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RESUM

La idea del ascensor espacial ha existido durante más de un siglo cuando Konstantin Tsiolkovsky inventó el concepto por primera vez en 1895. Sin embargo, el concepto solo se encuentra en el ámbito de la ciencia ficción, ya que nunca ha sido tecnológicamente viable hasta ahora. Por esa razón, este artículo ofrece una discusión sobre la teoría detrás del concepto de ascensor espacial, que es una combinación de investigación de estudios científicos y publicaciones de ciencia ficción. De ambos tipos de recursos se analizarán diseños diferentes y luego se elegirá el mejor diseño en base a las justificaciones adecuadas. El resultado de este trabajo conduce a la revelación del mejor material para construir el cable del ascensor espacial hasta el día de hoy, que son los nanotubos de carbono. Para el diseño del cable, se elige el diseño del modelo Estándar ya que tiene una mayor resistencia que el diseño Hoytether. El estudio sobre el cable del ascensor espacial ha revelado la importancia de incorporar un diseño "tapered" al cable para evitar colapsos. Otro resultado de este trabajo también revela la posibilidad de incorporar la propulsión electromagnética como el mecanismo principal de propulsión del trepador en lugar del sistema de track y roller comúnmente propuesto. Se cree que este tipo de propulsión proporciona mayores ventajas a pesar de que se necesita un mayor desarrollo en el sistema de levitación magnética que ya existe. Aparte del aspecto técnico, este documento también incluirá las posibles amenazas al ascensor espacial que son causadas principalmente por factores ambientales como el clima y el entorno atmosférico. Desde una perspectiva de seguridad, este estudio enfatiza la necesidad de tener en cuenta el impacto de estos desafíos ambientales junto con el sistema de seguridad propuesto para el ascensor espacial. Al final de este documento, se discuten las oportunidades para un mayor desarrollo en otras industrias relacionadas con el ascensor espacial.

Paraules clau (màxim 10):

Ascensor espacial	Trepador	Contrapeso	Ascensor espacial en la ciencia ficción
Nanotubo de carbono	Propulsión electromagnética	Órbita geoestacionaria	
Cable del ascensor espacial	Modelo Diseño Hoytether		

ABSTRACT

The idea of space elevator has existed for more than a century when Konstantin Tsiolkovsky first discovered the concept back in 1895. However, the concept only lies in the science-fiction realm since it has never been technologically feasible until now. For that reason, this paper provides a discussion about the theory behind the space elevator concept, which is a combination of research from scientific study and science-fiction publications. From both type of resources, different designs will be analysed and then the best design is chosen based on suitable justifications. The outcome of this paper leads to the reveal of the best material to build the cable of the space elevator up to this day which is carbon nanotubes. For the cable design, the Standard model design is chosen since it has a greater strength than the Hoytether design. The study about the cable of the space elevator has revealed the importance of incorporating taper design to prevent collapse. Another result from this paper also reveal the possibility of incorporating electromagnetic propulsion as the main driver mechanism of the climber instead of the commonly proposed track and roller system. This type of propulsion is believed to provide greater advantages even though further development is needed in the readily existing maglev system. Other than technical aspect, this paper will also enclose the possible threats to the space elevator which are mainly caused by the environmental factors such as the weather condition and atmospheric surroundings. From a safety perspective, this study emphasizes the need to take into account the impact of these environmental challenges along with the proposed safety system of the space elevator. At the end of this paper, the opportunities for further development in other industries related to the space elevator is discussed.

Keywords (10 maximum):

Space elevator	Climber	Counterweight	Space elevator in science-fiction
Carbon nanotubes	Electromagnetic propulsion	Geostationary orbit	
Cable of space elevator	Model Hoytether design		

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GLOSSARY

F_U	Upward force due to the upper element of the tower [N]
F_C	Upward centripetal force [N]
F_D	Downward force due to the lower element of the tower [N]
W	Weight of the tower due to gravity [N]
$a_{gravity}$	Acceleration due to the gravity [m/s^2]
$a_{centripetal}$	Acceleration due to the centripetal force [m/s^2]
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}]
T	Stress (or force per unit area) in elevator cable [GPa]
m_c	Mass of counter weight [kg]
dr	Differential length of the cable [km]
H	Distance of the top of the cable from the Earth center [km]
dA	Area difference between upper and lower section of the element [km^2]
A_g/A_s	Taper ratio of the cable
L_c	Characteristic length [km]
S/m	Electrical conductivity [S/m]
r_d	Radius of the debris [m]
w	Width of the cable [m]
f	Cross-sectional fraction of cable that must be destroyed to sever it [m^2]
∅	Angle between the cable face and the incoming trajectory of the debris (in horizontal plane) [°]
θ	Angle in the plane of the cable face between the debris trajectory and the cable's long axis (in vertical plane) [°]
UTS	Ultimate tensile strength [MPa]

1. INTRODUCTION

The origination of the space elevator concept has started since the late of 19th century, when a Russian scientist, Konstantin Tsiolkovsky was inspired by the Eiffel Tower in Paris [1]. According to the record, he imagined creating a compression structure that outstretches all the way up to the geostationary orbit. Years after that many organizations took part in the research to make space elevator become a reality. By taking into account physics concept, engineering theories and science fiction model, the development of this new form of transportation to space seems feasible. However, as of 2021, the proposal seems to still stay in the realm of ideas and only comes into realization through science fiction publications.

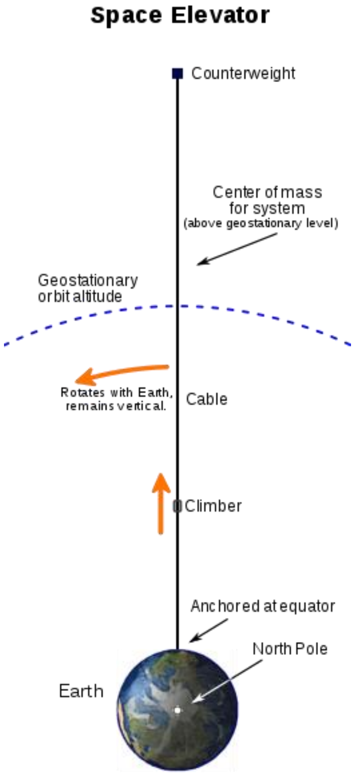


Figure 1.1. A diagram of the standard space elevator concept. Source: [2].

After years of studies and researches, mankind is progressively approaching the implementation of space elevator in today's world as more and more discoveries are being unlocked. The progress would have even been better if there is a material that is extremely strong and thin enough to make the tether. Until then, space elevator might never be technologically feasible.

Also known as the bean stalk, orbital tether or the nonsynchronous orbital skyhook in the scientific literature world, space elevator is said to be a transportation system from earth to space whose concept is actually closely resembling that of the conventional elevator in the apartment. However, that might not be the case in assigning the materials for the components and also the engineering calculation part since the project scale of a space elevator is much more complex.

It is a proposed structure of a tower-like bridge that provides vertical passage from the surface of the earth to the geosynchronous orbit. The main component that makes up a space elevator includes strong lightweight cable, a tether, a ballast weight, a geostationary station and also a climber unit**.** In the standard setting of a space elevator, the whole structure is under an equilibrium state, with no resultant force coming downward or upward from the system. Since the end of the cable extends up to the geosynchronous orbit, the whole assembly will synchronize exactly with the Earth's rotational speed.

The geosynchronous orbit is referred to an orbit which is about 35,786 kilometers from the Earth's surface where satellites are positioned particularly for telecommunication, weather monitor and surveillance purposes. It is believed to have the same rotation as the Earth at any given inclination, in which both of them take 23 hours 56 minutes and 4.09 seconds to complete a single rotation around their respective axes. For this reason, the satellite will always appear at the same position, motionless from the Earth's surface.

The main gain from space elevator is that it is believed to be a much cheaper alternatives for transportation than a conventional rocket that is still being utilized until this day. Apart from a few limitations such as environmental effect and take-off or re-entry noise, these rockets are also considered as an obsolete piece of technology even though now it is the only reliable mean of propulsion ever invented. Thus, by taking advantage of the geosynchronous orbit, geosynchronous station is located at 35,786 kilometers from the Earth's surface, as one of the components that ensures the space elevator's fixed position.

2. OBJECTIVE

The main objectives to be accomplished from this thesis is to conduct a research about the space elevator and the physical theory behind it. The combination of engineering and science-fiction theory behind this topic makes it more interesting and as a student doing the study, I am personally curious about the feasibility of this concept. Thus, I have outlined several in-depth objectives hoping that they can be accomplished upon the completion of this research.

1. To analyze the viability of space elevator as a new form of transportation from earth to space.
2. To design the structure of the space elevator and assigning the suitable material for its main components.
3. To compare and combine models coming from science-fiction with a real engineering-based model in designing a 3D model of space elevator.

3. HISTORICAL BACKGROUND AND DEVELOPMENT

Looking at the number of progress space engineers and scientists around the world had achieved in today's world, it is safe to say that we have come a long way in the journey of making the space elevator becomes a reality.

Konstantin E. Tsiolkovsky (Kaluga, Russia 1857 – Kaluga, URSS 1935)

Recalling back to over a century ago in the year 1895, the first pioneer of the space elevator idea was Konstantin E. Tsiolkovsky who was a rocket scientist and engineer from Russia [1]. The concept of space elevator appeared in Tsiolkovsky's mind when he laid his eyes on the newly built Eiffel Tower in Paris that same year and got inspired by it. In the original key concept, he imagined space elevator as a gigantic tower located in the equator that outstretches all the way up to the high orbit [3].

This was the continuation of his experiments of ways to nullify the Earth's gravitational force and get into the space. He suggested that as the height of the tower increases towards the top, the gravity will also gradually diminish and in fact at the geosynchronous altitude the gravity will disappear. Beyond this altitude on the other hand, the gravity will be reversed in direction where the centripetal force becomes the new artificial gravity. His thought was that the imaginary tower is subjected under compression with the presence of angular velocity at its top.

Yuri N. Artsutanov (Leningrad, URSS 1929 – Saint Petersburg, Russia 2019)

65 years later, the space elevator idea was rediscovered once again by Yuri N. Artsutanov who was a fellow Russian engineer [1]. A structure that works in compression is mechanically infeasible due to the fact that the main challenge is to find the best material that works in compression. He then came up with the idea of constructing the tower upside down, where the base started at the geosynchronous orbit and extends downward towards the ground on the Earth. This said alternative appeared to work under traction which is analyzed to be relatively easier to set up and maintain from the previous Tsiolkovsky's suggested structure.

The construction of the space elevator will be carried out in a way that the cable will be deployed from the geosynchronous satellite and at the same time a counterweight is extended away from the satellite. This is to ensure the center of mass of the cable is always at the same position above Earth. In other word, the counterweight serves as a crucial component to compensate for the cable's mass so that the structure is in equilibrium. He also suggested to incorporate a series of parallel and interconnected thread in the cable construction instead of a single one as a prevention of any possible damaged cause by meteor impact.

John Isaac

In 1966, a group of American engineers including John Isaac of the Scripps Institute of Oceanography conducted a research on determining the materials required to construct a space elevator [3]. By visioning the structure to be as simple as a thin straight cable with uniform cross section all the way through, they expected there was a material with sufficient strength to take the job until the verdict shows that the material would need twice the strength of the strongest existing material at that time.

However, their contribution was significant as they suggested the installation scheme of space elevator that is still valid until today's research. The strategy involves a deployment of cable from the geostationary orbit and it would be hooked to its anchor as it touches the ground. This prime cable will be then utilized to assemble the first cabin with a second cable to reinforce the first one. By repeating the procedure, the result will be a strong and sturdy set of cables that is managed to withstand the loads from the operation of the space elevator.

Jerome Pearson

Another discovery came to light in 1970 when an American engineer Jerome Pearson properly studied the concept of space elevator without being aware of the previous work on the scope [3]. By considering the tapered cross section of cable that was also briefly mentioned in an article published by Artsutanov, he believed that to be a better design than a uniform cross section cable. This is due to the fact that the force on the cable is not the same at every height. Since a cable will be experiencing the weight of it below, the top of the cable therefore is subjected to the greatest tension force.

In his design, the tapered cable will be incorporated into the system in the sense that the top cable will be thicker than the base to cope with the higher load comparison. Moreover, this design require less extreme material properties as the lower cable can be built thinner and lighter.

4. ROCKET HAS LIMITATIONS

4.1 General background

Being the most reliable vehicle in the mission to break through the Earth's atmosphere to the space, rocket is undeniably well known for that function. This not so latest invention has taken its time to progress since the first rocket designed in the 13th century by the medieval Chinese dynasty [4]. At the beginning of the creation, rockets were mainly used for military purpose in siege and only in 1861 that William Leitch first suggested the possibility of rocket being operated for human spaceflight [5]. Since then, rocket has evolved through many upgrades and changes to adapt to its whole new function.

The main mechanism of conventional rockets is propulsion, identical to that of jet airplanes. In this case, the thrust force is generated at the rocket engine where combustion takes place between the propellant, the fuel and the oxidizer. As a consequence, hot exhaust gas is produced from the combustion which will flow through the nozzle at high velocity and create propulsion.

In this propulsion mechanism, the principle of conservation of momentum is applied. Since the rocket continuously burns the fuel during the launch, the mass of the system is no longer similar to the original mass. As a result of the change in mass, the velocity of the rocket increases. In other word, the rocket's momentum changes by the same amount and the total change of the rocket's velocity will depend on the amount of mass of fuel that is burned. However, that dependence is not linear.

Figure 4.1.1. A 186-foot-tall (56.6-meter) H-2B rocket fires into the sky from Tanegashima Space Center, Japan on 20 May 2020. Source: [6].

4.2 Heavily propellant-dependent

In order to travel from the Earth to space, an enormous amount of energy is essential for rocket launching. The need of propulsion mechanism is crucial to defy the gravitational pull on the rocket thus makes it heavily dependent on propellant. Moreover, propulsion is also required for maneuvering and changing orbits, and for handling the attitude of the rockets.

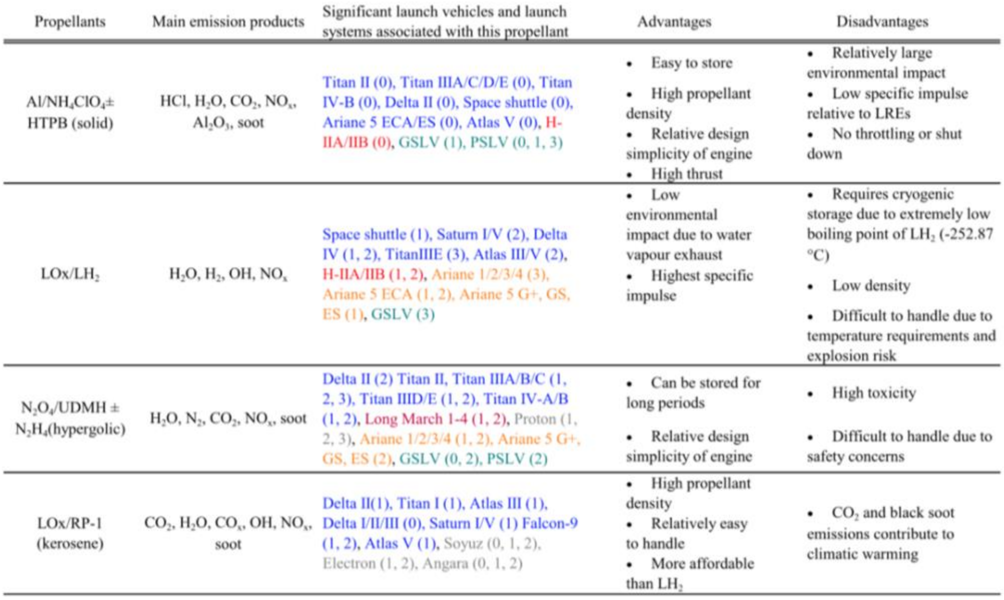
Unfortunately, the mass of the needed amount of propellant, thrusters, tanks, pipes and valves often make up a major part of the total rocket mass. For instance, the Venus Express spacecraft of the ESA which was launched on 9 Nov 2005, had a total mass of about 1270 kg when it was sent on its way [3]. Not less than 570 kg of this was propellant, while the propulsion hardware had a mass of 60 kg and the propulsion subsystem thus accounted for about 50 percent of the total mass [3].

In addition, unlike jet airplanes that draw oxygen from surrounding air into their engines in order to burn the fuel, rocket on the other hand needs to incorporate their own oxygen supply into space, since there is no air there. This constant need of oxygen adds up the mass of the total weight of the rocket.

Apart from that, rockets are expendable, which is they can only be used once. Along the journey, rockets will deploy their empty stages so as to discard the dead weight of the rocket. These parts will then fall back down to the Earth and either splash into the ocean or burn up in the atmosphere. Thus, no component of the vehicle is left to be reused. Even though we can incorporate retrieval equipment such as parachute, the additional mass will be unfavorable to the launcher.

4.3 Environmental effect

The environmental effect originated from rockets launching are sickening. According to the Journal of Cleaner Production, rocket launches are the only source of ozone-depleting chemicals that are deposited directly into the stratosphere [7]. Subsequently, an increased number of launches could cause significant damage.



Propellants	Main emission products	Significant launch vehicles and launch systems associated with this propellant	Advantages	Disadvantages
Al/NH_4ClO_4± HTPB (solid)	HCl, H_2O, CO_2, NO_x, Al_2O_3, soot	Titan II (0), Titan IIIA/C/D/E (0), Titan IV-B (0), Delta II (0), Space shuttle (0), Ariane 5 ECA/ES (0), Atlas V (0), H-IIA/IIB (0), GSLV (1), PSLV (0, 1, 3)	• Easy to store • High propellant density • Relative design simplicity of engine • High thrust	• Relatively large environmental impact • Low specific impulse relative to LREs • No throttling or shut down
LOx/LH_2	H_2O, H_2, OH, NO_x	Space shuttle (1), Saturn I/V (2), Delta IV (1, 2), TitanIIIE (3), Atlas III/V (2), H-IIA/IIB (1, 2), Ariane 1/2/3/4 (3), Ariane 5 ECA (1, 2), Ariane 5 G+, GS, ES (1), GSLV (3)	• Low environmental impact due to water vapour exhaust • Highest specific impulse	• Requires cryogenic storage due to extremely low boiling point of LH_2 (-252.87 °C) • Low density • Difficult to handle due to temperature requirements and explosion risk
N_2O_4/UDMH ± N_2H_4(hypergolic)	H_2O, N_2, CO_2, NO_x, soot	Delta II (2) Titan II, Titan IIIA/B/C (1, 2, 3), Titan IIID/E (1, 2), Titan IV-A/B (1, 2), Long March 1-4 (1, 2), Proton (1, 2, 3), Ariane 1/2/3/4 (1, 2), Ariane 5 G+, GS, ES (2), GSLV (0, 2), PSLV (2)	• Can be stored for long periods • Relative design simplicity of engine	• High toxicity • Difficult to handle due to safety concerns
LOx/RP-1 (kerosene)	CO_2, H_2O, CO_x, OH, NO_x, soot	Delta II(1), Titan I (1), Atlas III (1), Delta I/II/III (0), Saturn I/V (1) Falcon-9 (1, 2), Atlas V (1), Soyuz (0, 1, 2), Electron (1, 2), Angara (0, 1, 2)	• High propellant density • Relatively easy to handle • More affordable than LH_2	• CO_2 and black soot emissions contribute to climatic warming

Table 4.3.1. A table describing four most commonly used space rocket propellant and their primary emission products. Source: [7].

In addition, launch emissions have the potential to impact climate changes through the release of black carbon into the stratosphere. They can also impact the ecosystem and human health through the release of toxic chemicals that can enter water surfaces and persist in the soil.

4.4 Expensive technology

All in all, rockets are an expensive transport to space. Taking into account the cost of building the rockets and its launch pad, the average cost for each mission alone is said to be $450 million [8]. For a single-use transport, this amount of money is extremely massive. In terms of transporting cargo up to space, the current cost fluctuates between $5000 to $20000 per kilogram. Thus, space elevator concept is introduced to be an economical transport, with the cost to transport cargo is assumed to be as low as $10 per kilogram [3].

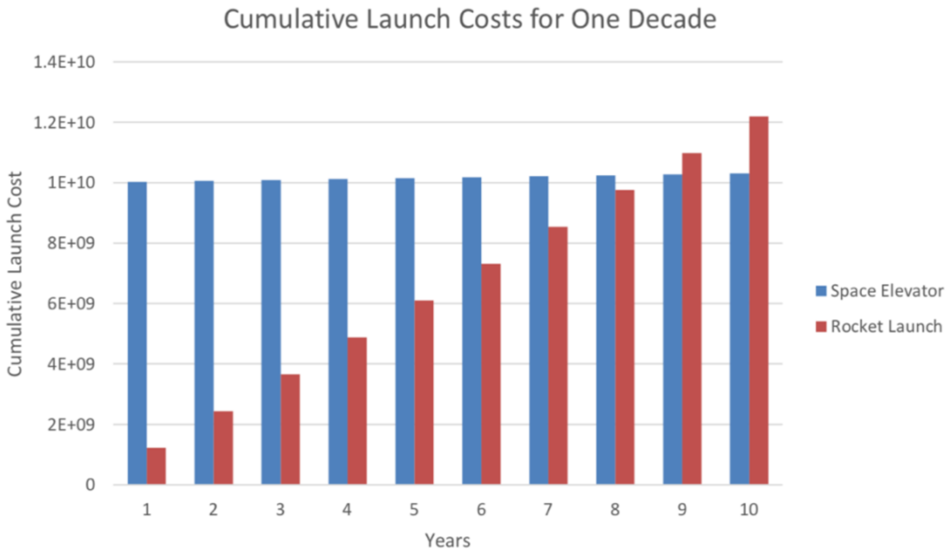


Figure 4.4.1. Cumulative launch cost for space elevator and traditional rocket launch. Source: [9].

Even though the launch cost for space elevator is relatively low to that of conventional rockets, the initial construction cost could be expensive. However, looking at the fact that it is reusable, a study reported that the space elevator will be non-economical for over 9 years, as shown in the previous diagram [9]. The data is taken based on latest launch costs which is equal to 1,000 launches of 1,000 kg payloads at average cost [9].

4.5 Reusable rocket

Space shuttle on the other hand can be used more than once. However, it demands for an additional cost for maintenance and inspection. In fact, more money needs to be spent for each flight of a space shuttle than a conventional rocket. As an example, the Space Shuttle orbiter requires a maintenance team of about 90 peoples, each working about 1000 hours after each mission [3]. The cost for this maintenance labor alone per flight reaches $8 million [3]. Besides, being able to be reused means that the vehicle will be assembled with reentry into atmosphere, descent and smooth landing equipment altogether. Indeed, the component of the space shuttle will be inspected regularly which will lead to more other infrastructure such as maintenance building and spare parts storage. Plus, new external tank will always be needed for every new mission since it will be discarded during each flight.

Up till this day, the most advanced space exploration company is SpaceX which was founded by Elon Musk back in 2002. One of the company's remarkable achievement includes the invention of Falcon 9, the first reusable two-stage rocket [10]. The design of this new space vehicle allows expensive components of the rocket such as the booster to be reconvened and later be reused in other launch. According to an online publication by ElonX, while the current booster has just completed its 39th launch in practice, theoretically the rocket component is able to be relaunched up to 100 times [11]. Consequently, this approach managed to tear down the cost of space launch. The standard commercial launch cost for Falcon 9 with a new booster is said to be $62 million [11].

Figure 4.5.1. An image of Falcon 9 boosters during refurbishment. Source: [11].

The invention of the reusable rocket opens the door for the durability and reusability factor of space technologies. Instead of being used once, some of the principal components such as the rocket booster can be utilized for a few batches of launch which is highly beneficial for both construction time and production cost. However, in comparing the reusability of the component, space elevator truly exceeds reusable rockets since the whole structure can be utilized for a long period of time without the need to replace or discard any part of the structure.

4.6 Reference from other work developed at EPSEVG

Previously a study under the same topic has been done in EPSEVG which is a work by Ahmad Hatim Bin Ahmad Takhiuddin. The title of the paper is Designing space elevator as a low-cost transportation to space [12].

The paper discussed about the physics theory behind the space elevator concept. Ahmad conducted the research by analyzing the principal concepts such as the mass, height and the cost of the space elevator. To comply the title of the research which indicates the space elevator as a low-cost alternative to space, Ahmad included a detailed cost plan for the first few years of the space elevator operation. As a result, the cost of launching payload can be proven to reduce drastically by space elevator if compared to rockets.

