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RESUM

La exploración espacial ayuda a abordar preguntas fundamentales sobre nuestro lugar en el universo y la historia de nuestro sistema solar. Sin embargo, llegar al espacio es muy costoso, ya que se necesitan alrededor de 500 millones de dólares en costo de lanzamiento para llevar un satélite a una órbita geosíncrona. Un ascensor espacial podría reducir el costo y crearía una conexión permanente de la Tierra al espacio. Esto haría que los viajes al espacio sean más frecuentes y abriría el espacio a una nueva era de desarrollo.

La idea original surgió en 1895 de un físico ruso Konstantin Tsiolkovsky que identifica el concepto de que una estación espacial podría construirse más allá de la órbita geosincrónica que soportaría la parte de la torre debajo del geosíncrono utilizando una fuerza externa debido a la rotación de la Tierra. En este documento, abordaré los componentes técnicos básicos de un elevador espacial, así como para corregir la necesidad y el potencial de tener un elevador espacial para el desarrollo espacial. También se creará un modelo de elevador espacial utilizando un software comercial NX Siemens PLM versión 12 y en este documento se analizará un análisis más detallado del modelo.

Paraules clau (màxim 10):

Ascensor especial	Nanotubo de carbono	Torre libre	Fuerza de tension
Atar	Trepador	Ancla	Contrapeso
Siemens NX12	Órbita geosíncrona		

ABSTRACT

Space exploration helps to address fundamental questions about our place in the universe and the history of our solar system. However, getting to space is very costly as it takes around 500$ million in launch cost to get a satellite to geosynchronous orbit. A space elevator could reduce the cost and would create a permanent Earth to space connection. This would make trips to space more frequent and would open up space to a new era of development.

The original idea came in 1895 from a Russian physicist Konstantin Tsiolkovsky which identifies the concept that a space station could be built beyond geosynchronous orbit that would support the portion of the tower below geosynchronous by using an outward force due to Earth's rotation. In this paper, I will address the basic technical components of a space elevator as well as redressing the need and potential of having a space elevator for space development. A space elevator model will also be created by using a commercial software NX Siemens PLM version 12 and further analysis of the model will be discussed in this paper.

Keywords (10 maximum):

Space elevator	Carbon nanotube	Free-standing towe	Tensile strength
Tether	Climber	Anchor	Counter weight
Siemens NX12	Geosynchronous orbit		

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GLOSSARY

F_u	Upward force due to the upper element of the tower [N]
F_c	Upward centrifugal force [N]
F_D	Downward force due to the lower element of the tower [N]
W	Weight of the tower due to gravity [N]
G	Newton's constant of gravitation [Nm^2/kg^2]
m	Mass of the Earth [kg]
r	Radius of Earth [km]
ρ	Mass density of elevator cable [kg/m^3]
ω	Rotational angular velocity of Earth [s^{-1}]
m_c	Mass of counter weight [kg]
ρ	Mass density of elevator cable [kg/m^3]
T	Stress (or force per unit area) in elevator cable [GPa]

1. Introduction

The idea of a space elevator has been around for quite some time and this is because it offers us an inexpensive and easy way to transport loads and materials into the outer space. While using a rocket to transport passengers and cargo might be faster, it would be much cheaper to use the space elevator instead because it can be used continuously.

The idea of space elevator was first described by Konstantin Tsiolkovsky in 1895 [1]. He identifies the concept that a space station could be built beyond geosynchronous orbit that would support the portion of the tower below geosynchronous by using an outward force due to Earth's rotation

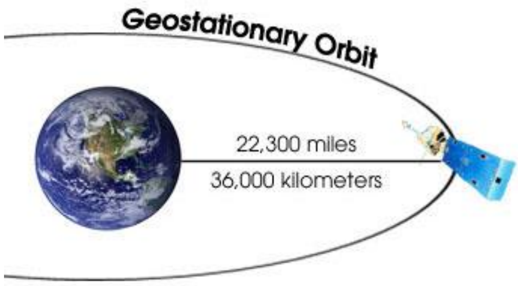

Figure 1.1. Distance of geostationary orbit to Earth. Source: [2]

A geostationary orbit is a circular geosynchronous orbit approximately around 36,000 kilometres above Earth's equator and following the direction of Earth's rotation. In simpler terms, the space elevator would seem motionless in a fixed position in the sky to the ground.

With the invention of a space elevator, it will enable us to place heavy and fragile payloads in Earth orbit or send them to other planets, bring payloads from space and deliver payloads to space at a small fraction.

There will be 4 major components for the space elevator which is the base station (anchor), the climber (the elevator carriage), the tether (the cable that connects the surface to space), and the orbital space station (counter weight).

The biggest obstacle for the construction of the space elevator is the lack of material with high tensile strength and elasticity with low density. Building a space elevator will seems to be a challenging but not impossible task.

In this paper, we will investigate the physics and mechanics of the operation of space elevator along with its components and the possible materials. A space elevator model will also be created by using Siemens PLM version 12 and further analysis of the design will be made.

2. Objective

The general objective of this thesis is to study the theory of physics of the space elevator and the major components involved in building the space elevator. The specific objectives of this study are to:

- To do an extensive exploratory literature review and detail explanation about the requirements and specifications of components needed to operate a space elevator.
- To create a model of a space elevator based on the criteria explained by using NX12 Siemens PLM Software.
- To do a further analysis of the operating system of the space elevator model created.
- To do a study on the challenges of building the space elevator.

3. Literature review

3.1. Introduction

The original idea came in 1895 from a brilliant Russian physicist Konstantin Tsiolkovsky which identify the concept that a space station could be built beyond geosynchronous orbit that would support the portion of the tower below geosynchronous by using an outward force due to Earth's rotation [1].

This idea was proposed again by Yuri Artsutanov, a Russian engineer, in 1960. Artsutanov developed his idea and proposed his idea using satellite beyond geosynchronous orbit which is remain over a fixed point on the equator to construct the tower [3]. He suggested to use the satellite as a counter weight and lowering the cable until it reaches Earth's surface where it will be retrieved and anchored safely. This idea is to make sure the centre of mass of the cable to remain at the same height above Earth atmosphere.

In September 2018, a group of engineers from Shizuoka University held a research and launched two ultrasmall cubic satellites into the space from the International Space Station (ISS) [4]. Each cubic satellite was connected by a 10-metre steel cable with a small container acting as an elevator car to move along the cable. A camera is attached on the container to study the movements and behaviour of the container while operating in space.

Having a space elevator will help ease our journey to the space as it can create a permanent Earth to space connection. This can allow us to make more frequent trips to space due to the lower cost of operating a space elevator compared to using a rocket.

As of 2000, conventional rockets cost about $18,500 per kilogram for transferring it to space [5]. Recent space elevator design proposal envisions payload prices starting at $200 per kilogram [1]. Other than cheaper orbiting satellites, a space elevator could benefit us in many ways such as:

a) Lower cost of delivery of satellites to space
b) A manned space station at geosynchronous orbit
c) Removal of debris in Earth orbit
d) Mining of nearby asteroids for valuable metals
e) Research facilities in space

3.2. Theory of a free-standing tower

A free-standing tower will only able to withstand itself if the force upward is equal to the force downwards. Therefore, in this case the weight of the tether and climber need to be counterbalanced by the outward centrifugal force due to the rotation along the geostationary orbit.

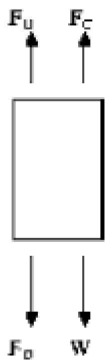

Figure 3.1 Summation of the forces acting on the tower at the geostationary height. Source: [6]**.**

There will be a few forces that is applied to this system which is gravitational force, centrifugal and tension forces acting on it.

$$\boldsymbol{F_U} + \boldsymbol{F_C} = \boldsymbol{F_D} + \boldsymbol{W} \quad \textbf{(1)}$$

Where:
F_u: upward force due to the upper element of the tower [N]
F_c: upward centrifugal force [N]
F_D: downward force due to the lower element of the tower [N]
W: weight of the tower due to gravity [N]

For a tower at a geostationary height, the weight and centrifugal force taking account that the height is at a distance from the Earth's centre equal to the radius of the stationary orbit, the forces should be (**F_c** = **W**) and therefore the other equation should be (**F_u** = **F_D**) for an equilibrium to be achieved.

For an element below the geostationary height, the weight force **W** is greater than **F_c** and thus the other equation (**F_u** > **F_D**) for it to be in equilibrium. On the contrary, the equation (**F_u** < **F_D**) should be met for the element above the geostationary height for it to be at equilibrium.

In both cases, the forces will be at maximum at the geostationary height and the tension drops at zero at both ends. This will only occur if any of the following case is satisfied. Firstly, the tether should end further than the geostationary orbit to counter the forces pulling downwards.

The other option would be building a terminus station which is a bit further than the geostationary height that can be used for other purposes such as creating a liveable environment and space for human to live and can also serve as a rest and service areas for space craft. Figure 3.2 is a representation of the forces that is acting on the tower at the geostationary height.

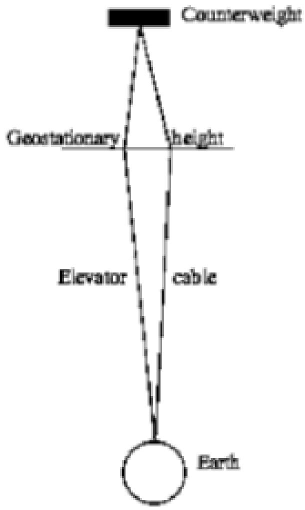

Figure 3.2 Representation of the summary of forces along the cable. Source: [6].

3.3. Height of a free-standing tower

Consider a small element of the tower with length *dr* whose lower end is a distance *r* from the Earth's centre. Replacing $\mathbf{F_U} - \mathbf{F_D}$ as *AdT* where *T* is the tensile stress of the tower. Based on the calculation done by P.K. Aravind [6]:

$$AdT = \frac{GM\,(Adr\rho)}{r^2} - (Adr\rho)\omega^2 r \quad \textbf{(2)}$$

Where:
G: Newton's constant of gravitation [Nm^2/kg^2]
M: mass of the Earth [kg]
r: radius of Earth [km]
ρ: mass density of elevator cable [kg/m^3]
ω: rotational angular velocity of Earth [s^{-1}]

Dividing both side with Adr, the equation would be:

$$\frac{dT}{dr} = GM\rho\left[\frac{1}{r^2} - \frac{r}{R_g^3}\right] \quad \textbf{(3)}$$

Integrating the equation from r = R to r = R_g, where T(R) = 0 gives that the tensile stress at geostationary height R_g as:

$$T(R_g) = GM\rho\left[\frac{1}{R} - \frac{3}{2R_g} + \frac{R^2}{2R_g^3}\right] \quad \textbf{(4)}$$

H can be determined by integrating r = R_g and r = H subject to the boundary condition T(H)=0 which means that the tension is zero at both end of the tower.

$$T(R_g) = GM\rho\left[\frac{1}{H} - \frac{3}{2R_g} + \frac{H^2}{2R_g^3}\right] \quad \textbf{(5)}$$

Equating both equation by using $T(R_g)$ as a subject and note that H=R is a solution of the resulting cubic H. We can reduce the equation from cubic down to quadratic equation.

$$RH^2 + R^2H - 2R_g^3 = 0 \quad \textbf{(6)}$$

Finding the only positive root is 150000 km with radius of Earth taken account. Therefore, the height of the tower is found to be 144,000 km above Earth's surface.

While a space elevator can be built at lower height, a larger and heavier counterweight will be needed to balance out the tension at the tether. Therefore, there are a few factors that needed to be considered before we can determine the optimum length to build the counterweight. The factors are the availability of the material, our ability to ship and build large infrastructure in space and the cost of raw materials.

Where the properties of a material play a significant role in building the space elevator, the tether can be tapered at the upper part making it wider which lets it hold up a longer length. By increasing the taper ratio, the breaking length will also increase as it is getting further from the planet which will weakens the gravity experienced by the cable. Increasing the taper ratio will increase the strength of the cable.

While hypothetically any substance can be used for a space elevator by increasing the taper ratio, it is very unlikely to be done as building a tall object with wider bases will have a practical limit.

3.4. Mass and length of a space elevator

Based on the previous calculation, it is found that the total length of the elevator to be about 144,000 km. The total length of the space elevator could be shortened if a counterweight is used and attached at the upper end of the cable. The counterweight will provide a centrifugal force to compensate with Earth's gravitational force and maintain the necessary tension to keep the cable taut.

