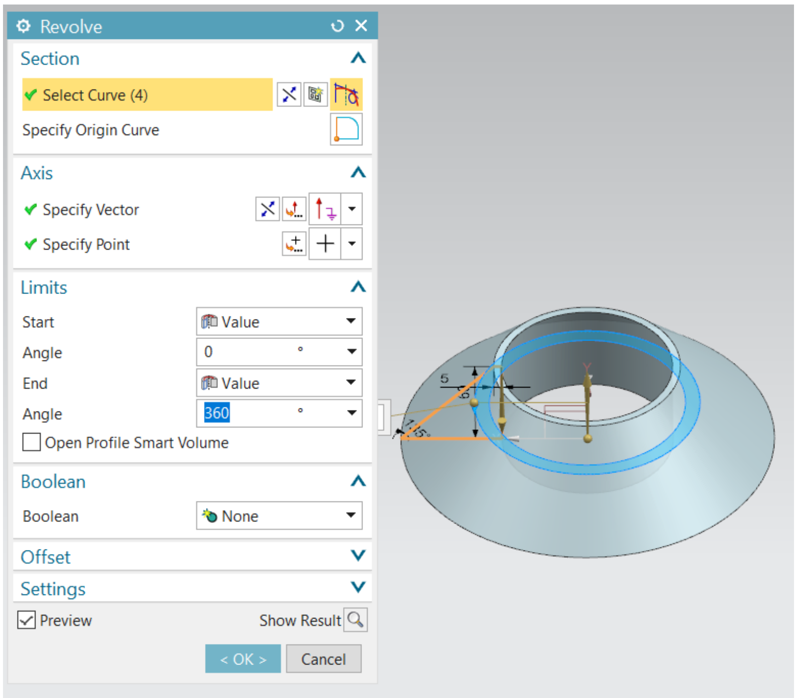


Figure 57: Revolve of the right-angled triangle creating a inner mirror ring [Own Source]

2) Revolve the right-angle triangle at 360 degrees by making Y-axis as revolve axis and the previous stated centre point as revolve point.

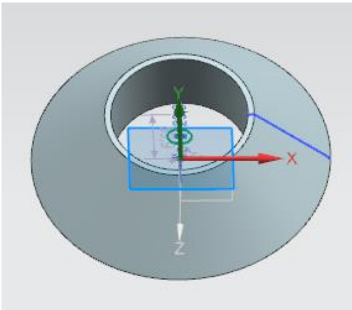


Figure 58: XY-sketch plane [Own Source]

3) As the inner mirror ring is done, we can now move on designing the tubes that connect the inner mirror ring to the outer ring (habitat). Start a new sketch by making XY plane of the centre point as the sketch plane.

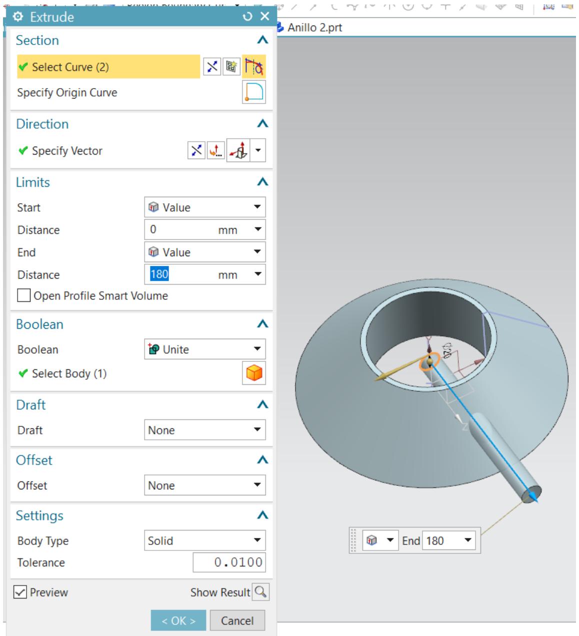


Figure 59: Extrusion of the tube [Own Source]

4) At exact vertical centre of the inner mirror ring, sketch a 20 mm circle and then extrude it at a distance of 180 mm.

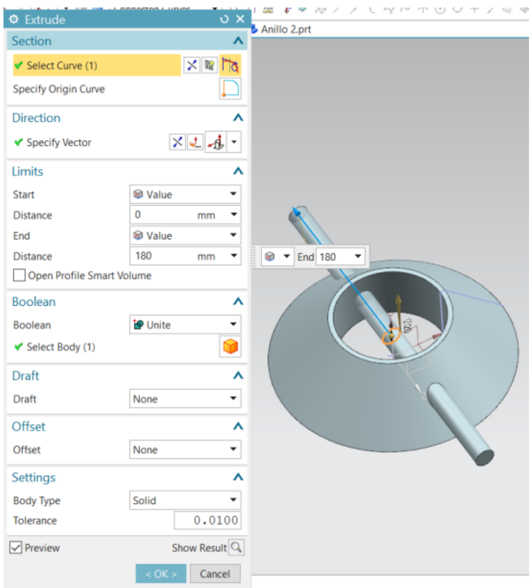


Figure 60: Extrusion of the tube on the opposite site [Own Source]

5) Repeat the extrusion part but change its direction to the opposite direction. The design should be as above.

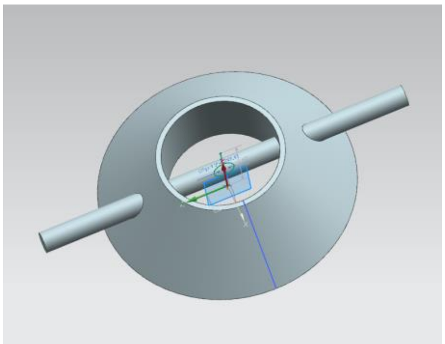


Figure 61: YZ-sketch plane [Own Source]

6) Create a new sketch plane on YZ plane of the centre point.

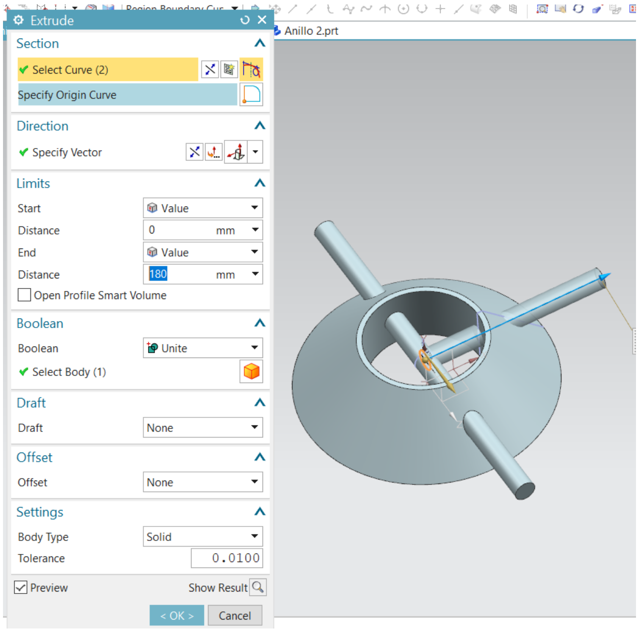


Figure 62: Extrusion of the third tube [Own Source]

7) At exact vertical centre of the design, create a 20 mm circle and extrude it at 180 mm as seen in figure above.

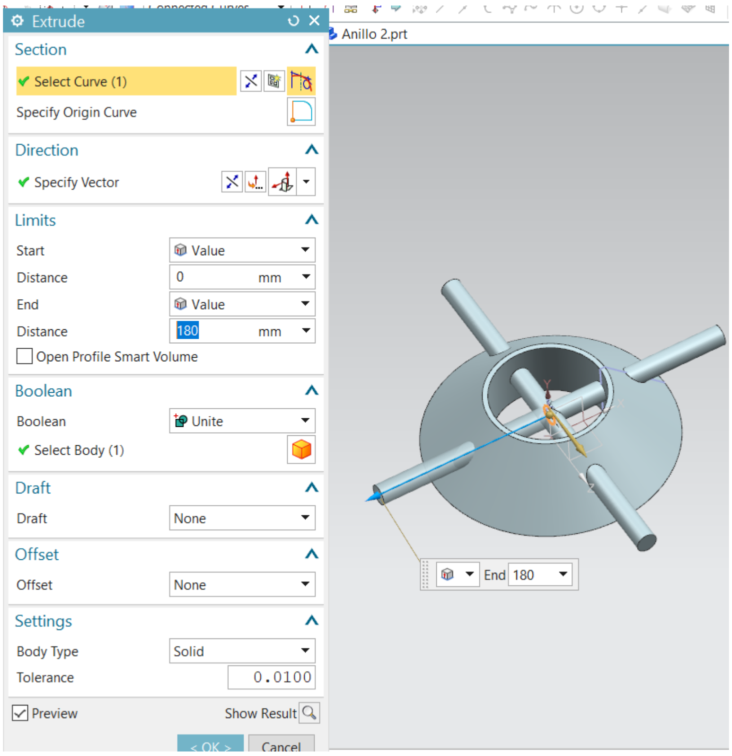


Figure 63: Extrusion of the 4th tube [Own Source]

8) Extrude the circle again but in opposite direction with the same distance (180 mm).

Then, we have to eliminate the tube in the centre of inner mirror ring.

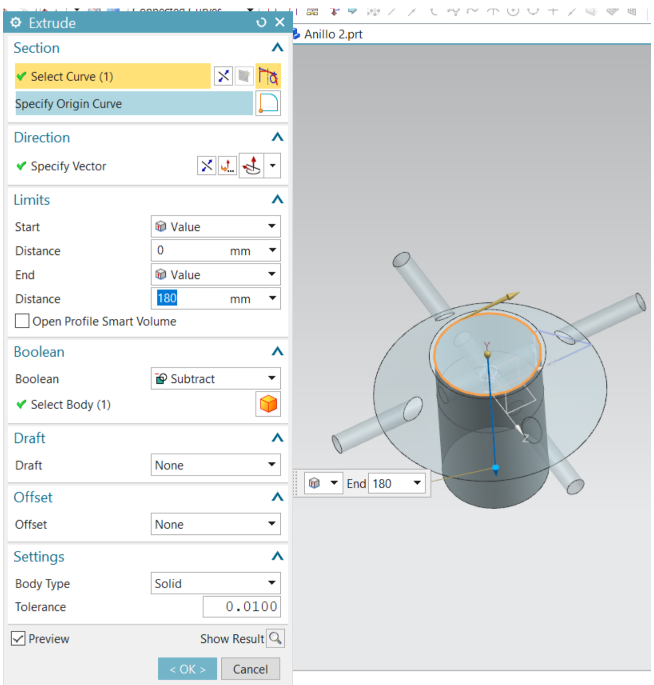


Figure 64: Subtract extrusion [Own Source]

9) Extrude the inner circle line of the design and extrude it downward. Make sure to change the Boolean to 'subtract' as this step is to eliminate the excess tube.

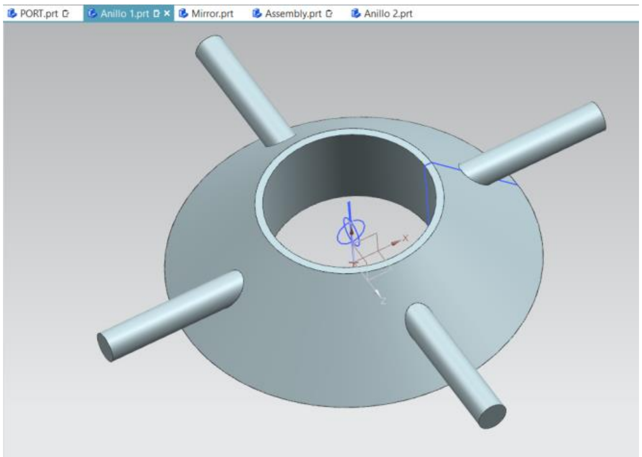


Figure 65: Completed inner mirror ring with the tubes [Own Source]

We then have completed the inner mirror ring with its tubes as we can see in figure above. Now, we can start designing the outer ring (habitat).

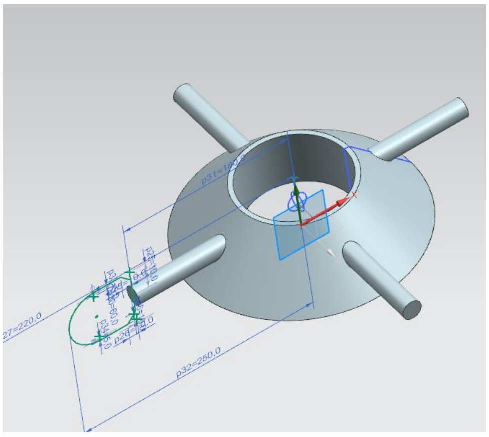


Figure 66: Sketch plane for the outer ring [Own Source]

10) To design the outer ring, start by making the XY-plane of the centre point as the sketch plane. Then start sketching at the end of the tube (as seen in figure above).

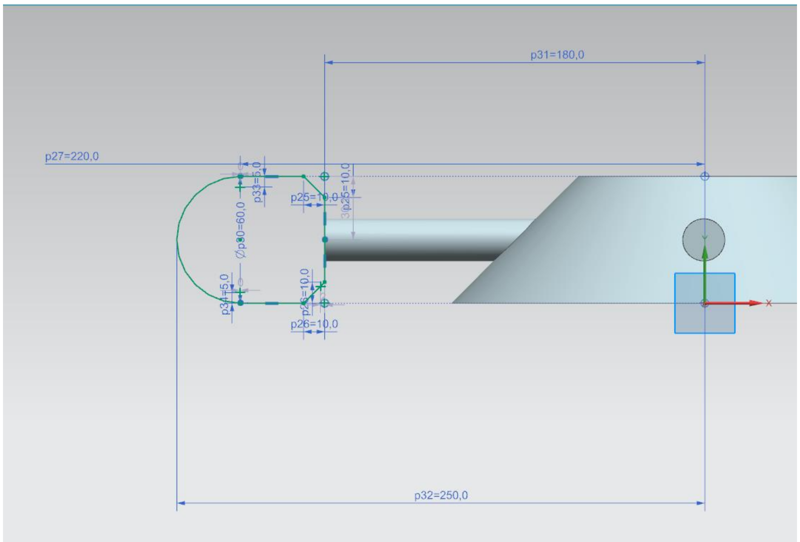


Figure 67: Measurements of the outer ring [Own Source]

11) Sketch the 2D lines with the measurements as above. Make sure the right vertical line touches the tube so that the outer ring is connected to the tube.