Towards the end of the study, he proposed a design for the space elevator which leads to the engineering part of the project. A 3D model is created for every major component of the space elevator with their respective technical drawings. After analysing his work, I have identified certain parts that could be improved and also addition of more topics that has not been discussed yet.

5. THE IDEOLOGY BEHIND SPACE ELEVATOR

5.1 Physics theories

The concept of space elevator can be simplified down to a structure that has its bottom end tethered to a point on the Earth's surface and the other end located at the geosynchronous orbit. These two parts of the structure will be connected via a thin light-weight cable which will happen to be the most critical component of a space elevator.

5.1.1 Geostationary orbit

At the geostationary orbit which is located at a height of 35,786 kilometers above the Earth's equator, any satellite will have its rotation period similar to that of the Earth, which will be 24 hours. Since both revolutions is synchronized, the satellite will always appear at a fixed position from Earth. However, if the 24-hour orbit has an inclined plane relative to the equator, it will be classified as geosynchronous orbit.

5.1.2 Forces

In the case of space elevator, the satellite at the geostationary orbit will have to withstand the weight introduced by the cable and components attached below it. Here, the resultant force at the satellite point will no longer equal to zero since the downwards force from the weight of the cable exceeds the centripetal force. So, in order to keep the space elevator in static equilibrium, a ballast weight will be connected to the satellite beyond the geostationary orbit.

This component will act as a counterweight to balance the weight mentioned earlier. In this case, the centripetal force can be varied according to the downward force and the counterweight is attached to the satellite by a cable. This part will travel fast enough since it is subjected under a dominant centripetal force. To summarize the force that will act on the space elevator at the geostationary height, a free-body diagram is illustrated as follows. Keep in mind that this situation is analyzed for a cable with a uniform cross-sectional area.

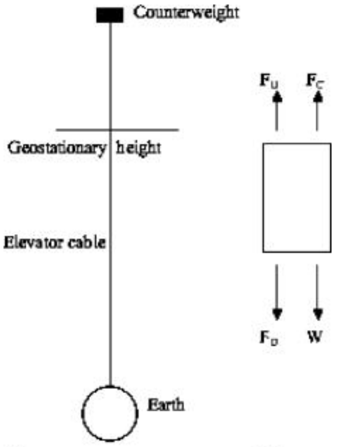


Figure 5.1.2.1. Summation of the forces acting on the space elevator at geostationary height. Source: [13].

The equation to express the forces acting on the space elevator at geostationary height is shown as follows.

$$F_U + F_C - F_D - W = 0 \quad (1)$$

There will be a few forces involved. Starting from the bottom side, the forces acting on the satellite are the weight of the space elevator component below geostationary altitude and the tension of the cable. This weight covers the weight of the cable, climbers and all other lower parts of the space elevator. On the upper side, the satellite will experience tension force from the cable and also centripetal force.

It is crucial to maintain the balance between the upward and downward forces since any disproportion could lead to lethal tragedies. If the centripetal force exceeds the gravitational force, the cable may break thus swinging the satellite away at great acceleration to the space. On the contrary, the structure may collapse down to the Earth in the case when gravitational force is greater.

In the modern concept of space elevator, it is a structure which is modelled under tension. Yet the tension along the cable varies with height due to different gravitational field. Given that the gravitational field is the summation of the gravitational force on the lower cable due to the Earth and also the centripetal force by cause of the upper cable's rotation.

$$a_{gravity} = -\frac{GM_{Earth}}{r^2} \quad (2)$$

$$a_{centripetal} = \omega_{Earth}^2 r \quad (3)$$

$$F = m(a_{gravity} + a_{centripetal}) \quad (4)$$

From the equations above, we can say the downward gravitational force decreases as the square of the distance from the center of Earth while the upward centripetal force increases linearly with the function of that distance. Therefore, it can be proven that the net force on the lower cable will be towards the Earth while the upwards for the upper cable. Assuming that the counterweight as the center of mass of the space elevator, it has to be positioned high enough beyond geostationary orbit to offer enough tension so as to withstand the weight of the whole structure.

5.2 Base anchor concept

5.2.1 Equatorial region specification

An anchoring point is the point where the cable will be tethered on the Earth's surface. Previous researches have shown that the location of this base point must be at the equator for some reasonable justifications. First, the location will have the same angular velocity relative to that of the center of the Earth. Therefore, the station at geostationary altitude will always hang about the same point above the equator as the Earth rotates on its axis and the cable will always be stationary and vertical.

Other than that, the equatorial region often experiences very mild climate if compared to those of the southern and northern region. It is indeed an ideal zone for space elevator construction and operation since the weather hazard is at minimum level. Given that there is no Coriolis force at the equator, hurricanes and tornados hardly form there thus providing a safe atmosphere for the fragile thin cable. There are two possibilities of the base station form. The anchor can either be a fixed station on land or a floating anchor. Both options offer its own strengths and weaknesses.

Just like any other tall building construction on Earth including those Egyptian pyramids, it takes a lot of space to form the base platform for the structure. This platform serves as support to the building and act as the core strength to ensure the building is stable. For the construction of space elevator which obviously involves a far much higher structure, we cannot afford to exploit a very vast space on Earth’s surface just to build the base platform. Therefore, base station should be critically designed to prevent failure.

5.2.2 Land-based station

Building a platform for an enormous structure requires a huge stability and a land-based station can provide that while ocean platform cannot. A solid ground will definitely facilitate the whole space elevator project from the beginning of the construction to its operation. Plus, the whole structure will always stay at a fixed position and the tension of the cable will always be kept in a taut condition. However, this property might later create a weakness for the space elevator in the situation where it is expected to prevent any orbital collision.

Space elevator also can be benefitted from equatorial mountains as a platform. The presence of mountain itself can serve as a physical advantage since the structure can be connected to the mountain instead of all the way to the ground level. Yet, extra work is required in order to transport the equipment to the top of mountain or even mountaintop mining if necessary. Apart from the high altitude, mountains are surrounded by low density air where the wind force is maintained minimum.

5.2.3 Mobile platform

Since most of the region at the equator is made up of oceans, mobile platform is an ideal choice since there is a vast location to choose from. Most importantly, a floating platform situated on a remote location can provide an assurance of safety in the case of the first attempt of space elevator operation went bad. In a worst-case-scenario, a failed structure would not have imposed as much damage as it would have been if the base is located on land, where any other facilities and infrastructure can be found nearby. Moreover, placing the platform on a remote location also give efficient protection against any attempt of sabotage or terrorist attack.

Additionally, being located in international waters also favor any international collaboration needed in managing the project. This strategic location will also encourage any other nation to involve in space elevator development instead of just the nation along the equator. Another significant advantage of incorporating a floating platform is that it can be slightly moved in order to dodge possible hazard.

Nevertheless, a platform floating on the ocean would be susceptible to corrosion due to exposure to salt water. In other word, the platform and its component must be provided extra protection so as to ensure their longevity. Further disadvantage is that the mobile platform will move due to ocean current and waves. This situation will require a relocating system added so that the platform return to its position as well as to keep the tension in the cable in control.

A previous oil exploration base or drilling ship is most likely to be a preferrable platform since it provides living amenities and power supply.

Figure 5.2.3.1. An illustration of a mobile platform of the space elevator. Source: [14].

5.3 Height of space elevator

In accordance with the free body diagram shown earlier in this research, the forces need to cancel each other so as the structure stays in a static equilibrium. Assuming a differential element of the length of the cable, *dr*, where its lower end has a distance of *r* from the center of the Earth. Recalling the previous equation (1), we substitute F_U-F_D as *AdT*. In this case, the term *T* represents the tensile stress of the cable. Given that *M*, *R* and ω are the mass, radius and rotational angular velocity respectively.

$$m = Adr\rho \tag{5}$$

$$F_u - F_D = W - F_C \tag{1}$$

$$AdT = \frac{GM(Adr\rho)}{r^2} - (Adr\rho)\omega^2 r \qquad (6)$$

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}]

Suppose we divide both side of the equation by *Adr*, a differential equation is created as follows.

$$\frac{dT}{dr} = \frac{GM\rho}{r^2} - \rho\omega^2 r \qquad (7)$$

Since $R_g=(GM/\omega^2)^{1/3}$, we can rewrite the equation.

$$\frac{dT}{dr} = GM\rho\left[\frac{1}{r^2} - \frac{r}{R_g^3}\right] \qquad (8)$$

By integrating Eq. (8) from r=R to r=R_g, where T(R) = 0 results to the tensile stress at geostationary altitude R_g as:

$$T(R_g) = GM\rho\left[\frac{1}{R} - \frac{3}{2R_g} + \frac{R^2}{2{R_g}^3}\right] \qquad (9)$$

If the distance of the top of the cable from the Earth center is represented by letter H, it can be calculated by integrating Eq. (8) from r=R_g to r=H where T(H)=0 indicates that the tension fall to zero at the upper and lower end of the cable.

$$T(R_g) = GM\rho\left[\frac{1}{H} - \frac{3}{2R_g} + \frac{H^2}{2{R_g}^3}\right] \qquad (10)$$

If we solve both Eq. (9) and Eq. (10) to find the T(R_g) and note that H=R is a solution of the resulting cubic H. The equation can then be further simplified to a quadratic equation.

$$RH^2 + R^2H - 2R^3g = 0 \qquad (11)$$

Solving H as the subject resulting with

$$H = \frac{R}{2}\left[\sqrt{1 + 8\left(\frac{R_g}{R}\right)^3} - 1\right] = 150\ 000\ \mathrm{km}$$

Hence, the height of the cable above Earth's surface can be figured out by subtracting the Earth radius from the value of H, which resulting in 144 000 km after rounded up to three significant figures.

6. THE NEED OF TAPERED DESIGN FOR THE CABLE

Discovering the fact that the tension of the cable would not be similar at each section of the cable when it is vertically installed, a tapered cable is proposed. This design is considered to be efficient so as to keep the tension in the cable remain the same at whichever altitude examined. In this case, an increase in force is dealt with an increase in cross-sectional area thus resulting in constant tension all the way through.

In a uniform cross-sectioned cable, the downward gravitational pull is much bigger at the geosynchronous altitude than the section near Earth's surface. This is because the cable at certain height will have to withstand the weight of the cable below it. In other words, the higher the cable, the more weight it has to support in order to remain upright. Hence, a tapered cable will solve the problem where thicker parts is designed to provide greater strength. This design also needs less extreme material properties which will be further discussed later.

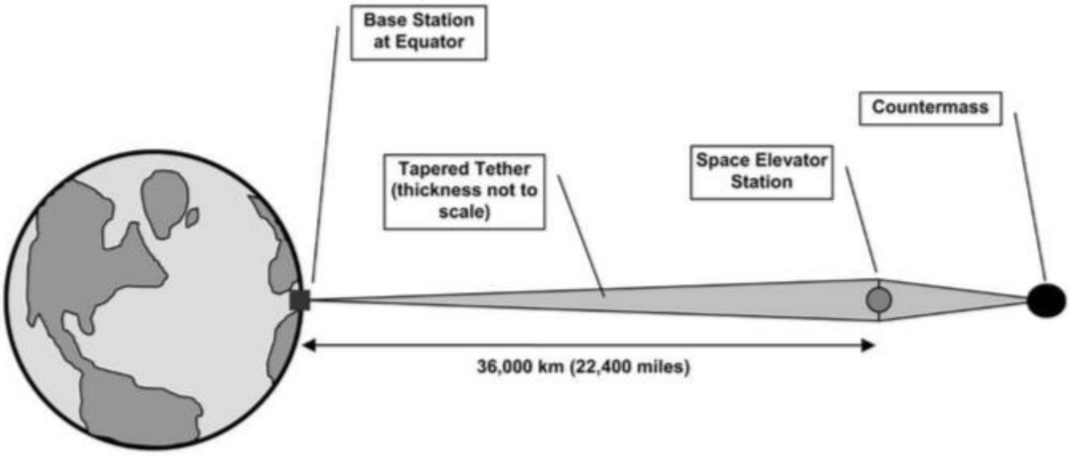


Figure 6.1. Variation of the thickness of the cable. Source: [3].

According to established researches, the tapered design involves a cable that increases exponentially in cross-sectional area as it reaches the geostationary altitude [3]. The same design is also incorporated for the cable connecting the counterbalance, with the thickest section situated at geostationary station.

Taking a small element of the tapered cable with length *dr* and its bottom end situated at distance *r* from the center of the Earth. The free-body diagram of this element is represented as follows.

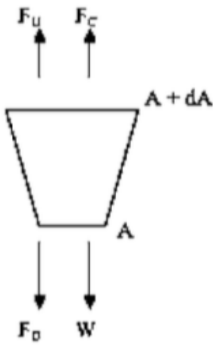


Figure 6.2. Summation of the forces acting on the space elevator at geostationary height. Source: [13].

In equilibrium state, this element will obey the equation (1) but the different is now is F_U-F_D=*TdA*, where *T* is the constant stress in the cable and *dA* is the area difference between upper and lower section of the element. Thus, Eq. (1) can be written as

$$\frac{dA}{A} = \frac{\rho g R^2}{T}\left[\frac{1}{r^2} - \frac{r}{R_g^3}\right] dr \qquad (12)$$

Where *g*=GM/R^2 is the gravity acceleration on the Earth's surface. By integrating Eq. (12), the cross-sectional area of the cable will follow the equation below.

$$A(r) = A_s \exp\left[\frac{\rho g R^2}{T}\left\{\frac{1}{R} + \frac{R^2}{2R_g^3} - \frac{1}{r} - \frac{r^2}{2R_g^3}\right\}\right] \qquad (13)$$

where A_s is the value of A at *r=R.* The above equation proves that the value of A increments exponentially with the altitude from the ground level to geostationary height before decreases exponentially.

The distance H of the top of the cable from the Earth's center can be determined by the requirement that the area of the cable at its upper end have the same value as its lower end, which can be expressed by the condition *A(H)* = A_s*.* Using the previous equation, we can find the height of the tapered cable.

$$H = \frac{R}{2}\left[\sqrt{1 + 8\left(\frac{R_g}{R}\right)^3} - 1\right] = 150\,000\ \mathrm{km}$$

Looking at the value of H, it has the similar value as the height of the space elevator calculated earlier.

6.1 Tether tapering optimization

Taper ratio is a parameter that defines the ratio between the top chord and root chord. In the space elevator context, it is referred to as the ratio between the cross-sectional area of the cable at the upper and lower end.

Given that $A_g \equiv A(R_g)$ signify the cross-sectional area of the tapered cable at geostationary altitude. The taper ratio of the tower is defined as A_g/A_s, that is, the ratio of its area at geostationary height to that at ground level. We find from Eq. (13) that

$$\frac{A_g}{A_s} = \exp\left[\frac{R}{2L_c}\left\{\left(\frac{R}{R_g}\right)^3 - 3\left(\frac{R}{R_g}\right) + 2\right\}\right] \qquad (14)$$

Where $Lc=T/\rho g$ is the characteristic length. It is a material property that determines the taper ratio A_g/A_s of the cable constructed out of that material.

It is shown that the ratio in the above equation depends heavily on the material strength to density ratio. In simpler words, the higher the taper ratio, the smaller the material strength to density ratio will be. In selecting the suitable material for the cable, the taper ratio must be considered as small as possible. This is due to the fact that a high taper ratio will result in large cross-sectional area of the cable in the geostationary station. For instance, assuming a material with taper ratio of 10,000 is used. A base area of $1m^2$ at the base will require $10,000m^2$ at the top end.

7. MATERIAL ANALYSIS FOR SPACE ELEVATOR CABLE

As mentioned earlier, the strength to density ratio is essential in the selection of material for the cable. Generally, the material should not only strong, but it must be lightweight too so that the cable would not suffer from overload failure. Therefore, these two properties will be analyzed carefully with its corresponding taper ratio. Taking into account both science fiction publications and scientific journals, each material proposed for the cable of the space elevator will be examined.

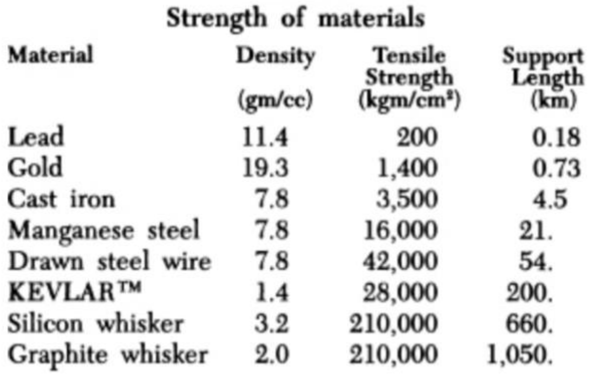
7.1 Doped silicon/ crystalline silicon fiber

Doped silicon was suggested as the material for the load-bearing cable in the novel The Web Between the Worlds by Charles Sheffield in 1979 [15]. The construction material is said to be dislocation-free and twenty times tougher than graphite whiskers. In this context, whisker is referred to as a single crystal of a material in a filament form without any dislocations. Fortunately, this material has a quite good strength under tension and shear strength. However, the compressive strength is bad. In comparison with graphite, these doped silicon whiskers can be manufactured economically cost-wise.

Even though the cable has to support the weight of its own of 35,786 kilometers, in reality the weight is lesser than the weight of a similar length of cable on Earth. Since the gravitational pull decreases as the square of the distance from the center of Earth, the tension in the cable is reduced. In addition, the tension also decreases due to the increment of centripetal force which is linearly proportional to the distance.

After some calculation, the tension in a uniform cross-section cable will be similar to the weight of 4,940 kilometers of the same cable on Earth. Despite the fact that the cable will be tapered instead, this value still serves as a useful information to narrow down the materials for the cable. In the novel, the author relates the previous information with the material that is readily exist. Since the novel is published in 1979, all the data will be of that year.

The author defined support length of a material as the length of itself that a cable of such material will support before it breaks due to its own weight, under Earth's gravity. Below is the table consisting of different material with its respective support length.



Strength of materials

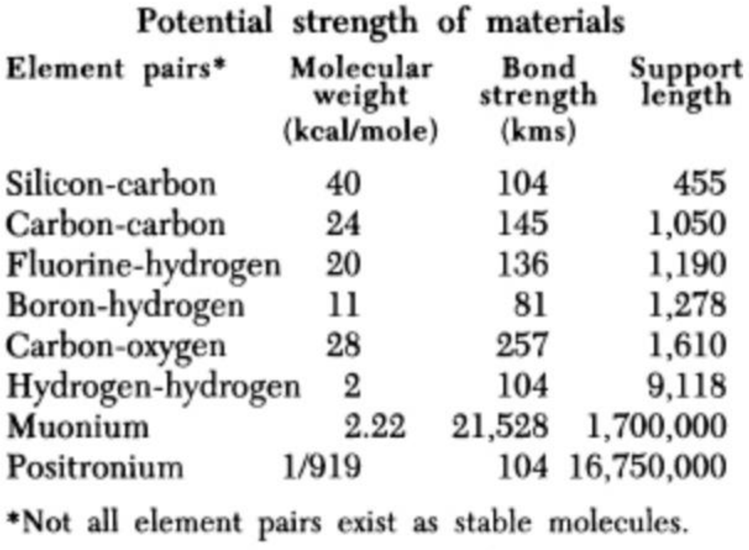
Material	Density (gm/cc)	Tensile Strength (kgm/cm^2)	Support Length (km)
Lead	11.4	200	0.18
Gold	19.3	1,400	0.73
Cast iron	7.8	3,500	4.5
Manganese steel	7.8	16,000	21.
Drawn steel wire	7.8	42,000	54.
KEVLAR™	1.4	28,000	200.
Silicon whisker	3.2	210,000	660.
Graphite whisker	2.0	210,000	1,050.

Table 7.1.1. Strength of materials available. Source: [15].

For a support length of 4,940 kilometers, there is clearly no substance good enough to build a space elevator around that time due to undeveloped material industries. The best choices were silicon and graphite whiskers, despite the fact that their support lengths lack by a factor of five.

7.2 Solid hydrogen

In the same science- fiction novel, the author also suggested that the strength of a material is highly depending on the bonding between the outer electrons of its atom. Apart from having great strength, the material choice for the space elevator cable should also be lightweight. Therefore, we expect that the lightest material will be made up of the best strength-to-density ratios.



Potential strength of materials

Element pairs*	Molecular weight (kcal/mole)	Bond strength (kms)	Support length
Silicon-carbon	40	104	455
Carbon-carbon	24	145	1,050
Fluorine-hydrogen	20	136	1,190
Boron-hydrogen	11	81	1,278
Carbon-oxygen	28	257	1,610
Hydrogen-hydrogen	2	104	9,118
Muonium	2.22	21,528	1,700,000
Positronium	1/919	104	16,750,000

*Not all element pairs exist as stable molecules.

Table 7.2.1. Potential strength of materials available. Source: [15].

Based on the table, hydrogen-hydrogen bond is used in the strongest material by far. In this case, the presence of only a single electron for every hydrogen atom involves in the bond while at the same time the absence of neutron makes it as light as possible.

Observing at the support length of a solid hydrogen cable, the value exceeds the required amount, which is favorable for the construction of the cable. In addition to a taper ratio of 1.6, the cross-sectional area required at geostationary altitude would not be extreme. For instance, a cable with $1m^2$ at the lower end will only result in $1.6m^2$ upper end, which is not much of a difference. However, solid crystalline hydrogen is off-limit as a working material.

7.3 Hyperfilaments

In the science fiction novel The Fountains of Paradise written by Arthur C. Clarke in 1979, a material named hyperfilament was used for the construction of the cable [16]. The author envisioned hyperfilament as a continuous pseudo-one-dimensional diamond crystal. Even though the material is not necessarily made out of pure carbon, it possesses great strength, comparable to that of pure diamond. In the late of 20th century, hyperfilament is created but since its production require a completely zero gravity conditions, the price is rather on the pricey side.

Apart from being incredibly strong, cables made up of hyperfilaments are also microscopically thin. It is mentioned that the thickness is as low down to a few microns, far thinner than a spider web.

7.4 Buckminsterfullerene

Later in the novel The Fountains of Paradise, another possible material is mentioned which is buckminsterfullerene [16]. It is a molecule with hollow ball structure made up of carbon atoms. These atoms are bonded to each other via an alternating hexagonal then pentagon pattern of a soccer ball.

The material emerged by condensing very hot carbon vapor before forming soot with unrecognized geometric atomic arrangement. The structure of the molecule is tiny enough and even known as sub-microscopic.

This spherical molecule possesses a spectacular strength due to its arrangement of individual atoms. In this case, the carbon atoms are packed in a close soccer ball pattern, thus resulting its comparable strength to that of diamond crystals. The author later conveyed his determination that another type of carbon, Buckminsterfullerene, would play the role of hyperfilament in a real space elevator.

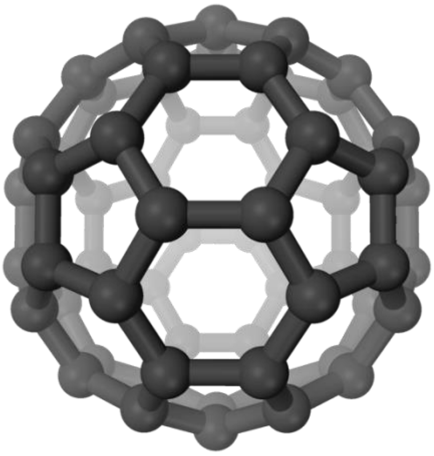


Figure 7.4.1. A cage-like fused-ring structure of buckminsterfullerene. Source: [17].

7.5 Carbon nanotubes

7.5.1 Discovery

Based on the recent discoveries, an ideal material for space elevator cable is uncovered which acquires both lightweight and incredibly strong characteristics. It is carbon nanotubes, founded by a Japanese physicist Sumio Iijima in 1991 [18]. The newly discovered material is the result of electrically charged superhot carbon soot which leads to the creation of various cylindrical, thin-walled structures of chained carbon atoms in the condensed soot.

The properties of the tubes were nanoscopic, with a maximum of 2 nm wide and numerous lengths. In comparison to the strength of other existing strong materials, carbon nanotube is proven to be ten times stronger than Kevlar while a hundred times stronger than steel. On the other hand, the long nanotubes can also be interlinked together into flexible yet super strong fibers of any desired length. These mentioned characteristics are precisely required for a space elevator.