In this part, the steps and calculation for the length and mass of the space elevator was calculated by P.K. Aravind [6].

$$\boldsymbol{m_c} = \frac{\rho A_s L_c \, exp\left[\frac{R^2}{2L_c R_g^3}\left\{\frac{2R_g^3+R^3}{R} - \frac{2R_g^3+(R_g+h)^3}{R_g+h}\right\}\right]}{\frac{R^2(R_g+h)}{R_g^3}\left[1-\left(\frac{R_g}{R_g+h}\right)^3\right]} \qquad \textbf{[7]}$$

Where:

m_c: mass of counterweight [kg]
ρ: mass density of elevator cable [kg/m^3]
T: stress (or force per unit area) in elevator cable [GPa]

Note that $m_c \to \infty$ as h→0 and decreases with increasing h. The value of the parameters in this calculation is as following; ρ= 1500kg/m^3, T= 100GPa and A_s= 1.5x10^{-7} m^2. A further calculation of the maximum distance a spacecraft could reach if released from the counterweight was done by using a 107,000 km length of space elevator. The obtained distance for the maximum distance for a spacecraft is 7.95x10^{11} km which is equivalent to 5.3 AU (Astronomical unit) which is a little larger than the mean orbital radius of Jupiter. A cable of about 100,000 km in length is generally a good choice for the proposed idea.

Therefore, the height of the space elevator is assumed to be about 100,000 km in this and the upcoming chapters. By using the previous equation, and incorporating a safety factor of 2 into the design, it is found that the mass of the counterweight to be 52.7×10^3 kg. The stress in the cable is only 50 GPa everywhere which is half from the maximum stress allowed.

3.5. Cheap alternative to space

Space elevator is the cheaper alternative to send payloads to the space compared to rockets. The development and building a space elevator require a massive budget and a long time to finish. Rockets on the other hand, require a huge amount of rocket fuel just to get a small amount of cargo into space. At current prices, the cost to send a kilogram of payload to space is about US$18,500 [5]. Therefore, it could cost billions to launch rockets to deliver payloads for further space development. This immense cost is one of the major limitations of human spaceflight. In table 3.1, a breakdown of the cost of operating a space elevator up until the fourth ribbon is shown. Since the table was taken from a book with United States customary units background, the M (million) prefix is equivalent to 10^6 while the B (billion) is equivalent to 10^9.

Component	**First ribbon**	**Second ribbon**	**Third ribbon**	**Fourth ribbon**
Launch cost to GEO	$1,000M	0	0	0
Spacecraft	$587M	0	0	0
Ribbon production	$390M	$150M	$75M	$30M
Climbers	$161M	$80M	$40M	$30M
Power beaming station	$2,100M	$1,600M	$1,000M	$600M
Power generating station	$40M	$40M	$40M	$30M
Anchor station	$120M	$120M	$100M	$100M
Tracking facility	$36M	0	0	0
Admin facilities	$202M	0	0	0
Operation	$210M	$30M	$20M	$10M
Miscellaneous & contingency	$1,154M	$280M	$125M	0
Total	≈$6B	≈$2.3B	≈$1.4B	≈$0.8B

Table 3.1 Cost of operating a space elevator. Source: [1].

The cost of sending a kilogram of payload to space would therefore be quite expensive in the first few years and will decrease over time. Assuming the cost of the construction of the space elevator to be US$10.5 billion up until the fourth ribbon, then this project will recoup the initial losses after hundreds launching at most or one million tons of payload which is close to the weight of two international space station. Hence, in the long-term application, it is more economical to transfer payload to space with space elevator compared to rockets.

3.6. Initial deployment

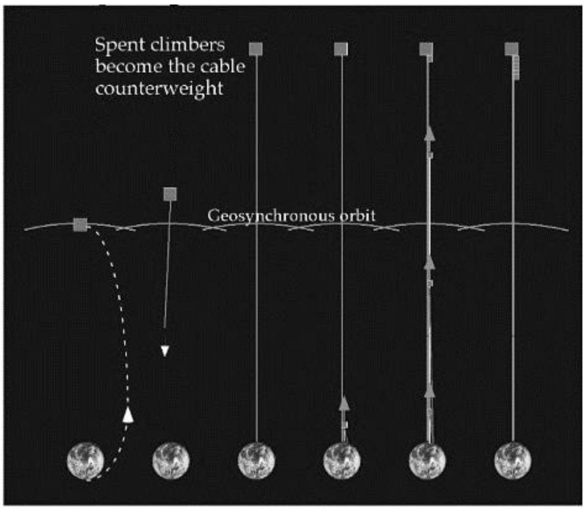

Figure 3.3 Steps of deployment of the space elevator. Source: [7].

First step of the deployment for the space elevator is a spacecraft is sent to geosynchronous orbit where it begins deploying a small ribbon. As the ribbon is deployed, the spacecraft will float outward due to Newton's third law of motion. Newton's third law states that for every action, there is an equal and opposite reaction which resulted in the movement of both the ribbon and spacecraft. Then, when the ribbon reaches Earth surface, it will be retrieved and anchored securely. Climbers will be sent up the to provide support and strengthen the initial ribbon.

4. Major components of the space elevator

In this chapter, the basic requirements and specifications of the components of space elevator based on latest technology will be explained and discussed. Shown in figure 4.1 are the four main components in a space elevator which consist of an anchor, tether, counterweight and climber.

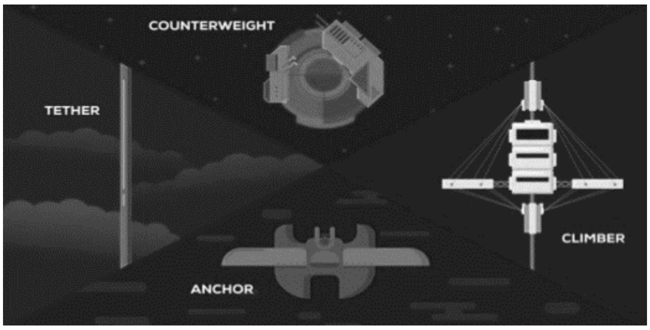

Figure 4.1 The main components of the space elevator. Source: [8]**.**

4.1. Initial spacecraft

This will be the initial spacecraft in building a space elevator. This spacecraft will have a short lifetime as it is only used to deploy and assemble the cable in outer space. After the first deployment happened, a support spacecraft will be sent to strengthen the structure and assemble the remaining parts. The first spacecraft will contain the few most important components in building a space elevator. Further explanation on the components on the climber will be explained in detail in the specification of the commercial climber.

Basic components in the initial spacecraft:

1. Cable
2. Support structure for the deployment of the cable
3. Power system
4. Communication system
5. Thermal control system
6. Attitude control system

In space, every material is subjected to vacuum, intense ultraviolet radiation (UV), ionizing particles, debris impacts and thermal cycling which can cause material damage if exposed for a long time. A research was done to investigate the behaviour of material in space. Long Duration Exposure Facility (LDEF) was left to remain in LEO for 5.8 years. It is found that under LEO environment, the condition of the materials was damaged dramatically especially polymers and metals [9]. Therefore, in order to protect the components from the harsh space environment, a durable material and coatings should be used for the components.

4.1.1. Cable deployment

If a tower is built at 35,900 km above the equator, you could step off at the top and not fall down. At that altitude, the top tower is moving at the same speed as what is needed to orbit the Earth at that height. The height at which the tower is an orbiting is called geostationary height. The case for the geostationary orbit is only true if it is above the equator and in circular orbit.

The cable deployment process will be initiated when the spacecraft is maintained at its geosynchronous orbit. When the spacecraft is maintained at that height, the lower end of the cable will be released. As the ribbon is deployed, the spacecraft will float outward due to Newton's third law of motion. Newton's third law states that for every action, there is an equal and opposite reaction which resulted in the movement of both the ribbon and spacecraft. Therefore, the ribbon will continue descending until it reaches Earth and the counterweight will move further outward from Earth. Then, when the ribbon reaches Earth surface, it will be retrieved and anchored securely. Climbers will be sent up the to provide support and strengthen the initial ribbon.

The lower end of the cable will hold a small contained craft. This craft contains a beacon signal device to transmit signals that will alert the location of the cable end to the authorities so that it can be retrieved later. This craft will also act as a ballast for the cable and provide gravitational torque that will keep the cable aligned as it is descending.

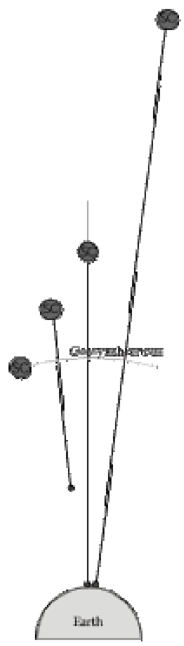

Figure 4.2 Deployment of the initial cable. The cable will be maintained at its geosynchronous orbit and the lower end of the cable will descend. Source: [1]**.**

4.1.2. Spacecraft structure

The spacecraft structure will provide the support that is needed for the first deployment of the cable. We will need to take advantage of the availability of the carbon nanotubes in building the spacecraft. This is because if the total mass of the spacecraft is lighter, this will allow the spacecraft to bring more load to outer space.

The structure of the spacecraft will be made of few materials such as carbon nanotubes, metallic alloy and composites that have a high specific strength (ratio of material strength to material density). The usage of these types of materials will allow them to be shaped into light yet robust structures that can withstand the harsh conditions in outer space.

4.1.3. Power system

The power required for the initial spacecraft is very low. The power will only be use to power up the central processing unit (CPU), attitude control, thermal system and communication systems. While the spacecraft will maintain at geosynchronous orbit, solar panels can be installed and be use to supply power. The power from the sun will be enough to sustain the needs for the electronics components on the spacecraft.

4.1.4. Communication system

The communications with the craft will only be used for commands and diagnostic downloads. The would be no need for high technology antenna as a two or three wide-angle antenna may be sufficient for the communication system.

4.1.5. Thermal control system

Thermal control is used to monitor and maintain the temperature within a range required to function properly. The main heat sources in a spacecraft are from the solar radiation and circuit boards. When the system detects an excessive heat, the thermal control will remove heat by rejecting the heat from radiator to space. The system consists of heater, heat pipes, radiator and thermal switches.

4.1.6. Attitude control

The attitude control system is responsible for its orientation in space. It will determine its position, velocity, attitude motion. This is very important as the spacecraft will need to be very specific to maintain its height at geosynchronous orbit. Besides, attitude control system will also be needed on the cable end to specify the orientation and angle during the initial angular momentum of the cable deployment.

4.2. Tether

One of the most fundamental part of space elevator is the tether (cable). The cable depends on the physics and the tensions that is acting along the cable. The cable below the geosynchronous orbit will experience a downward force due to the weight of the cable while the other part will experience a centrifugal force due to the rotation of Earth. The cable is tapered on both ends and will has the largest cross-sectional area at the geosynchronous orbit where the tension is at maximum.

4.2.1. Carbon nanotube

The biggest challenge in building a space elevator is the lack of material that has high elastic modulus and tensile strength. In 1991, Dr. Sumio Iijima discovered tubular and buckytubes that is made up of carbon atoms which is called nanotubes [10]. Nanotubes are tubes that is made up of hexagonal lattice of carbon atoms.

In the process, periodic boundary conditions are imposed over the length of this roll up vector to produce a lattice with helical symmetry on the cylinder surface. Shown in figure 4.3 are microscopic view of carbon nanotubes.

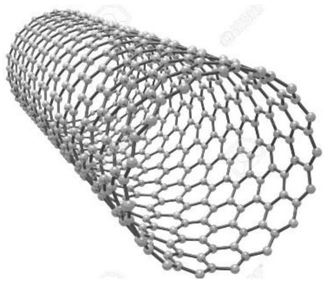

Figure 4.3 Carbon atoms rolled up of the Bravais lattice vectors. Source: [11]**.**

Without the usage of counterweight at the end of the tether, the length of the cable would be 144,000 km but the cable can be anywhere above 35,900 km if counterweight is taken into account. This is the minimum height required to build the counterweight. Any height below this will not work as building a space elevator require the counterweight to be above the geostationary height.

While a space elevator can be built at lower height, a larger and heavier counterweight will be needed to balance out the tension at the tether. Therefore, there are a few factors that needed to be considered before we can determine the optimum length to build the counterweight. The factors are the availability of the material, our ability to ship and build large infrastructure in space and the cost of raw materials. But in this study, the cable is assumed to be about 100,000 km in length due to the reasons discussed in chapter 3.4.

4.2.2. Mechanical properties of carbon nanotubes

Tapering refers to the change of width from root to tip and taper ratio can be calculated as the ratio of the width of the root to the tip. This is important as every material has its own taper ratio depending on its properties.