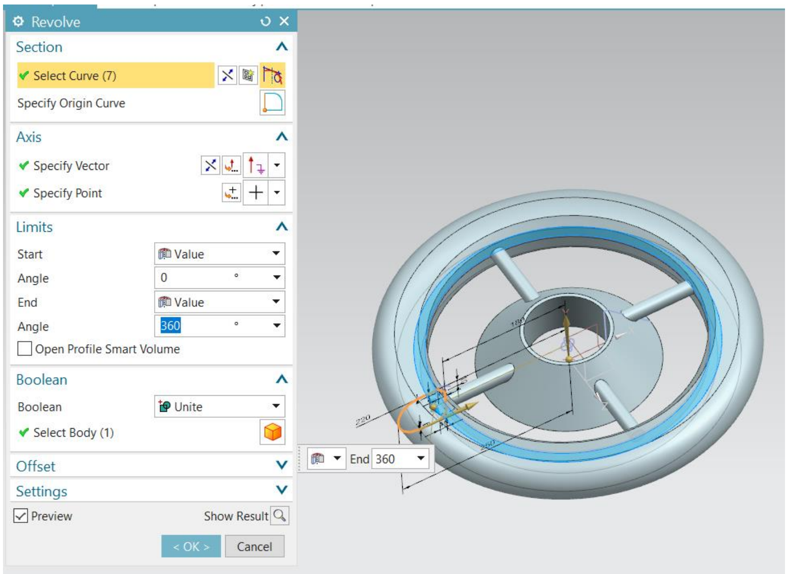


Figure 68: Revolve of the outer ring [Own Source]

12) Then revolve the previous sketch at 360 degrees by making the positive Y-axis as revolve vector and the centre point as revolve point.

We are done with the inner mirror ring, tubes and outer ring. The last step is designing the habitat area within the outer ring.

13) As we are designing the interior of the outer ring, change the shade of the design into static wireframe so that we can clearly see the lines.

Figure 69: Measurements of habitat within outer ring [Own Source]

14) Use the same XY-plane and start sketching the habitat by using the measurements as above (green lines).

15) Revolve the sketch by setting positive Y-axis as its vector and the centre point as the revolve point. Make sure to set the boolean as "subtract" as the interior of the outer ring needs to be hollow for the habitat of the colonies.

The design of Habitat Ring 1 and 4 is done. The cross-sectional view is in figure below;

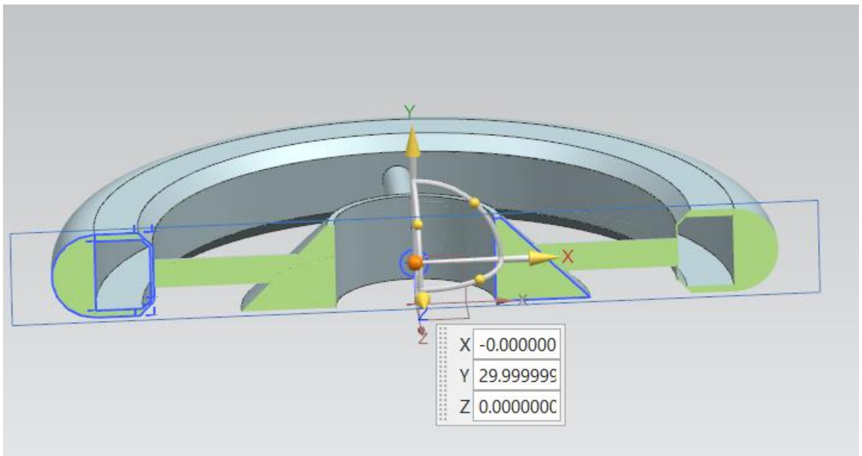


Figure 70: Cross-sectional view of Habitat Ring 1 and 4 [Own Source]

6.3 DESIGNING HABITAT RING 2 AND 3

The process of designing Habitat Ring 2 and 3 is quite the same. We started with designing its inner mirror ring.

1) Start a new sketch on XY-plane.

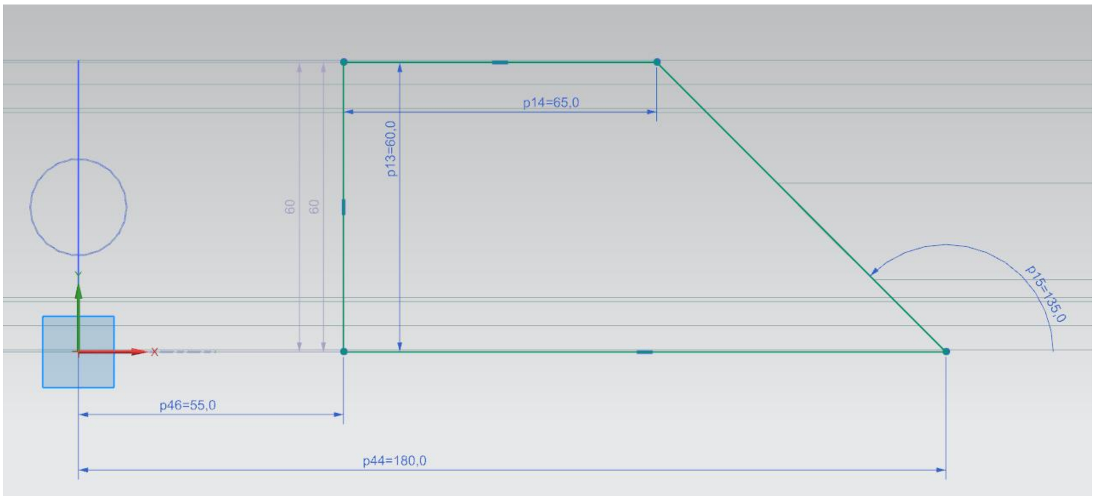


Figure 71: Inner mirror ring sketch [Own Source]

1) Sketch the lines same as the figure above. Make sure the hypothenuse line is 45 degrees as the hypothenuse part is where the mirror will be installed at. Put the centre point of the plane (blue square in the figure) 55 mm to the left of the vertical line.

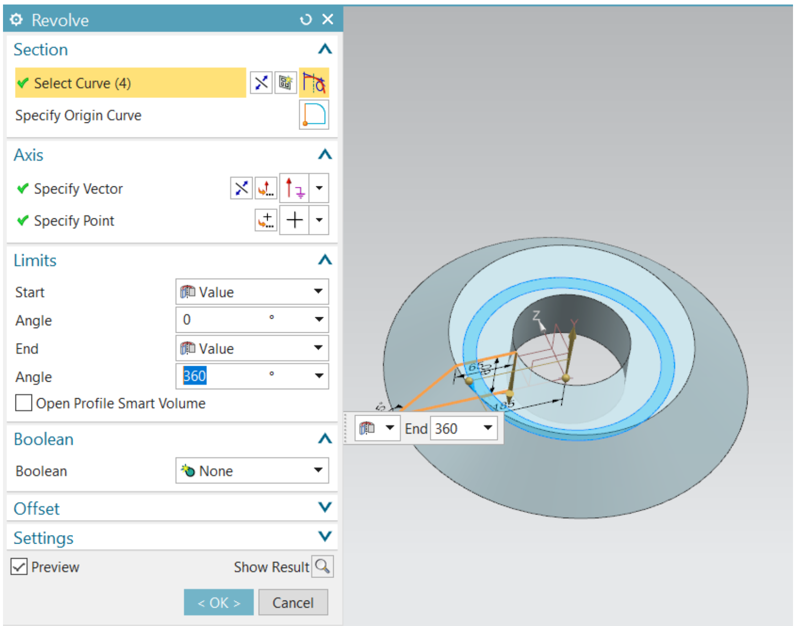


Figure 72: Revolve of the inner mirror ring [Own Source]

2) Fully revolve the previous sketch by setting the revolve vector at positive Y-axis and revolve centre at the centre point of the sketch plane. Inner mirror ring is completed.

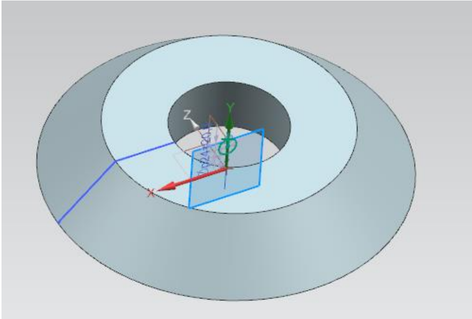


Figure 73:XY-plane as sketch plane [Own Source]

3) Then set again the XY-plane of the centre point as the sketch plane to start designing the tubes.

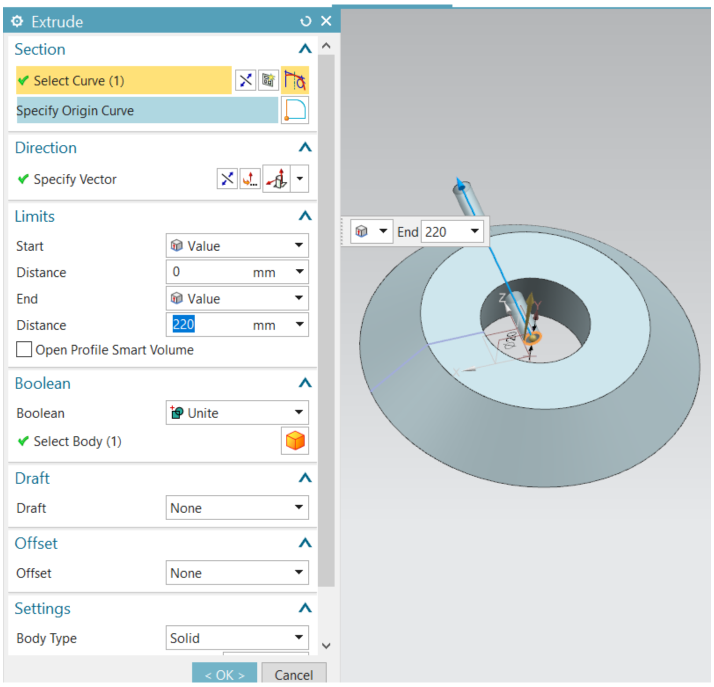


Figure 74: Extrusion of the first tube [Own Source]

4) Sketch a 20 mm circle at the exact vertical centre of the inner mirror ring. Then extrude the circle at 220 mm in the direction of positive Z-axis as seen in figure above.

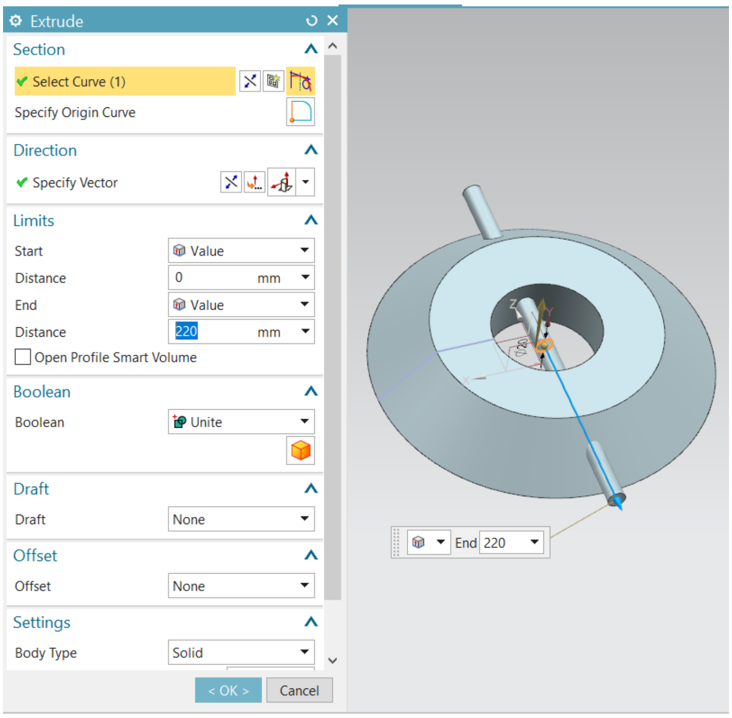


Figure 75: Extrusion of the second tube [Own Source]

5) Then extrude the same circle again at the same distance (220 mm) but in opposing direction which is negative Z-axis.

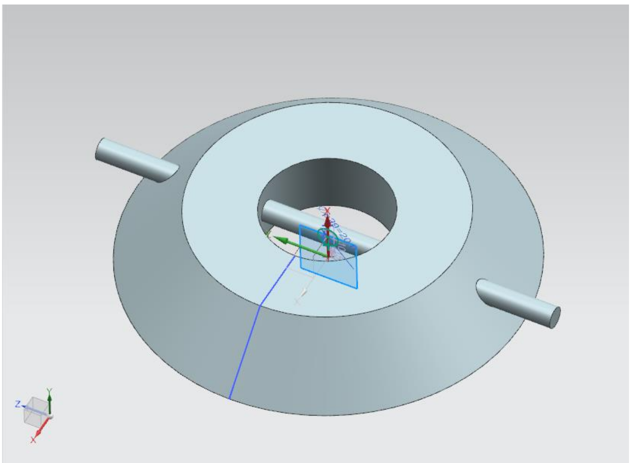


Figure 76: XZ-plane as sketch plane [Own Source]

6) Next, start a new sketch on XZ-plane of the centre point. Draw a circle of 20 mm at the vertical centre of the inner mirror ring.

