Escola Politècnica Superior d'Enginyeria de Vilanova i la Geltrú

UNIVERSITAT POLITÈCNICA DE CATALUNYA

FINAL DEGREE PROJECT

Title: Design of A Solar Sailing Prototype for Interstellar Journey

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ABSTRACT

The main objective of this project is to design a solar sailing prototype which can be used to make a journey to outer space, or scientifically called Interstellar Journey. This study is solely to make an improvement in this field in terms of efficiency in both mechanical or material properties. To realise that particular project, two stages have been carried out. First, the study of state of art, which is a very important step to determine the current technologies of propulsions including solar sailing that has been developed by physicist and engineers, also the problems occurred if any. The second one is the designing part as to what characteristic best to have in the prototype. All this design is roughly sketched through application NX 12, as to give the idea of how the design would look like. The project will be focus on what materials is good to use on this solar sail, for an instance the Kapton or the Mylar, the maximum velocity that can be reached, and the effect of reflectivity on the spacecraft itself. All of this will be discussed later in the designing part after all comparison and calculation has been made. As a result, an improvement towards world's spacecraft for journey to the space could be optimised.

Keywords (10 maximum)

Interstellar Journey	Solar Sail	Application NX 12	Space Propulsion	Reflective Material
IKAROS	COSMOS-1 Project			

RESUMEN

El objetivo principal de este proyecto es diseñar un prototipo de vela solar que se pueda utilizar para hacer un viaje al espacio exterior, o científicamente llamado Viaje interestelar. Este es un estudio únicamente para hacer una mejora en este campo en términos de eficiencia, ya sea en propiedades mecánicas o materiales. Para realizar ese proyecto en particular, se han llevado a cabo dos etapas. Primero, el estudio del estado del arte, que es un paso muy importante para determinar las tecnologías actuales de las propulsiones, incluida la navegación solar desarrollada por físicos e ingenieros, también los problemas que se produjeron. La segunda es la parte de diseño en cuanto a qué característica es mejor tener en el prototipo. Todo este diseño está esbozado a través de la aplicación NX 12, para dar la idea de cómo se vería el diseño. El proyecto se centrará en qué materiales son buenos para usar en esta vela solar, por ejemplo, el Kapton o el Mylar, la velocidad máxima que se puede alcanzar y el efecto de la reflectividad en la nave espacial. Todo esto se discutirá más adelante en la parte de diseño después de que se hayan realizado todas las comparaciones y cálculos. Como resultado, se podría optimizar una mejora hacia la nave espacial para el viaje al espacio.

Palabras clave (10 máximo)

Viaje Interestelar	Vela solar	Aplicación NX 12	Propulsión espacial	Material reflectante
IKAROS	COSMOS-1 Project			

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Acronyms

ISS	International Space Station
NASA	National Aeronautics and Space Administration
IKAROS	Interplanetary Kite-craft Accelerated by Radiation Of the Sun
JAXA	Japanese Aerospace Exploration Agency
EPSEVG	Escola Politècnica Superior d'Enginyeria de Vilanova i la Geltrú (The Polytechnic University of Catalonia, Vilanova I La Geltru)
AU	Astronomical Unit of distance, equal to about 150 million km (approximate distance Earth-Sun)
UHMWPE	Ultrahigh Molecular Weight Polyethylene

Symbols

P	Momentum (kg.m/s)
E	Photon or Flux energy (W/m^2)
c	Velocity of light (299,792 km/s)
ŋ	Efficiency (%)
a_0	Acceleration (m/s^2)
$\boldsymbol{\rho}$	Density Volumetric (kg/m^3)
A	Area (m^2)
V	Velocity (m/s)
σ	Sail loading (N/m^2)
I_{sp}	Specific Impulse (N.s/kg)
g	Gravity (m/s^2)
m	Mass (kg)
h	Planck constant (J.s)
v	Frequency (Hz or 1/s)
W_E	Energy flux (W/m^2)
L_S	Solar Luminosity (W)
R_E	Distance sun and earth (km)

1. Introduction

Exploring the world is one of the most popular desire of human being. Not limited to the earth only, scientist have been discovering various ways how to make an exploration to other planets in our solar system, Milky Way, is possible. Since 1980, the idea of solar propulsion and navigation has been proposed to this field with various number of spaceflight mission to test it.