The taper ratio for steel is 1.6×10^{33}, Kevlar is 2.5×10^{8} and carbon nanotube is around 2 and 20, which means that if a 1 centimetre cable is at the bottom, it would have to be around 2 to 20 centimetre at the geostationary height at which the tension is the strongest [1].

Besides, carbon nanotube is a strong material with tensile strength far stronger than steel just at one fifth of the weight. As an example, for a cable with one-centimetre square, for nanotubes, it can hold up to 300 GPa compared to steel at only 4.2 GPa, Kevlar at 3.6 GPa, and graphite whiskers at 21 Gpa. This is important as the taper ratio of the cable is dependent on the strength to weight ratio of the material. As a result, carbon nanotubes increase the feasibility of producing a manageable cable for the space elevator.

Material	Tensile strength (MPa)	Breaking Length (km)
Graphene	130,500	6,366
Colossal carbon tube	6,900	6,066
Kevlar	3,620	256
Aluminium alloy	572	20.8
Concrete	2-5	0.44

Table 4.1 Tensile strength and breaking length for different materials. Source: [12]**.**

4.2.3. Ribbon design

The ribbon design proposed by Brad Edwards will have a 3 mm^2 cross sectional area of 10-micron diameter fibres or roughly 30,000 fibres at the anchor width [1]. The cable will consist of many individual fibres that are arranged in parallel with cross-connections, or straps, across the ribbon at 10 cm interval or more. The connections between fibres will be made up of composite materials which are 60% nanotubes and 40% epoxy.

As a result, when one of the fibre breaks, it will contract, pulling through the cross connectors until the tension drops below 1 GPa at each cross-connections. When this happens, the tension is transferred from the severed fibre to the neighbours through many cross-connectors and dissipating the energy.

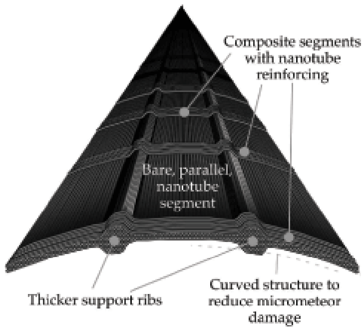

Figure 4.4. Cut-away view of the proposed ribbon. Source: [13]

4.2.4. Alternative design

Another design was done by Hoyt under a study for NASA's institute for Advanced Concepts [14]. The space tether consists both of straight fibres and crossed diagonal fibres to take up and distribute the load in the case of a meteor damage. It is also more robust in terms of handling meteor damage. This ribbon design could be approximately 64% heavier for the same load compared to the design proposed by Brad Edwards. Other problems will arise as it would increase the system mass and launch mass by a factor of four.

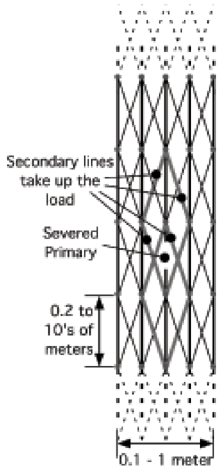

Figure 4.5 Hoyt's tether design. Source: [13]

4.3. Climber

There a few types of climbers needed in building and maintaining the space elevator which are regular climber, malfunctioning climber and repair climber. The first 200 climbers design is slightly different than the main climber. The main job of these climbers deployed are to strengthen the existing ribbon. Each climber will add a few additional ribbons to the edge of the initial ribbon. The climber will be deployed until the diameter reach roughly 30 centimetres wide. Only after the ribbon has been fully strengthen, the commercial climber will be allowed to operate.

In the following part, I will focus on the components on the commercial climber because there are a lot of variations of climbers. All of them serve different purposes and therefore the design and size of each climbers differs from each other. But on this topic, I have decided to only cover the regular climber design.

List of the basic components in the climber:

1. Motor
2. Track and roller system
3. Power system
4. Thermal control system
5. Control system
6. Communication system

4.3.1. Motor

The basic performance specifications for the motor that is compatible with our track and roller system are:

1. Kilowatts / megawatts of mechanical power
2. High efficiency
3. High power to mass ratio
4. Able to operate in air and vacuum
5. Able to operate in continuous operation without fail
6. Able to operate in constant power
7. Able to operate in a variable speed mode

The motor will need to be able to operate at a constant power that is supplied by the power beaming system. As the climber moves upward, the load will be decreasing due to the decreasing gravitational acceleration from 1 G to 0 G. Therefore, a constant power implies a constant increase in the speed of motor or a variable transmission is required.

A study done by B.C Edwards and A.W Eric, a motor based on permanent magnet brushless multipole technology along with a liquid cooling system fulfils all of the stated requirements. By using a 100kW motors, the mass of the motor would be 105kg with 20kg of control electronics. The motor can run above 90% efficiency during the ascending of the climber to the space [1].

4.3.2. Track and roller system

The track and roller system must be designed to grab and hold the cable without damaging it. The track system should have a mechanism that can grab the small structures of the cable uniformly and deformable on the micron scale. The base design is to clench the ribbon between the two tracks.

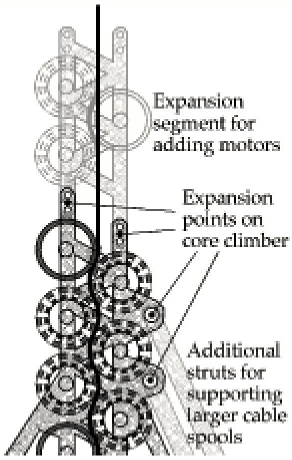

Figure 4.6 Examples of expansion points on core climber. Source: [13]

This track and roller system design is proposed by B.C Edwards [1]. The system will have an expansion points to allow for easy increase in climber size without a complete redesign. By implementing this design, the load of the climber can be increased to satisfy the demand and can be used for different purpose.

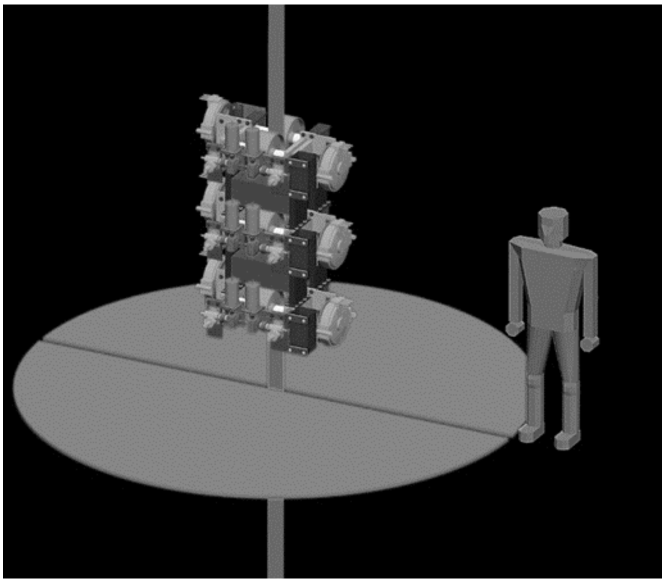

Figure 4.7 Overall view of the original conceptual design in 2004. Source: [13]**.**

Because the properties of the carbon nanotubes that is still well known, the frictional properties needed to be examined before the locomotion system can be designed. In addition, the track and roller system should be flexible to operate with increasing diameter of the cable due to the taper ratio of carbon nanotubes that is unknown.

The system should equip with a braking system for safety requirements. This is also a very important factor that needed to be considered in case the power is interrupted. There are 2 situations at which the climber could experience a power interruption.

1. Power interruption below geosynchronous orbit
2. Power interruption above geosynchronous orbit

For the first scenario, the braking system should be able to operate for it to stay at the altitude until the power resumes or if there is a malfunction in the motor, until a backup climber arrives to retrieve the stuck climber.

If the climber got stuck above 2600 km where the gravitational acceleration is less than 0.5g, a second climber without a payload will be sent up to release the malfunctioning climber. The climber must be available to release the track from the cable externally for safety purposes.

For the second scenario, as it passes geosynchronous orbit, it will experience negative ''gravity''. This means that the climber will experience a centrifugal force that pulling the climber outward. The usage of power supply at this point is very minimal and the braking system will operate fully with the forces is now in a reversed direction than initial.

4.3.3. Power system

The usage of traditional combustion is not ideal for space elevator as it would require a high amount of fuel to generate thrust for a possible of 7-day outer space journey. As a result, a big storage tank will be needed to store the fuel which only add more load to the already heavy climber.

Therefore, the elevator will be powered by using a laser beaming on a tower that is located on Earth. This wireless power transfer is called power beaming. The power is transferred by beams of electromagnetic radiation which is called microwaves or laser beams at 2.45GHz frequency [15]. The electromagnetic radiation emitter will be located nearby the base station on Earth's surface and two 3-meter diameter receiver are installed at the bottom of the climber.

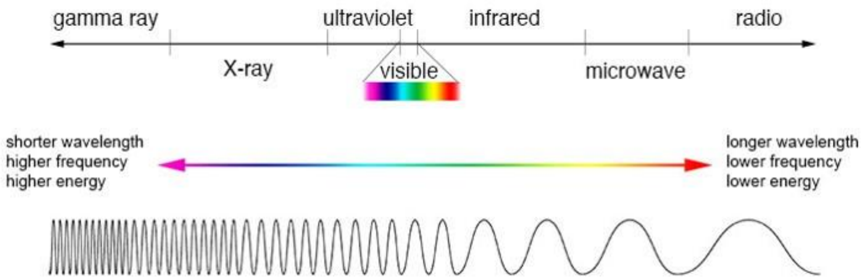

Figure 4.8 Electromagnetic waves spectrum. Source: [16].

By using a high-gain antenna, the electromagnetic radiation can be focused into narrow beam and aimed at the receiver which is useful for long range power transmission. The proposed dimension of the station may be up to 1 km in diameter and using 320 MW of photovoltaic arrays as a means to operate a 20 GW microwave for a short duration of time.

The power system should capable of dissipating excess energy that will be generated once the climber passes geosynchronous orbit. Depending on the velocity, the power system should also capable of dissipating and storing power up to several days or weeks.

Space-based microwave (SBM) power stations can provide alternative for power supply for the climber or light craft vehicle that is ascending from low Earth orbit (LEO) to geosynchronous orbit (GEO) or anywhere within the station's power beaming range [17].

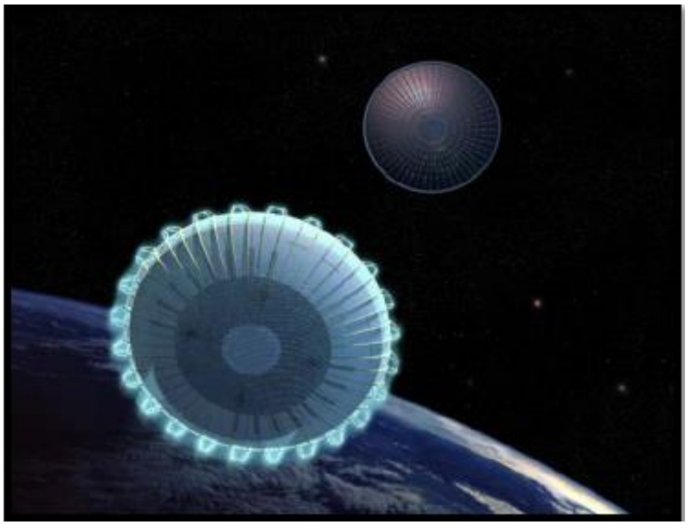

Figure 4.9 Light craft ascending a microwave beam. Source: [15]**.**

4.3.4. Thermal control system

The function of the thermal control system (TCS) is to keep all of the climber's component systems within acceptable temperature ranges. The temperature of the systems can vary as the climber is exposed to high level of solar flux and radiation in space. The thermal control system is responsible to keep the components functioning at optimum performance. Specific components such as optical sensors and atomic clocks are kept within a specified temperature to ensure that they perform efficiently.

Passive thermal control components include:

1. Coatings for the external surface
2. Multi-layer insulation
3. Thermal doublers on the radiator surface
4. Mirrors to improve the heat rejection capability

For passive thermal control, the coatings and mirrors can change the thermo-optical properties on the external surfaces. This type of protection can improve the heat rejection capability of external radiators and also reduce the absorption of external solar fluxes. Next, the multi-layer insulation is installed to protect from excessive solar or planetary heating when exposed to radiation in space. The thermal doublers are used on the radiator surface to maximize the heat dissipation by the equipment.

Active thermal control components include:

1. Thermostatically controlled resistive electric heaters
2. Fluid loops
3. Heat pipes
4. Thermoelectric coolers

Active thermal control system operates by using moving fluids and mechanisms and is monitored at all times. The electric heaters will be used when the temperature drops below a certain threshold. Next, the fluid loops are used to transfer the heat emitted to the radiators. The heat pipes also help in transferring and dissipating thermal energy. The fluid in heat pipes absorbs heat and evaporates and later condensed back releasing the thermal energy during the process.