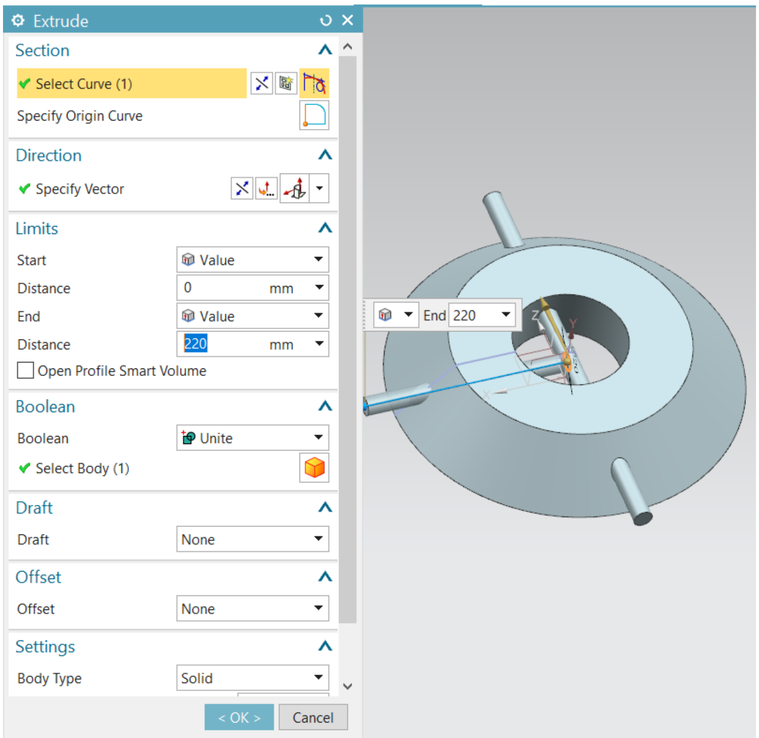


Figure 77: Extrude of the third tube [Own Source]

7) Repeat the extrusion process by extruding the 20 mm circle at 220 mm in the positive X-axis direction.

8) Then extrude the same circle at the same distance (220 mm) but in negative X-axis direction. The result is seen as the figure below;

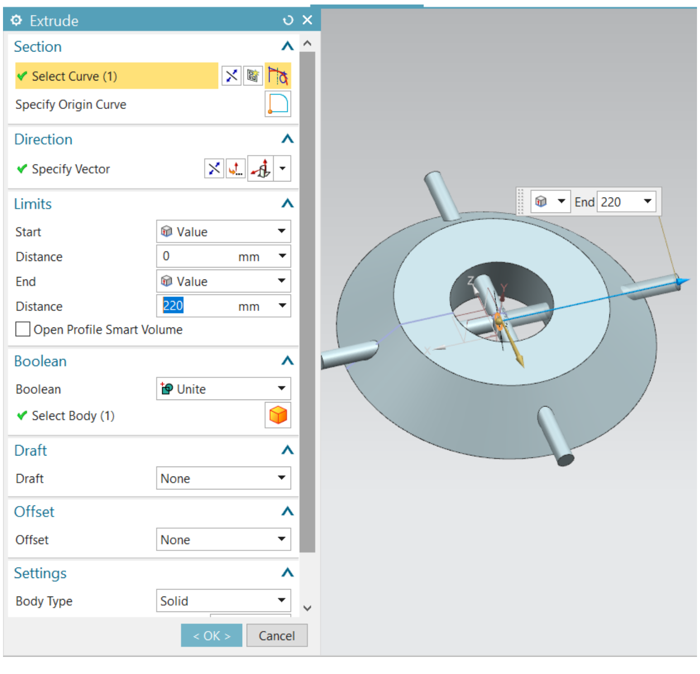


Figure 78: Extrude of the fourth tube [Own Source]

To eliminate the excess tube, we have to use subtract extrude as the next step.

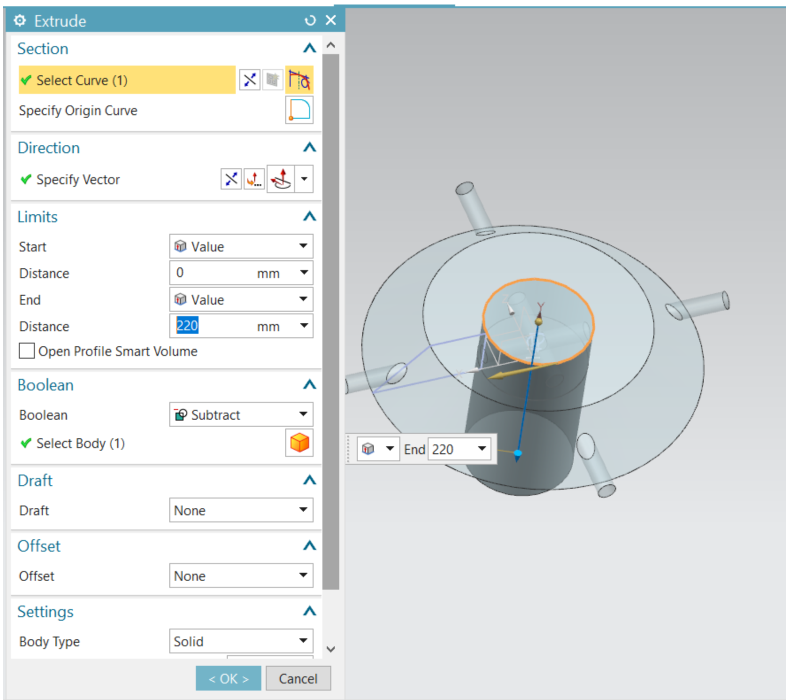


Figure 79: Subtract extrude of the inner circle [Own Source]

9) Extrude the inner circle of the design (as seen in figure above) downward. Make sure to set the Boolean as subtract as this step is an elimination process.

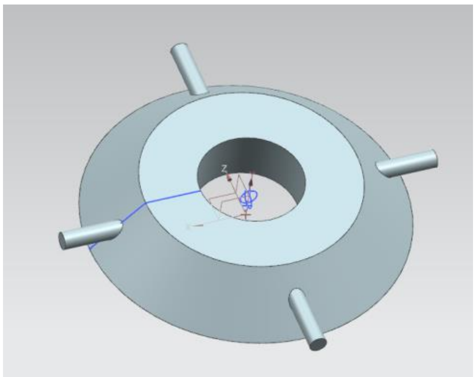


Figure 80: Completed inner mirror ring and its tubes [Own Source]

As we can see in the above figure, the inner mirror ring and the tubes for Habitat Ring 2 and 3 are now done. The next step is to design its outer ring.

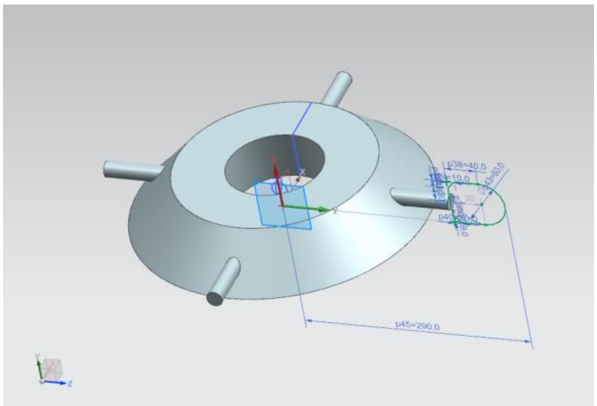


Figure 81: Sketch plane for designing outer ring [Own Source]

10) Start a new sketch at YZ-plane on the centre point and sketch the lines at the end of the right tube.

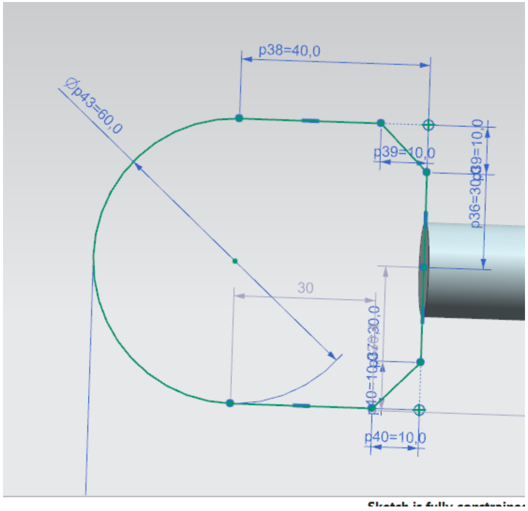


Figure 82: Measurements of the outer ring [Own Source]

11) Sketch the lines exactly like the figure above. Make sure the end of the tube touches the sketch as the outer ring needs to be in contact with the tube.

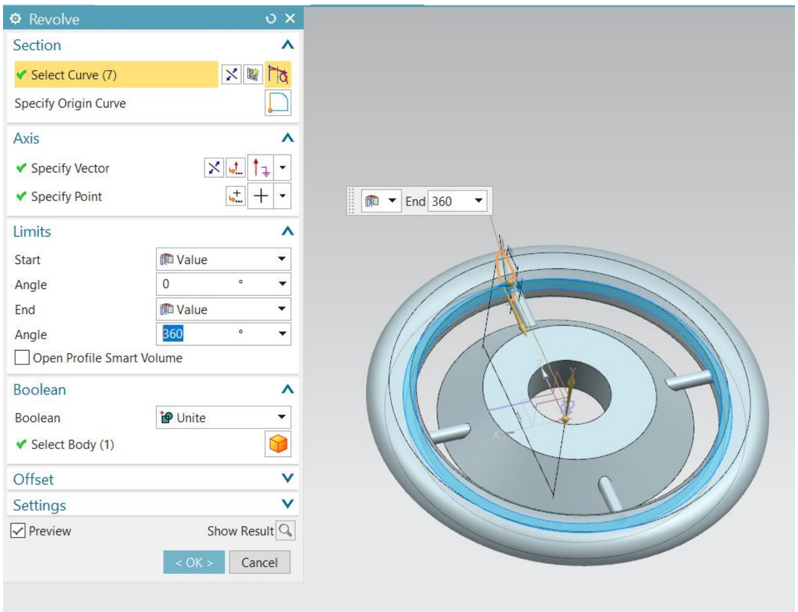


Figure 83: Revolve of the sketch creating the outer ring [Own Source]

12) Next, revolve the sketch at 360 degrees by referring upwards as its vector and centre point as the revolve point.

Now, the only part left in designing Habitat Ring 2 and 3 is the habitat within the outer ring.

13) As we are about to design the interior of the outer ring, change the shade of the design into static wireframe so that we can design the interior clearly.

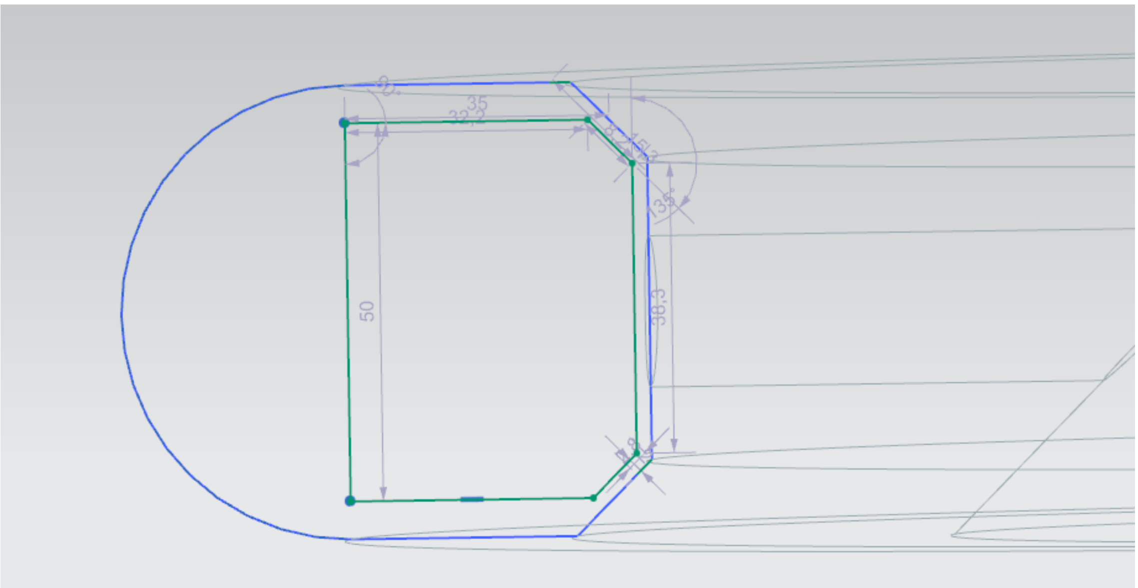


Figure 84: Measurements for the habitat within the outer ring [Own Source]

14) Use the same plane as in step 10 and start sketching the lines with measurements as figure above.

The design process of Habitat Ring 2 and 3 is now completed. The cross-sectional view of the ring will be seen as the figure below;

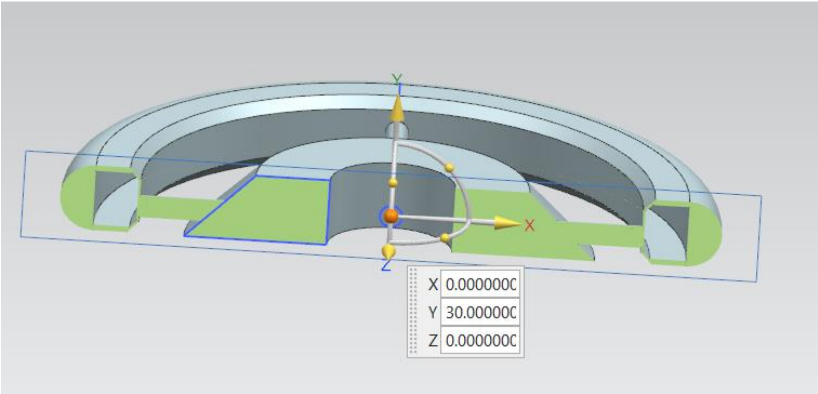


Figure 85: Cross-sectional view of Habitat Ring 2 and 3 [Own Source]

6.4 DESIGNING THE MAIN MIRROR

The main mirror designing process is quite simple.