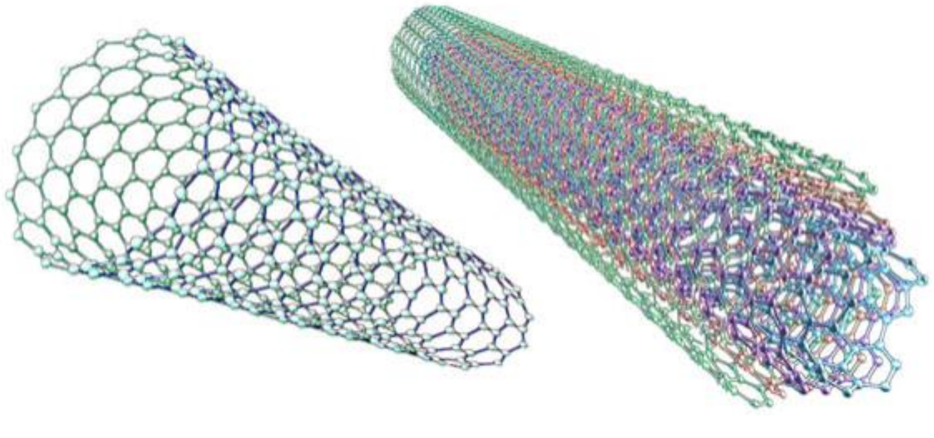


Figure 7.5.5.1. Single and multi-walled carbon nanotube. Source: [19].

7.5.2 Adaptation challenges

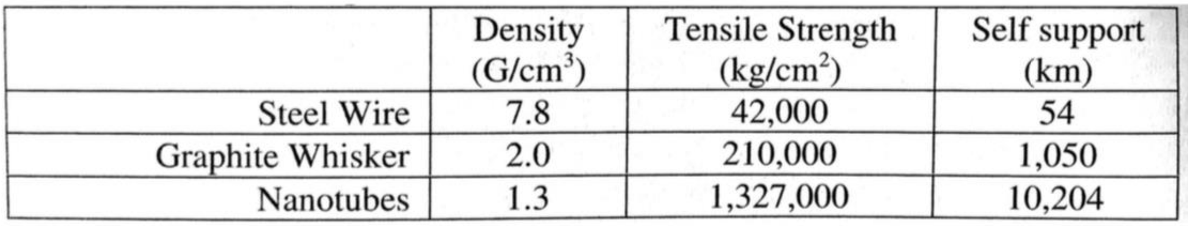
According to Bradley C. Edwards, the preferable tensile strength for the space elevator is 150 GPa or higher [1]. Unfortunately, the performance of cables which can currently built out of carbon nanotube is not yet up to space elevator standard. Theoretically, the tensile strength of a unit of carbon nanotubes is between 100 and 200 GPa. Yet due to weak shear interaction between adjacent molecules and tubes, that value came out lower than anticipated during experimental procedures for multi-walled carbon nanotubes.

Based on laboratory reports by Japan Science and Technology Agency, it is found that there is a relation between the strength lies in the nanotubes with their chiral structures [20]. However, with the high rate of discoveries and progress in this field, a carbon nanotube composite fiber with a tensile strength greater than 100 GPa might be created in no time in the near future.

7.5.3 Ideal taper ratio

In the modern space elevator concept, carbon nanotubes are in fact the material of choice. Therefore, its ideal taper ratio is essential to sustain the strength to carry the payload. By having a taper ratio of as small as 1.9, there will not be a huge difference between the lower and upper end of the cable in term of cross-sectional area. For example, a cable with 10 mm thickness would only thickens up to 19 mm at geostationary altitude. This advantage gives possible chance to widen the thickness of the cable as necessary to support the electromagnetic systems needed for the climb.

In addition to having one sixth of the weight of steel, the cable will have sufficient strength to support the cable below it while including the climber unit. Since the required support length for the cable is said to be 4940 km, studies show that the nanotubes material surpasses that amount. From the table, the unit stated for density is G/cm^3 where G is gram.

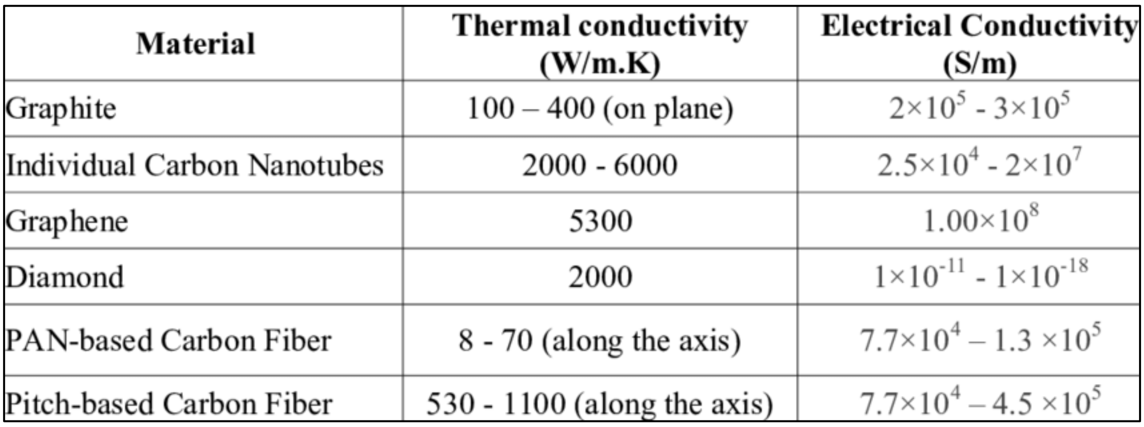


	Density (G/cm^3)	Tensile Strength (kg/cm^2)	Self support (km)
Steel Wire	7.8	42,000	54
Graphite Whisker	2.0	210,000	1,050
Nanotubes	1.3	1,327,000	10,204

Table 7.5.3.1 A comparison of tensile strength ad self-support length between three strongest materials. Source: [1]**.**

7.5.4 Electrical conductivity

Carbon nanotubes are electrically and thermally conductive. These conductivities are proven to be the result of a function of their diameter as well as their chirality, which is the degree of the molecular twist. The capability of transporting electricity is absolutely beneficial to the operation of the space elevator since the material can be utilized as a good power conductor for the systems. From the table, the unit stated for electrical conductivity is S/m where S indicates Siemens which is equal to Ohm^{-1}.



Material	Thermal conductivity (W/m.K)	Electrical Conductivity (S/m)
Graphite	100 – 400 (on plane)	2×10^5 - 3×10^5
Individual Carbon Nanotubes	2000 - 6000	2.5×10^4 - 2×10^7
Graphene	5300	1.00×10^8
Diamond	2000	1×10^{-11} - 1×10^{-18}
PAN-based Carbon Fiber	8 - 70 (along the axis)	7.7×10^4 – 1.3×10^5
Pitch-based Carbon Fiber	530 - 1100 (along the axis)	7.7×10^4 – 4.5×10^5

Table 7.5.4.1 A comparison of conductivity between materials. Source: [1].

8. CABLE STRUCTURE

8.1 Standard model

The key concept in determining the design of the cable focuses on minimizing the mass so that the structure is as light as possible whereas the strength is maximized axially. In order to comply these two conditions, a ribbon-type design is proposed for an ideal carbon nanotubes composite [1]. The characteristic of this ribbon-like cable is having a thin length and relatively big width.

Firstly, the arrangement of nanotubes fiber must be designed in such a way that they are parallel to each other. By positioning each nanotubes side by side, the strength in vertical direction is increased while having a low mass. At the same time, the individual nanotubes fiber strand is linked together by adding a few cross or diagonal components in the horizontal plane.

The benefit of this design is that it prevents the cable from being seriously damaged in the case of any hazardous situation such as orbital debris collision. Instead of snapping the whole structure away, the cable will only suffer from small holes, so the risk of failure is reduced. This formation also gives a large surface area of uniform traction for the climbers [1].

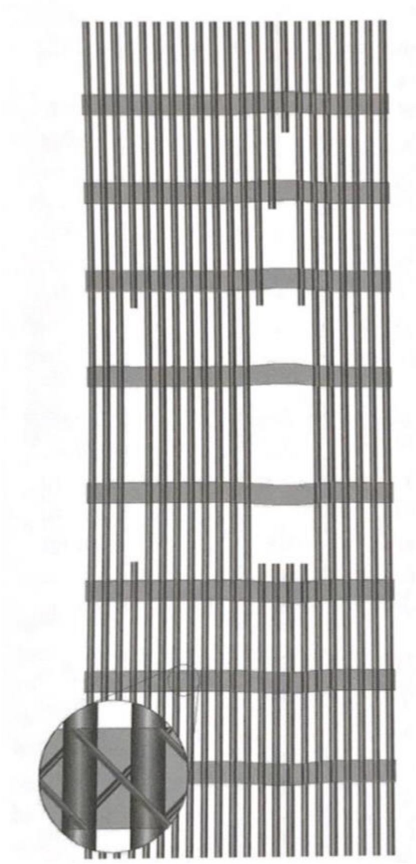


Figure 8.1.1 Proposed ribbon-design. Source: [1].

In the design, thousands of individual fibers with small diameter are interlinked together by cross-connections. These connectors are tape sandwiches, which allows the fiber to support a maximum of 1 GPa tension for a 10 microns diameter fiber.

Once the applied tension exceeds the maximum value, the fiber will escape from the interconnectors due to the elastic contraction. Then the tension will fall below 1 GPa at each cross-connection and transfer the tension to its neighboring fibers. Hence, it is very crucial to provide sufficient strength to the fibers since any slipping has a potential to cause domino-like slip to other fibers.

Bradley C. Edwards suggested that the fibers should at least have 100GPa breaking strength and will be used at 50 GPa tension [1]. Also, in his proposal, a ribbon with of 3 mm^2 cross-sectional area of 10-micron diameter fibers or roughly 30,000 fibers at the anchor were recommended [1].

8.2 Hoytether design

This alternative design is recommended by Robert Hoyt [21]. However, space tether with a Hoytether structure will most probably carry a heavier weight than the original Standard Model.This characteristic alone has defied the main concept of having minimal mass.

The carbon nanotube fibers in Hoytether design are arranged in a vertical configuration while having a supporting fiber in between them. The support is provided by placing cross shaped fiber which can distribute the load in any debris encounter. This arrangement makes this Hoytether a reliable design in preventing any damage to the space tether.

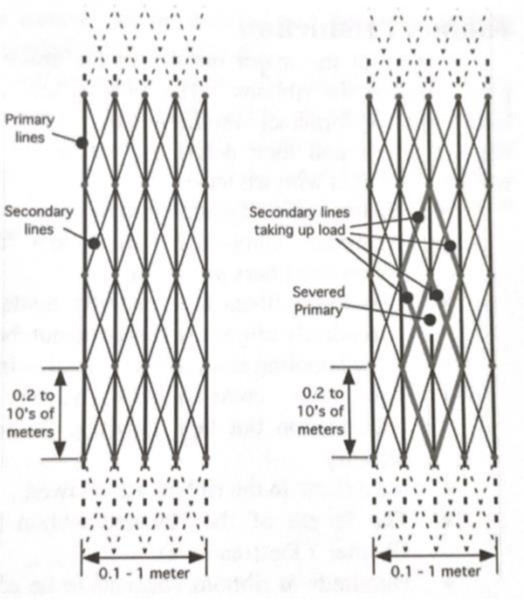
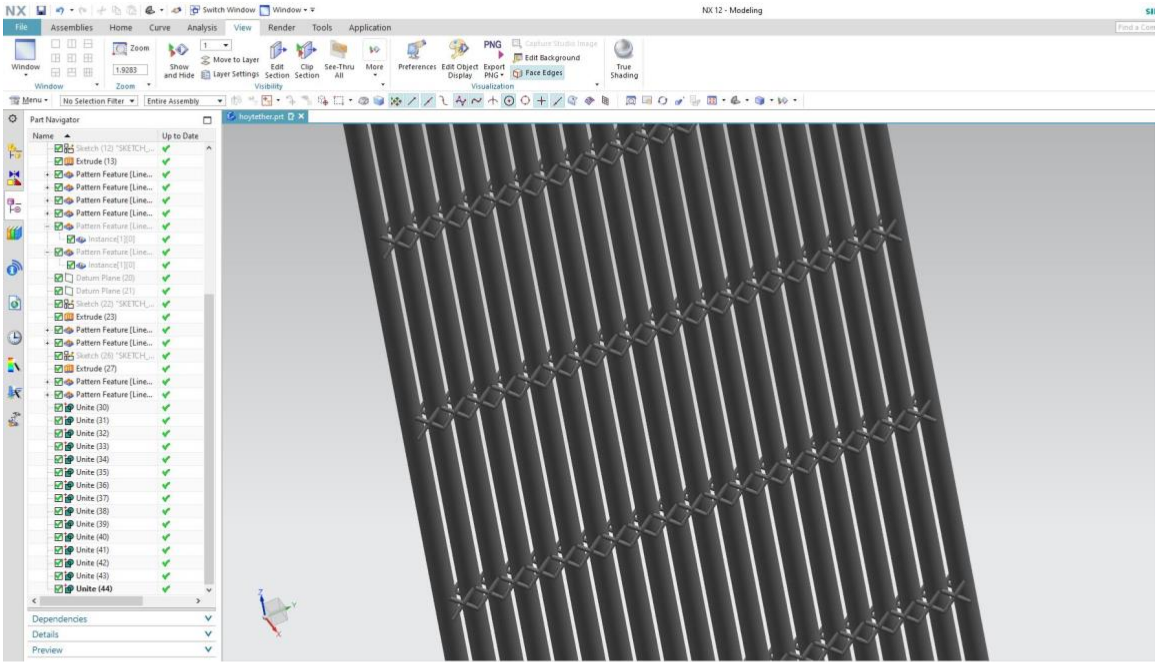


Figure 8.2.1. The Hoytether design. Source: [1]

8.3 Strength analysis

Both the design of the cable will undergo 3D modelling before being put in a stress analysis test in Siemens NX. Since it is impossible to do a full-scale test on the cable of the space elevator, only a small section of the cable is put under stress analysis. In both designs, the diameter of carbon nanotube strand is kept constant to provide fair comparison.



Name	Up to Date
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Extrude (13)	✓
Pattern Feature [Line...	✓
Pattern Feature [Line...	✓
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Pattern Feature [Line...	✓
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Instance[1][0]	✓
Datum Plane (20)	✓
Datum Plane (21)	✓
Sketch (22) "SKETCH_...	✓
Extrude (23)	✓
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Sketch (26) "SKETCH_...	✓
Extrude (27)	✓
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Figure 8.3.1. A 3D model of the standard design of the cable. Source: [own source]

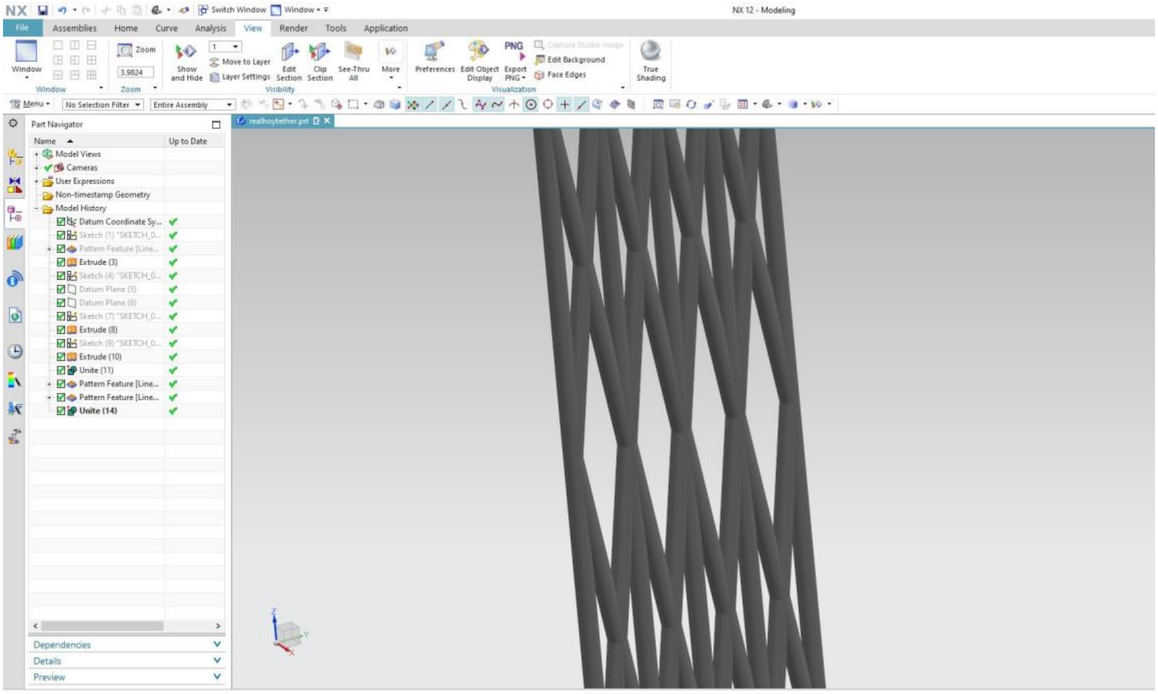


Figure 8.3.2. A 3D model of the Hoytether design of the cable. Source: [own source].

Using the simulation function in the Siemens NX software, both segments of the cable are put under fixed constraint at the upper end of the design. On the other hand, a similar amount of load is applied to the bottom ends in vertical downward direction so as to indicate the load of the real space elevator cable. The designs of both cables with fixed constraint and applied load are included in the appendix.

The stress in the cable can be illustrated based on the color distribution. Based on Figure 8.3.3, it can be seen that the vertical strands are bearing a greater amount of stress than the horizontal connectors. In addition to that, the horizontal connectors are more closely packed than the vertical fiber, which result in greater surface area. Consequently, the horizontal connectors experience a significantly less stress distribution.

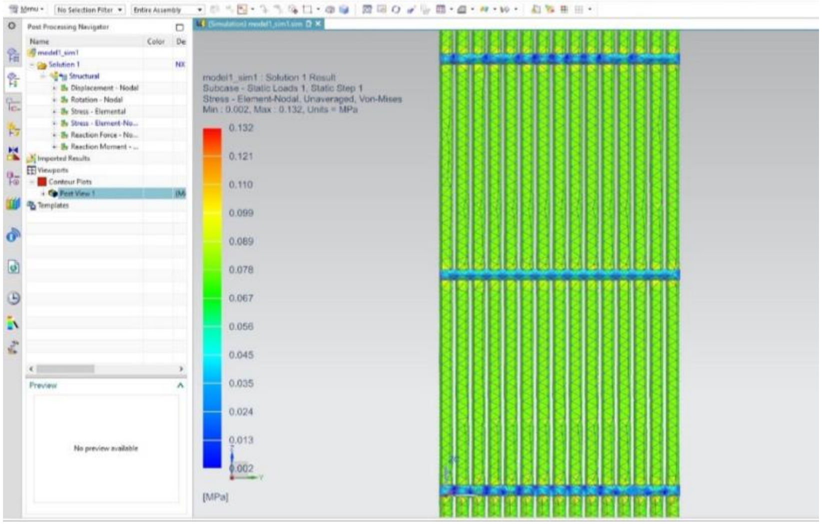
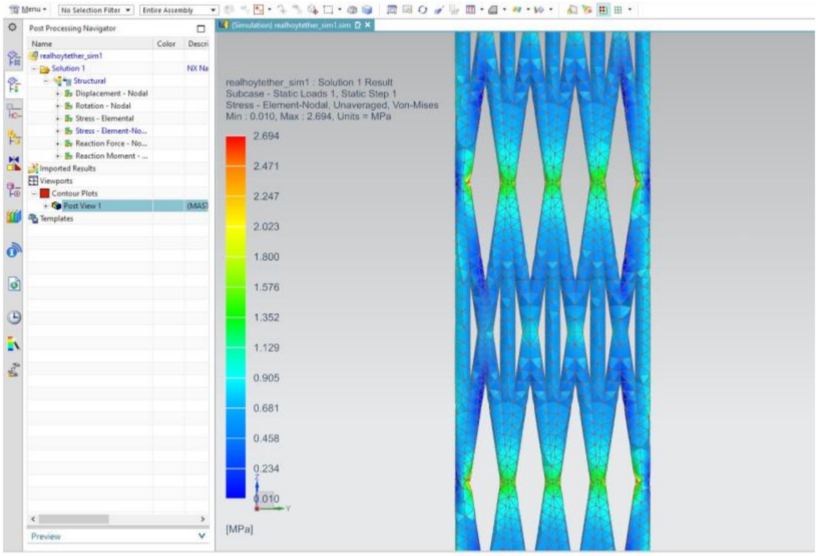

model1_sim1 : Solution 1 Result
Subcase - Static Loads 1, Static Step 1
Stress - Element-Nodal, Unaveraged, Von-Mises
Min : 0.002, Max : 0.132, Units = MPa

Figure 8.3.3. Stress distribution of a Standard model design. Source: [own source].

As for the Hoytether design, it can be seen that most of the stress is concentrated at the joints of the cable. In comparation to the strength of the Standard model, the Hoytether is relatively weaker based on the stress distribution diagram below.