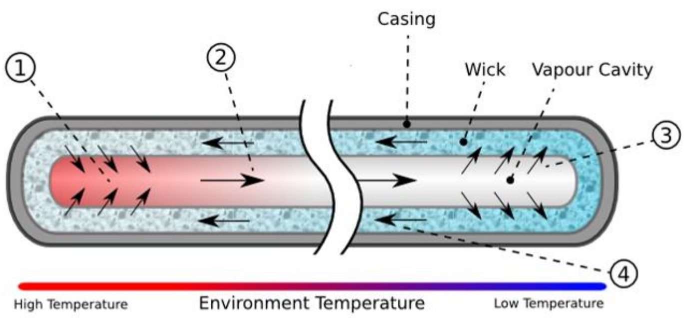

Figure 4.10 Heat pipe thermal cycle. Source: [18].

4.3.5. Control system

A control system manages and directs the behaviour of machines by using the command that is programmed beforehand or received from the control station on Earth. The control system in the climber will be responsible to monitor the speed of ascent, the tension in the cable and keep track of the climber location.

During the ascending phase, there will be little complexity required in the control system. Beyond geosynchronous point, the climber will to apply the brake and adapt from climbing mode to a braked descent. During the final stage, the control system will need to stop the descent and lock the climber at the counterweight station on the far end of the tether.

4.3.6. Communication system

The communication between the climber and control station of Earth is minimal. The climber will be equipped with a transmitter and a receiver for radio waves as a way to interpreting the information received and acting on it. The same system used in the initial spacecraft can be used as both climbers will be used for commands and diagnostic downloads.

The second option for the communication system would be using NASA's Deep Space Network [19]. There are three stations scattered around the world make it possible to communicate with spacecraft in space.

The stations are located in Goldstone Complex California, Madrid Complex Spain and Canberra Complex Australia. The three facilities spread roughly at about 120 degrees around the globe and each station contain multiple parabolic dishes that are 70 meters across. These parabolic dishes are capable of receiving very low-strength signals from very distant spacecraft.

Figure 4.11 Parabolic antenna in Goldstone, California. Source: [20].

4.4. Anchor

Earth's rotation creates an upward centrifugal force on the counterweight hence a base station is needed to held down the cable and keep the cable in taut. It also anchors the whole system to the surface of the Earth.

There are two types of base station which are land-based anchor and ocean-based anchor and both are imposed to its own advantages and disadvantages. There are few technical specifications that needed to be consider which include:

1. Available real estate to allow for mobility of the ribbon anchor.
2. Ease of construction, access and operations.
3. Located near the equator.
4. Located near to a power beaming station.

After assessing the above criteria, locating a base station on a movable ocean-based platform outweigh the advantages over a land-based anchor. The advantages include:

1. Excellent mobility to move the cable from low Earth orbit objects and storms.
2. Can be located near the equator with less lightning strikes and calm weather.
3. Can be located in international waters.
4. Impose less threat to the local community in case of a break in the ribbon.
5. Easier to ship large scale objects on sea compare to the land.

Figure 4.12 Ocean-based anchor. Source: [21]**.**

The anchor for the space elevator should be place on the most remote location possible so that the safety of human population is guaranteed in the event of catastrophic failure. The centre of mass of the space elevator will be located higher than the geostationary orbit so that if it breaks, it will not have the tendency to fall on Earth's surface.

The base of the space station should be developed as a floating platform and not be anchored or supported from the ocean floor. This method of anchoring will allow the space elevator to be mobile so that it can be placed at the safest location away from lightning strikes and other potential threats.

Therefore, it is wise to locate the base station at the equator. This is because all types of winds such as hurricanes, tornados, and cyclones will never occur at the equator. At the equator the winds can rotate in any directions but cannot sustain the high concentrations of angular momentum required for the formation of destructive windstorms.

The project of this scale will attract a lot of international issues due to its location. Therefore, locating the anchor in international water may be an advantage for every party by providing freedom from constraints and safety concerns that might be implemented by governmental bodies on land.

The space elevator ribbon could be anchored on a refurbished oil platform. For example, an old mobile drilling rig can be converted into self-propelled semi-submersible mobile base station. This has been the case for ***LP Odyssey*** which undergo renovation from late 1995 to May 1997 [1].

Figure 4.13 LP Odyssey, mobile spacecraft launch platform refurbished from an oil platform. Source: [22]

This platform has sufficient mass not to be affected by the total mass of the ribbon and on top of that, has a self-propelled speed of 12 knots which provides sufficient mobility to avoid collision with objects.

4.5. Counter balance mass

The function of a counter balance mass is to compensate the weight of the system with a centrifugal force that is acting on the counter weight due to the Earth's rotation and keeping the cable taut. Other than that, the length of the cable could be shorten by using a counter weight. Without the counter balance mass, the space elevator structure would have approximately 144,000 km in length.

Based on the calculation done by P.K Aravind, assuming the mass of the climber to be 1000 kg and incorporating a safety factor of 2 into the design, the mass of the counterweight could be 52.7 x 10^3 kg with 100,000 km for the length of the cable [6].

It has been suggested to use as asteroid as a counter balance of the system, but in this study, I will propose the possibilities of development for space infrastructure at the counter balance mass at the higher end of the cable.

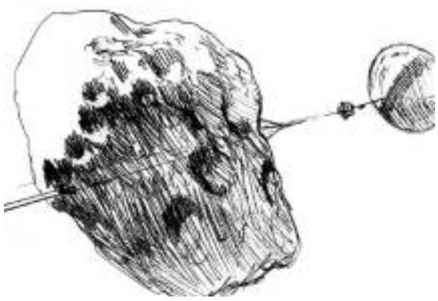

Figure 4.14 Asteroid as a counter weight. Source: [9]

A space elevator that is extending beyond geosynchronous orbit could provide escape velocity for propellant-free transfer orbits to the nearby planet such as Mars or the Moon. This is done by using the tower's rotational energy to launch spacecraft. A dock is built at the top of the space station so that spacecraft can be tethered and launched by using the Earth's rotation.

One might be wondering, what is the furthest distance from the sun that a spacecraft can reach if released at rest from the top of a tower. A calculation was done by P.K Aravind, which considered the height of the tower to be 100,000 km, obtained a distance of 7.95x10^{11} km [6]. The distance is equivalent to 5.3 AU (Astronomical unit) which is a little larger than the mean orbital radius of Jupiter. Therefore, a spacecraft released at rest from the top of the space elevator tower would be able to reach Jupiter.

The International Berthing and Docking Mechanism (IBDM) will be used at the space station. This is because the European mating system is capable of docking and berthing large and small spacecraft [23]. The IBDM is also designed to be compliant with the International Docking System Standard (IDSS) and is hence compatible with any future or current space facilities. The dock has a circular transfer passage with 800 mm diameter.

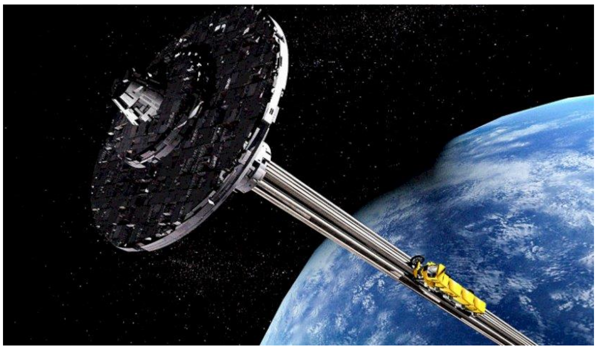

Figure 4.15 A space station at the upper end of the cable. Source: [24]

There are few other possible long-term applications of the space station other than using the counterweight to launch spacecraft. A space facility that is built on GEO station could lead to many new space industry developments such as travel and tourism, entertainment, medical facilities and materials development. The space station could also be used as a research facility that could identify and realistically deal with any potential threat to Earth from large asteroids.

5. Design and modelling

This chapter will introduce readers about the process of designing and describing the components of the space elevator. The requirements analysis and research that have conducted in the previous chapter will be used in this chapter where it will guide the project on how it will be developed. The design will be presented using illustrations and words for a better explanation.

The software that will be used in the designing process is NX12 Siemens PLM Software. This software is fully associative of CAD/CAM/CAE applications. It touches the full range of the development process and simulation. The design and modelling are drawn according to scale therefore all the dimensions shown in the figures are in millimetres except for the cable. In order to get the measurement in meter, the dimension shown in the figure need to be divided by one thousand. The measurement of the major components will be explained in meter and more detail dimension of every components can be found in appendix.

5.1. Components

There are four components of the space elevator as explained in the previous chapter. The components that I will be focusing in this chapter are the climber, tether and the counter weight. A simplified version of the base station (anchor) will be used to replace the complicated model of the base station. The requirements of the base station of the space elevator is as discussed in part 4.4 anchor which is a semi-submersible mobile base station. A more detail view and dimension of the individual component of the space elevator can be found in appendix.

In figure 5.1 is the final model of the space elevator. All of the components have been assembled by using the assembly constraint function in NX12. Concentric and touch type of assembly constraint was used to assemble the four main components.

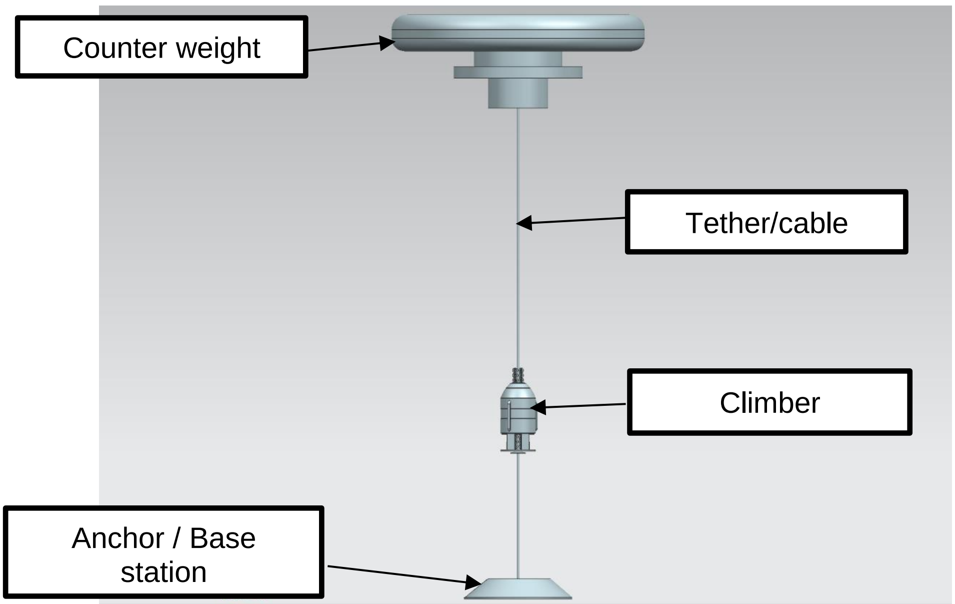

Figure 5.1 Side view of the assembled space elevator [own source].

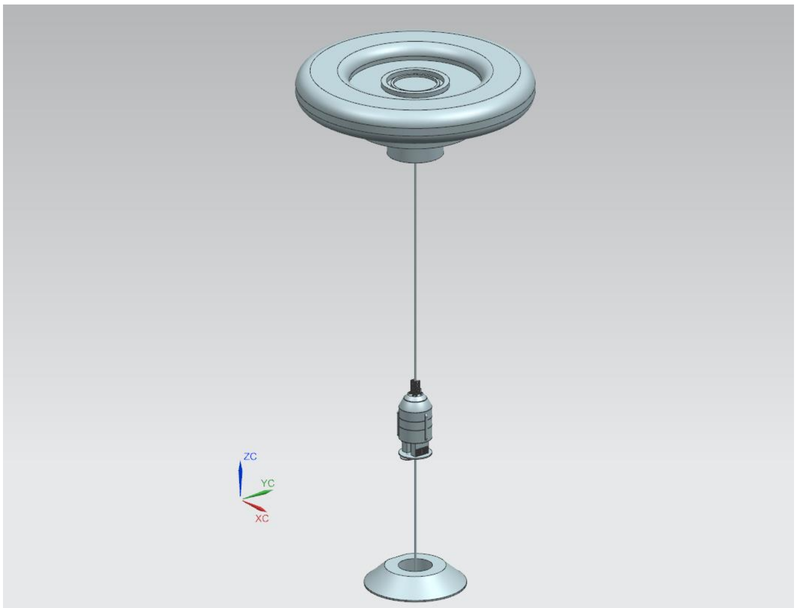

Figure 5.2 Isometric view of the assembled space elevator [own source].