1) Firstly, set XY-plane as the main sketch plane and sketch a circle with a diameter of 524 mm and then extrude it in the positive z-axis direction at 5 mm as seen in figure below;

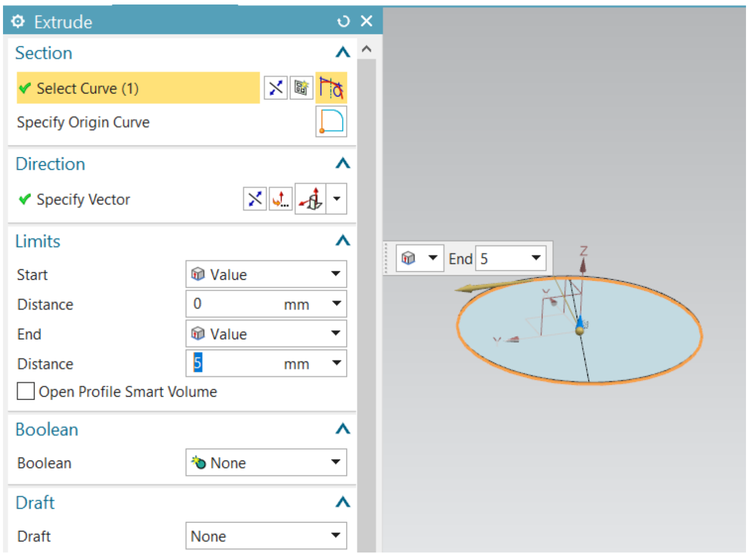


Figure 86: Extrude of the circle [Own Source]

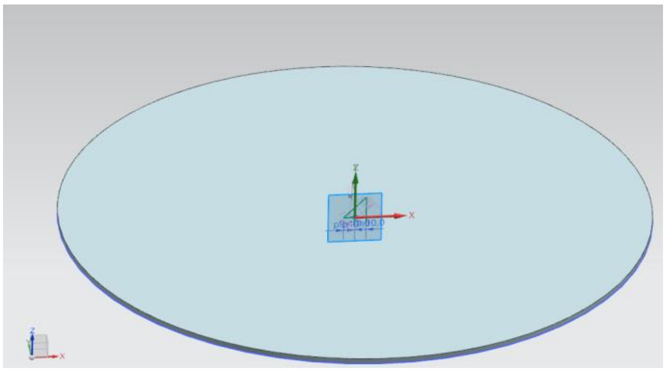


Figure 87: Right-angled triangle sketch on the main mirror [Own Source]

2) Sketch a right-angled triangle on XZ-plane of the centre point.

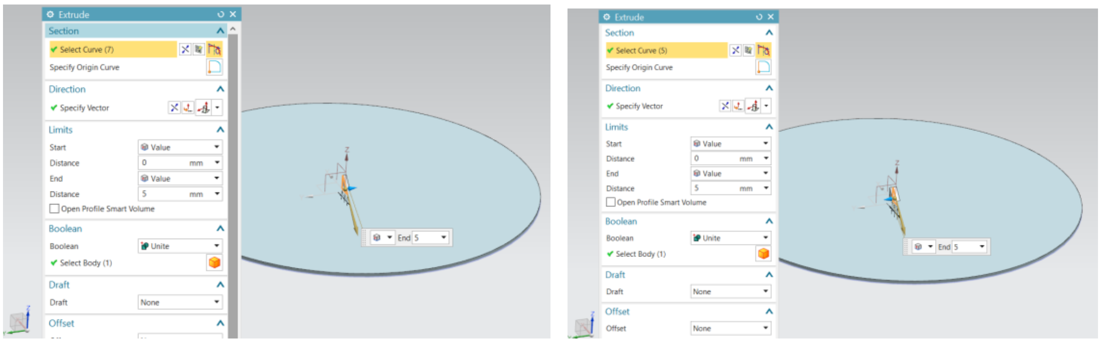


Figure 88: Extrude process of the triangle [Own Source]

3) Extrude the triangle 5 mm in both positive and negative Y-axis direction.

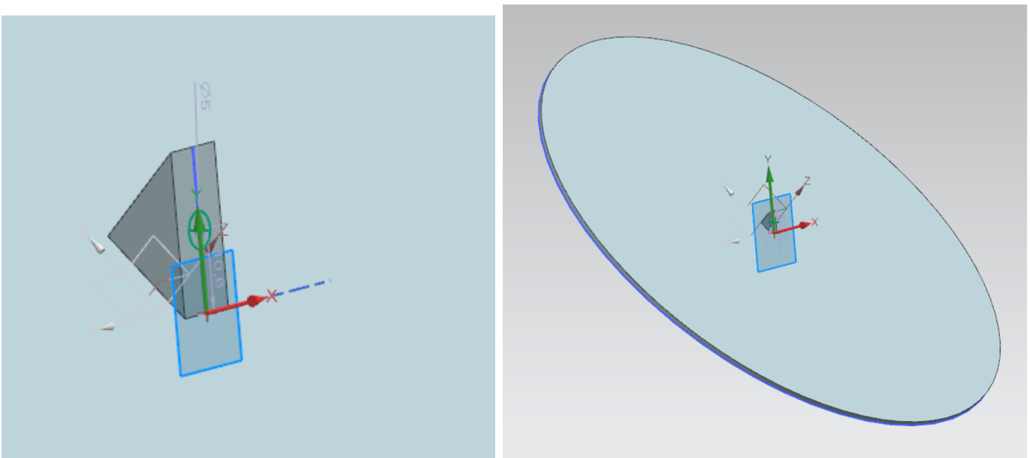


Figure 89: Sketch on the hypothenuse plane [Own Source]

4) On the hypothenuse plane, draw a circle of 5 mm.

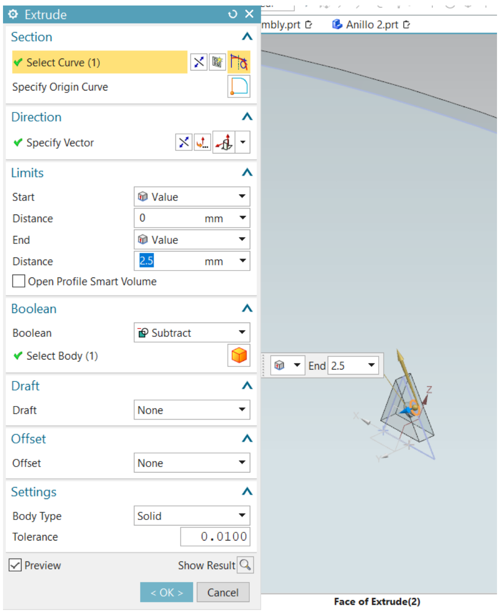


Figure 90: Subtract extrude of the circle [Own Source]

5) Extrude the 5 mm circle inwards for 2,5 mm and set the Boolean as subtract. This is the hole where the tube from Non-Rotating Station will fit in.

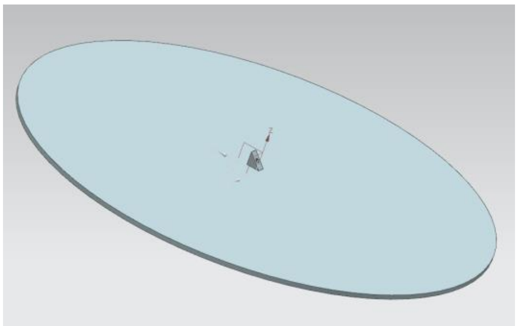


Figure 91: Complete design of main mirror [Own Source]

6.5 DESIGNING THE BEARING

The outer diameter of the bearings need to be 110 mm and its inner diameter needs to be 55 mm so that it can fit in between habitat rings and Non-Rotating Station.

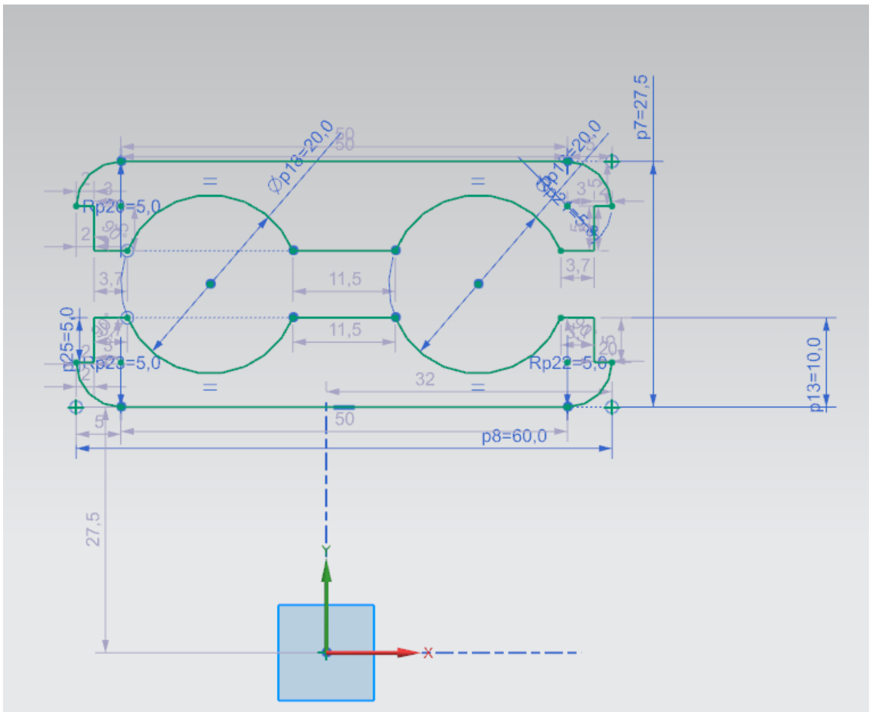


Figure 92: 2D sketch of the bearing [Own Source]

1) Sketch the lines as figure above on a XY-plane. Make sure the centre point of the sketch plane (blue square) is 27,5 mm below the sketch.

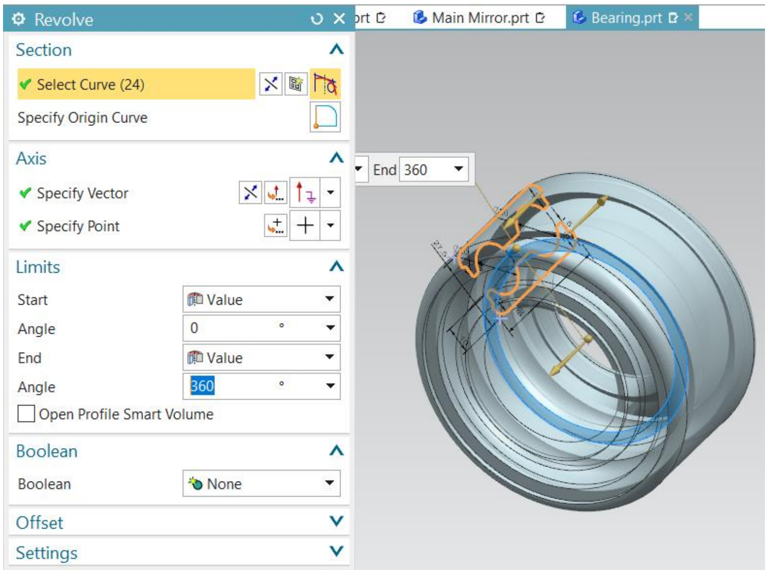


Figure 93: Extrude of the bearing sketch [Own Source]

2) Revolve the previous sketch fully by referring positive X-axis as its vector and the centre point as the revolve point.

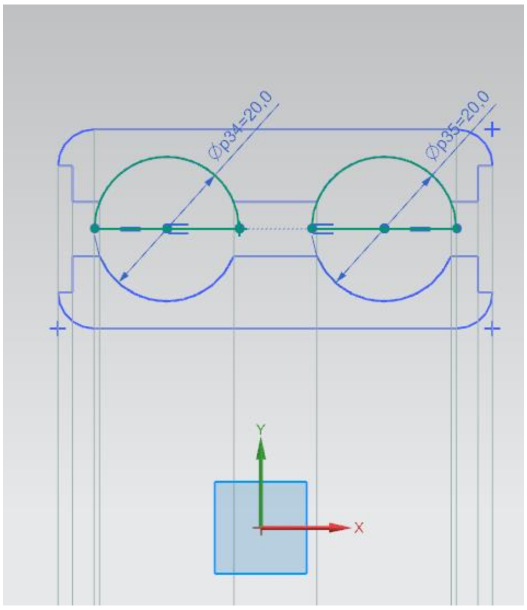


Figure 94: Semicircles sketch for designing ball bearing [Own Source]

3) Then, sketch 2 semicircles at a diameter of 20 mm at the same area of the previous sketch (refer figure above).

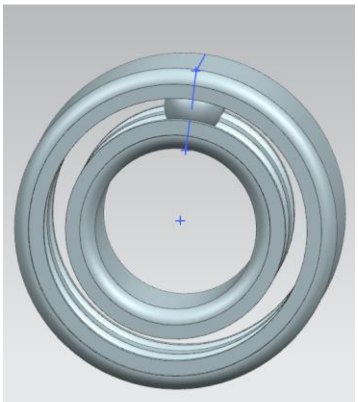


Figure 95: Incomplete ball bearings [Own Source]

4) Revolve both semicircles by referring the centre of semicircles as the revolve point. The ball bearings will be formed as seen as figure above.

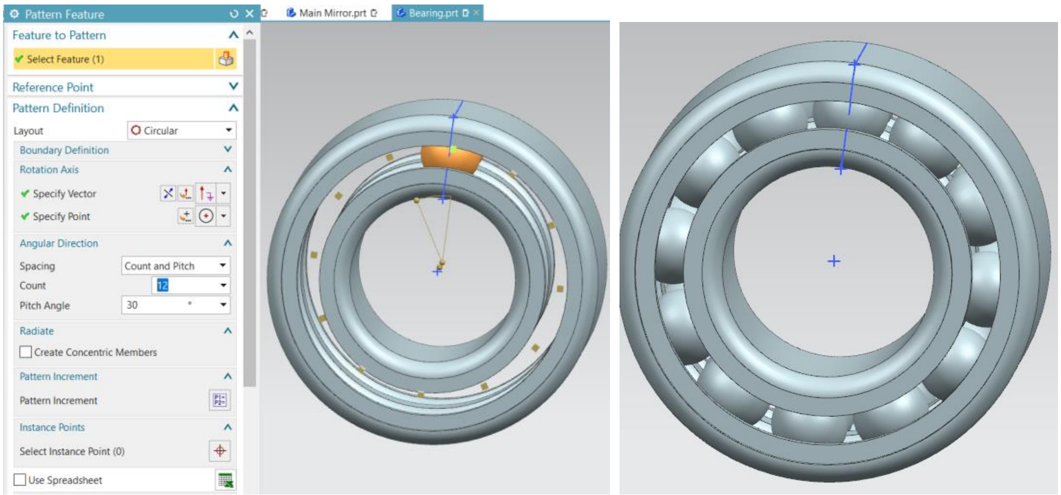


Figure 96: Pattern feature of the ball bearings [Own Source]

5) Use the pattern feature to the ball bearings to create multiple of them. Set the layout as circular, set 12 as the count and pitch angle at 30 degrees.