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realhoytether_sim1 : Solution 1 Result
Subcase - Static Loads 1, Static Step 1
Stress - Element-Nodal, Unaveraged, Von-Mises
Min : 0.010, Max : 2.694, Units = MPa
```

Figure 8.3.4. Stress distribution of a Hoytether design. Source: [own source].

9. CABLE DEPLOYMENT

The initial phase in the construction of the space elevator must be the launching of the spacecraft to geostationary orbit. This spacecraft serves a purpose to deploy the cable down to the Earth’s surface prior to any other development step.

Admitting the fact that the initial spacecraft is relatively larger than any other spacecraft, it is sent up to low earth orbit in a few pieces before being assembled together there. The same procedure will be done to the cable since it is tremendously long to be transported in a single launch. The whole assemble will then move up to geostationary orbit.

During the deployment of the cable, the spacecraft will simultaneously be cruising in its own orbit to its final stationary position at 100,000 km from Earth where it takes up permanent residence as a counterweight [1]. On the other hand, the lower end of the cable will be secured as an anchor at the platform base station on Earth.

In order to facilitate detection once it enters Earth atmosphere, an ‘end mass’ will be attached to the lower end of the cable. This component will also act as a pulling force as well as to control the direction of fall.

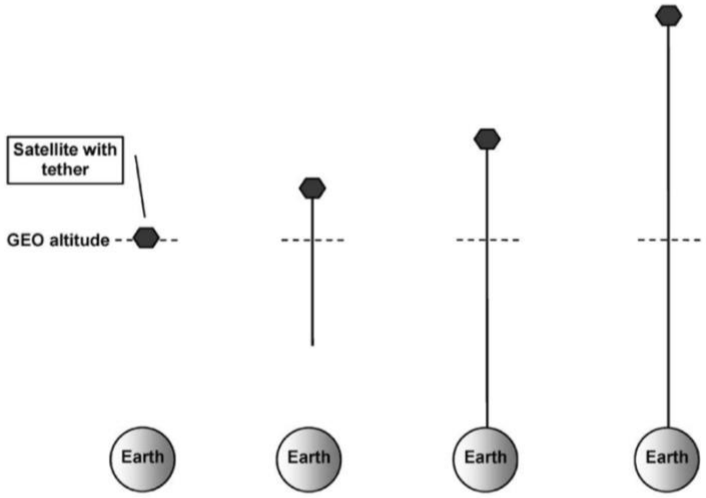


Figure 9.1 Deployment of an initial space elevator cable. Source: [1].

9.1 Spacecraft propulsion

The initial spacecraft will incorporate the modern Magneto-plasma-dynamic or MPD type engine into its propulsion system [1]. The main reason is that this engine would not require a huge mass as well as fuel mass since the spacecraft will be powered by electric drives. This is due to the fact that the power will be supplied from the Earth so there is no extra mass on board. Additionally, MPD type engine is tested to be highly efficient which is up to 85%.

The mechanism works by creating both electric and magnetic field which will thrust the fuel ions at very fast speed. These drives use high current as their method, rather than the voltage-based ion engines [1]. In recent research, the suggested engine life is said to be 10,000 hours [1].

Anyhow these engines also imposed some disadvantages. Journey wise, the spacecraft will take more time than other chemical rockets due to low thrust production. Theoretically, it would need 138 days to reach geostationary orbit from LEO. Another issue is that there is no suitable power source for this system. The one we already have are either to massive, such as nuclear fission reactors which produce up to 50MW. For that reason, the plan is to beam the power to the spacecraft via laser and receive the power with a Gallium Arsenide (GaAs) photovoltaic panel on board [1].

9.2 Spacecraft amenities

i) Internal power

In the spacecraft, the main priority for power supply is given to the MPD engine during the journey form LEO to geostationary orbit together with the cable deployment. This power requirement is mentioned to be about 800 kW. Meanwhile some on-board features require a minimal continuous power supply, connecting them to batteries is adequate. Apart from that, power beam also works as power source for requirements like sensors and video. In addition, the power produced from cable deployment also can assist the original power source.

ii) Communication

The spacecraft is designed in a way that it can communicate with the ground control and vice versa. Since the journey is rather long, the system is unlikely to be fully automated. Settings like navigation, engines and fuel supply system need to be under surveillance constantly.

iii) Attitude control

Attitude control is essential in keeping the spacecraft moving in the right direction without rotating. Any rotation will cause distraction to the power beam since the photovoltaic panel will most likely out of target. It is also responsible for ensuring the spacecraft is always in vertical orientation direction when cable is being deployed to the Earth.

10. COUNTERWEIGHT

The height of the space elevator has been determined earlier which turns out to be 144 000 km. Mass producing the material in order to meet the desired length would be an inconvenience. Luckily, we can shorten this length by compensating the counterweight mass. By adding more mass to the counterweight, the cable can maintain the necessary tension in the cable while having a relatively shorter length than the original design. The mass of the counterweight can be determined by the following equation [13].

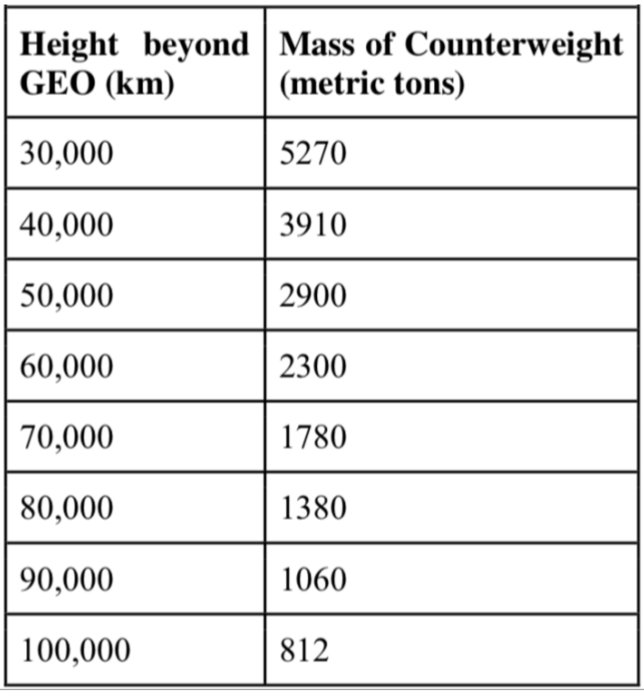
$$m_c = \frac{\rho A_s T exp\left[\frac{R^2 \rho g}{2TR_g^3}\left\{\frac{2R_g^3+R^3}{R} - \frac{2R_g^3+(R_g+h)^3}{R_g+h}\right\}\right]}{\frac{R^2(R_g+h)}{R_g^3}\left[1-\frac{R_g}{R_g+h}^{3}\right]\rho g} \tag{15}$$

m

m_c is the mass of the counterweight in kilogram and h is the height of the counterweight above geostationary orbit in meter. Based on the equation, note that m_c approaches infinity as the value of h reaches zero.

Since the counterweight mass in influenced by the length of the cable between geostationary altitude and counterweight, it should be precise since any overweight or underweight could possibly affect the space elevator stability.

Parts of the analysis are shown in the chart below and it was decided that a total length of 116,000 km and mass of 1375 metric tons would be the best balance between height and mass in terms of the ability of aeronautics agencies to launch the elevator into space [22]. Notice that from the table, the unit stated for mass of counterweight is metric tons, where 1 metric ton= 1000 kg.



Height beyond GEO (km)	Mass of Counterweight (metric tons)
30,000	5270
40,000	3910
50,000	2900
60,000	2300
70,000	1780
80,000	1380
90,000	1060
100,000	812

Table 10.1. Counterweight vs. height above geostationary orbit. Source: [22].

11. CLIMBER CHARACTERISTICS

11.1 Electromagnetic driver mechanism

In contrast to mechanical climbers, electromagnetic climber provides a faster transportation while maintaining no contact with the railing system. Zero contact will prevent both the climber and cable structure from wearing down due to friction and subsequently saving a lot of maintenance cost.

According to analysis, about 60 MJ/kg is needed to operate the climber up to geostationary altitude [23]. If the vehicle moves with an average speed of 125 km/hr then the journey will complete within 12 days at most. However, an electromagnetic sled is most likely to achieve greater speed which will result in lesser travel time.

In deciding the type of propulsion to use for the climber, certain steps need to be observed. Since the space elevator can be built for both human and non-human payloads, different approaches are required for both systems. This is due to the fact that the human body can only experience up to 3 Earth gravity level, so this type of payload is only suitable for low gravity systems. In this propulsion, the acceleration is controlled so that the passengers on board would not be exposed to any harm including health effect upon riding the space elevator. In this section, I will only focus on low gravity system.

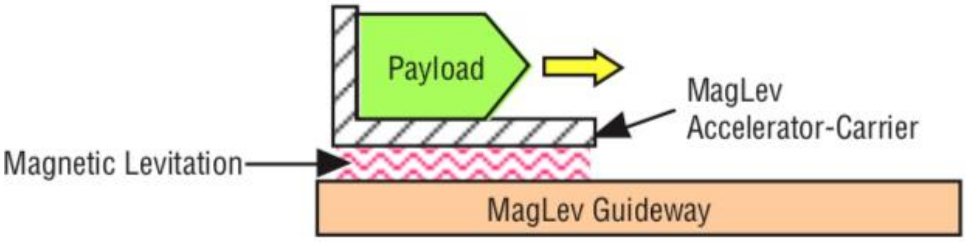


Figure 11.1.1 Electromagnetic launch system. Source: [23].

Electromagnetic climber incorporates the same mechanism as bullet train which is MagLev. It is a system in where the vehicle will be levitated at short distance from the guide rail for thrust production powered by electromagnets. This mechanism works by placing powerful electromagnets on both side of the cable while ferromagnetic material is attached to the resonance point on the cable. At the same time, magnetic accelerator is incorporated into the outer part of the climber for levitation and propulsion reaction to take place.

The thrust force is generated by the alternating magnetic force between each pole. For a levitation to take place, magnets with same pole will have to be against each other so as that to repel and push the climber upward. So as to achieve propulsion, the climber will move in the sense that the alternating poles along the guiderail will continuously pushes the climber along it. In this case, like poles will repel to each other and since there is an opposite pole ahead, the magnet will attract to the opposite pole while advancing forward. In this context, strong magnetic force is required to overcome the downward gravitational force of the climber and its payload, while at the same time to create levitation.

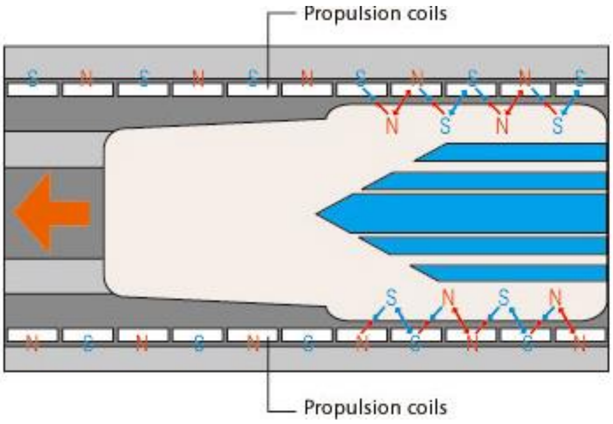


Figure 11.1.2. Electromagnetic propulsion system. Source: [24].

However, advance development in material technology might allow magnetic dopants to be directly included into the cable structure itself, so that there is no need to individually attach the large number of individual magnets along the cable. Future research is still needed to determine the accessibility of this new technology in space industries.

11.2 Power system

An enormous amount of energy is involved in sending the climber up to geostationary orbit. Instead of bringing on-board power supply, power beaming is preferrable in the space elevator concept since some of the load can be left on Earth while transmitting the energy directly to the climber. In this study, the technique analyzed is the laser power beaming. About 2.4 MW of power is necessary to be transmitted to the climber for the system to be functional [1].

11.3 Receiver system

Principally, an external laser beam will be directed to the climber which will then be use in the generation of electricity during the climb. For this reason, the climber will be equipped with a receiver system which consists of photovoltaic panel. In theory, this panel will be situated at the bottom side of the climber to facilitate the laser light absorption process.

One of the highly efficient photovoltaic cells is Gallium Arsenide (GaAs) solar cell. With a conversion efficiency of 59%, this type of cell is chosen for the space elevator system [25].

11.4 Supporting infrastructure

The laser beam will be directed from a power station situated on the Earth surface. So as to ensure an effective transmission, the infrastructure is recommended to be built at high altitude site. This is important to eliminate any atmospheric distortion to the laser which will prevent the beam to be focused precisely on the receiving panel.