In figure 5.3 is the side view of the assembled space elevator with dimension. The cable was not modelled according to scale with respective to the other components of the space elevator. This is because if modelled with the same scale with the other components, it is impossible to have a picture of the assembled space elevator due to the cable being extremely long. Therefore, the total length of the space elevator is 110,522 km with the counter weight attached to the upper end and anchored at the base. The length of the cable itself would be 100,000 km.

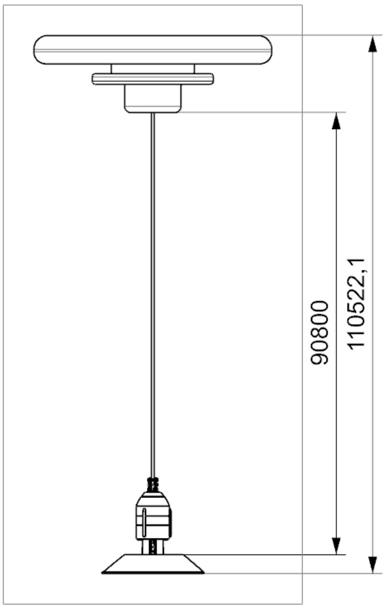

Figure 5.3 Side view of the assembled space elevator with dimensions (km) [own source].

5.2. Climber

In figure 5.4 is the prototype of the climber. The space elevator consists of 5 main components as labelled in the figure. Visible on top of the climber is the track and roller system that is designed to hold the cable while ascending it. At the top part of the climber is where the secondary motor is located.

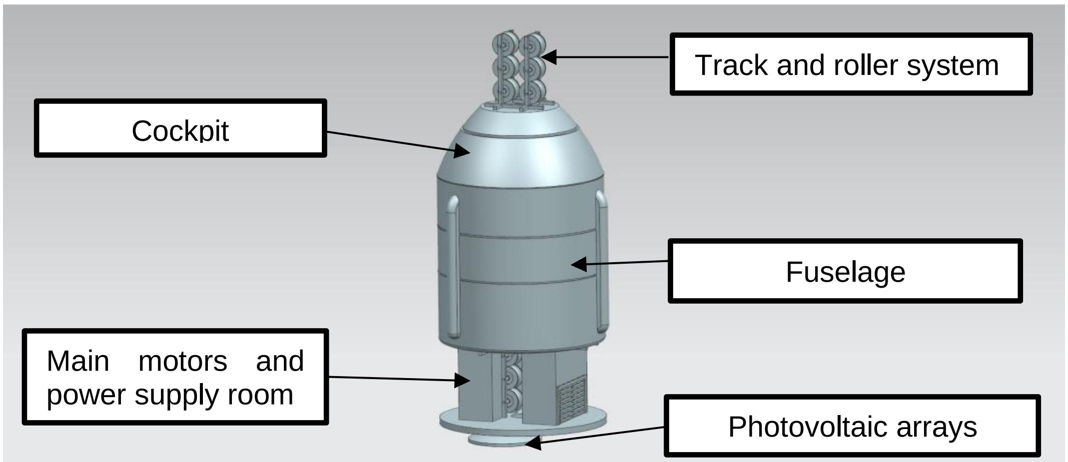

Figure 5.4 Isometric view of the climber [own source].

The fuselage is the centremost piece of the aircraft. It is responsible for the structural integrity of the climber. The pilots will sit in the cockpit in front of the fuselage. Passengers and cargo are carried in the middle and rear section of the fuselage.

At the bottom part of the main body is the compartment for the main motors, power supply and thermal control. Attached at the bottom plate are the photovoltaic arrays which are responsible of receiving laser beam from power stations on Earth. The purpose of the side fin is for easier docking process at the anchor or the counter weight.

In figure 5.5, we can see the dimension of each compartment of the climber. The middle section of the fuselage will be the living space for the passengers. It is 6.82 m in height and the interior will be divided into two level. The number of passengers will be explained in the following part. In figure 5.6, we can see the diameter of the fuselage which is 6.80 m with a 1 m diameter circle at the centre of the body to allow the cable to pass through during ascending. Both figures 5.5 and 5.6 were drawn according to scale and shown in the figures are the dimension in millimetre.

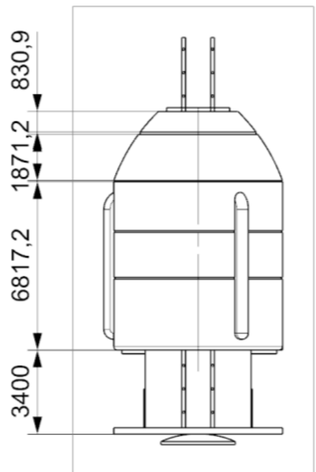

Figure 5.5 Side view of the climber with dimensions (mm) [own source].

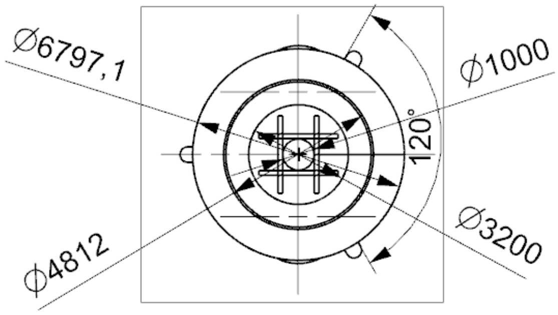

Figure 5.6 Top view of the climber with dimensions (mm) [own source].

5.2.1. Number of passengers

In order to figure out the room capacity for the passenger in the climber, the area of the fuselage is calculated beforehand. The fuselage of the climber will be divided into four levels. The uppermost level will be the cockpit for the pilots operating the climber. Located on the same level is the control room serving as a central space where a large physical facility dispersed service can be monitored and controlled.

At the middle part of the fuselage is where the passengers and cargo are located. The middle fuselage will be divided into 3 levels. The two upper level will be the assigned space for the passengers and the lower part will be for the cargo. The assigned space for the passengers will have 2.5-meter height and the cargo room will have 2-meter height. The width of the room consistent throughout the climber which is 2.9-meter. For more detail of the dimension of the climber can be found in appendix.

The calculation of the area for the assigned space for the passengers by using the modified formula of area of the circle is as follow;

$$\boldsymbol{A = \pi(R^2 - r^2)} \quad \textbf{(8)}$$

$$A = \pi(3.398^2 - 0.5^2)$$

The available area in a level of the fuselage is 35.49 m^2. For two level of assigned space for passengers, the area obtained in the previous part is to be multiplied by 2 which resulted in 70.98 m^2 of space available.

Based on table 5.1, the recommended minimum area per person can be found. Considering the flight duration and the comfortability of passengers in the case of space elevator, the type of room selected for the climber will be similar to hotel room with 5 m^2 per person.

Type of building	Type of room	Area per person (m^2)
Assembly building	Lecture room	0.6
	Library	5
Hotels	Rooms	5
	Lobby	0.6
	Assembly room	1.5
Offices	Single office	10
	Meeting room	1.5

Table 5.1 Recommended minimum area per person. Source: [25]

By using the 5 m^2 for the area per person, it is assumed that every passenger will be placed in an individual cabin. The maximum number of passengers that can be carried on the climber at a time can be calculated by using the data obtained;

$$\text{Area per person} = 5\ m^2/\text{person}$$
$$\text{Total area available} = 70.98\ m^2$$
$$\text{Maximum number of passengers} = 70.98\ m^2 \times \frac{1}{5m^2/person}$$
$$\text{Maximum number of passengers} = 14.2\ (\approx 14\ passengers)$$

Therefore, the maximum number of passengers that can be carried at a time is 14 passengers including the pilots and space elevator crews.

5.2.2. Modelling the main structure of the climber

This is the first part in the design part of the model. The sketch is done in 2D according to the measurement. The sketch was displaced by 0.50 m to allow the space for the cable to pass through the climber. The height and radius of the climber are 9.66 m and 2.90 m respectively. The sketch will be revolved around Y-axis to create a cylinder as the main body.

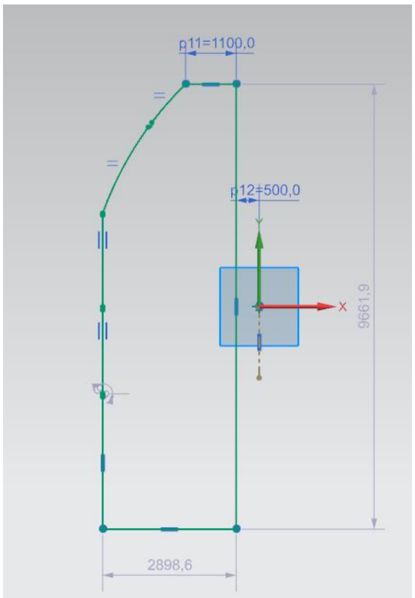

Figure 5.7 Two-dimensional sketch for main body of the climber [own source].

Figure 5.8 Three-dimensional main body of the climber [own source].

5.2.3. Track and roller system

The measurement of the radius of the tether and the roller have been taken to design the placement of the support metal bar. The metal bar will act as a support for the small motor and the roller. The metal bar was sketched on the top of the climber and was extruded for 0.25 m.

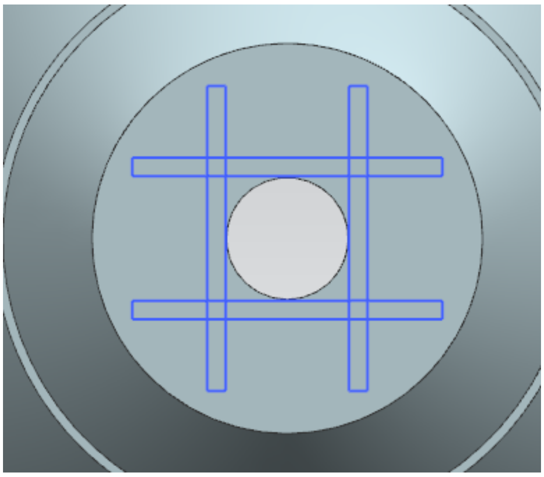

Figure 5.9 The two-dimensional sketches of the metal bars [own source].

Later four identical metal bars will be extruded for 2.84 m for the housing of the rollers. The dimensions of the roller are 0.47 m radius and 0.6 m width. The rollers have a 0.14 m diameter hole at the axis for it to be connected with the metal bars. The edge blend function in Siemens NX12 will be used to create a rounder edge for the metal bars.

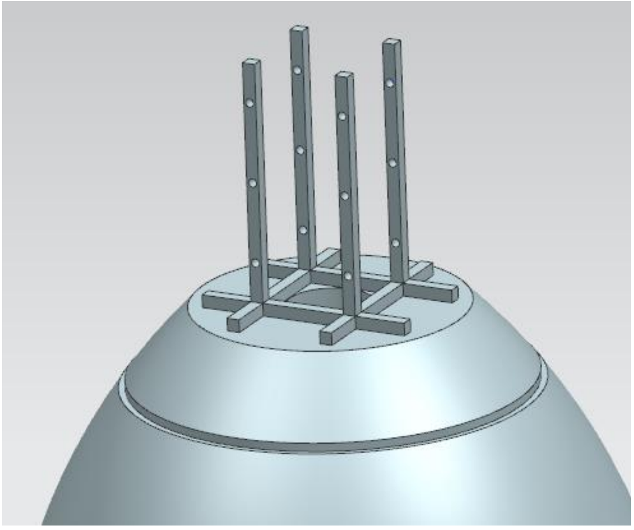

Figure 5.10 Isometric view of the metal bars [own source].

The pattern feature function will be used to copy the previous features and to be applied at the lower end. Pattern feature was used because it can copy feature into many patterns or layouts with various options for pattern boundary, instance orientation, clocking and variance. Linear layout was used in this process and few adjustments was made to fully occupy the large area at the bottom end.

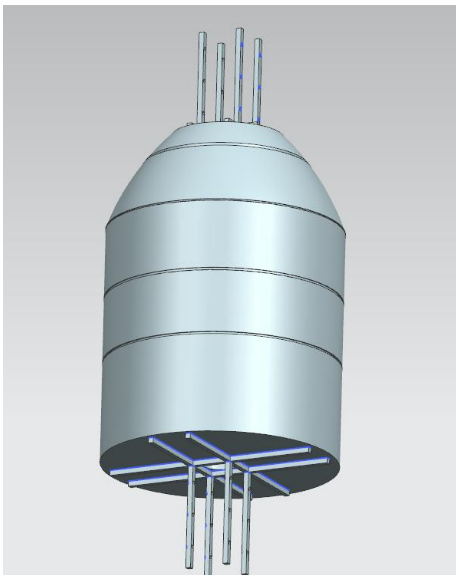

Figure 5.11 Lower end of the climber with support bars [own source].