As the bearings used needs to be a closed-bearing, a plate that cover the ball bearings have to be created.

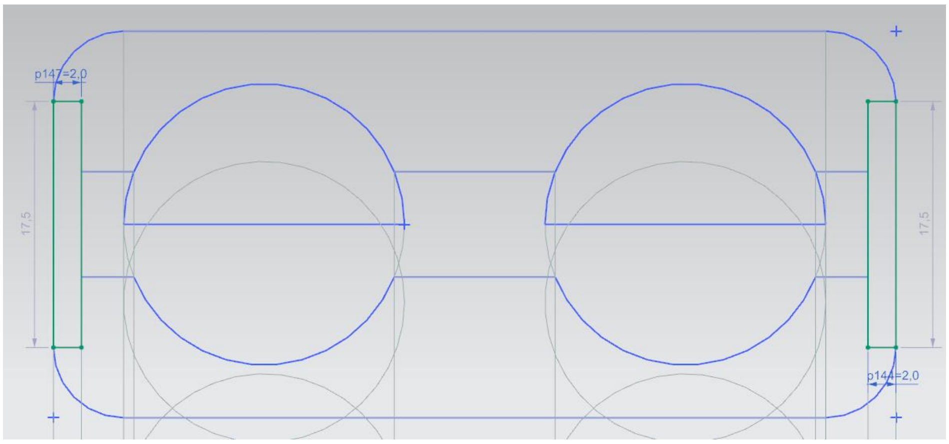


Figure 97: Rectangles sketch for designing the cover of the ball bearings [Own Source]

6) Sketch 2 rectangles, each on the left and each on the right as seen in figure above (green lines).

7) Then revolve the rectangles by referring the centre point of the bearing as revolve centre. The bearing design process is now completed. The result is as seen below;

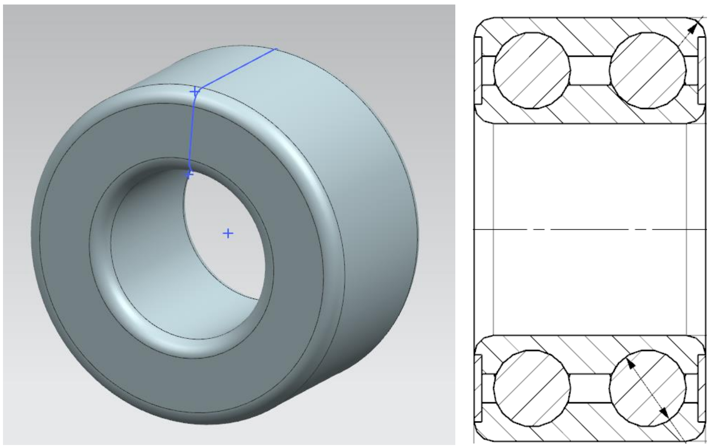


Figure 98: Completed design of the bearing [Own Source]

6.6 ASSEMBLING THE COMPONENTS

The next step of designing process of the prototype is to assemble the components all together creating a full complete look of the prototype.

Initially, we must put the bearings first before putting habitat rings.

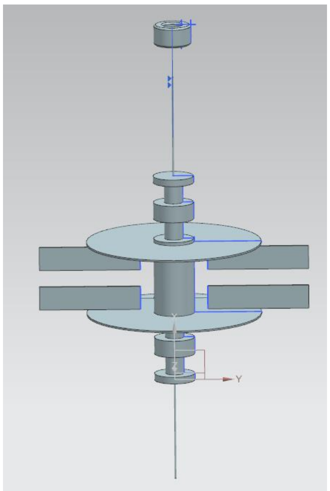


Figure 99: Aligning process between bearing and Non-Rotating Station [Own Source]

1) First, infer the centre axis of the bearing to the centre axis of the Non-Rotating station as seen in figure above.

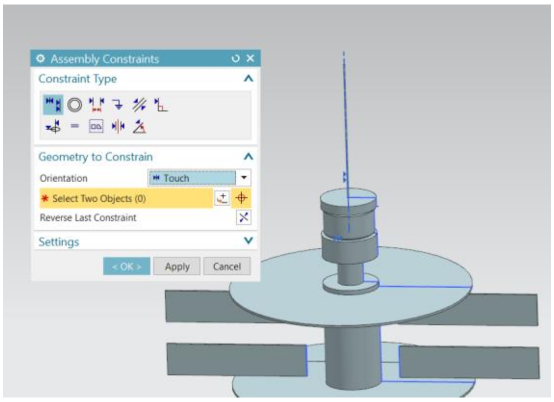


Figure 100: Locking process between bearing and the station [Own Source]

2) Use assembly constraints setup and choose touch feature to contact the surface of the bearing with the surface of station (refer figure above).

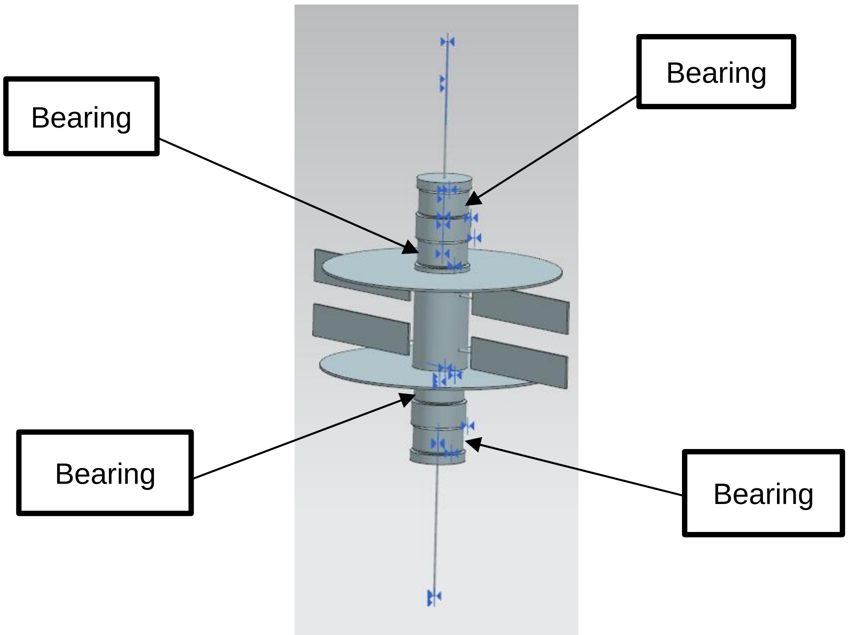


Figure 101: Non-Rotating Station with complete set of bearings [Own Source]

3) Put another 3 bearings into the station by applying the same step 1 and 2. The result should be the same as figure above.

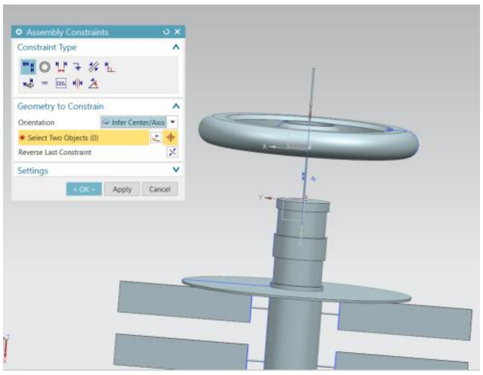


Figure 102: Aligning process between Habitat Ring 1 and Non-Rotating Station [Own Source]

4) Next align the centre axis of Habitat Ring 1 to the centre axis of the station

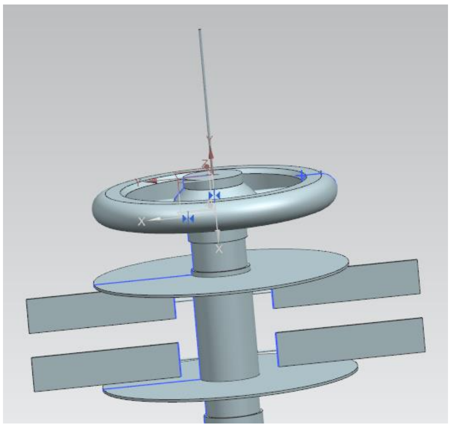


Figure 103: Habitat Ring 1 assembled with the station [Own Source]

5) And then lock the surface of inner part of Habitat Ring 1 and the outer surface of the first bearing.

6) Repeat step 4 and 5 to put the other 3 habitat rings in their position. Habitat Ring 2 needs to be located at the second bearing, Habitat Ring 3 needs to be located at the third bearing and Habitat Ring 4 needs to be located at the fourth bearing. Make sure to invert Habitat Ring 3 and 4 upsides down. The prototype should be looking like figure below;

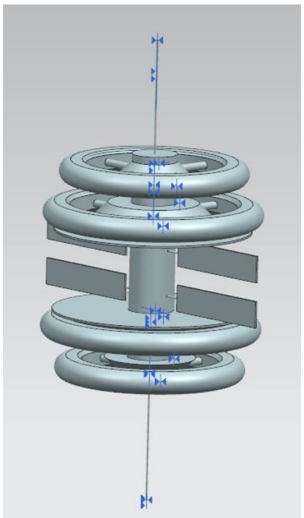


Figure 104: Fully assembled habitat rings with the station [Own Source]

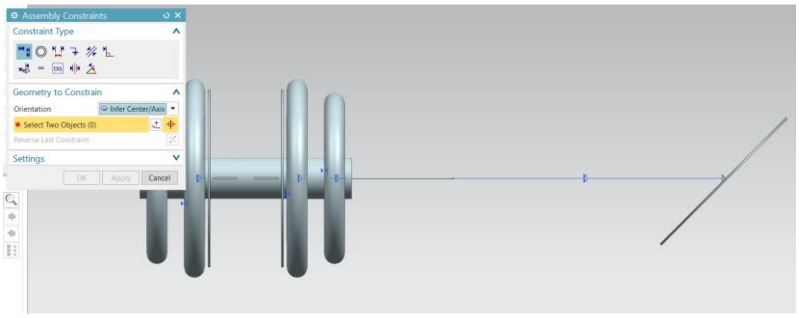


Figure 105: Aligning Process between Main Mirror 1 and the station [Own Source]

7) Next, align the centre of the hole in the Main Mirror 1 with the axis centre of the station. Make sure to set the mirror at 45 degrees.

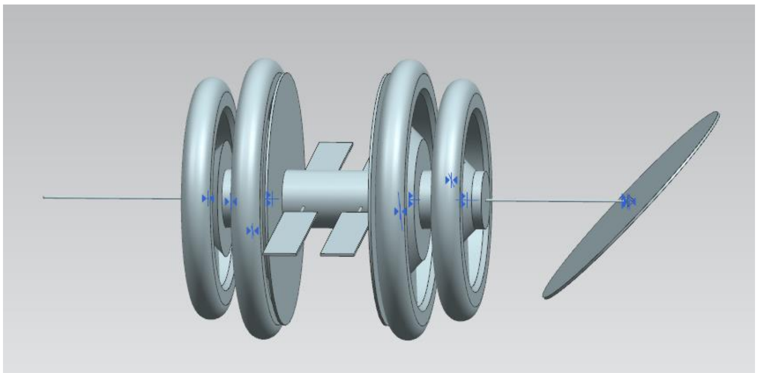


Figure 106: Locking process between Main Mirror 1 and the station [Own Source]

8) Then, insert the tube into the hole of the mirror by using touch feature in assembly constraints.

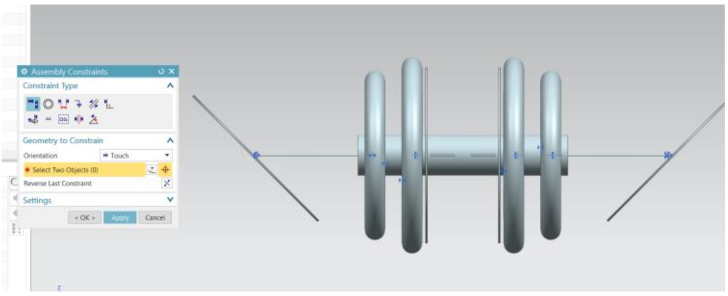


Figure 107: Fully assembled prototype [Own Source]

9) Repeat step 8 to connect Main Mirror 2 with the opposite side of the tube. The assemble process of the prototype is now complete.

7 SIMULATION OF ROTATION OF THE PROTOTYPE

The main focus of the simulation is to show the rotation of the habitat rings to the Non-Rotating Station. As the result of the simulation cannot be presented in this module, its visual representation will be shown during the oral presentation.

7.1 LINKS AND JOINTS

1) Using the assembled prototype from section 5.6, choose a motion application and then start a simulation.

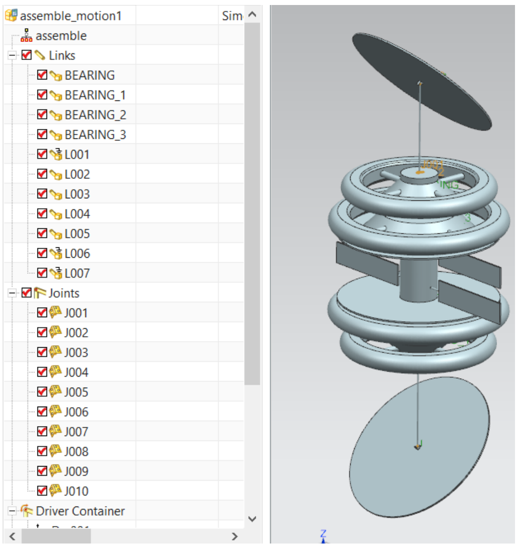


Figure 108: The links and the joints in the prototype [Own Source]

2) Make sure that all the components are categorised as links as seen in figure above.

3) Make sure to combine the connected components as “revolute joints”.

4) Lock the components that will remain static which are Non-Rotating Station, Main Mirror 1 and Main Mirror 2.