The main objective of this work is to design a solar sailing prototype that is suitable for interstellar journey. Interstellar journey is a travel to nearby stars at typical distances of some light-years. To make sure a most perfect prototype is created, a complete study of existing current methods and models has been analysed thoroughly. This includes the maximum speed, the dependability and the longevity of the solar sailing spacecraft to perform the journey.

However, there is always a limitation or barrier in making a breakthrough in any field. For the journey to the outer space, a lot of physics and aeronautical concepts has been developed and been studied by various number of research companies. As I am only a mechanical engineering student, with reference from the state of art that I would perform in the next part, I would like to specialize this study solely towards the design of the spaceflight (its material and characteristic) and also the best propulsion mechanism to be install to it.

2. Objectives

The objectives of this project are based on the principal concept of an interstellar journey that are needed to take into account before designing a solar sailing prototype and monitoring their feasibility for the journey.

- Make an analysis of the existing state of art of interstellar journey including propulsion methods different from solar sail
- Study the real space probe's characteristics (from a real mission) that has been built by the engineer as reference in building a new improved design of ship for the journey
- Study completely how does a spacecraft works including its mechanism of deployment and movement
- Make a design of the prototype for the solar sail by taking into account the study on previous part

3. Investigation of State of Art

For this section, I will perform the study of different space propulsion methods and ideas before proceeding to the next part. Only few propulsions that are related to the outcome of this project will be selected and studied. At the end of this part, I will compare all the advantages and disadvantages of each propulsion in form of a table.

3.1 Propulsions

One of the main things in realization of interstellar journey, which has been explained in introduction part, is the propulsions methods of the spacecraft itself. Propulsion is the pushing or pulling action to move a body forward. In term of spacecraft, it is the mechanism or system used in the particular probe to make itself moves to wherever desired. There are many types of propulsions in this interstellar field, but I will focus on few methods that will contribute most to our main objective.

3.1.1 Bussard Ramjet

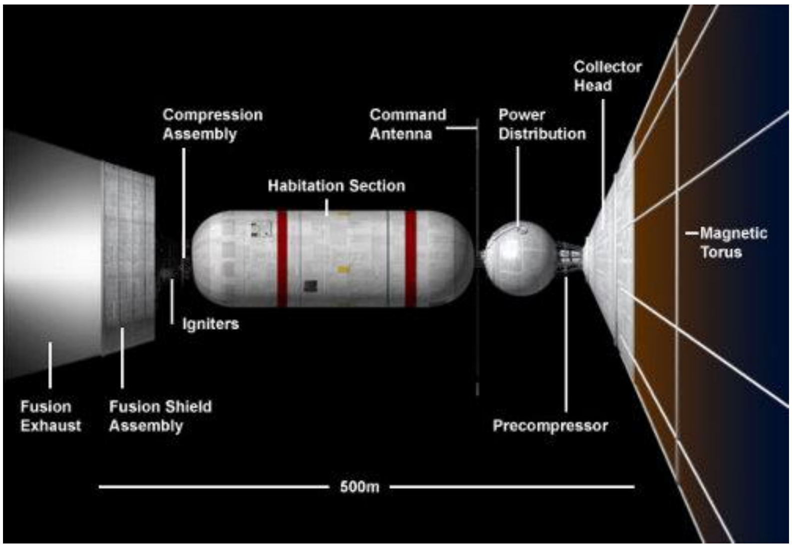

Figure 1: Bussard Ramjet's propulsion model [1]

Bussard Ramjet is a method that works based on the proton to proton fusion. In this case, the idea proposed by the physicist, Robert W. Bussard, was to use a large number of electromagnetic fields to scoop up hydrogen's atoms (by using the collector head) along the way of travel path [2]. Then the hydrogen is compressed until that desired thermonuclear fusions occurred which later directed as rocket exhaust towards the opposite direction of the spaceship. The maximum speed achievable through this method is 100 000 m/s.