However, there is a possibility of laser transmission failure due to cloudy weather. For safety reason, a second power station is proposed to serve as a backup system in order to ensure for a continuous power supply. Bradley C. Edwards advised that a preferable second infrastructure should be situated in a different weather zone from the main one [1].

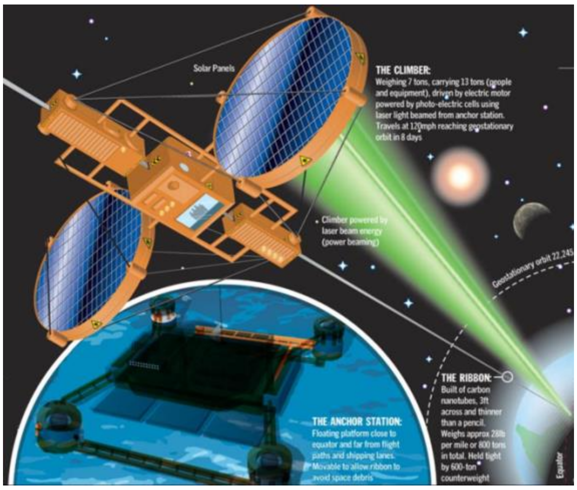


Figure 11.5.1. An illustration of the principle of power beam. Source: [26]**.**

12. THREAT OF ORBITAL IMPACT

12.1 Main concern

Since the space elevator will remain as stationary as possible during its operation, the risk of encounter with orbital debris or meteoroids is inevitable. As of May 2021, ESA's Space Debris Office has provided that about 129 million of debris is tracked to be in the orbit and 128 million of them alone are small pieces with size ranging from 1 mm to 1 cm [27]. Furthermore, any collision with orbital debris will possibly result in structural damage. A collision with large sized objects could lead to short-term destruction such as penetration to any component. On the other side, tiny particles are more likely to impose a long-term effect such as impact wear, degradation of components and also minor damage. Considering the fact that these hazardous debris are moving with an average impact velocity of 10km/s, a space elevator should be prepared to overcome this risk [28].

By observing the component of a space elevator, the cable, the geostationary station and the counterweight are assumably prone to the risk of encounter with orbital debris. This is due to the fact that these parts of space elevator are kept motionless in their respective position and are highly susceptible to damage due to constant exposure to the debris. However, the climber which are periodically moving up and down the structure is not less vulnerable to the collision. Handling the problem of orbital impact is entirely challenging since the vast majority of the debris are too small to be detected.

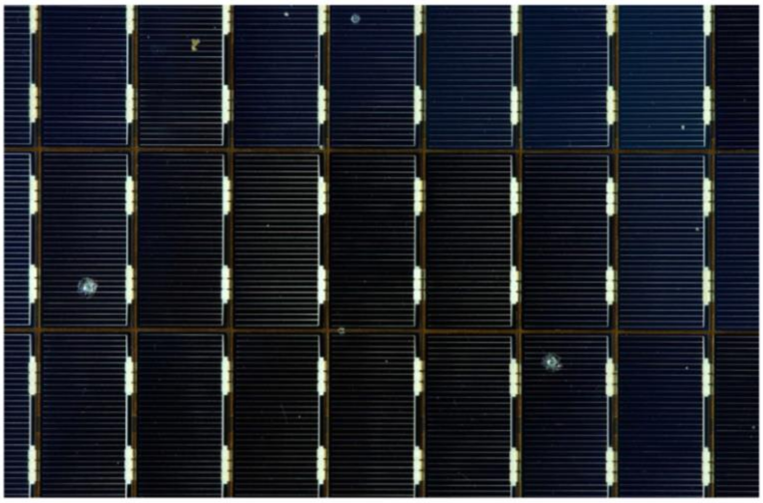


Figure 12.1.1. Impact craters on Hubble Space Telescope solar cells retrieved in March 2002 after 8.25 years in space. Source: [29].

12.2 Solution 1: Cable Reinforcement

The following formula indicates the criteria in which debris will do damage to the cable of the space elevator.

$$r_d + \frac{r_d \, sin(\emptyset)}{\tan(\theta)} \geq \frac{wf}{2} \tag{16}$$

Where,

r_d: the radius of the debris
w: the width of the cable
f: the cross-sectional fraction of cable that must be destroyed to sever it
$\emptyset$: the angle between the cable face and the incoming trajectory of the debris (in horizontal plane)
θ: the angle in the plane of the cable face between the debris trajectory and the cable's long axis (in vertical plane).

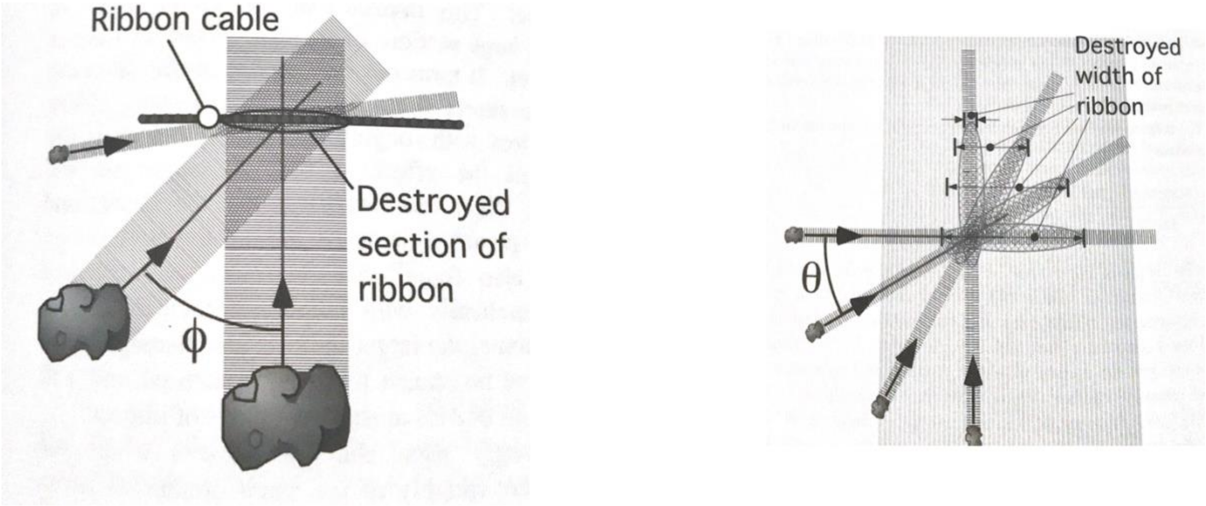


Figure 12.2.1. The representation of angle of impact respect to the axis of the cable.
Source: [1].

We can find the fraction of the debris that can break the cable as a function of its radius by integrating the relevant angles from the equation. In this case, we are assuming the debris to travel over the cable while crushing everything in its way. This situation is analyzed with a completely flat cable.

A journal called International Journal of Impact Engineering mentioned that any debris will be deflected out of the plane of the target once it hit the target [30]. Logically the debris will not move in its original trajectory after the impact. Moreover, the journal reported that an increase in incident angles of debris and target thickness will most likely result in more damage area [30].

Bradley C. Edwards proposed that the flat cable will be modified into a curvature to overcome the problem [1]. This is because a non-flat surface would eliminate the presence of any plane of the cable, which will then minimize the chance of being destroyed by debris. For this reason, the concept is that the cable will be made up of more than one strand of carbon nanotubes intertwined together instead of just a single strand all the way up to the geostationary altitude. Another precaution method includes coating the cable with a layer of gold or platinum for a few microns thick [3]. However, this method is unpractical since the solution is high-priced.

In a more generic perspective, the most efficient way to prevent orbital impact is to carry out an overall cleanup of the Earth orbit so as to provide a safer surrounding to the space elevator performance. Other than that, future development in the tracking system would be useful if the technology manages to detect and capture the undetectable tiny debris on the orbit. A specific mission is being planned by European Space Agency (ESA) to gather all space debris from the orbit which will be conducted in 2025 called ClearSpace-1 [31]. The issue is deeply concerning since the population of space debris will increase time to time as new debris will be created due to collision. Therefore, by implementing a fresh project named Active Debris Removal In-Orbit Servicing (ADRIOS), ESA team would be the first party to tackle this problem soon in the near future [31].

12.3 Solution 2: Protection for climber and counterweight

Unlike the cable, other component of the space elevator can adapt some of the readily recommended protection plan. In this section, we can reflect on the safety design of a spacecraft and customize it for the space elevator components since both of the systems accomplish quite similar mission.

The main concern is to provide a perforation-resistant multi-walled system with the purpose to minimize damage upon any hypervelocity impact. In this way, the space elevator components that are exposed to the orbital environment will have a significant improvement in protection against failure. In a journal written by W.P. Schonberg, he mentioned the possibility of using a non-metallic material for the multi-walled system [32].

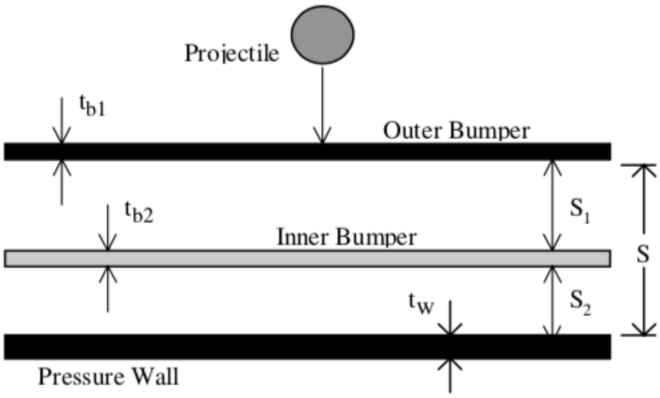


Figure 12.3.1. The structure of a multi-wall system. Source: [32].

12.3.1 Material for pressure wall

Firstly, composite materials such as graphite/epoxy is believed to be beneficial as a pressure wall of the component for several justifications.

Based on the experiment carried along with the journal, graphite/epoxy material has resulted in a better outcome in withstanding any critical cracking upon impact in comparison to the conventional aluminum pressure wall [32]. Furthermore, the graphite/epoxy material has a greater ballistic performance than aluminum for impact velocities. Other than that, it is relatively easier to repair a hole in graphite/epoxy panel than that of aluminum since the material is essentially non-deformed.

12.3.2 Material for inner bumper

In this case, the best material for inner bumper in the double-bumper systems varies based on the debris projectiles. Kevlar/epoxy inner bumper is more preferable in the situation where the impact velocities is low and small projectile [32]. This is due to the fact that this material will absorb a great amount of energy from the impacting debris which then results in minimal damage to pressure wall.

In contrast, the suitable bumper material for larger projectiles and high impact velocities is Spectra/epoxy [32]. Similar to the Kevlar/epoxy bumper, Spectra/epoxy bumper is also able to absorb the impact energy from the debris. However, this material is believed to be effective since it has a relatively low melting point which is around 140-150°C. At this point, the impacting debris is capable of melting the material which will then result in less concentrated perforation on the bumper panel. As a consequence, the debris passing through the bumper will have lower energy, fewer particles and less dense since most of its energy is transferred to the lamination of the bumper.

13. ATOMIC OXYGEN EXPOSURE EFFECT ON CARBON NANOTUBES

The components of space elevator located on the low earth orbit will be exposed to the atomic oxygen continuously. Unlike other oxygen compounds such as ozone (O_3) and oxygen gas (O_2), atomic oxygen is very destructive due to its high reactivity property. As a consequence, any component of space system that is subjected to this surrounding will result in erosion.

In a study of the carbon nanotubes behavior, the hypothermal collision between the nanotube wires and atomic oxygen is reported to have an erosion rate of 2.64×10^{-25} cm^3/atom [33]. Since the collision takes part at the surface of the material, the surface structure of nanotubes after being exposed to atomic oxygen will have lesser carbon but increase in oxygen. Over a long time, the nanotube surface will become rough due to constant exposure which can affect its mechanical properties.

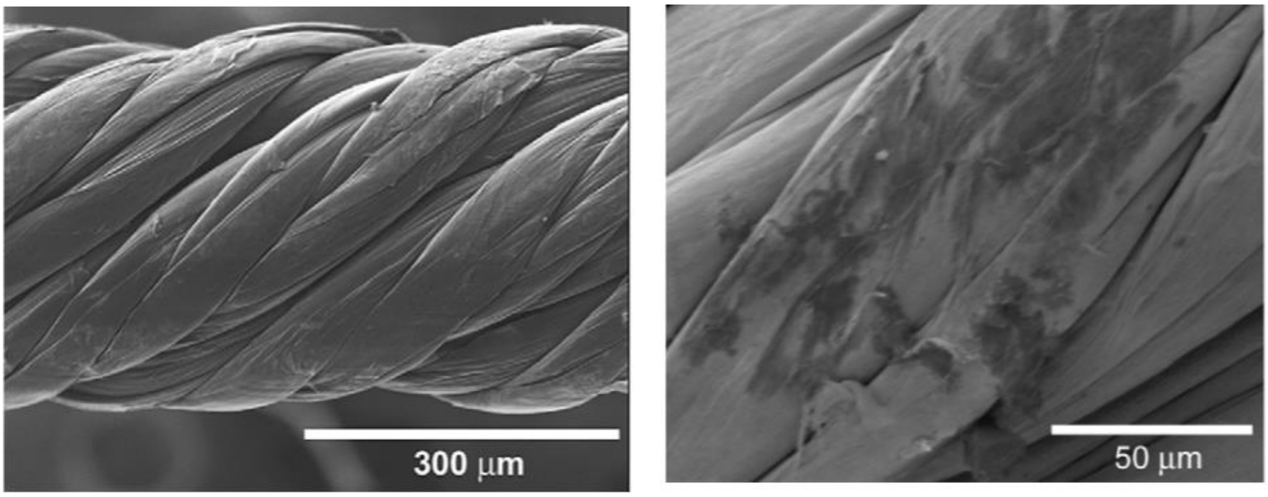
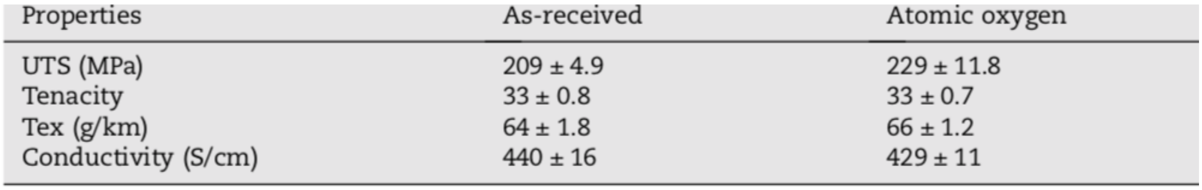


Figure 13.1. A scanning electron microscopy (SEM) images showing the comparison of a before and after effect of atomic oxygen exposure. Source: [33].

13.1 Mechanical properties

Even though carbon nanotube is currently the most ideal material for space tether application, any noticed degradation of its mechanical properties due to atomic oxygen exposure would severely threatens the long-term durability of space elevator. A test was conducted to analyze the changes in different properties when carbon nanotubes are put in contact with atomic oxygen [33].



Properties	As-received	Atomic oxygen
UTS (MPa)	209 ± 4.9	229 ± 11.8
Tenacity	33 ± 0.8	33 ± 0.7
Tex (g/km)	64 ± 1.8	66 ± 1.2
Conductivity (S/cm)	440 ± 16	429 ± 11

Table 13.1.1. Properties of 30-yarn carbon nanotube wire. Source: [33].

13.1.1 Tensile strength

Based on the results, there is no significant changes in the tensile strength of carbon nanotubes after being exposed to the mentioned surrounding. This is because the erosion only takes place on the outer surface of the strand and the damage only represent a small percentage from the entire structure. Therefore, the strength of the nanotube bulk is not significantly affected.

13.1.2 Electrical conductivity

However, it is observed to be a decrease in the electrical conductivity of nanotube after being bombarded with atomic oxygen. A reduction of 2.5% is recorded in table when the data drops from 440±16 to 429±11 S/cm. Since there are erosion and blister on the surface of the nanotube, these flaws will therefore impose a minor distraction in the direction of electron flow. Hence, the electrical resistivity increases which leads to reduction of conductivity of the carbon nanotube.

13.2 Solution

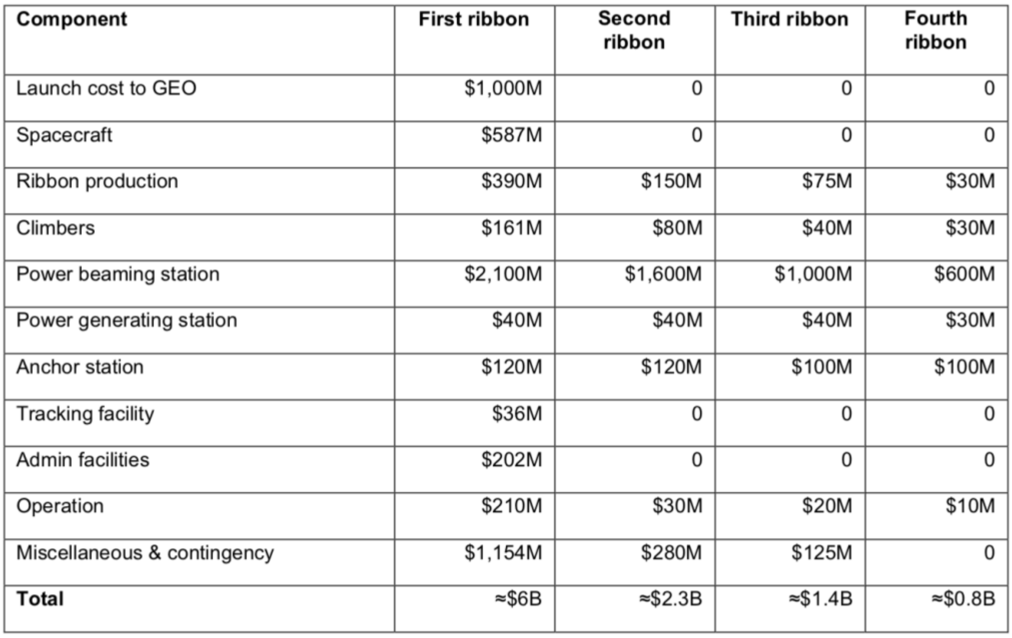