7.2 SETTING UP ANGULAR VELOCITY

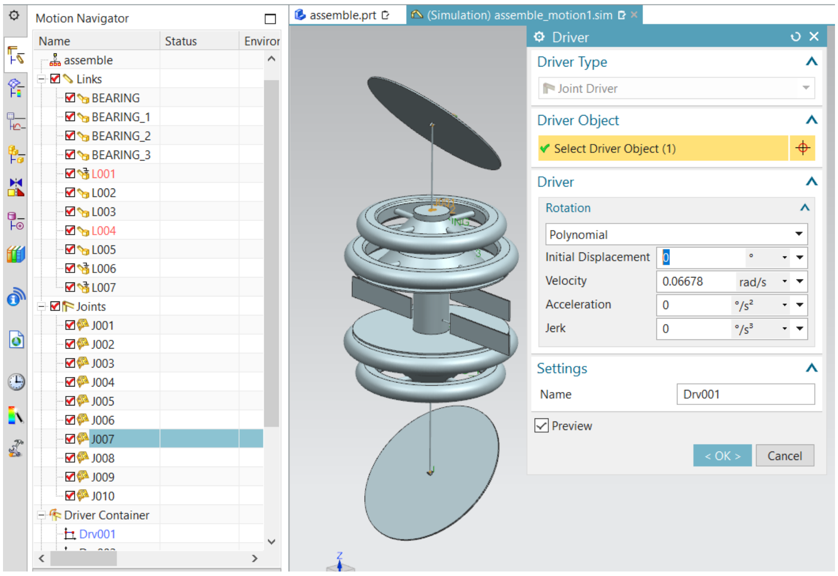


Figure 109: Setting the angular velocity of the Driver 1 (Habitat Ring 1) [Own Source]

1) Based on section 4.3.1, the angular velocity of Habitat Ring 1 would be 0,06678 rad/s. Thus, choose “Driver” for revolute joint on Habitat Ring 1 and then set the angular velocity to 0,06678 rad/s.

2) Choose the second driver for revolute joint on Habitat Ring 4, and put in the same angular velocity as step 5. This is because both Habitat Ring 1 and 4 have the same angular velocity but in opposite direction of rotation. No need to put negative sign on the value for Habitat Ring 4, it will rotate in opposite direction as it is in invert position.

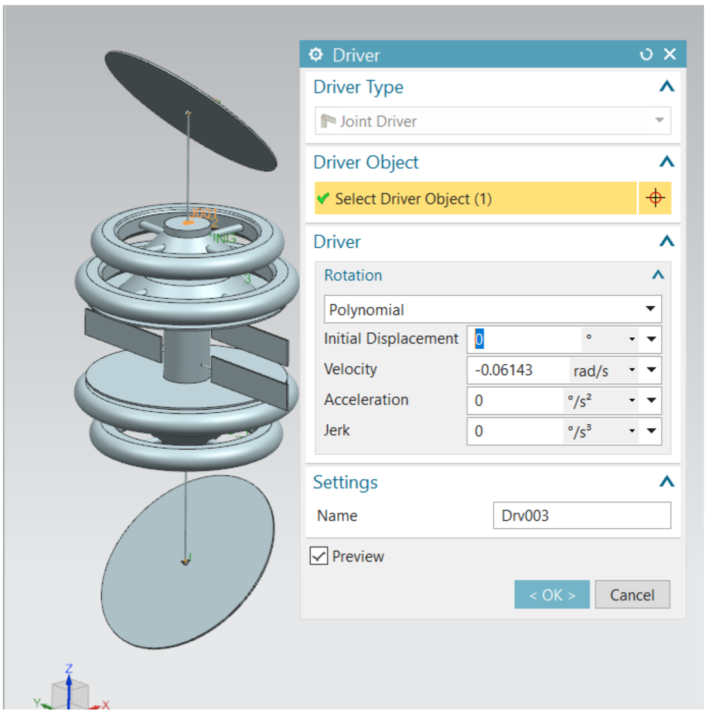


Figure 110: Setting up the angular velocity for Driver 3 (Habitat Ring 2) [Own Source]

3) As stated in section 4.3.1, the angular velocity for Habitat Ring 2 would be 0,06143 rad/s. Therefore, create a third driver for Habitat Ring 2 and set its angular velocity to -0,06143 rad/s as it rotates in opposing direction to Habitat Ring 1.

4) Create the final driver on Habitat Ring 3 and set its angular velocity to -0,06143 rad/s as it needs to rotate opposed to the direction of rotation of Habitat Ring 4.

7.3 CREATING A SOLUTION

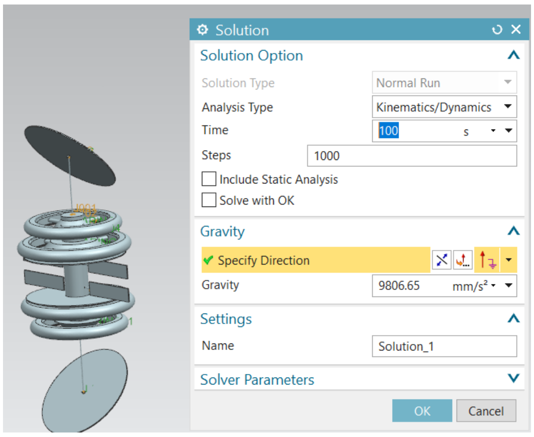


Figure 111: Steps and time for the simulation video [Own Source]

9) The final step is to chip in the time and the steps for the simulation. Click 'solution' and then put in 100 s and 1000 steps as seen in the figure. And then click 'solve'.

The simulation process is now complete. The visual simulation will be shown during the final presentation of this project.

8 DESIGN COMPARISON

As the prototype design had been explained, now is time to compare this prototype with both Stanford Torus and O'Neill Cylinder to see if the objective in designing this prototype is achieved.

8.1 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 maximum.
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 3: 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 figure 15).

8.2 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 a several parts of my prototype that cannot match with O'Neill Cylinder and the parts need a deep researches and 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 4: Inconveniences of 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.

8.3 PROBLEMS ENCOUNTERED

The main problem encountered is the material. As this design is smaller, complex and will experience extreme stresses from 300.000 colonies, there are no materials that have properties that can suit the requirements.

But that doesn't mean that the suitable materials don't exist. Currently, we are still lacking resources and knowledge about materials for space use. Extensive testing on wide variety of materials, and alloys need to be made, more researches and studies on materials need to happen. It might take generations to find the suitable materials.

9 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 researches. 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 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 inhabitants.
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 colonies 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 researches 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 figuring out 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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It was challenging to finish this project during this pandemic as EPSEVG library had been closed for months and I had to find useful articles and bibliographies online. Despite this tough couple of months, I still able to finish my TFG, even from home, and for that, I am really grateful.

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11 BIBLIOGRAPHY

[1] **N. T. Redd,** "How Old Is Earth?," 7 December 2019. [Online]. Available: https://www.space.com/24854-how-old-is-earth.html. [Last access: 10 February 2020]

[2] "Current World Population," 9 June 2020. [Online]. Available: https://www.worldometers.info/world-population/. [Last access: 10 February 2020]

[3] "World Population Prospects 2019," [Online]. Available: https://population.un.org/wpp/. [Accessed 20 March 2020].

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

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

[6] **Z. Hausfather,** "Analysis: Why scientists think 100% of global warming is due to humans," 13 December 2017. [Online]. Available: https://www.carbonbrief.org/analysis-why-scientists-think-100-of-global-warming-is-due-to-humans. [Last access: 20 March 2020].

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

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

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

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

[11] **T. L. McKendree,** "Implications of Molecular Nanotechnology Technical Performance Parameters on Previously Defined Space System Architectures," 1995.

[12] **M. Garcia,** "International Space Station Facts and Figures," 9 April 2020.

[Online]. Available: https://www.nasa.gov/feature/facts-and-figures. [Last access: 10 June 2020

[13] **Johnson,** "Preface," in *NASA Study*, p. VII.

[14] **P. E. Gaucher,** Power From the Sun: Its Future, vol. 162, 1968, p. 857.

[15] **Johnson,** in *NASA Study*, p. 46.

[16] **N. Marteralo,** "Powering the Stanford Torus," 18 May 2017. [Online]. Available: http://large.stanford.edu/courses/2016/ph240/martelaro2/. [Last access: 19 June 2020]

[17] **R. Guidice and N. ,** Artists, *Toroidal colonies, cutaway view, exposing the interior.* [Art]. NASA Ames Research Center, 1970 (Uploaded on 26/8/2012).

[18] **J. Lucas,** "What Are Centrifugal & Centripetal Forces?," 10 May 2019. [Online]. Available: https://www.livescience.com/52488-centrifugal-centripetal-forces.html. [Accessed 6 June 2020].

[19] **R. D. Johnson and C. Holbrow,** "Space Settlements: A Design Study," 1977, p. 201.

[20] **R. Guidice and N. ,** Artists, *A pair of O'Neill cylinders.* [Art]. 1970.

[21] **G. Clovis,** Artist, *O'Neill Cylinder Space Colony Mk.3.* [Art]. Freelance Digital Artist, 2015.

[22] **T. Heppenheimer,** "L5: A Place in Space," [Online]. Available: https://space.nss.org/what-is-l5/. [Accessed 15 April 20].

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

[24] **L. Bogan,** "An Explanation of the Coriolis Force," November 1998. [Online]. Available: http://www.bogan.ca/physics/coriolis.html#:~:text=The%20coriolis%20force%20is%20always,rim%20of%20the%20space%20station. [Last access: 1 June 2020].

[25] "Mass as a Measure of the Amount of Inertia," [Online]. 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].

[26] "Is there any resistance to movement in space for DS1?," [Online]. 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.. [Accessed 13 June 2020].

[27] "What Materials Can Survive in Space?," 7 June 2019. [Online]. Available: https://www.nts.com/ntsblog/materials-survive-in-space/. [Last access: 13 June 2020]

[28] **S. S.** "What's the Temperature of Outer Space?," Space.com, 1 March 2012. [Online]. Available: https://www.space.com/14719-spacekids-temperature-outer-space.html#:~:text=Some%20parts%20of%20space%20are,is%20minus%20455%20degrees%20Fahrenheit. [Last access: 11 June 2020].

[29] **S. Anthony,** "The International Space Station will soon become the coldest place in the known universe… for science!," 3 February 2014. [Online]. Available: https://www.extremetech.com/extreme/175932-the-international-space-station-will-soon-become-the-coldest-place-in-the-known-universe-for-science#:~:text=As%20you%20probably%20know%2C%20space,there%20can%20be%20no%20heat.. [Last access: 11 June 2020].

[30] **B. Dunbar**, "Why Space Radiation Matters," 9 October 2019. [Online]. Available: https://www.nasa.gov/analogs/nsrl/why-space-radiation-matters.

[31] **M. Zheng,** "Pressure in Outer Space," 2002. [Online]. Available: https://hypertextbook.com/facts/2002/MimiZheng.shtml#:~:text=The%20pressure%20in%20outer%20space%20is%20so%20low%20that%20many,is%20almost%20zero%20or%20negligible.. [Last access: 13 June 2020]

[32] **W. Wassmer,** "The Materials Used in Artificial Satellites and Space Structures," 12 May 2015. [Online]. Available: https://www.azom.com/article.aspx?ArticleID=12034. [Last access 13 June 2020]

[33] **AZoM,** "Aluminum - Advantages and Properties of Aluminum," 4 June 2002. [Online]. Available: https://www.azom.com/article.aspx?ArticleID=1446. [Last access 15 June 2020]

[34] **NASA,** "STS-113 Space Shuttle Processing Questions & Answers (NASA KSC)," in *NASA KSC*, 15 November 2002.

[35] **F. Pozzi and C. Small**, "Vegetation and Population in Urban and Suburban Areas in The USA," *Vegetation and Population in Urban and Suburban Areas in The USA,* p. 4, June 2002.

[36] **N. and W. S. T. ,** "What is a Lagrange Point?," 27 3 2018. [Online]. Available: https://solarsystem.nasa.gov/resources/754/what-is-a-lagrange-point/.

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

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

[39] "Measuring the Universe," in *Astronomic Union*, 2012.

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

[41] "Solar Panels," 2020. [Online]. Available: https://us.sunpower.com/products/solar-panels. [Last access: 20 April 2020]

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

12 ANNEXES

PLANOS

1- Isometric view of the prototype.

2- Exploded view of the prototype.

3- 2D view of the prototype with height and width measurements.

4- Isometric view of Non-Rotating Station.

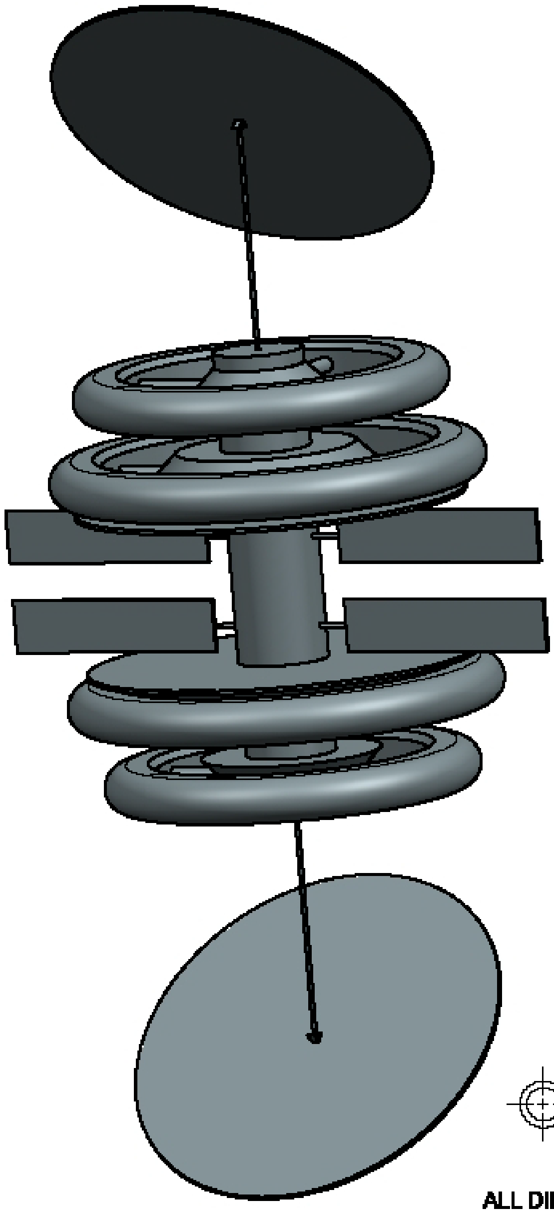
5- 2D view of Non-Rotating Station and dimensions.