5.2.4. Compartments for main motor and power supply unit

Datum plane was used to create a plane. Two circles with diameter similar to the main structure was drawn at the end of the metal bars and extruded to create a compartment for the main motor.

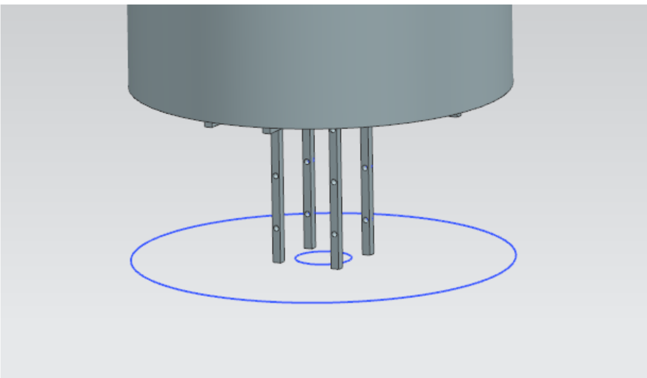

Figure 5.12 Two circles drawn on the plane at the bottom end [own source].

The next step is creating a closed compartment for the main motors, power supply and thermal control. Another sketch was drawn on the bottom plate as seen in figure 5.13. The sketch was drawn by taking account the width and diameter of the roller. The sketch is later extruded until it touches the next surface.

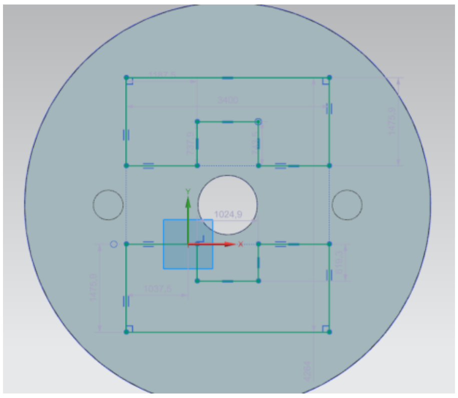

Figure 5.13 Sketching process for the main motor compartment [own source].

5.2.5. Photovoltaic arrays

In figure 5.14, two photovoltaic arrays of 1.5-meter diameter which was designed beforehand is attached on the bottom end of the climber. The type of assembly constraints used in the process are infer centre of circle and touch. These two functions were selected as it can fastened the position of the arrays to the bottom side of the climber.

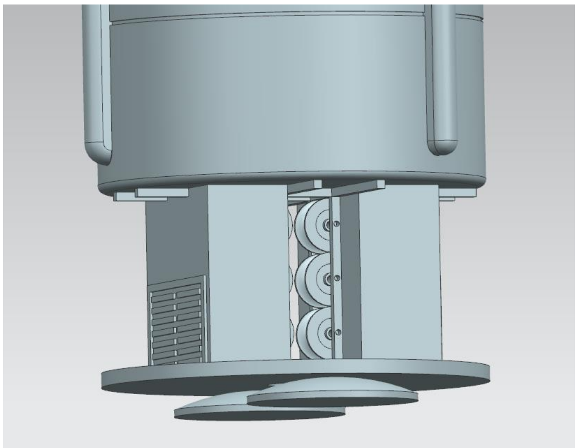

Figure 5.14 Two photovoltaic arrays attached at the bottom of the climber [own source].

5.3. Tether

The ribbon design of the tether was proposed by Brad Edwards [1]. The individual cable will have a 3 mm^2 cross sectional area and tapered in parallel with cross-connections at 10 cm interval. But due to the lack of studies and tests regarding the actual application of carbon nanotube for the tether, the accurate measurement of the length, width and the taper ratio of the tether is still unknown.

An approximation of the measurement was used to design the tether. The model was designed to give a simple visual representation of the tether and to illustrate the process of going to space. A GEO space station could operate at 35,758 km while the space elevator is at 100,000 km which also could vary depending on the mass of the counter weight. But in this study, the height of the space elevator is assumed to be 100,000 km.

5.3.1. Flight duration and speed

For the calculation of flight duration and speed, it is assumed the length of the cable to be 100,000 km with a counterweight of 52.7 x 10^3 kg as mentioned in the previous chapter. In order to solve this problem, it is best to understand the Coriolis force.

Coriolis force is an effect whereby a mass moving in a rotation system experiences a force perpendicular to the direction of motion and to the axis of rotation. The cable would stand vertically from a point on Earth's equator extending until the counterweight. As the climber ascended, its motion would cause the Coriolis force to pull the climber and the cable to the opposite direction of Earth's rotation.

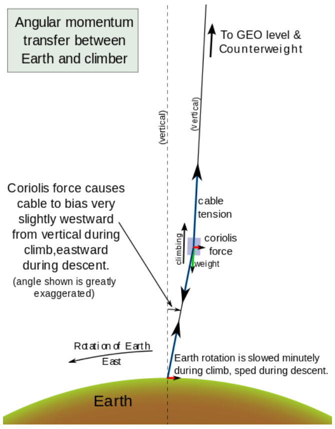

Figure 5.15 Coriolis force acting on the climber and cable. Source: [26]

This force would pull the climber and cable away from its initial resting position and causing it to oscillate back and forth. Having the climber to ascend at high speed will increase the effect and increasing the risk for the cable to break. Therefore, slowing the ascend of the space elevator could minimise the Coriolis force on the climber and ensure the safety of the climber.

In this calculation, I would be using the maximum speed for both wheel driven vehicles and maglev rail vehicles as an estimation for the speed of the climber. The maximum speed for wheel driven vehicle is 724 km/h and for maglev rail vehicle is 600 km/h [27] [28]. The effect of Coriolis force on climber is negligible if it operates within the speed mentioned earlier [29].

To space station located 100,000 km above Earth. For a climber with a speed of 724 km/h:

$$\frac{100{,}000\ km}{724\ \frac{km}{h} \times 24\frac{h}{day}} = 5.76\ days$$

For a climber with a speed of 600 km/h:

$$\frac{100{,}000\ km}{600\ \frac{km}{h} \times 24\frac{h}{day}} = 6.94\ days$$

Therefore, we could assume that the duration of the climber to arrive at the counterweight is roughly about 7 days. In this calculation, I did not account for the air resistance and the friction on the parts of the climber which in contact with the cable and limiting the maximum achievable speed of the climber.

5.3.2. Modelling process of the tether

In figure 5.16 is the sketch of the 2D design of the tether. The diameter of the tether is 0.6 m. Then, it was extruded for 0.1 km which represents 100,000 km in real life application.

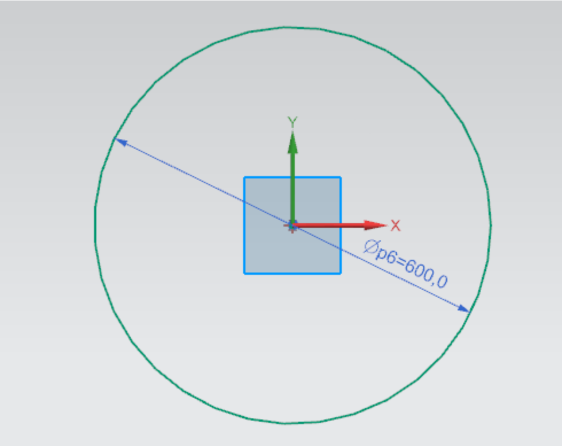

Figure 5.16 Modelling of the tether [own source].

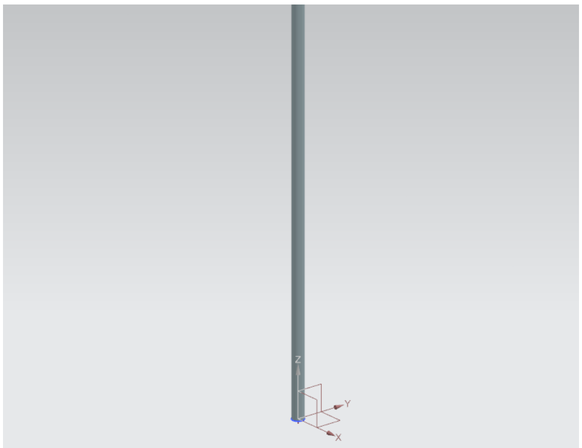

Figure 5.17 Isometric view of the tether [own source].

5.4. Counterweight

In figure 5.18 is the prototype of the space station which is located at the higher end of the tether. The space station which is also acting as a counter weight consists of three main components as labelled in the figure. At the top part of the space station is where the living space are located and at the middle part is the control room. Located at the bottom part of the space station is the docking port for the space elevator. The docking port for the space shuttle can be seen at the upper side of the space station in figure 5.19.

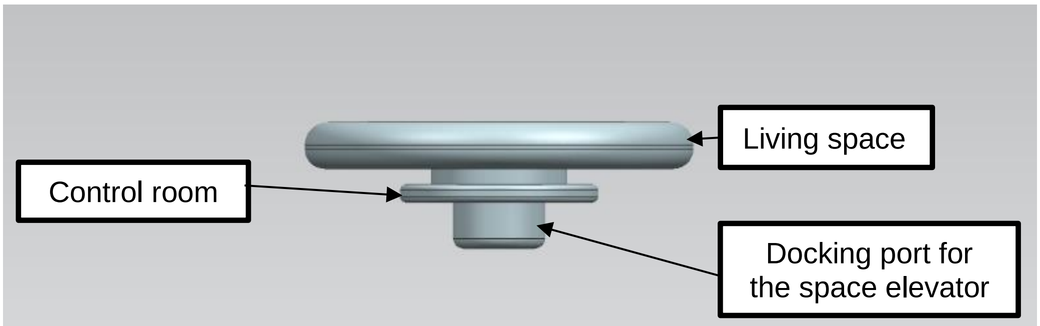

Figure 5.18 Side view of the space station [own source].

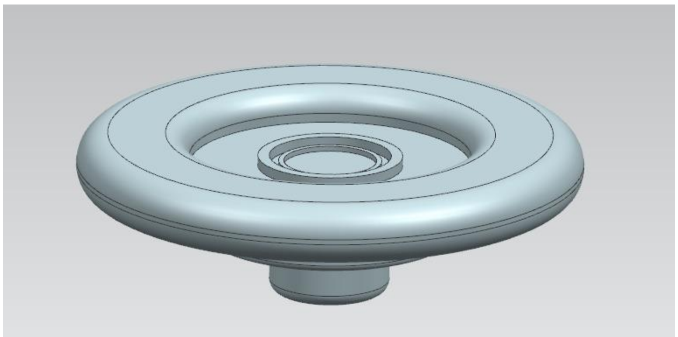

Figure 5.19 A docking port for space shuttle at the centre of the space station [own source].

In figure 5.20, we can see the detail measurement of the counter weight. The middle section of the counter weight will be the control room for the space station which is also directly above the docking platform for the space elevator. The total height of the counter weight is 15.8 m with 11.6 m in diameter for the living space. The depth of the climber's docking platform is 5.8 m with 7.6 m in diameter which can fully fit the climber inside the docking platform. At the top part of the space station is the docking platform which is used to provide the escape velocity for spacecraft by using Earth's rotational velocity. Both figures 5.20 and 5.21 were drawn according to scale and shown in the figures are the dimension in millimetre.

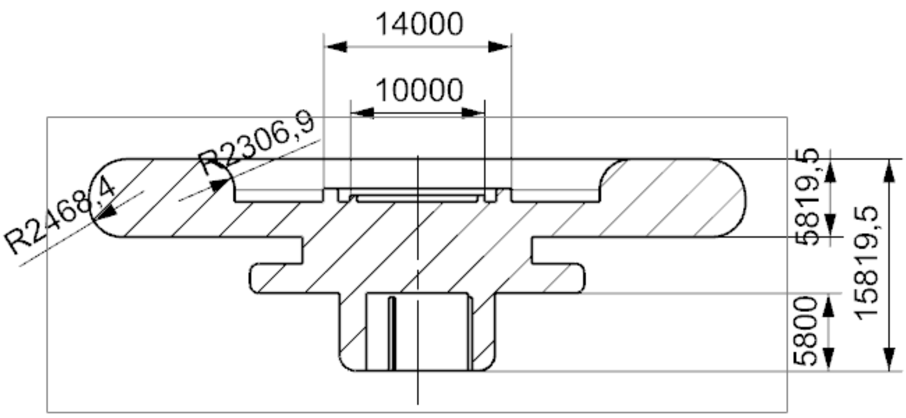

Figure 5.20 Side view of the counter weight with dimensions (mm) [own source].