Since most of the effects of atomic oxygen exposure associate with the surface of the material, some protective layer can be applied on the surface of the carbon nanotubes. This protection layer will serve as a barrier to the atomic oxygen to prevent any direct contact with the carbon nanotubes. For instance, silicon containing material or metal can be use as the protective coatings. In this situation, the protective layer is the one that will oxidize when being exposed to atomic oxygen, instead of carbon nanotube. However, the coating should be reapplied as much as necessary to keep the material underneath it secure and safe from damage.

14. ECONOMIC TRANSPORTATION

As mentioned earlier in the beginning of the study, space elevator is certainly an economical form of transport compared to conventional rockets. If we break down the cost required in operating the space elevator, the cost dropped by half each time a consequent cable is made. This is because of the elimination of the primary cost regarding the launch of the cable at first place. In addition, facilities and administration system costs are also being canceled starting the implementation of the second cable and so on.

Generally, the cost of the putting more cables into operation will follow a pattern in a way that it gets cheaper every time. We can say that all that costs are worthy since space elevator can be reused to transport payloads back and forth for numerous times. This is because when space elevator is completely built in the near future, rockets will no longer in favor for space transportation. Instead, space elevator will be the primary choice due to its economic characteristic. The initial cost will gradually be compensated when all force utilizes this transport as their first choice.

As a result of this relatively low cost than the rockets, the rate to send payload up to space would also become inexpensive. Thus, space elevator concept is introduced to be an economical transport, with the cost to transport cargo is assumed to be as low as $10 per kilogram [3]. For an overall view, the construction cost of space elevator will be around $10 B, which is one fourth of the current space programs [34]. Notice that from the table below, the letter B is used to indicate billion, where 1 billion is equal to 1000 million.



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 14.1. Cost of producing additional cables of space elevator. Source: [1]

15. EMERGENCY MODE

15.1 Docking adapter

In the space elevator concept from the science fiction publications, some of them included a backup system in a case where things go wrong. For instance, in the novel The Fountains of Paradise by Arthur C. Clarke, a docking adapter is designed at the geostationary station to reach the climber within a certain distance in between them [16]. A docking adapter is referred to as a connection accessory used to adapt a pressurized tunnel between two different space vehicle components.

This system will allow an escape route for the passenger on board when the climber could not continue its journey up due to technical issues. However, this method has its own limitation. The climber needs to be within certain distance from the geostationary station in order for the adapter to reach it.

In this case, the docking adapter will be extended from the geostationary station and then a connection between the station and the climber will be established via coupling system. Once attach, the docking adapter can be used as tunnel to escape. During the coupling, the main concern is to ensure that the seal is always airtight to prevent any leakage.

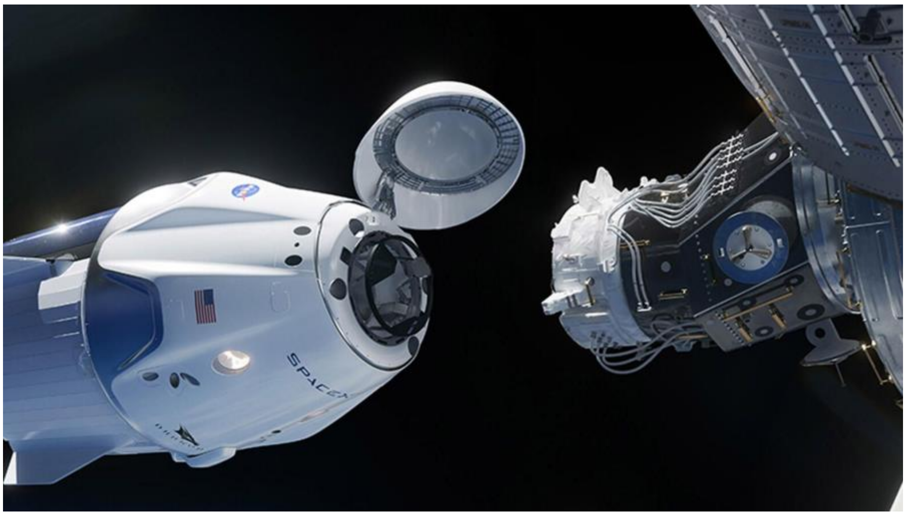


Figure 15.1.1. A docking system of SpaceX. Source: [35].

15.2 Parachute deployment

For the passenger escape plan in the event where the climber is facing system failure, parachute deployment system can be possible. This method is the most effective way since evacuating the climber is the only exit available. However, this method is only feasible in the condition where the climber is still within low altitudes in the Earth’s atmosphere. In addition, inflatable landing equipment can also be included to offer smooth and safe landing.

15.3 Boost to safe orbit

The most preferrable approach during system failure is to have a propulsion system to move the climber up to safe orbit. This altitude can be anything above 25,000 km from the ground and is considered safe to carry out repairing process or maintenance [23].

16. APPLICATION OF SPACE ELEVATOR

Space elevator concept can be practiced similar to rocket application and beyond that. Other than being cheap cost-wise, this new form of space transportation is also highly reusable. Human and non-human payloads can be transferred back and forth to geostationary altitude efficiently. For example, the climber could provide all the resources needed from the Earth and send it up to the orbit for space industries. On the contrary, all the minerals extracted from space mining can be transported down to Earth for further exploitation.

Other than that, the geostationary station can also be utilized as a transit point in the case where payload needs to be launched to another orbit. For example, the delivery of satellites into space can be assisted by space elevator in the future. By this method, a lot of work and money can be saved for the project. Furthermore, the transit point purpose can also be profited by providing maintenance services such as repair, refueling and also modification of satellites. In this case, the number of dead satellites in space can be slowly reduced by extending its lifetime.

From other perspective, the development of space elevator can also offer an opening of a new industry which is space tourism. The space can be promoted as a new holiday destination with an opportunity to enjoy zero gravity experience. The journey to the geostationary height itself is going to be breathtaking since the traveler will be able to witness a once-in-a-lifetime view of the horizon during the ascend.

The space elevator will be a direct bridge between the Earth and the space. For that reason, the geostationary station can be used as a base office for space industry. This is because the structure connects both worlds together and it is the most strategic place for space studies and researches. The scientist and engineers can go up and return to Earth frequently and in much lesser time than space craft. This new opportunity will absolutely provide greater outcome for microgravity industries than the current system. A development within this specific industry is crucial since the effect of microgravity will directly influence human health. Some of the examples of physiological problem due to the changes in gravity includes bone loss, cardiovascular deconditioning and recently discovered issue, spaceflight-associated neuro-ocular syndrome (SANS). In fact, there are a lot of other unmentioned health impact of microgravity to human bodies. For that reason, geostationary station of the space elevator is the most strategic location for further development in these industries. No doubt, there is a vast unforeseeable applications of space elevator in the future.

17. 3D DESIGN AND MODELLING

For this stage of the study, an AUTOCAD program named Siemens NX is involved in the process of 3D modelling. Just like the other design software, Siemens NX provide a flexible and efficient tool to create 2D and 3D model. Since I am familiar with how the program works, it gives me convenience from the beginning until the end of the modelling process to ensure that the space elevator design matches with what I have in my mind. The objective of creating a 3D model for every component of the space elevator is to illustrate a real-life image of the whole structure which can be comfortably viewed in a smaller scale compared to an original one.

In this part, a 3D model is designed for each component of the space elevator such as the climber, geostationary station, cable and counterweight. The images of the 3D model of the component are taken after the rendering process, where the appearance of the object is adjusted so that the model appears in a more realistic way. For that reason, a profound detail is given into the final product in which the material, color of component, background and lighting is taken into account. Other than the image of the 3D models, other part of the design such as the drawing, explosion diagram of the structure, isometric view of the structure and multiple views of the component are attached in the appendix.

17.1 Climber

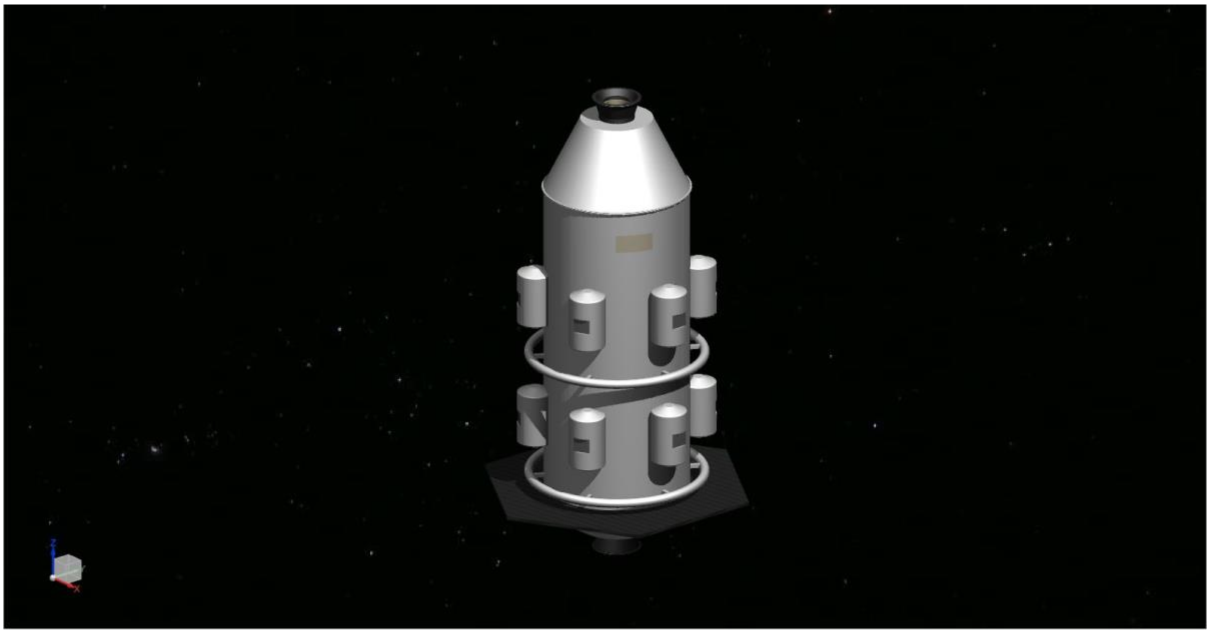
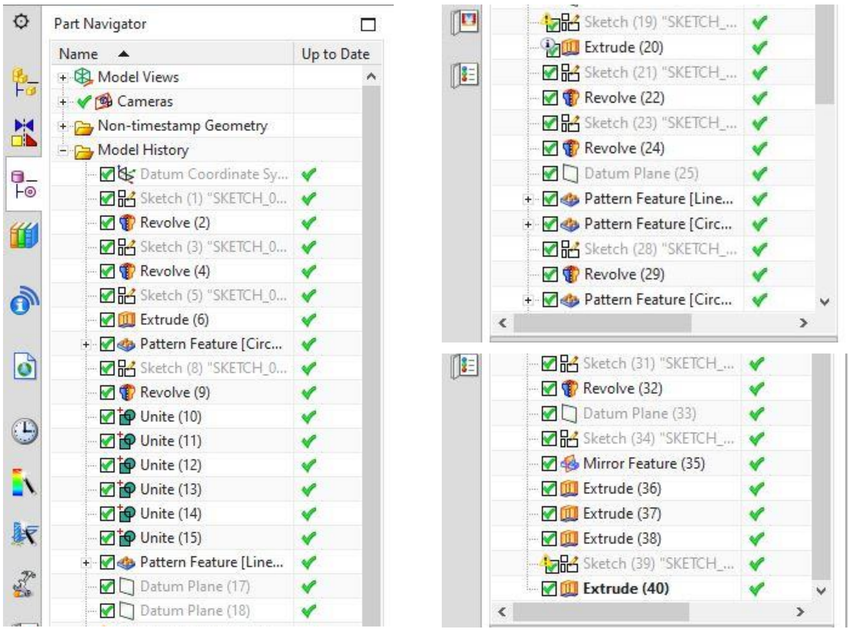


Figure 17.1.1. A 3D model of the climber of the space elevator. Source: [own source]

In the 3D modelling of the climber, several methods are used in order to design the component. For example, extrusion, revolution and pattern features are the most used program during the process of designing. Since the 3D model is in mm, the scale is 1:1000 in comparation to the real dimension.



Part Navigator

Name	Up to Date
Model Views	
Cameras	
Non-timestamp Geometry	
Model History	
Datum Coordinate Sy...	✓
Sketch (1) "SKETCH_0...	✓
Revolve (2)	✓
Sketch (3) "SKETCH_0...	✓
Revolve (4)	✓
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Revolve (32)	✓
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Sketch (34) "SKETCH_...	✓
Mirror Feature (35)	✓
Extrude (36)	✓
Extrude (37)	✓
Extrude (38)	✓
Sketch (39) "SKETCH_...	✓
Extrude (40)	✓

Figure 17.1.2. The list of steps in the 3D modelling process of the climber. Source: [own source].

The climber is portrayed as the moving component carrying payload back and forth to the geostationary station. For that reason, I personally design the climber in a way that it resembles a rocket but with several differential characteristics. As an example, the climber is equipped with a docking port at both upper and bottom end of the vehicle to facilitate docking process. Other than that, portholes are also included in the 3D modelling of the component. Even though there is no necessary reason for a rocket to have windows just like submarines, I included portholes considering the possibility of the passenger to have viewports inside the climber. The window will be made up of aluminum silicate glass which is the most common material used for space craft windows. The porthole feature will consist of 4 panes of glass to provide extra protection.

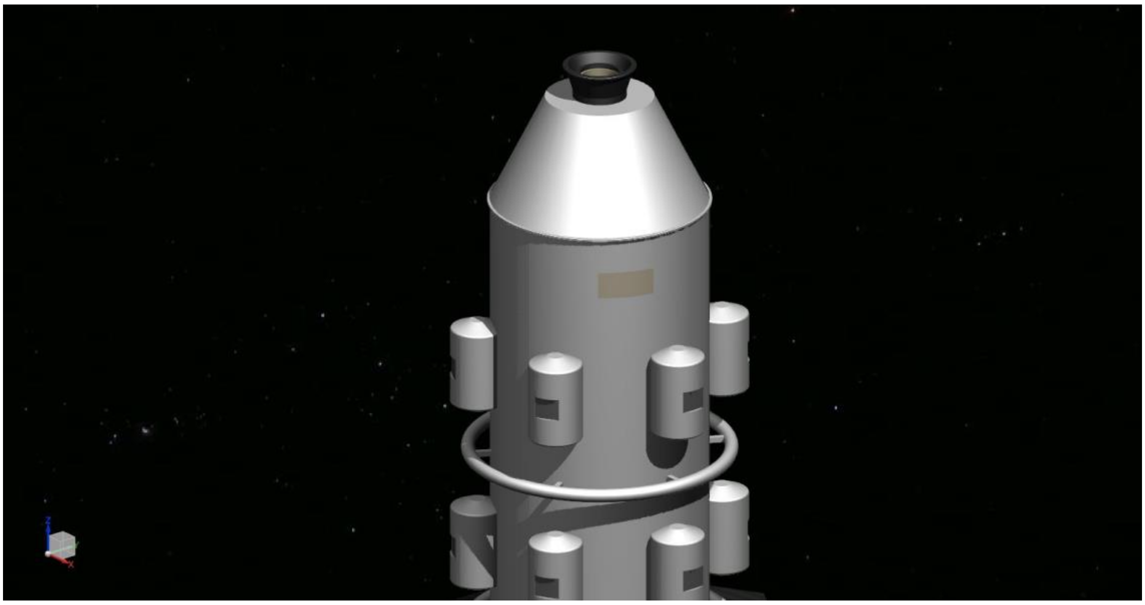


Figure 17.1.3. A magnified view of the upper part of the climber. Source: [own source]

Furthermore, a Gallium Arsenide (GaAs) photovoltaic panel is also included to the climber. Based on the Figure 17.1.4 below, the panel is located at the lower part of the climber to facilitate the laser receiving process. As a protection against the space debris, the climber's fuselage will be equipped with a multi-walled system as described in the previous subtopics. In this case, the pressure wall will be made up from graphite/epoxy material while the inner bumper will be made up of Spectra/epoxy materials.