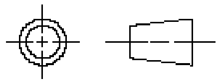
6- 2D view of Habitat Ring 1 and 4 and dimensions.

7- 2D view of Habitat Ring 2 and 3 and dimensions.

8- 2D view of Main Mirror and dimensions.

9- 2D view of Bearing and dimensions.





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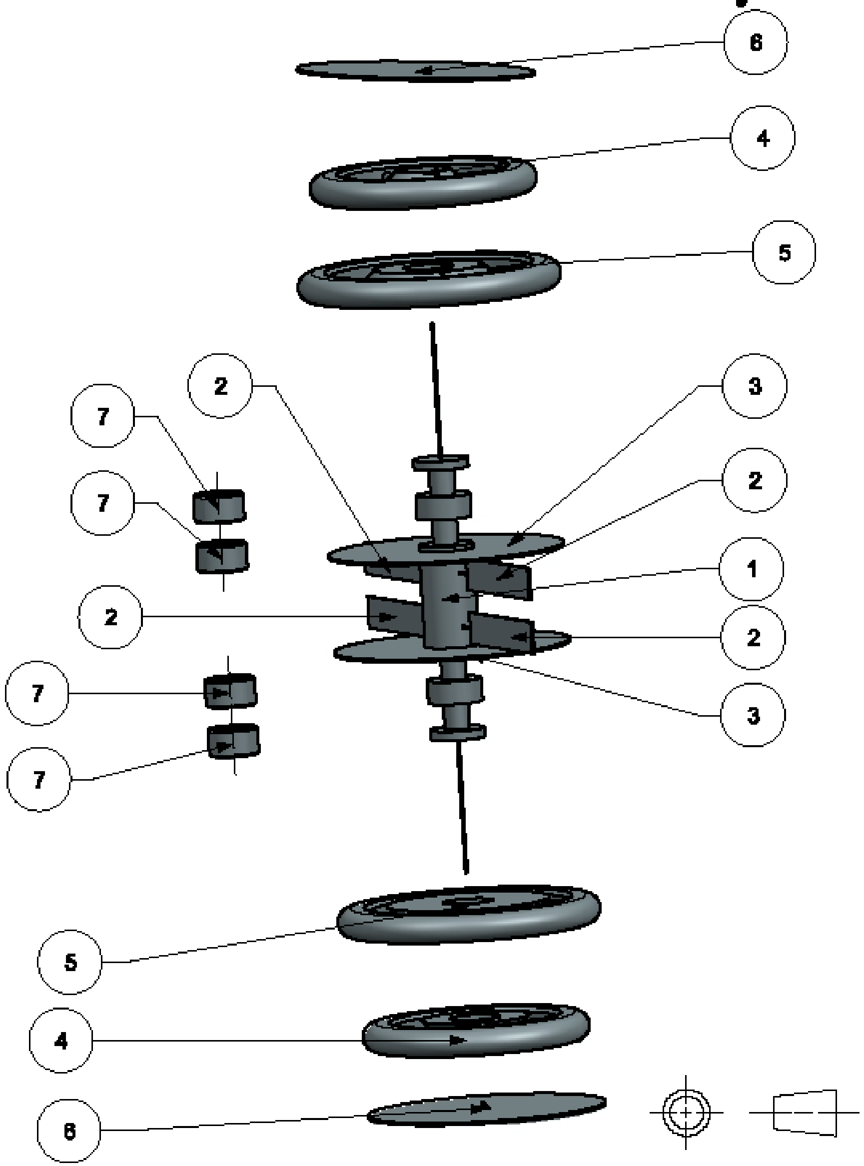

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2	SOLAR PANEL	4
3	RADIATOR DISC	2
4	HABITAT RING 1 AND 4	2
5	HABITAT RING 2 AND 3	2
6	MAIN MIRROR	2
7	BEARING	4
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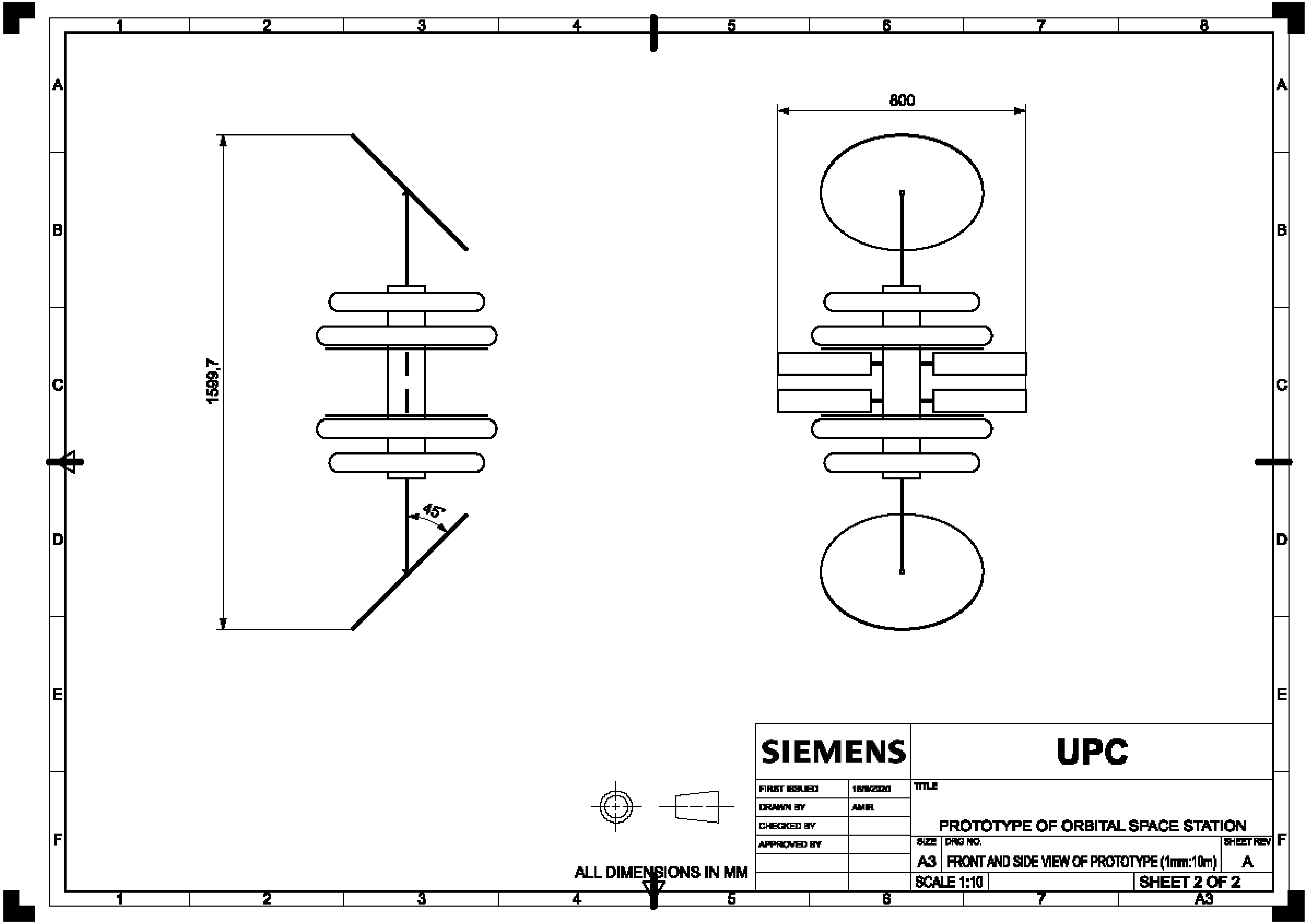
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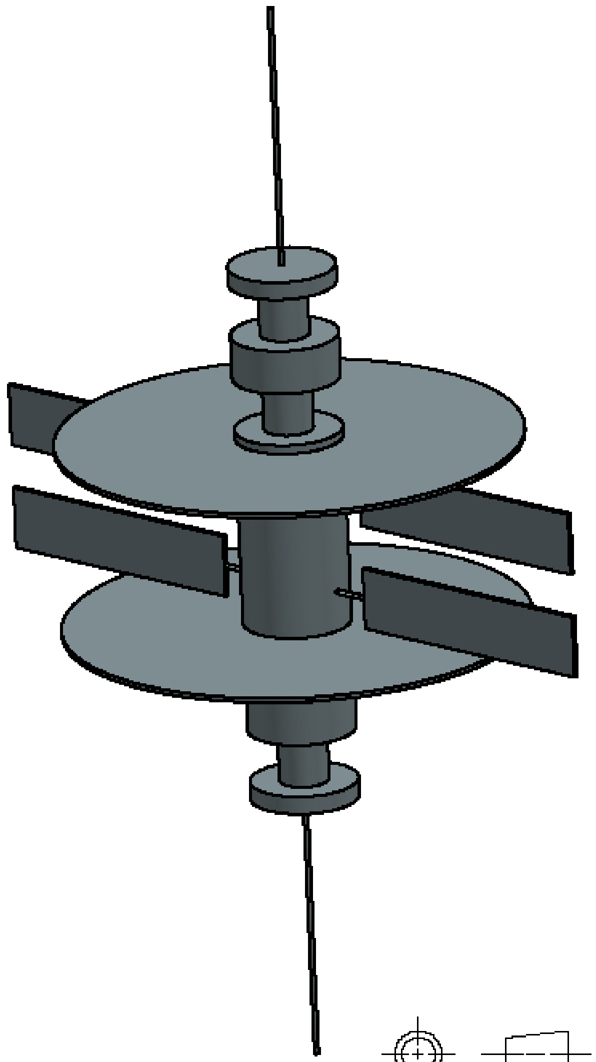

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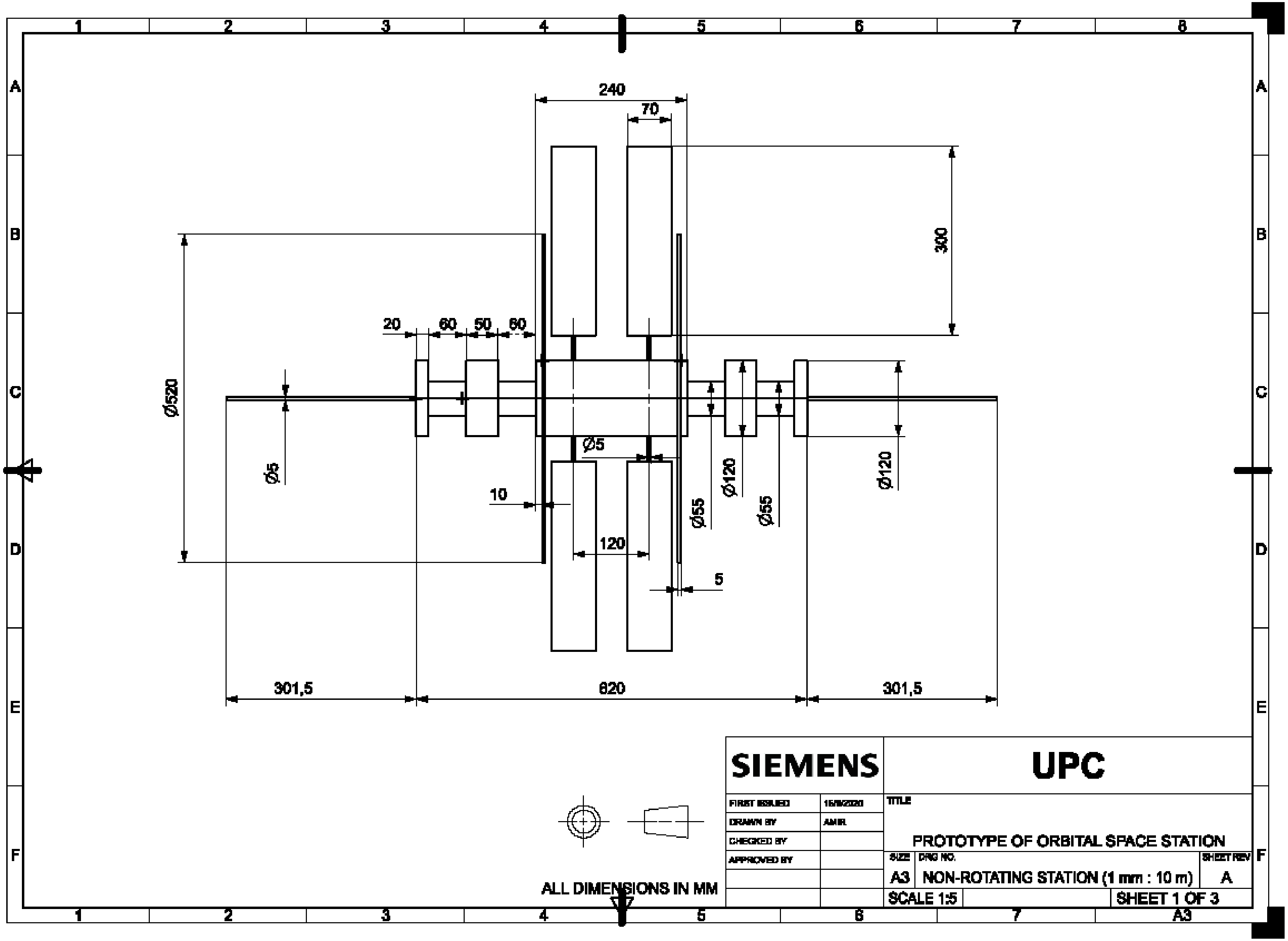
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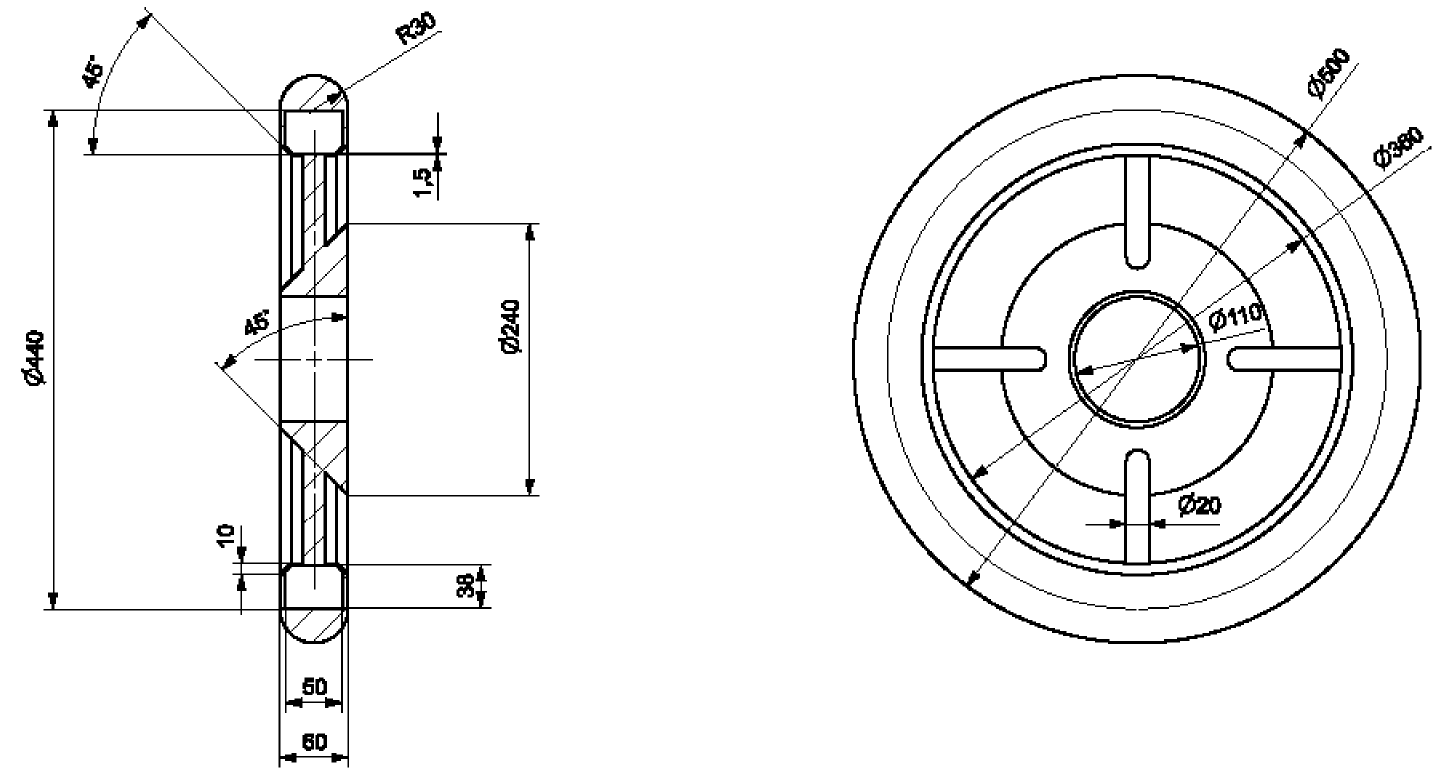