The idea sounds so nice as the fuel is renewable (collected from the space), but everything in this interstellar world has its own barrier. The amount of hydrogen atoms itself in the Solar System is at a low-density level. Thus, this method would be impossible to act as an efficient propulsion method for the spacecraft to make the interstellar journey as it depended on the intensity of hydrogen atoms in space [1].

3.1.2 Antimatter Rocket

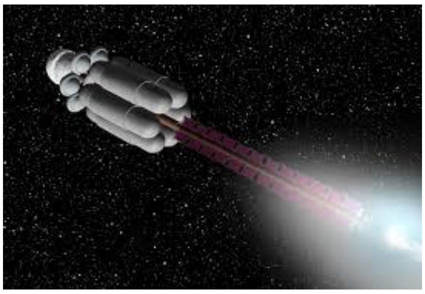

Figure 2: The Robert Frisbee, an antimatter ship of the middle Federation Age [3]

Next, we take a look at the antimatter rocket. Based on the name itself, we have clear imagination that this rocket works by using antimatter as their power source. Firstly, the physicist proposed this idea because the large fraction of 'rest mass' of matter/antimatter that can be converted to enormous amount of energy by using small amount of antimatter [4]. This is an excellent fact in this industry as we always try to minimise the fuel usage. In addition, the capability of this method is to match about 72 000 000 mph (32 186 880 m/s) around 10% of speed of light [5]. There are 3 different ways to works the rocket through this method:

1) Pure Antimatter: by means of direct usage of reaction products to provide thrust to the rocket itself
2) Heating of a propellant: the propulsion of the rocket solely operates by the extremely heat produced by the annihilation process.
3) Antimatter electrical power generation: as the annihilation process occurred, the outcome of that process is use to heat the specific fluid, which later is use to generate electricity in electric space propulsion system.

As to the current technology, we have not yet able to realize this method as we will face a problem of containing that particular antimatter. In terms of production and cost they are extremely difficult and costly even to create 1 gram of antimatter. As today, the cost needed for manufacturing 1 gram of it will be $62.5 trillion equivalent to €55 trillion [6]. This enormous amount of cost is a great barrier for realization of this methods of propulsion. Hence, even the speed is unbelievably fast, it is not an effective option for the scientist to consider them as an option yet.

3.1.3 Ion Thruster

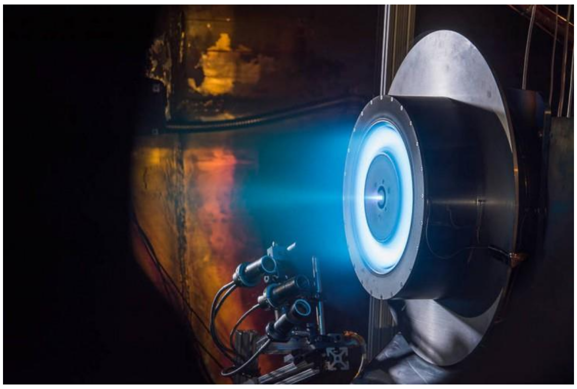

Figure 3:Ion thrust model [7]

Ion thruster is a form of electric propulsion invented for interstellar journey. By accelerating ions with electricity, a forward thrust is produced. In details discussion of how it works, it ionizes the neutral gas through extracting electrons out of the atom, in result creating a cloud of positive ions [8].