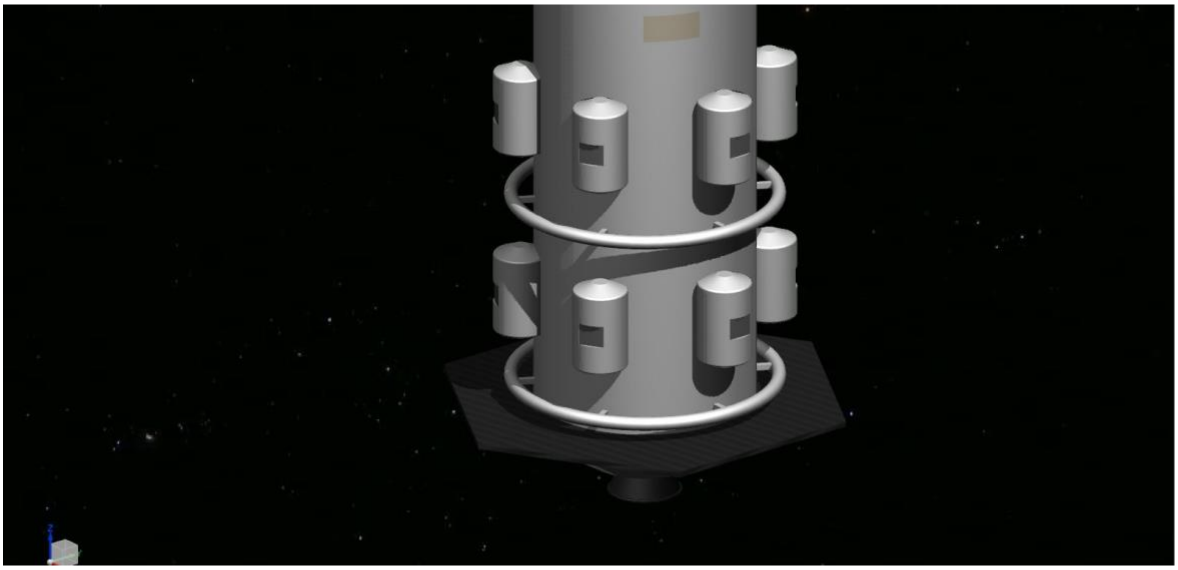


Figure 17.1.4. A magnified view of the bottom part of the climber. Source: [own source]

In the core of the climber where the propulsion mechanism takes place, the climber will be equipped with a pair of lateral guidance electromagnets as well as a pair of support magnet for levitation. The guidance electromagnet will keep the climber move in the right track as it operates.

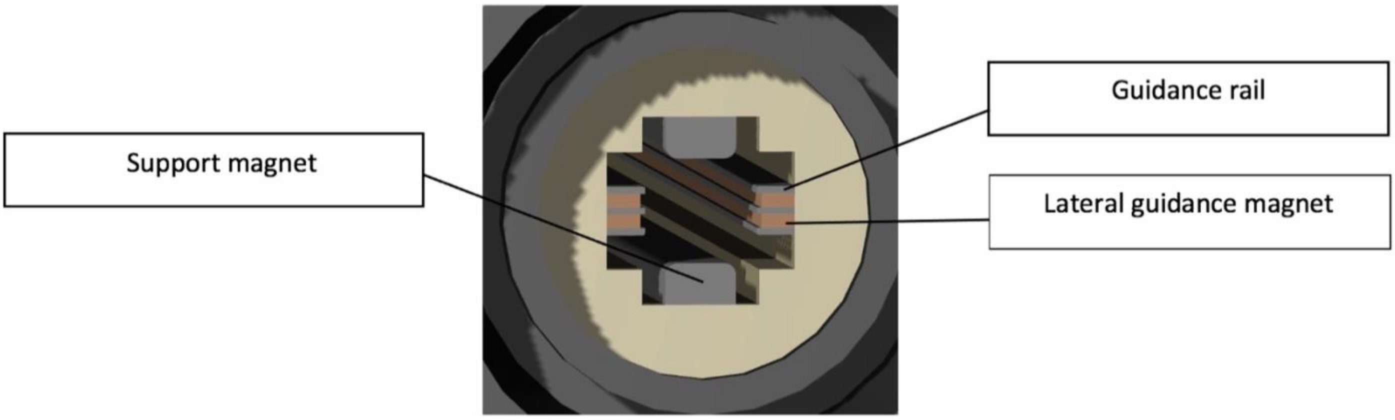


Figure 17.1.5. A magnified view of the magnetic drive system. Source: [own source].

17.2 Geostationary station

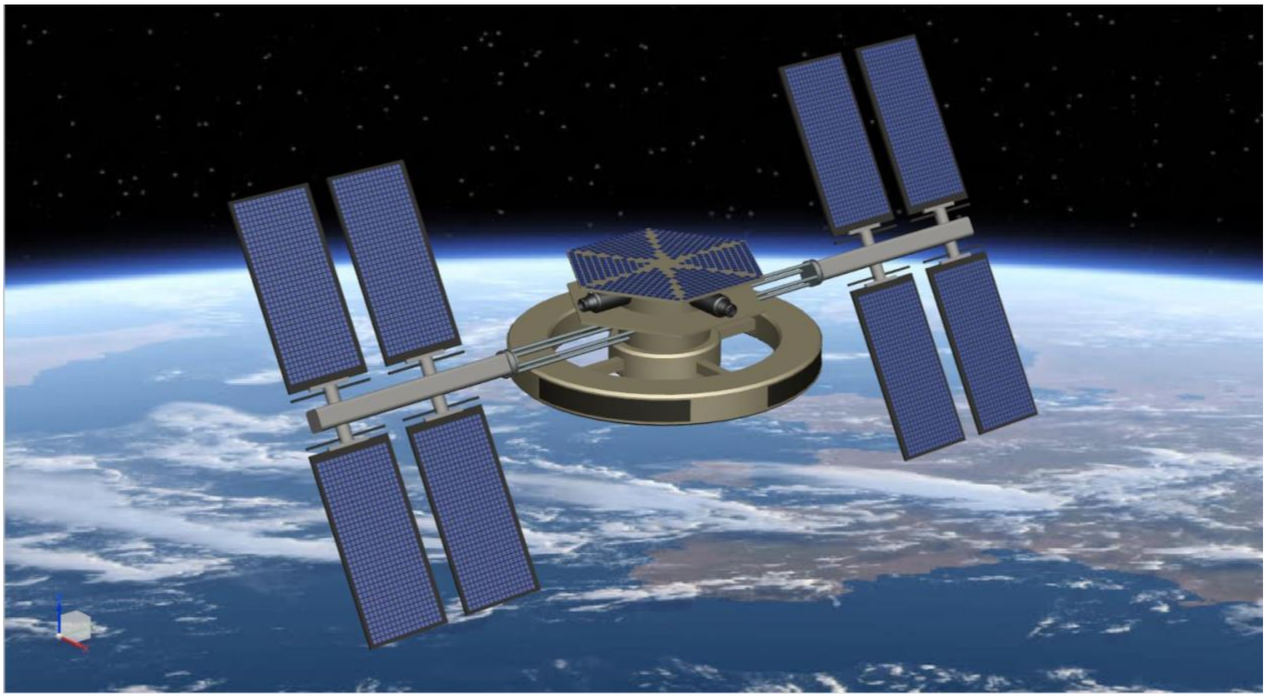


Figure 17.2.1. A 3D model of geostationary station of the space elevator. Source: [own source]

In the 3D modelling of the space station at the geostationary altitude, a few main features are displayed in the prototype as shown in figure 17.2.1. This specific station is conveyed is the main space hub where all the major transportation between the Earth and the space will take place. For that reason, the geostation will be equipped with amenities such as docking port to facilitate connection with other space vehicle. In addition to that, there is also a designated area in the geostation for the living space. This area includes the accommodation for the all the staff at the station and guests, control office, research laboratory and space elevator terminal. Just like the climber, the geostationary station will incorporate a multi-walled system to provide protection against space debris impact.

The main power supply used for the geostation is solar energy. For that reason, a wide number of solar panels is incorporated to the 3D design of the station. This is to maximize the direct absorption of sunlight for electric generation for the on-board usage. The design of the solar panel is inspired by the one used in the International Space Station by NASA [36].

The 3D model only displays the main component of the geostationary station without an in-depth detailing. Various method is utilized during the modelling process such as solid extrusion and revolve around specific axis. Another method that is frequently applied in the NX software was pattern feature. This method produces a cloning effect of selected object so as to facilitate the modelling of a multiple same parts. Since the 3D model is in mm, the scale is 1:1000 in comparation to the real dimension.

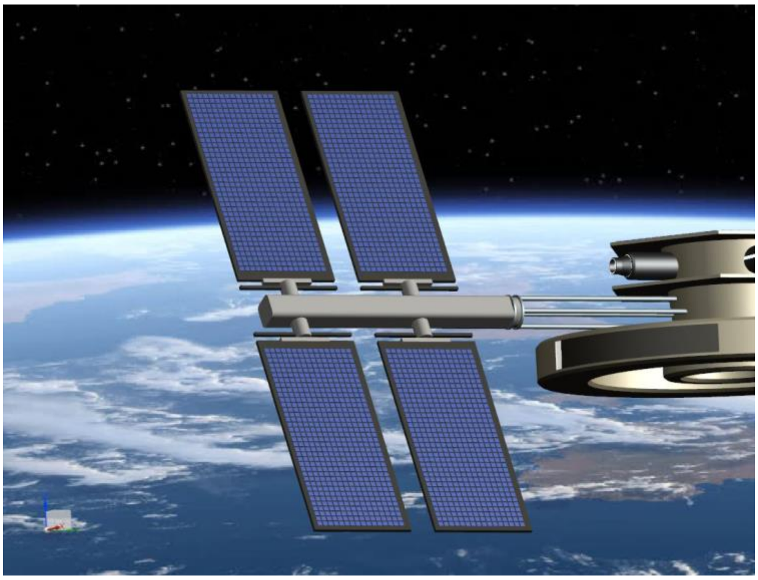


Figure 17.2.2. A magnified view of the solar panel of the geostationary station. Source: [own source].

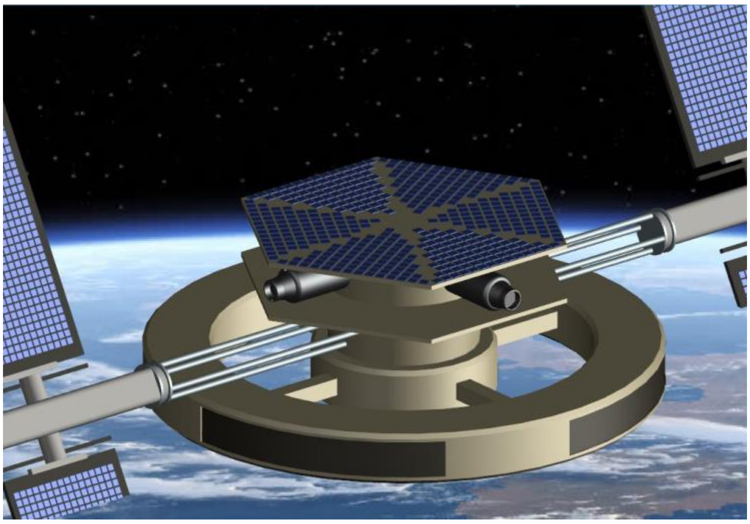
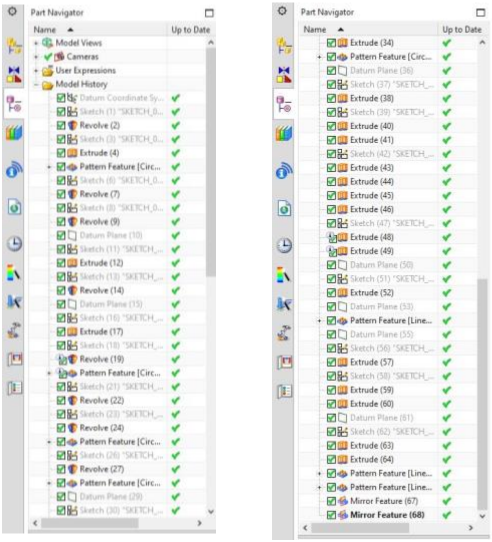


Figure 17.2.2. A magnified view of the station. Source: [own source].



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☑ Mirror Feature (67)	✓
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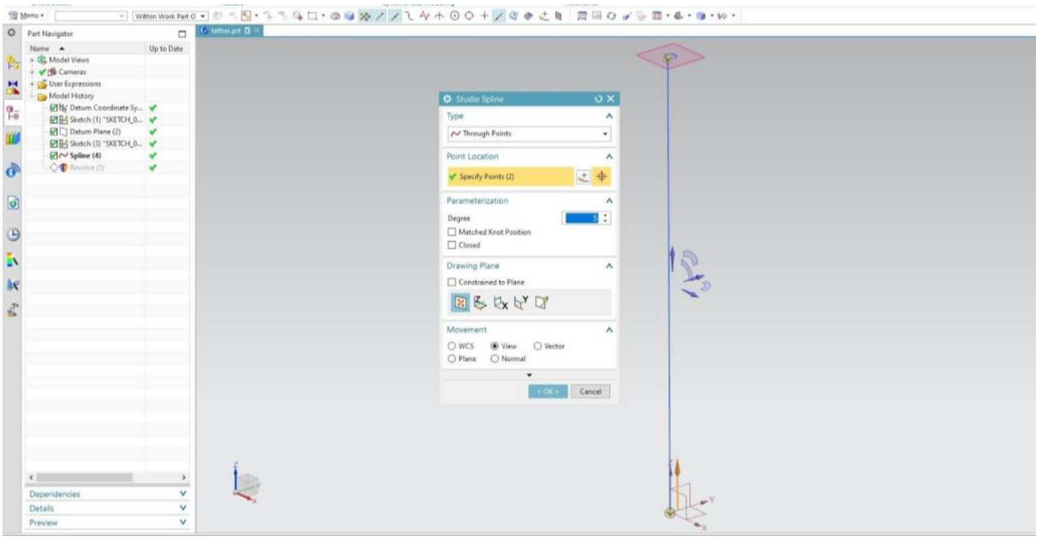
Figure 17.2.4. The list of steps in the 3D modelling process of the geostationary station. Source: [own source].

17.3 Cable

The cable is displayed as a simple tether that is connecting the geostationary station and the base station at the same time. In the Figure 17.3.1, the tapering effect of the cable is exaggerated. In real life situation, the tapering of the cable could not be easily notice due to the small taper ratio. As a precaution measure against atomic oxygen threats, the cable will be coated with silicon containing material or metal as the protective coatings.

The method used for the tapered cable in NX software is spline technique. The method is done by creating different curve which will then be connected to each other by an arch. The arch curvature can be adjusted to either be smooth or harsh based on the degree of spline. Since the 3D model is in mm, the scale is 1:50000000 in comparation to the real dimension.



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Revolve (5)	✓

Studio Spline

Type

Through Points

Point Location

✓ Specify Points (2)

Parameterization

Degree 5

☐ Matched Knot Position

☐ Closed

Drawing Plane

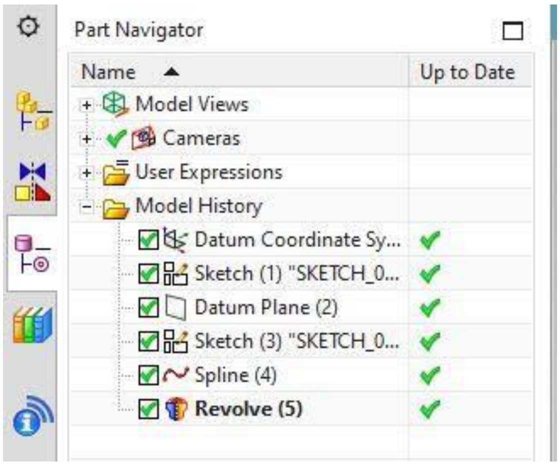
☐ Constrained to Plane

Movement

○ WCS ● View ○ Vector

○ Plane ○ Normal

Figure 17.3.1. A spline process in Siemen NX software. Source: [own source].



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☑ Spline (4)	✓
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Figure 17.3.2. The list of steps in the 3D modelling process of the cable. Source: [own source].

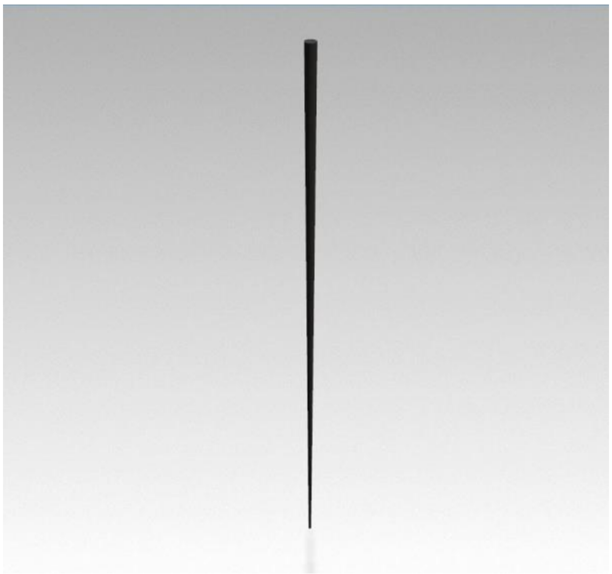

Figure 17.3.3. An isometric view of the cable. Source: [own source].

17.4 Counterweight

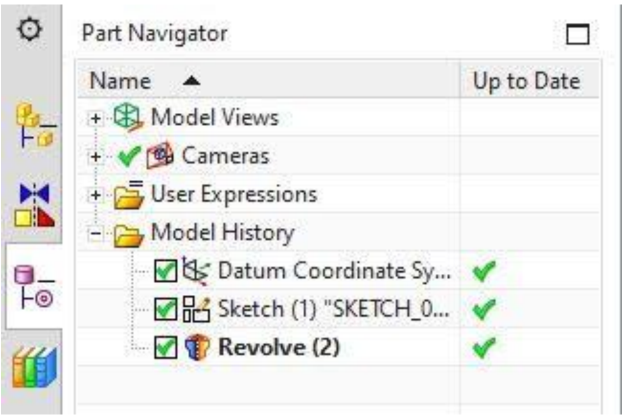

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Figure 17.4.1. The list of steps in the 3D modelling process of the counterweight. Source: [own source].

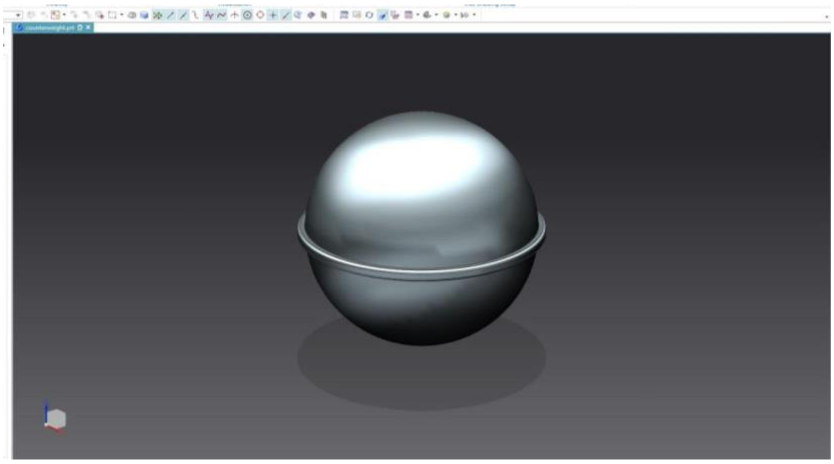

Figure 17.4.2 An isometric view of the counterweight. Source: [own source].

17.5 Assembly

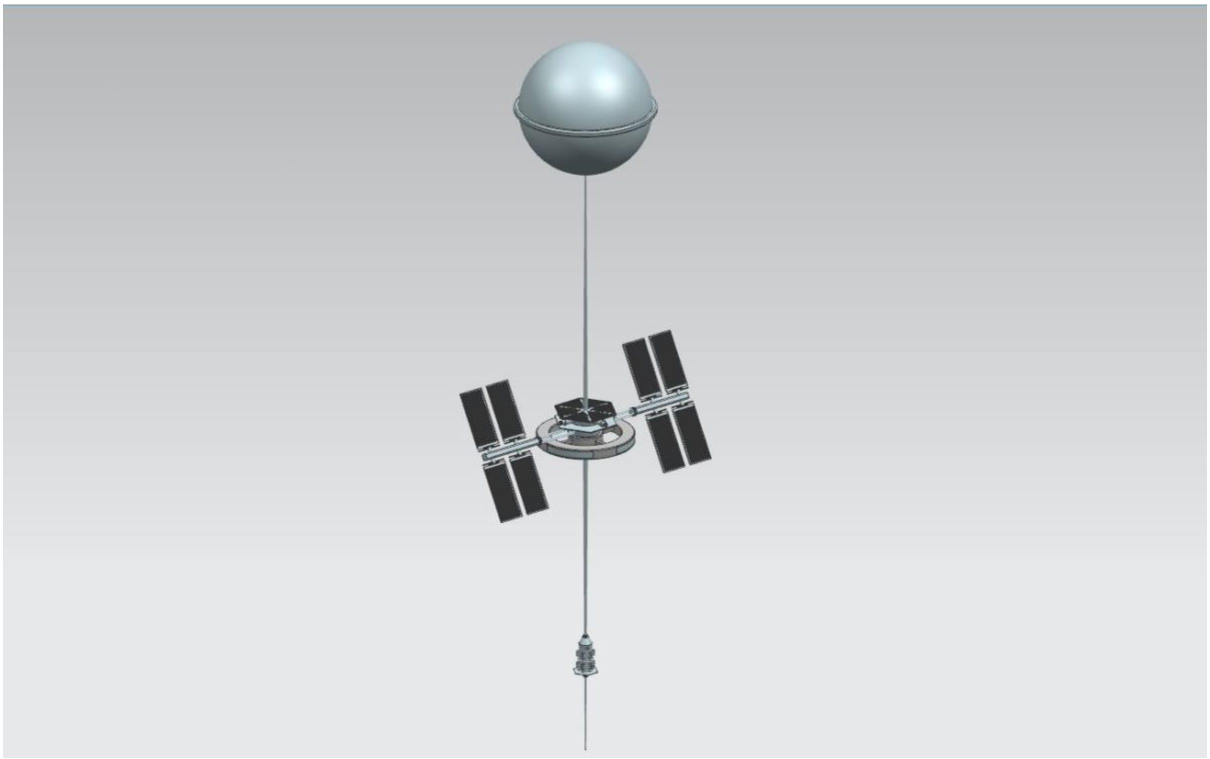

Figure 17.5.1. A 3D assembly of the space elevator excluding the base anchor. Source: [own source]

Component	3D model dimension	Main features	Ratio of 3D model to real scale
Climber	Height= 264,4 mm Diameter= 80 mm	I. Electromagnetic drive system II. Gallium Arsenide (GaAs) photovoltaic cell III. Docking ports IV. Multi-walled system	1:1000
Geostationary station	Height= 42,5 mm Outer diameter= 586 mm Inner diameter= 436 mm	I. Docking ports II. Solar panels III. Living space IV. Multi-walled system	1:1000
Cable	Length= 2880 mm Upper end diameter= 2,28x10^{-5} mm Lower end diameter= 1,2x10^{-5} mm	I. Tapered cable II. Protective layer coatings	1:50000000
Counterweight	Diameter= 800 mm	I. Initial cable deployment before serves as counterweight	1:10000

Table 17.5.1. A brief summary of the proposed space elevator design. Source: [own source].

In comparison to the design chose by Ahmad Hatim in his work in Subchapter 4.5, a few differences can be pointed out. For example, Ahmad proposed a mechanical propulsion mechanism of the climber instead of electromagnetic driver system [12]. For that reason, a modification can be identified at the middle part of the climber where I included the magnet pairs and guidance rail instead of track and roller. Since their working principle are different to one another, each mechanism has its own advantages and disadvantages. As an improvement to the climber model created by Ahmad, I included docking ports at both ends of the climber to facilitate the docking process. For more detailing, I added features like viewports and cabin space to my climber design.

For the geostationary station design, several improvements can be mentioned from the proposed design in this paper. I included more main features to the station such as solar panels, docking ports and a more defined living space. I have also specified some of the materials required for the components as well as their respective protection measures.

18. OPPORTUNITIES FOR FURTHER DEVELOPMENT

The space elevator concept not just involves the space technologies but also other related industries such as robotic and automotive industries. Concurrent development in those industries mentioned will brighten up the possibility of building a space elevator, even sooner than anticipated.

A proposal has been made from NASA publication on August 2000 about the chance of expanding the robotic field for further development of space elevator concept [23]. Based on the publication, robotic technologies can be beneficial for maintenance service of the space elevator structure. Apart from that, any assembly of the structure can also be carried out by high-tech robot. This being said, the robot will be the main force used in the construction process and also in moments where any component of the space elevator requires repair service. This approach will not only reduce the risk of human intervention, but also provide a high level of precision during its operation. Since the robot will be fully autonomous, it will fully recognize the task needed to be done according to the situation.

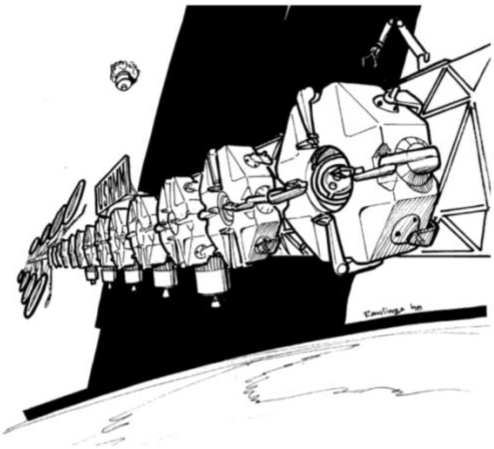

Figure 18.1 The proposed modular robotic systems for space assembly, maintenance, and repair. Source: [23]

For the automotive industry, a development is needed in adapting the propulsion mechanism of the climber. Since one of the possible methods is by using electromagnetic propulsion, several modification and adaption is needed for the climber. The readily existing electromagnetic levitation and propulsion mechanism is proven efficient for ultrahigh-speed transportation such as the bullet train. However, for the space elevator concept, the circumstances in which the vehicle moves have changed since the climber will accelerates vertically instead of horizontally. For that reason, specific adaptation must be made to ensure the propulsion mechanism practicability.

19. CHALLENGES

19.1 Mechanical resonance

One of the main challenges in the safety of the space elevator is mechanical resonance [3]. Even though the structure will be stationary, the cable will still be subjected to oscillation, be it transverse or longitudinal. Whereas any compression and tension force along the cable will result in longitudinal oscillation, any force that causes the perpendicular movement of the cable creates transverse oscillation. These movements may not be noticeable from visual observation, but they are present along the cable. On top of that, there is also torsion. These oscillation and torsion are categorized to internal movement of the system.

However, when there is an external force applied to the system, there might be a possibility of the cable to move similar to its resonance frequencies. Subsequently, this phenomenon will cause the cable to move vigorously due to an increase in amplitude. The main concern that can possibly provide an external force to the space elevator is the wind from the Earth atmosphere. Apart from that, the ultra-speed movement of the climber back and forth to the geostationary altitude can also be one of the factors that contributes to external force. For that reason, the climber will be prohibited to travel at certain speeds to avoid transverse oscillation of the cable. Another initiative to reduce vibration along the cable is by installing dampeners at the anchor base.

19.2 Environmental issues