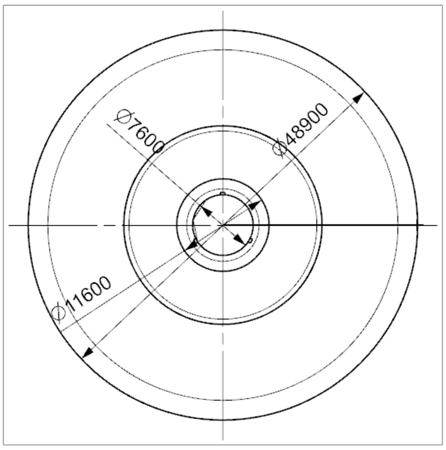

Figure 5.21 Bottom view of the counter weight with dimensions (mm) [own source].

5.4.1. Modelling the main structure of the space station

The first step in modelling the space station is to create a sketch of the main structure in 2D with the original datum coordinate system as the centre. Only half of the cross section of the space station is drawn. The bottom part of the space station was displaced by the radius of the space elevator. This is to ensure that there will be a space for the docking port of the space elevator.

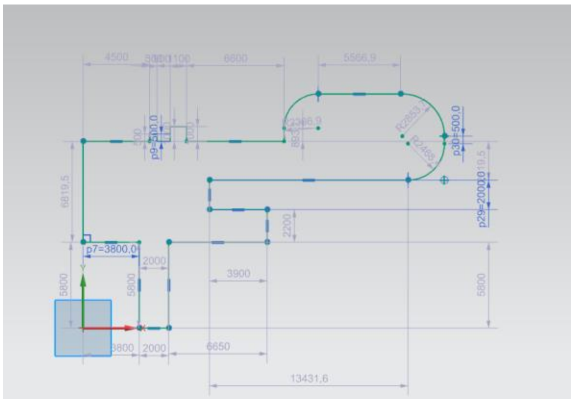

Figure 5.22 Two-dimension sketch of the structure of space station [own source].

After the sketch was drawn, the revolve function was used to create a solid body which revolves at Y-axis vector

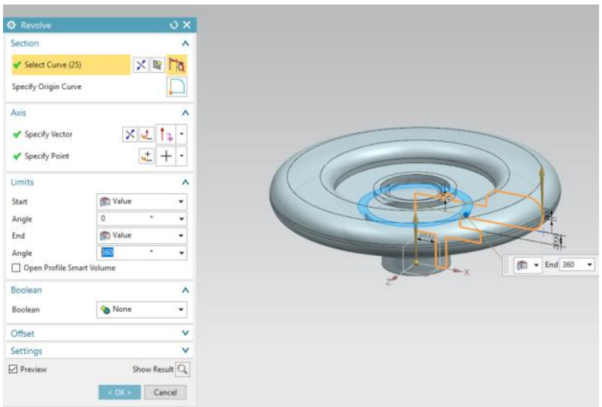

Figure 5.23 Revolve function to create a solid body [own source].

5.4.2. Docking port for the space elevator

In the next step is to use the datum plane function to create a drawable surface. The datum pane was placed on the bottom end of the space station. Then, three rectangles are drawn at the edge of the circle at 120° with dimension similar to the side fin of the space elevator. The function extrude with subtract Boolean function was used.

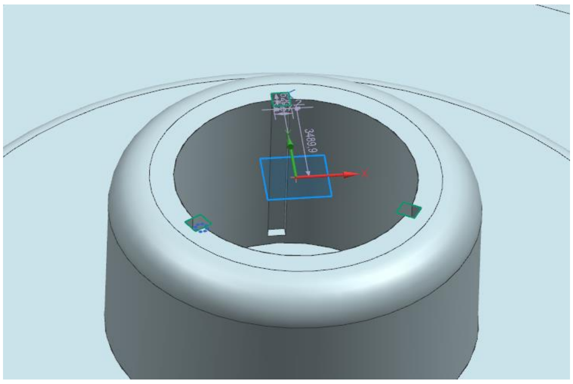

Figure 5.24 Docking port of the space elevator [own source].

6. Challenges

One possible event that could destroy the cable would be lightning strike. Lightning is an electrical discharge caused by imbalance between storm clouds themselves or with the ground. A typical cloud-to-ground lightning bolt can contain up to one billion volts of electricity and is sufficient to heat and destroy the space elevator.

The cable for the space elevator is made of carbon nanotube which is a better electric conductor than air. What this means is the lightning will jump a shorter distance through the air to the cable which has higher electrical conductivity rather than taking a longer air distance to the ground. The cable ribbon will appear to be the least resistance to ground compared to the air.

One could argue to build the cable with an extra resistor to increase the resistance. However, in the case of lightning storms, the cable will become wet due to rain and may form a conductive path to ground. One way to avoid this problem is to locate the base station in a ‘‘lightning-free’’ zone such as in Ecuador [1].

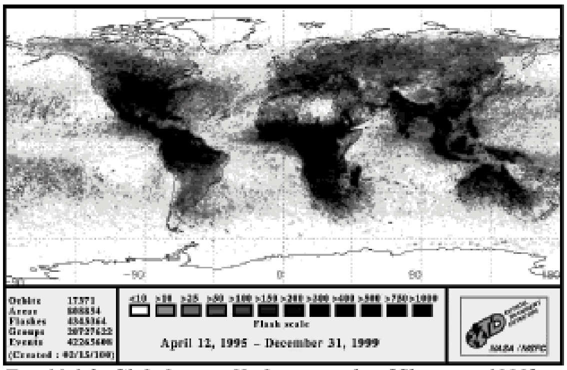

Figure 6.1 Global map of lightning strikes. Source: [14]

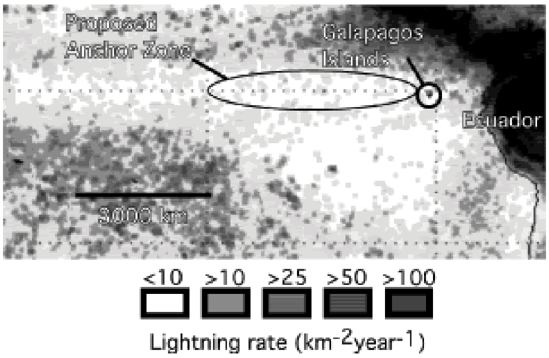

Figure 6.2 ‘‘Lightning-free’’ zone in the Pacific Ocean. Source: [14]

In these regions, lightning strikes only a few times over the course of a year. On top of that, if the anchor is built on a movable ocean-based platform, the space elevator should easily manage to move the lower end of the ribbon out of the path of the few storms that do occur in these regions. However, these solutions do not guarantee the safety of the cable from getting hit by lightning and further studies and experiments should be done to understand the risk.

7. Conclusion

The massive scale and the complexity of the space elevator is often cited as impossible to build which left the idea from being developed. The detailed study of the system for the space elevator was done in this paper which indicate that is indeed complex but comparable to other high rise building on Earth. The physics theory behind a free-standing tower was also discussed and calculated in the earlier chapter.

A space elevator model was also done by using NX12 Siemens PLM Software based on the criteria discussed. A further analysis of a possible operating system was also done based on the design created. The design proves that the construction of the space elevator can be initiated in near future with available technologies while relying on the future materials with a more desirable property.

The development of the counter weight as a space station can be started since the requirements are already known such as the minimum weight of the counter weight, the docking system for spacecraft and the docking system for the space elevator. A space station that is built at the higher end of the cable will create the construction capabilities needed for major developments beyond LEO which is absent in other space elevator design.

Furthermore, the operating analysis of the designed climber model was discussed and further development of photovoltaic arrays and power storage capacity are needed so that it can operate at high efficiency and travel for a long distance compared to other space elevator model using a conventional combustion engine.

In future work, the limitations in this project will be addressed and improved. These are the few recommendations for further development of the project. More study and research should be done to understand the requirement for the space station that is located at the higher end of the tether because of the artificial gravity that is acting on the space station. The internal design and how it operates will greatly differ than any high-rise building because of the outward force due to Earth's rotation.

In addition, the mechanism and the design of the climber should also be improved by taking account the difference in the gravity felt at different altitude during the climb to the space station. The internal design should incorporate the method of transporting the passenger in order to avoid the effect of negative g-force to human body that occurred during the climb to the space station.

Acknowledgement

The completion of this thesis would not have been possible without the support and encouragement of several special people. Hence, I would like to take this opportunity to show my gratitude to those that were involved in the process of completing this study.

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I also would like to express my very profound gratitude to my parents for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of writing this thesis. This accomplishment is dedicated to them and it would not have been possible without their help.

Finally, I also want to express my gratitude to everyone who directly or indirectly involved and contributed to the successful completion of this project. Thank you.

References

[1] Edwards, Bradley C; Westling, Eric A, The space elevator, San Francisco, CA : Spageo Inc., 2002.

[2] R. Duke, "Types of satellite orbits," [Online]. Available: https://www.djr04.com/satellite_orbits.html. [Accessed 6 March 2020].

[3] K. Tsiolkowskii, "V Kosmos na Elektrovoze"To the cosmos by electric train"," *1960,* 2004.

[4] S. Snowden, "Space.com," 7 September 2018. [Online]. Available: https://www.space.com/41278-japan-space-elevator-cubesats-experiment.html. [Accessed 15 March 2020].

[5] W. W. Cobb, "The conversation," 1 March 2019. [Online]. Available: https://theconversation.com/how-spacex-lowered-costs-and-reduced-barriers-to-space-112586#:~:text=Between%201970%20and%202000%2C%20the,billion%2C%20or%20%2454%2C500%20per%20kilogram.. [Accessed 23 March 2020].

[6] P. K. Aravind, "The physics of the space elevator," *American Journal of Physics,* vol. 75, no. 2, pp. 125-130, 2007.

[7] B. C. Edwards, "Design and deployment of a space elevator," *Acta Astronautica,* vol. 47, no. 10, pp. 735-744, 2000.

[8] B. Smith, "Gigazine," 16 March 2018. [Online]. Available: https://www.azom.com/article.aspx?ArticleID=15411. [Accessed 11 April 2020].

[9] Judith Yang, Kim de Groh, "Materials issues in the space environment," *MRS bulletin ,* vol. 35, no. 1, pp. 12-20, 2010.

[10] S. Iijima, "Helical microtubulles of graphitic carbon," *nature,* vol. 354, no. 6348, pp. 56-58, 1991.

[11] G. Ren, "Carbon nanotube," Britannica, 16 Nov 2018. [Online]. Available: https://www.britannica.com/science/carbon-nanotube. [Accessed 24 April 2020].

[12] "Wikiwand: Specific strength," [Online]. Available: https://www.wikiwand.com/en/Specific_strength. [Accessed 1 May 2020].

[13] R. G. Munck, "High Lift," [Online]. Available: http://www.mill-creek-systems.com/HighLift/chapter2.html. [Accessed 3 May 2020].

[14] E. M. Levin, Dynamic analysis of space tether missions, American Astronautical Society, 2007.

[15] M.P Garcia, J.O Sanchez, R.S Iborra, D.C Rebenaque, J.L.G Tornero, "Dynamic Wireless Power Transfer for Cost-Effective Wireless Sensor Networks Using Frequency-Scanned Beaming," pp. 8081-8094, 2019.

[16] “Humboldt State University,” [Online]. Available: http://gsp.humboldt.edu/OLM/Courses/GSP_216_Online/lesson1-2/spectrum.html. [Accessed 5 June 2020].

[17] D. E. Raible, “High intensity laser power beaming for wireless power transmission,” 2008.

[18] “Active Thermal Control System,” [Online]. Available: https://www.aero.iitb.ac.in/satelliteWiki/index.php/Active_Thermal_Control_System#Typical_operating_range_of_important_components. [Accessed 5 July 2020].

[19] N. T. Redd, “NASA's Deep Space Network,” Space.com, 2 Feb 2018. [Online]. Available: https://www.space.com/39578-deep-space-network.html. [Accessed 6 July 2020].

[20] “NASA: Deep Space Network (DSN),” 11 March 2016. [Online]. Available: https://www.nasa.gov/directorates/heo/scan/services/networks/dsn. [Accessed 11 June 2020].

[21] S. Nasralla, “OEDigital,” 12 March 2020. [Online]. Available: https://www.oedigital.com/news/476525-offshore-oil-rig-infection-exposes-coronavirus-dangers. [Accessed 18 June 2020].