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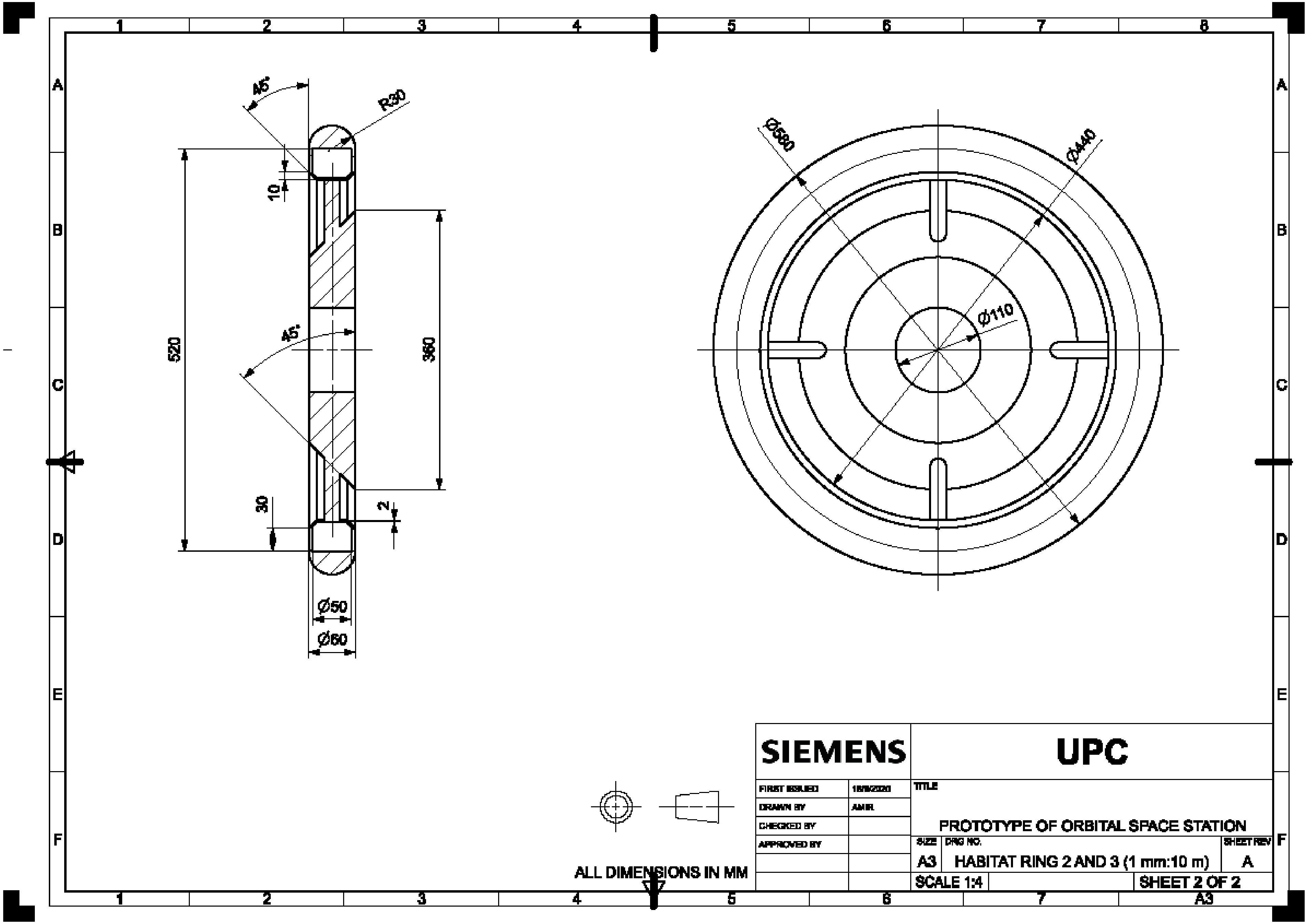
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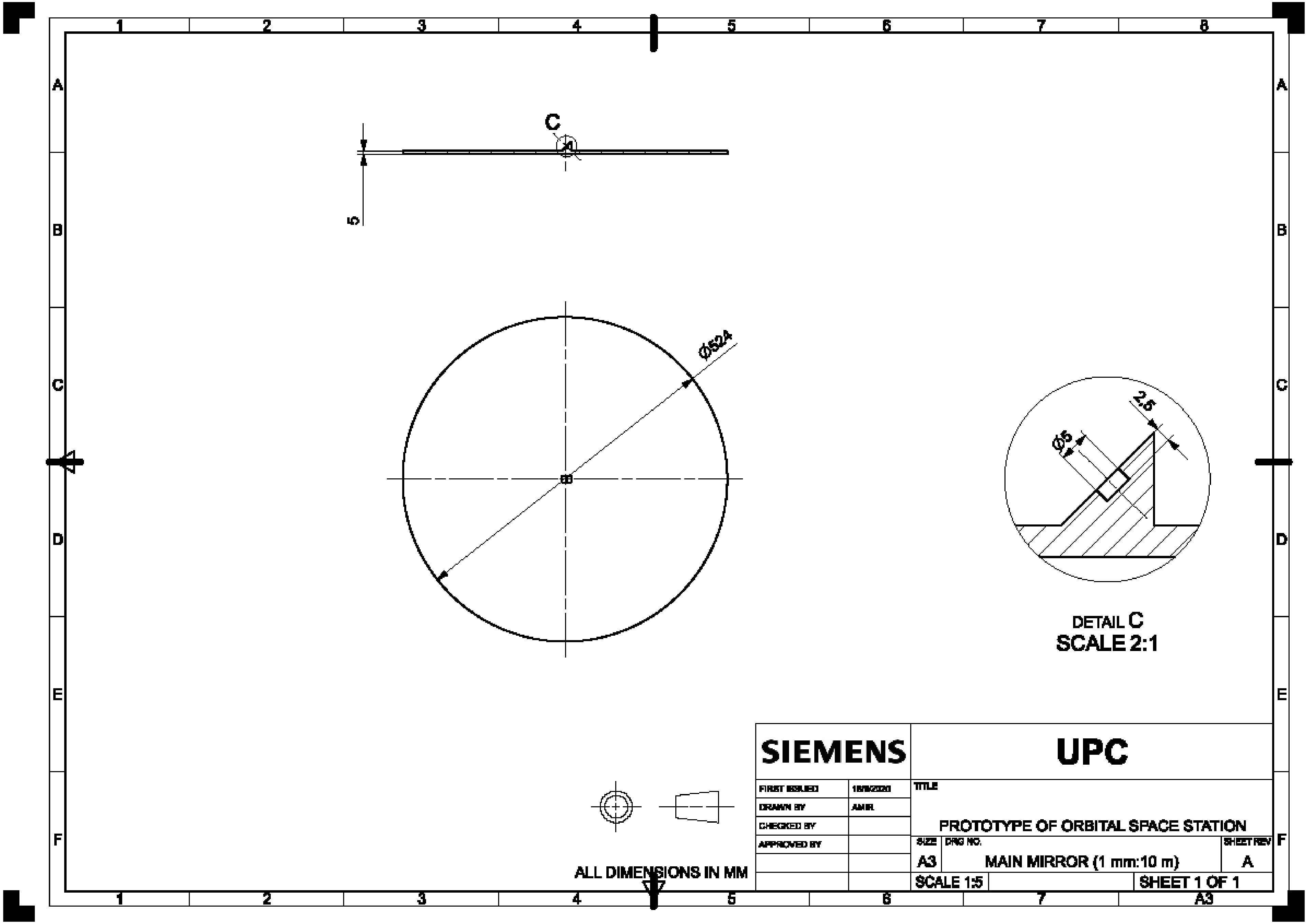
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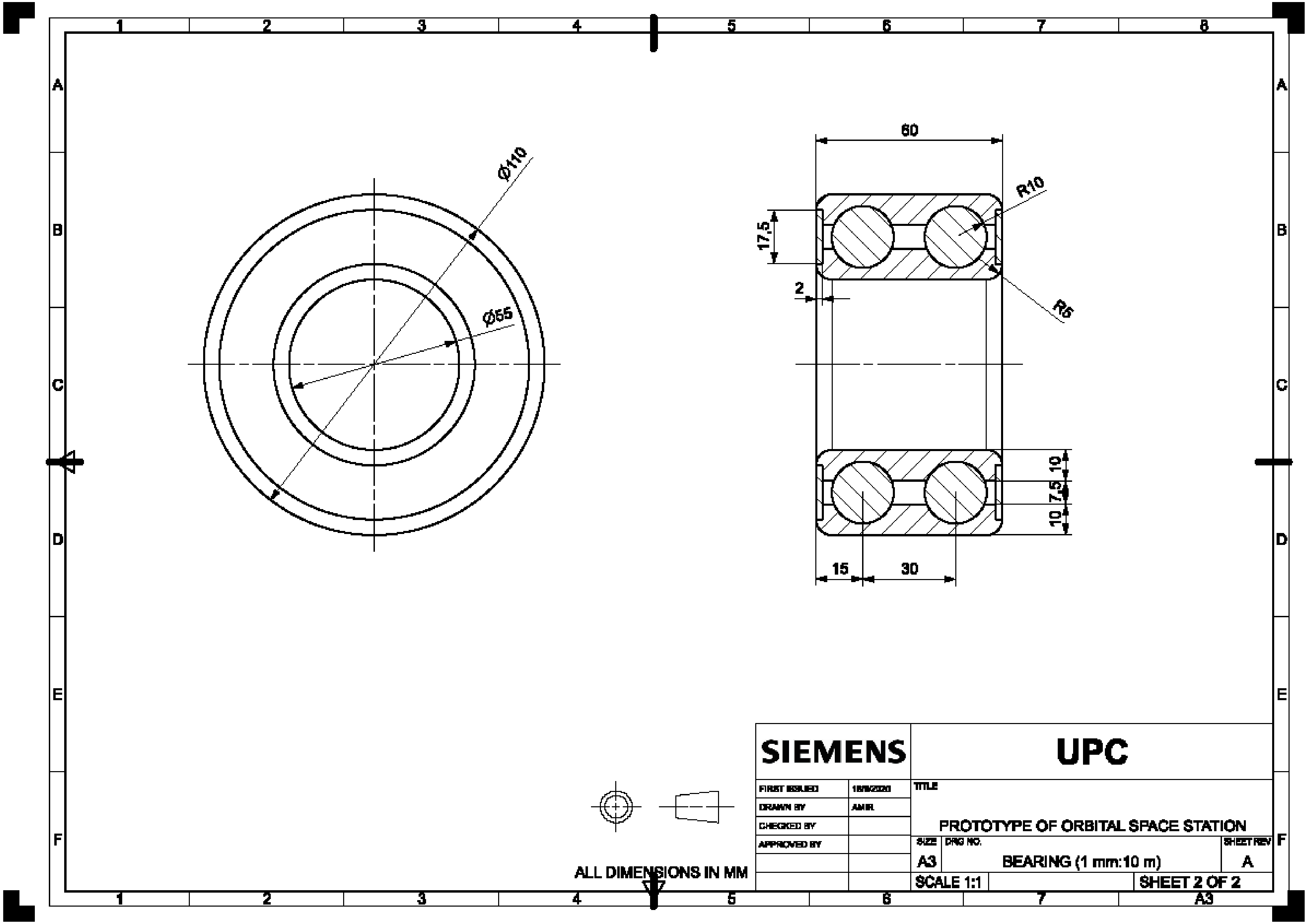
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