Since the space elevator connects both the Earth and the space, the structure will be exposed to various atmosphere which potentially causes damage to its components. In this context, the lower part of the space elevator is exposed to the Earth atmosphere, in which the main concern is the weather condition such as cloudy and windy. Apart from that, the upper part of the space elevator will be subjected to outer space, where the environment is much more extreme in term of temperature and radiation damage. There are numerous threats in the space environment such as meteoroids, space debris, ultraviolet radiation and atomic oxygen. These factors are significant enough to cause harm to the material used for space elevator components such as material erosion. For that reason, it is essential to study the space environmental effect before designing each component of the space elevator to ensure the prolong survivability of the structure. Aside from space surrounding, lightning strike in the Earth atmosphere could likely destroy the cable. This is due to the fact that an average lightning bolt consists up to one billion volts of electricity which is enough to snap the cable.

20. CONCLUSION

As a conclusion, the concept of space elevator would be a great development in the space technology. The reason behind this statement is that the space elevator will be known as a better transportation system between the Earth and the space, which offers the same service as conventional rocket, but at cheaper price point. However, the construction of this structure comes at a price. Prior to building space elevator, the parties involve should carry out an in-depth research for every inch of the space elevator concept due to its complexity. Based on the study done in this paper, there is a wide range of challenges that could result in the failure of the structure such as external threat, unavailability of suitable material for construction or even lack of appropriate technologies for the development of the space elevator.

Furthermore, a real-scale prototype for the space elevator is quite complex to make before the real construction of the structure. A real scale prototype is essential to analyze the behavior of the components when exposed to their respective surrounding and to make sure that the components are strong enough to survive in the atmosphere. However, it can be quite complicated since the development of a real scale prototype alone is time and cost consuming. Without this procedure, there is a possibility of other numerous threats that is overlooked during the research which may impose danger to the space elevator.

Based on the study, some conclusion can be made for the design of the space elevator. For the cable design, the Standard model design is chosen since it has a greater strength than the Hoytether design. This can be proved by a better stress distribution for the cable when it is put under the stress analysis through Siemens NX. This cable will be made up of the most suitable material for space elevator to date, which is carbon nanotubes. A protective layer coating made up of silicon containing material or metal is necessary to overcome the risk of atomic oxygen erosion.

As of the design of the climber, the component will incorporate an electromagnetic propulsion mechanism while using power beam as the power source. An electromagnetic propulsion mechanism which is inspired by the ultra-speed bullet train is believed to be a better choice than a conventional track-roller system which depends on mechanical system propulsion. Since electromagnetic driver system is more commonly used as the climber propulsion in the science-fiction publications, there is still a wide room for exploration under the topic. For example, further discoveries are needed to incorporate long stator to the cable. In addition, the climber will incorporate a multi-walled system to its fuselage as a protection measure against space debris impact. In this case, the pressure wall will be made up from graphite/epoxy material while the inner bumper will be made up of Spectra/epoxy materials.

For the geostationary station, the main power supply would be solar energy which will be absorbed by the solar panel installed to the station. The station will also be equipped with amenities such as docking adapter to facilitate connection with other space vehicle.

In the future work, more specification is required in the details of the climber. For example, the weight limit of the climber and its payload is not discussed in this study. This vague fact will bother the determination of maximum number of passengers on the climber during the journey up to geostationary station. Apart from that, further research can be done on the specific features of the geostationary station and climber. Up until now, there is still undeveloped ideas in certain part of the concept such as the electromagnetic propulsion mechanism for the climber. At the same time, mechanical properties like volume and weight of these component can be determine as well. In the science-fiction novel The Fountains of Paradise, Arthur C. Clarke had mentioned about the psychological fear that may be experienced by human payloads during the journey [16]. This topic is interesting but rarely be discussed about during the discourse of space elevator. Hence, future research can include this issue as an improvement. From my point of view, space elevator is not something impossible to achieve in the future even though not within the upcoming decades. That being said, a Japanese company, Obayashi Corporation plans to be the first creator of the space elevator in 2050 [37]. With sufficient infrastructures, suitable materials and advance technologies, space elevator is quite feasible.

Overall, I think I have fulfilled all the objectives for this project.

ACKNOWLEDGEMENT

Firstly, I would like to express my gratitude to Manuel Moreno Lupiáñez, my supervisor who have guided me since the beginning until the completion of this project. Reminiscing to the early stage of the project, my supervisor has helped me to choose a topic through his proposals and it was very helpful since I did not have any specific topic in my mind at that time. After several discussion and meetings, I made up my mind to do a project about the space elevator. I gained confidence in pursuing about space elevator after hearing some people's opinion including Manuel.

I also appreciate my supervisor for recommending every possible resource that would help me with my research. Undoubtedly, those resources were very helpful and informative which provide me a wide range of references to do my report. During the development of the project, I have received advices and recommendation from him about my report which helped me to make some improvement before the final delivery. Other than that, I am also super thankful for his ability to respond any inquiries instantly along the final dateline of this project. I could not ask for a better supervisor than him.

Other than that, I also would like to suppress my gratitude to my friend who have given me continuous support and comfort in finishing this project. Those words of encouragement really meant so much and was one of the driving forces that kept me going until the final submission of the project. These people have filled my last few months of my degree life with support and joy and I will surely miss that in the future.

Last but not least, I would like to thank everyone who is directly or non-directly involved in the process of completing this project. All of the help and support from you is very much acknowledged by myself in my heart.

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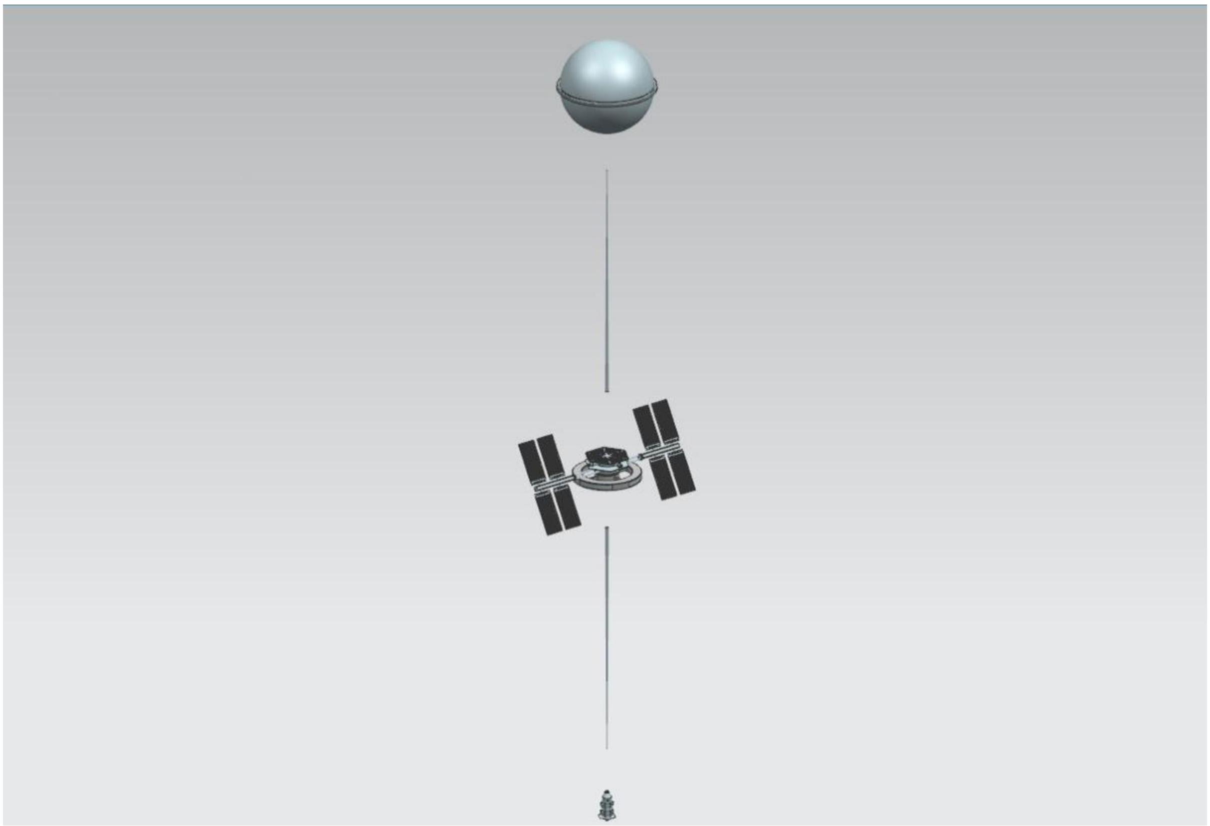
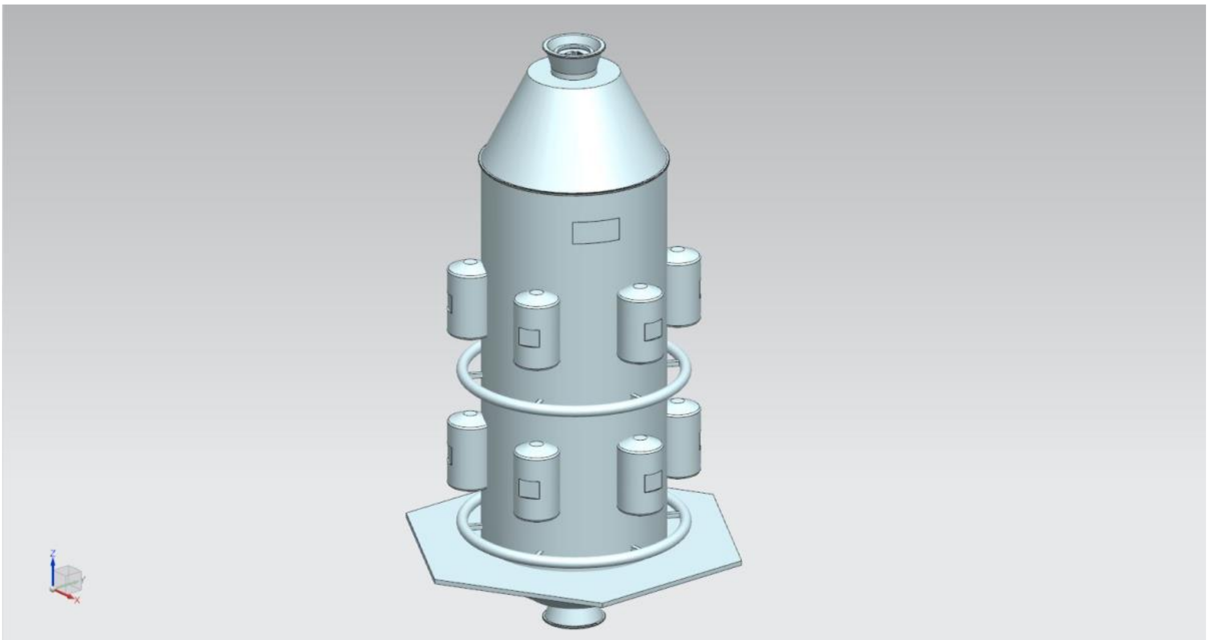
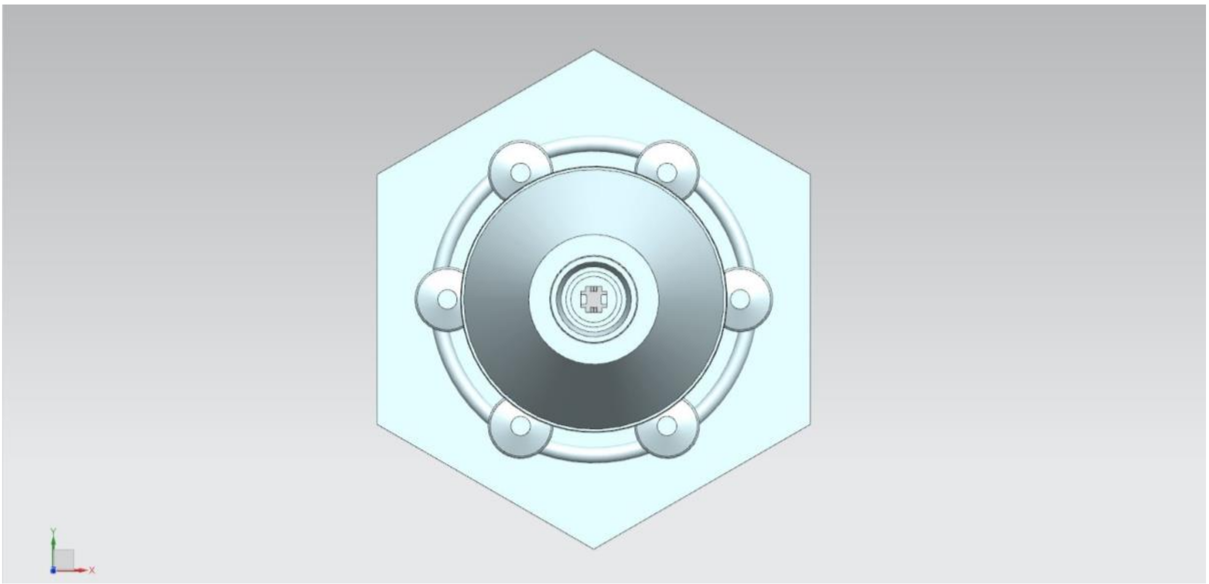
APPENDIX

An explosion diagram of the space elevator components.



Multiple views of the climber model.

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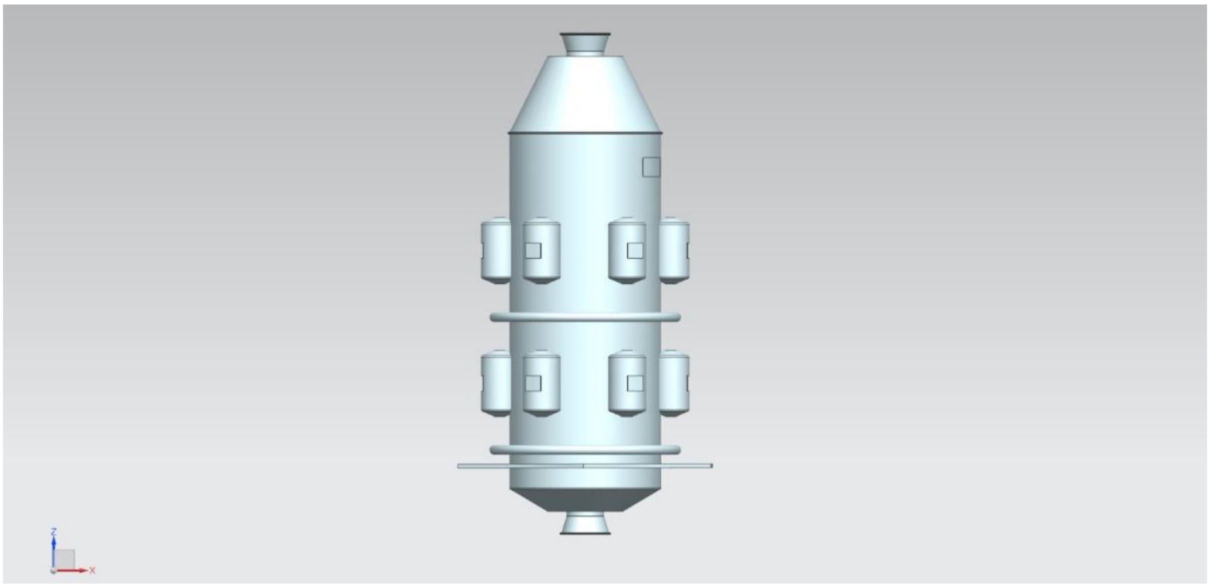
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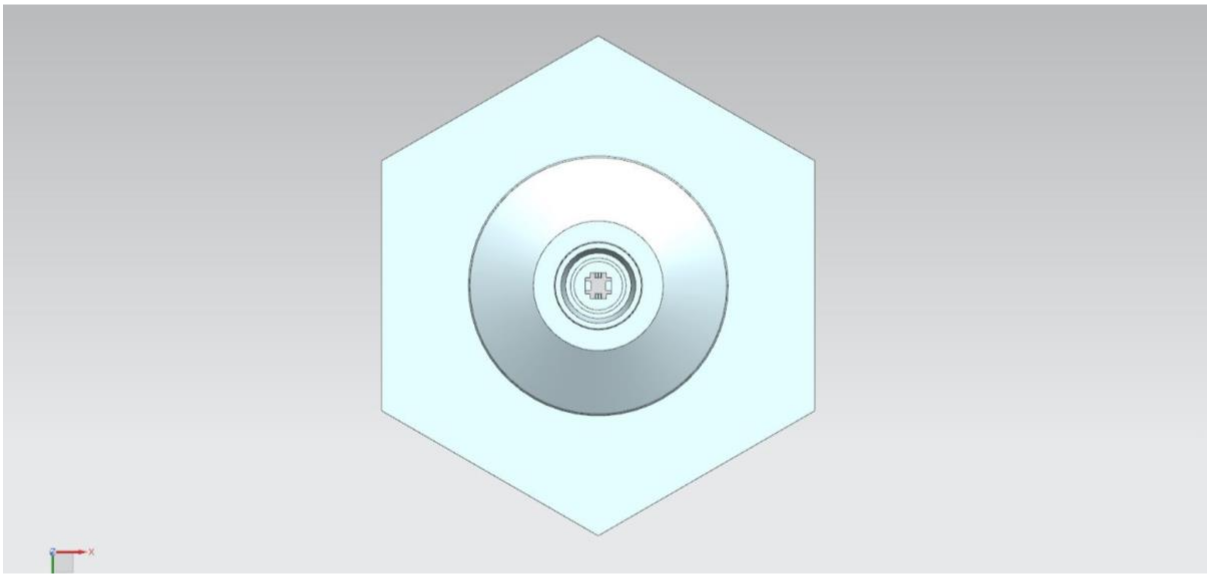
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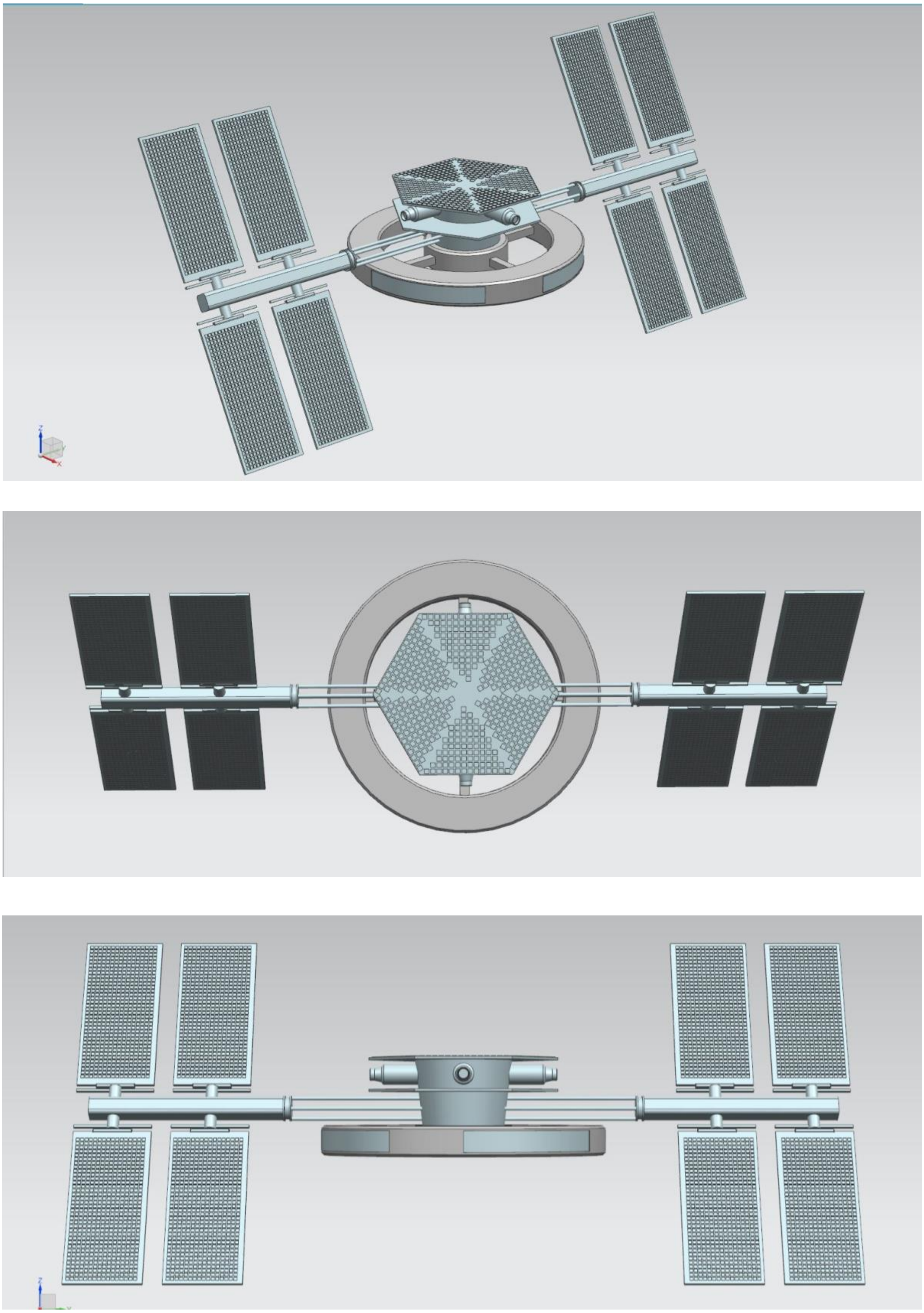
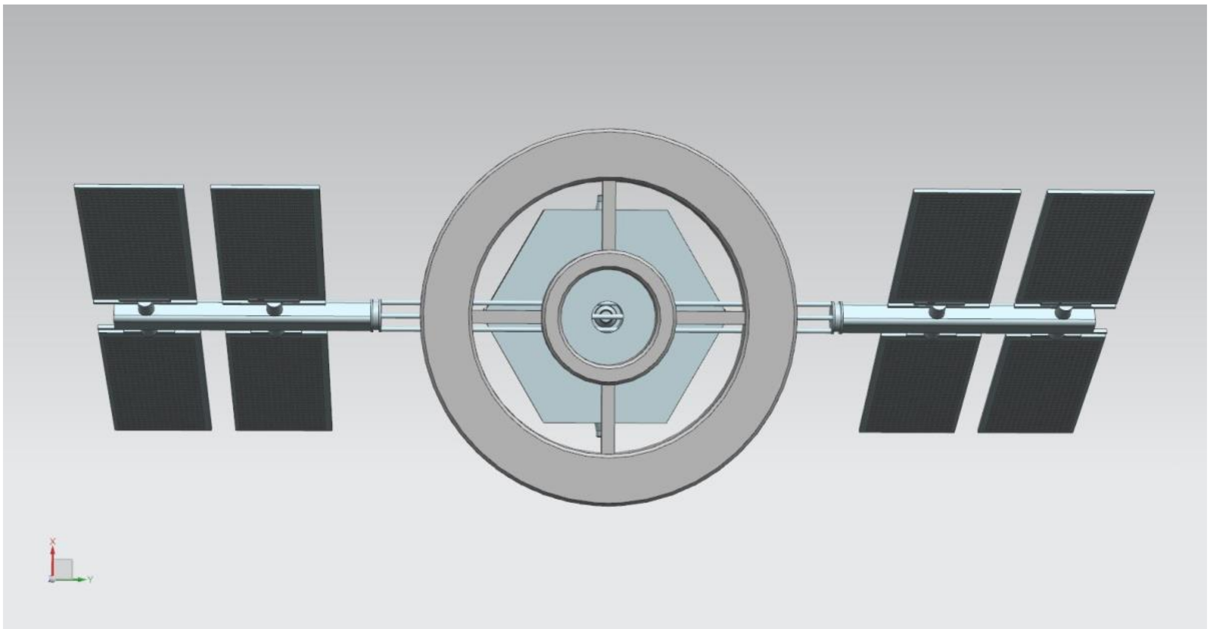
Multiple views of the geostationary station model.

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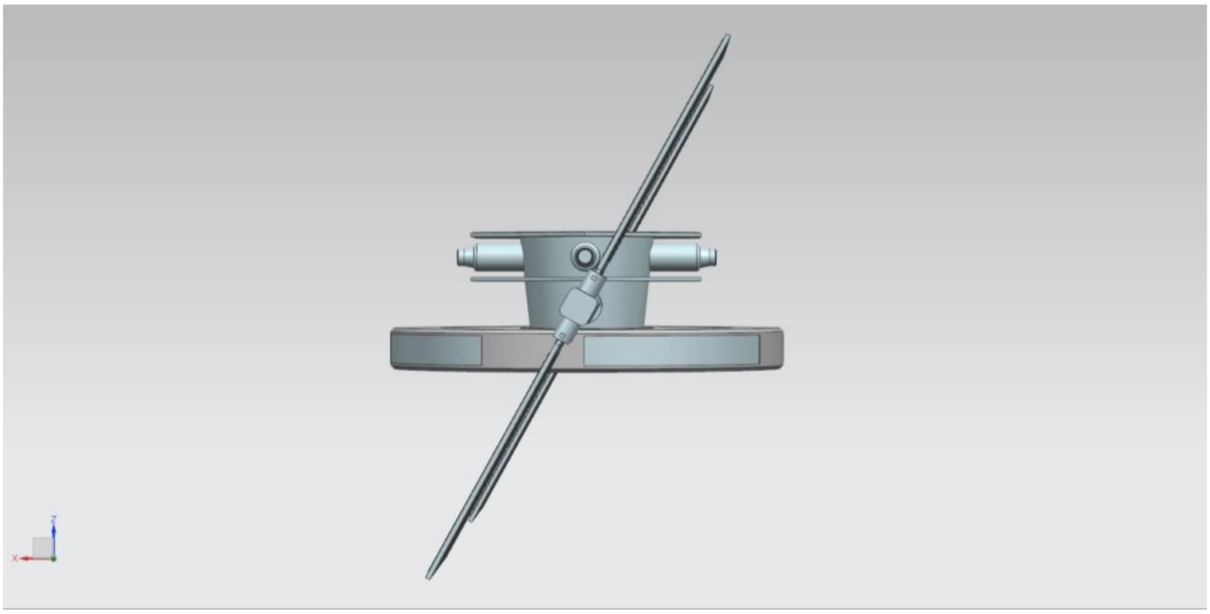
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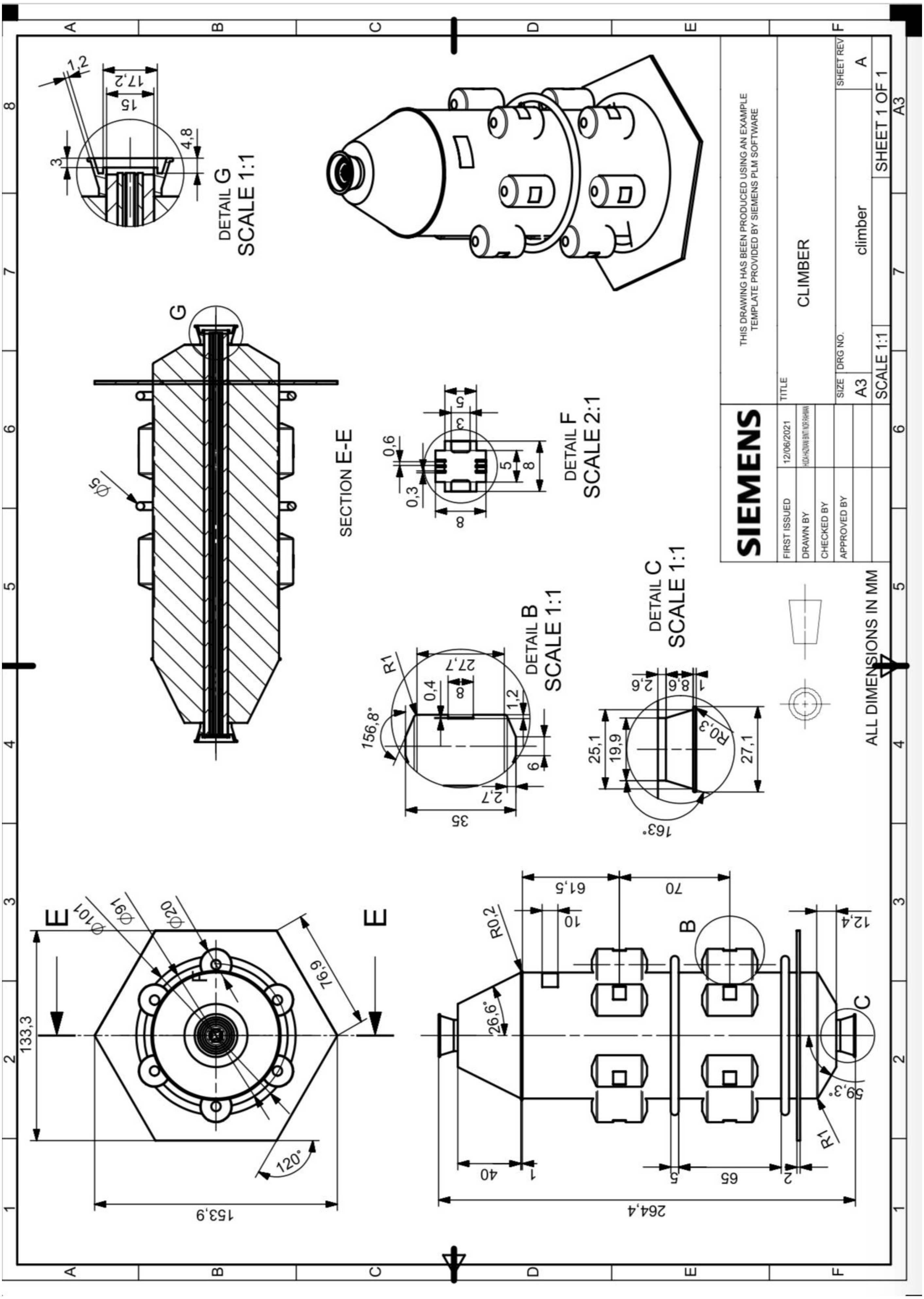
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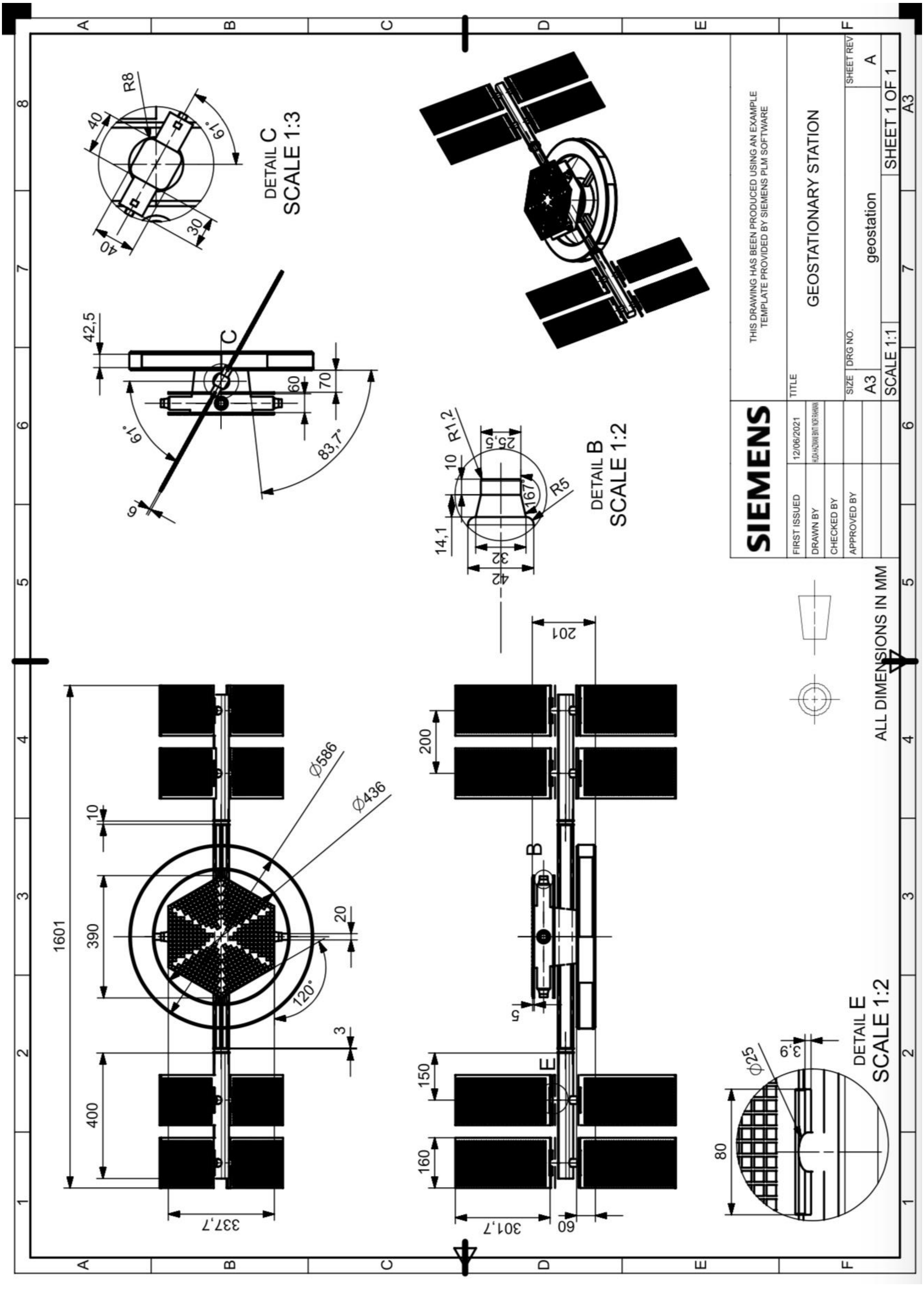
SCALE 1:1
SECTION E-E
DETAIL F
SCALE 2:1
DETAIL B
SCALE 1:1
DETAIL C
SCALE 1:1
G
B
C
F
E
E
1,2
17,2
15
3
4,8
Ø5
0,6
0,3
3
5
5
8
8
R1
27,7
0,4
8
1,2
156,8°
6
2,7
35
2,6
8,6
1
R0,3
25,1
19,9
27,1
163°
133,3
Ø101
Ø91
Ø20
76,9
120°
153,9
R0,2
61,5
70
10
12,4
26,6°
59,3°
R1
40
1
5
65
2
264,4
ALL DIMENSIONS IN MM
SIEMENS
THIS DRAWING HAS BEEN PRODUCED USING AN EXAMPLE TEMPLATE PROVIDED BY SIEMENS PLM SOFTWARE
FIRST ISSUED
12/06/2021
DRAWN BY
HUDA HAZWANI BINTI NOR RAHMAN
CHECKED BY
APPROVED BY
TITLE
CLIMBER
SIZE
A3
DRG NO.
climber
SHEET REV
A
SCALE 1:1
SHEET 1 OF 1
A3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R8
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30
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42,5
C
60
70
61°
83,7°
9
DETAIL B
SCALE 1:2
R1,2
10
25,5
167
R5
14,1
32
42
201
200
150
160
301,7
60
5
B
E
1601
390
10
20
3
400
337,7
Ø586
Ø436
120°
DETAIL E
SCALE 1:2
Ø25
3,9
80
ALL DIMENSIONS IN MM
SIEMENS
THIS DRAWING HAS BEEN PRODUCED USING AN EXAMPLE TEMPLATE PROVIDED BY SIEMENS PLM SOFTWARE
FIRST ISSUED
12/06/2021
DRAWN BY
HUDA HAZWANI BINTI NOR RAHMAN
CHECKED BY
APPROVED BY
TITLE
GEOSTATIONARY STATION
SIZE
A3
DRG NO.
geostation
SHEET REV
A
SCALE 1:1
SHEET 1 OF 1
A3
A
B
C
D
E
F
1
2
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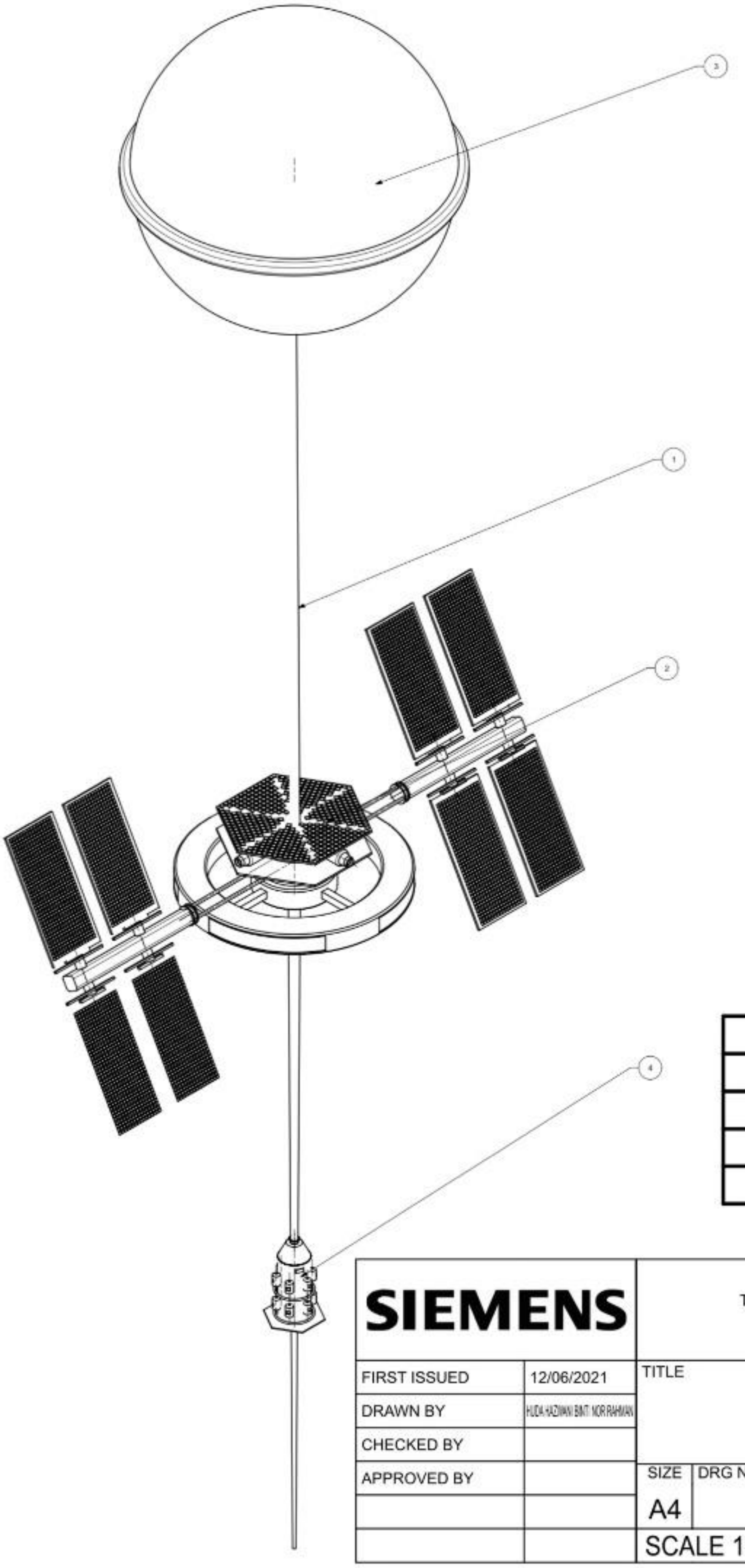
4
5
6
7
8



4	CLIMBER	1
3	COUNTERWEIGHT	1
2	GEOSTATION	1
1	TETHER	2
PC NO	PART NAME	QTY

SIEMENS

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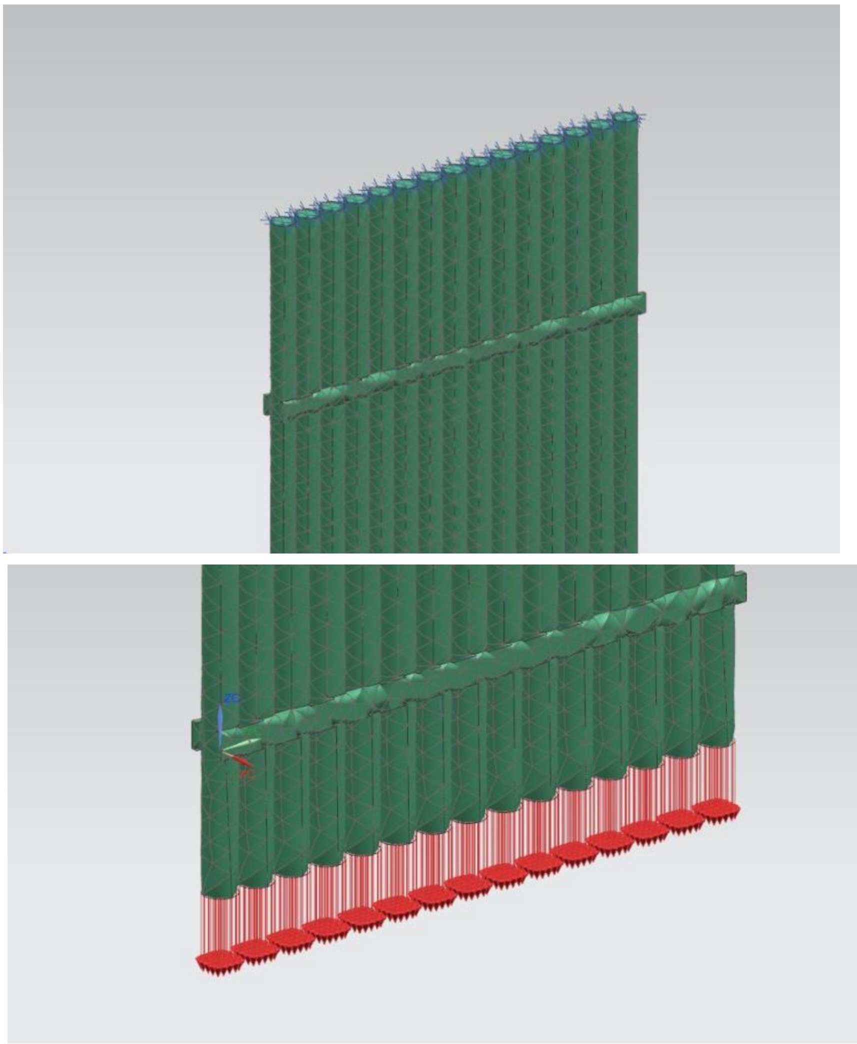
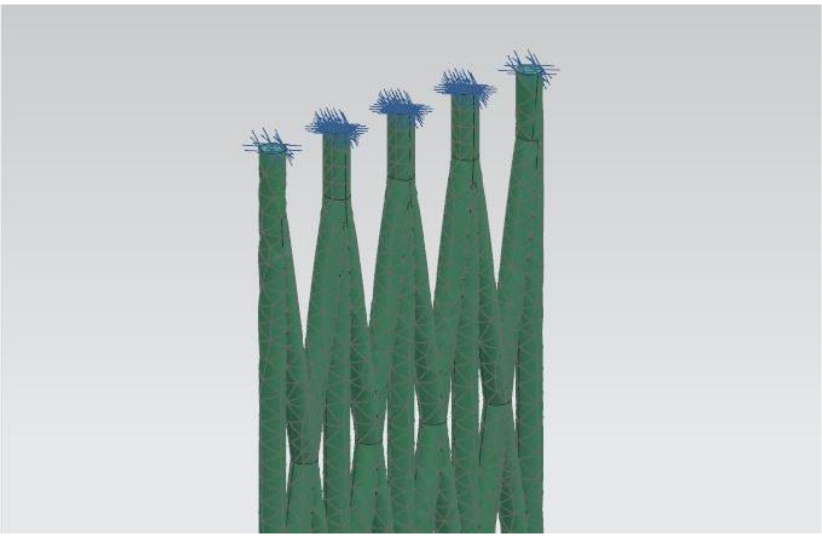
TITLE
SPACE ELEVATOR

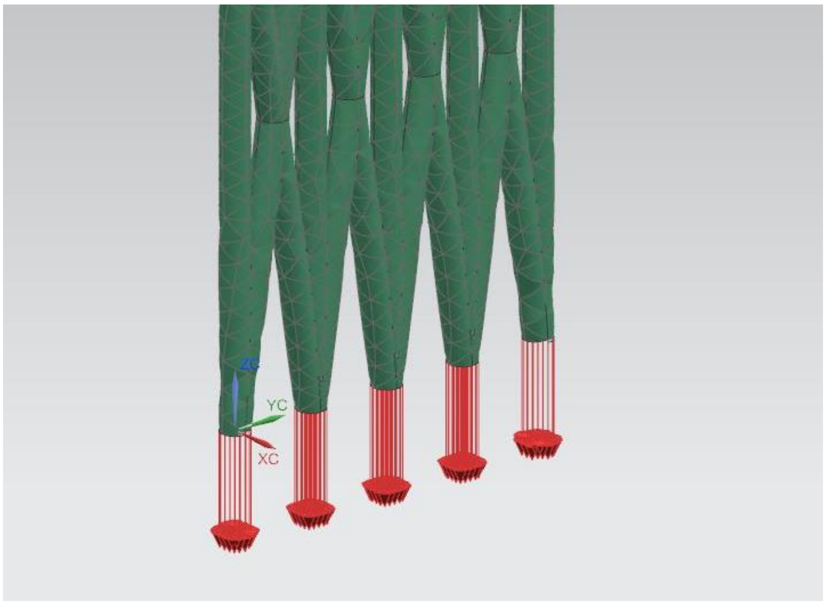
SIZE A4
DRG NO. assembly1
SHEET REV A
SCALE 1:1
SHEET 1 OF 1

The fixed constraint at the upper end and the applied load at the bottom end of Standard model design.

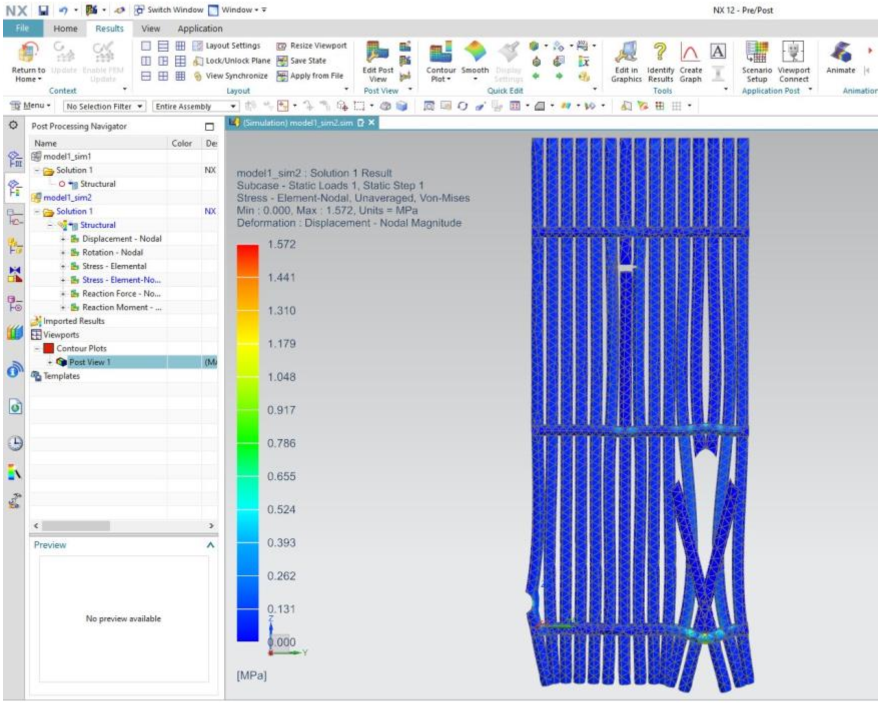


The fixed constraint at the upper end and the applied load at the bottom end of Hoytether design.



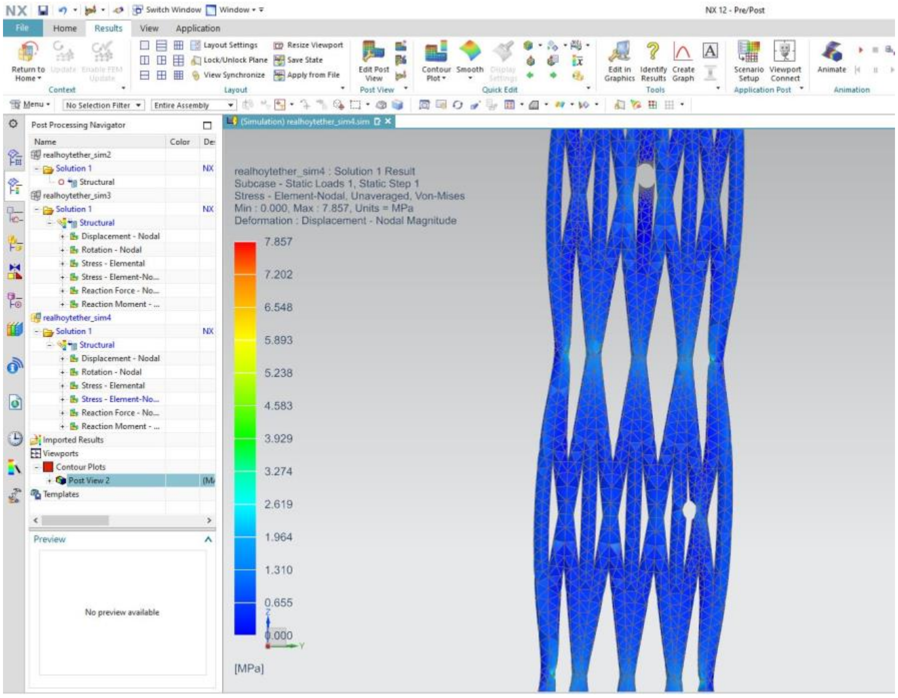


Stress distribution on a damaged Standard model cable design.



```
model1_sim2 : Solution 1 Result
Subcase - Static Loads 1, Static Step 1
Stress - Element-Nodal, Unaveraged, Von-Mises
Min : 0.000, Max : 1.572, Units = MPa
Deformation : Displacement - Nodal Magnitude
```

Stress distribution on a damaged Hoytether cable design.



realhoytether_sim4 : Solution 1 Result
Subcase - Static Loads 1, Static Step 1
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Min : 0.000, Max : 7.857, Units = MPa
Deformation : Displacement - Nodal Magnitude