[22] “Vessel Tracker,” [Online]. Available: https://www.vesseltracker.com/en/Ships/L-P-Odyssey-8753196.html. [Accessed 15 June 2020].

[23] William Gerstenmaier, Alexey Kransnov, Thomas Reither, Jean-Calude Piedboeuf, “International Docking System Standard (IDSS),” 2013.

[24] M. Blenkin, “Space Connect,” 19 July 2019. [Online]. Available: https://www.spaceconnectonline.com.au/r-d/3566-space-elevator-concept-one-step-closer-to-reality. [Accessed 20 July 2020].

[25] “The Engineering Toolbox,” [Online]. Available: https://www.engineeringtoolbox.com/number-persons-buildings-d_118.html. [Accessed 15 June 2020].

[26] Yoji Ishikawa, Kiyotoshi Otsuka, Yoshiki Yamagiwa, Hinata Doi, “Effects of ascending and descending climbers on space elevator cable dynamics,” *Acta Astronautica ,* vol. 145, pp. 165-173, 2018.

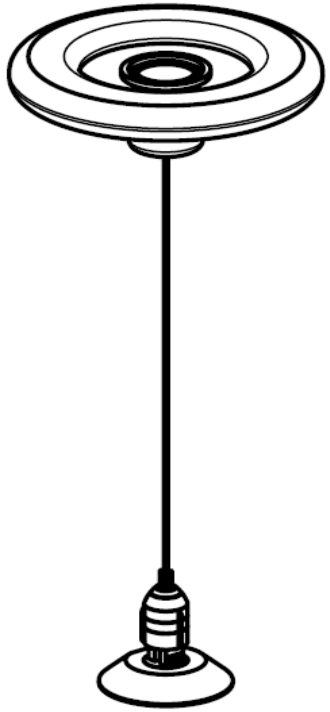
[27] C. Squatriglia, “Wired,” 8 August 2011. [Online]. Available: https://www.wired.com/2011/08/video-this-is-what-426-mph-looks-like/. [Accessed 17 June 2020].

[28] J. McCurry, “The Guardian,” 21 April 2015. [Online]. Available: https://www.theguardian.com/world/2015/apr/21/japans-maglev-train-notches-up-new-world-speed-record-in-test-run. [Accessed 20 June 2020].

[29] Stephen S. Cohen, Arun K.Misra, “The effect of climber transit on the space elevator dynamics,” *Acta Astronautica ,* vol. 54, no. 5-6, pp. 553-583, 2009.

Appendix

Detail view of the modelled space elevator



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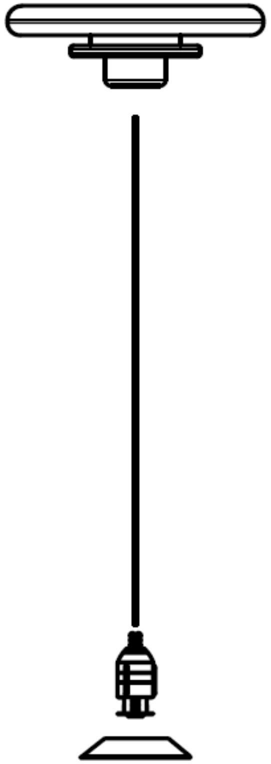

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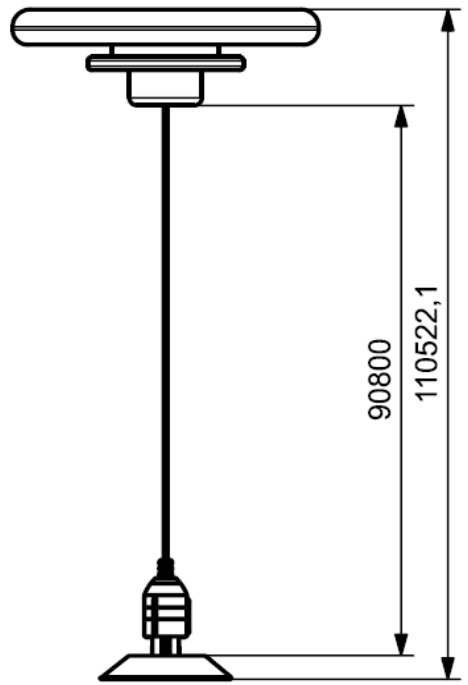

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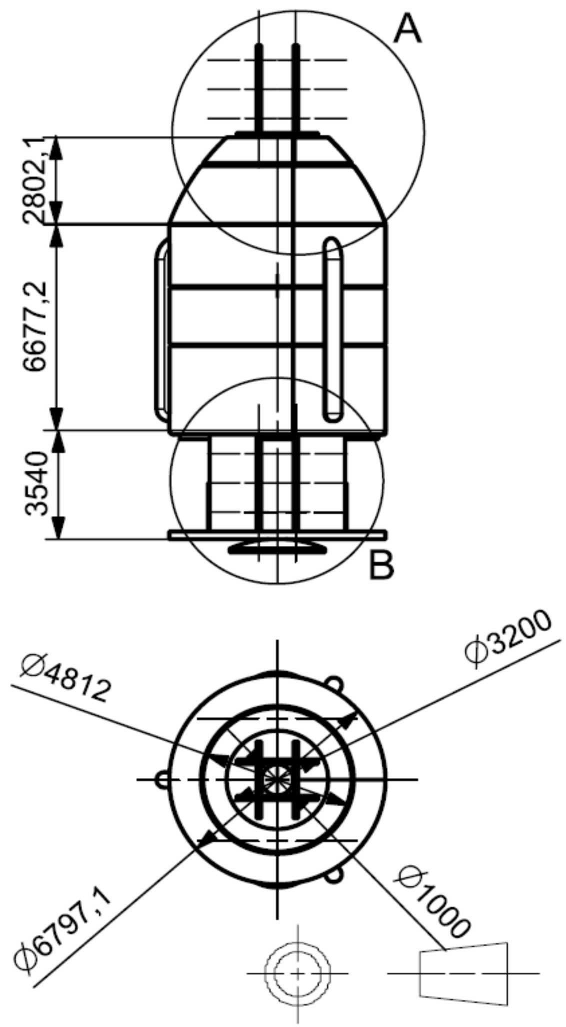

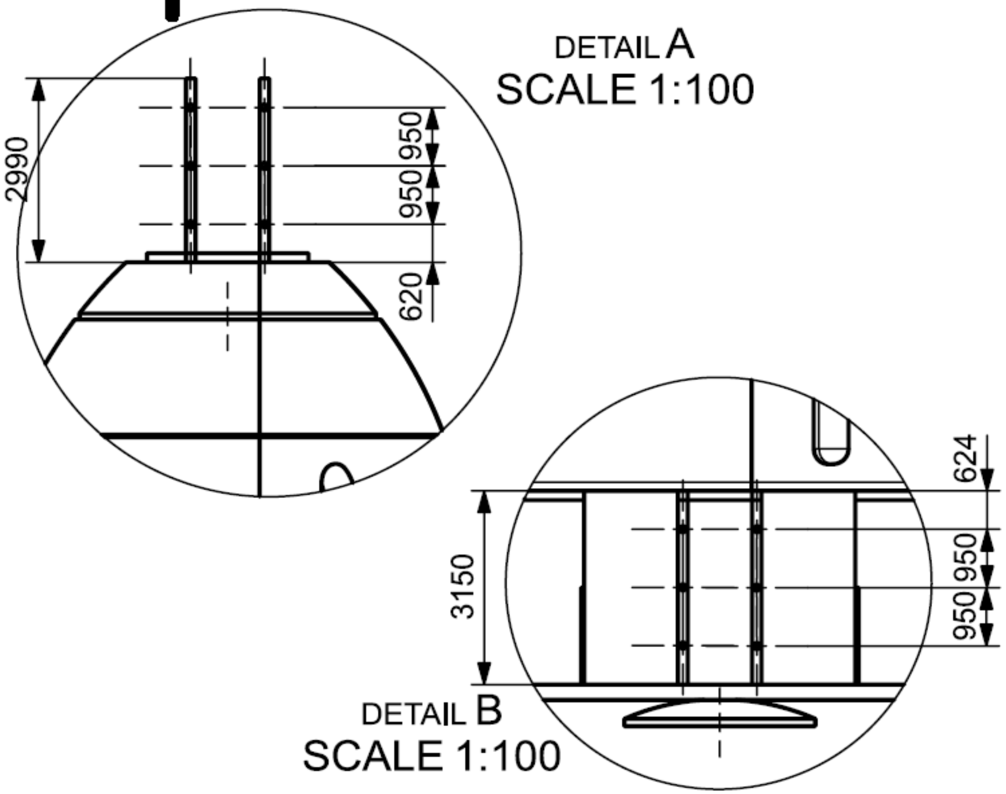

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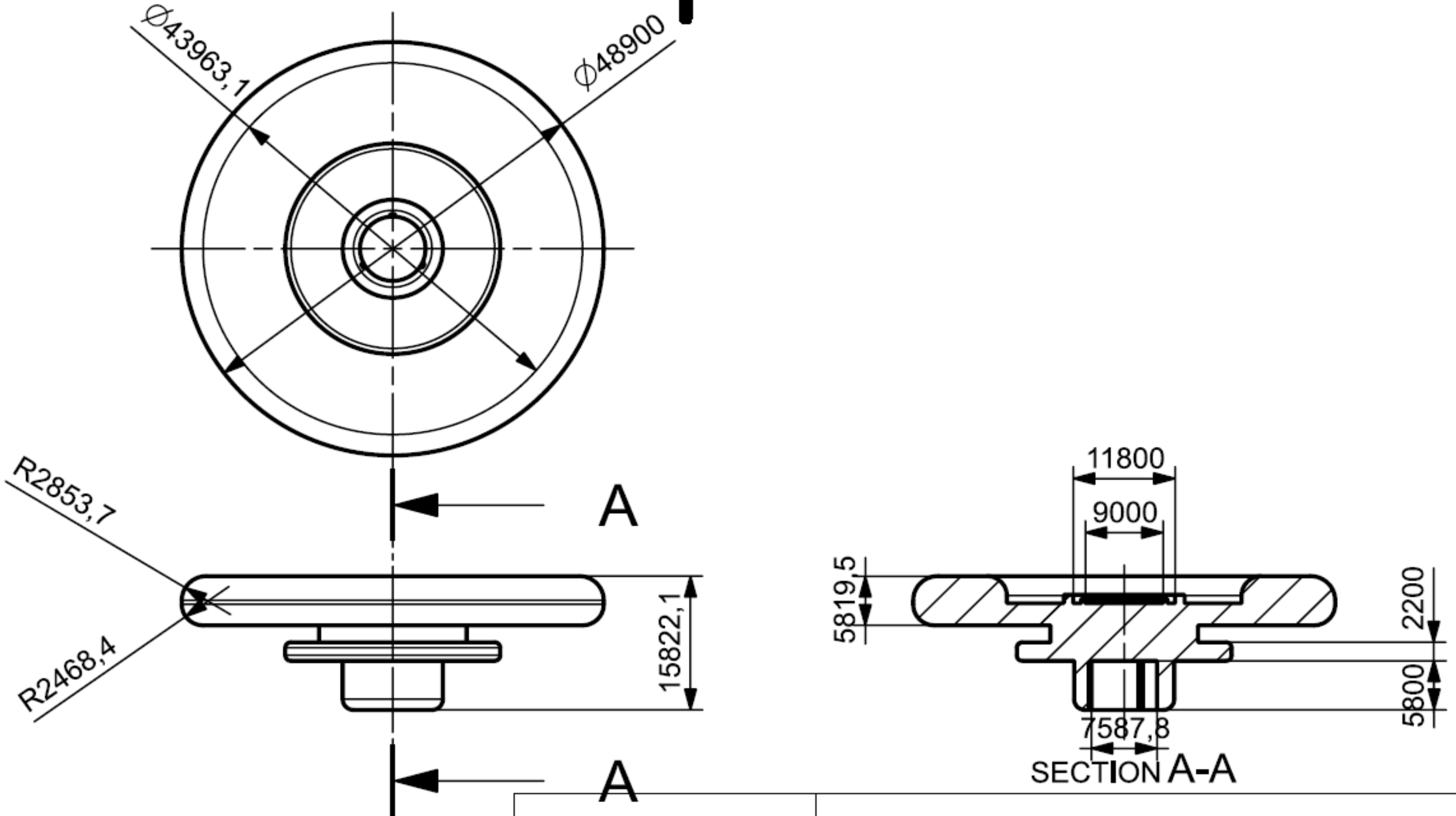
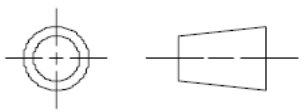


SECTION A-A



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