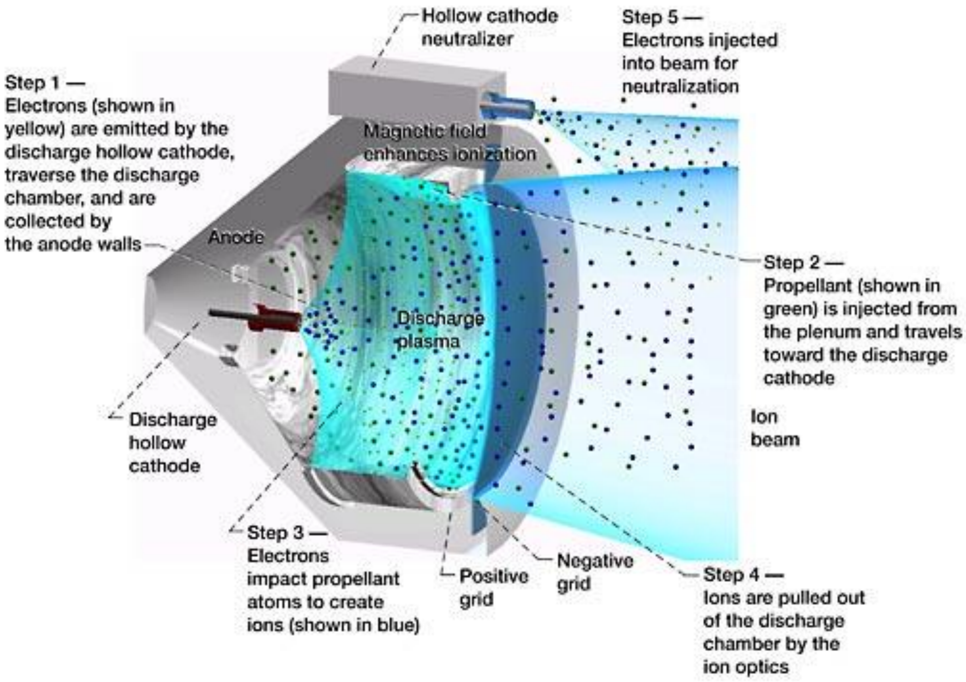

Figure 4: Ion Thruster Operation [9]

This positive ion is thrusted electrostatically out of the chamber to produce movement to the spacecraft. As soon the streams of positives ions leave the chamber, a temporarily stored electrons that has been removed earlier is reinjected to neutralize the Ion Beam before released to outer space [8]. This kind of propulsion method, start-up slows but will keeps accelerating even faster by times. The maximum recorded velocity of The Deep Space 1 and The Dawn spacecrafts are 4 500 m/s and 11 500 m/s respectively. This velocity even lower than the Bussard Ramjet as we studied earlier [10].

3.1.4 Solar Sailing

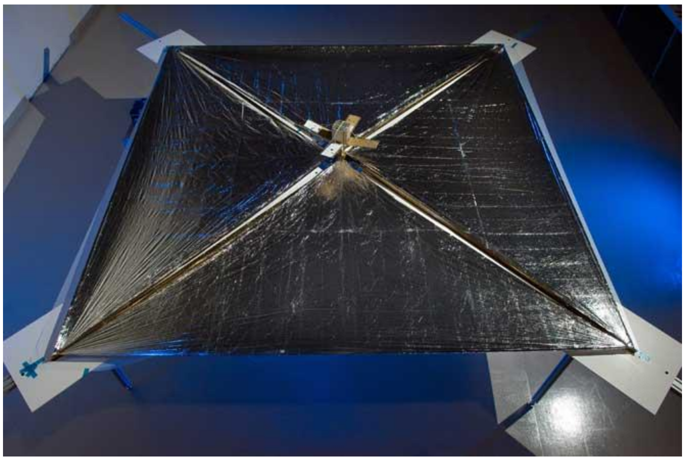

Figure 5: Blue Solar Sail [11]

Solar Sailing is one of the greatest inventions of spacecraft propulsion methods for interstellar journey. Without using any fuel to power up, t works completely by capturing energy from sunlight's particles as they bounce of the reflective surface. As the photons of light hits the reflective layer, a force is applied on the solar sail and make a forward thrust movement [12].

It is built with large surface area of reflective layer as many kilometres in extent. This is a to ensure a maximum number of photons of light can be captured and produce a large force on the solar sail in order to maximise its velocity. The maximum velocity that a solar sail can reach is 29 933 798 m/s which is 10% of speed of light just with a renewable source of energy as it fuels [13].

The only matters that should be taken into account is the materials of the solar sail itself as it must be selected from materials with properties of low density, strong, able to crush or folded until deployed, and also resistant to ionizing radiation [14].

3.1.4.1 Projects Solar Sail developed at EPSEVG

At the EPSEVG-UPC, two jobs have already been carried out with this theme.

Mecánica orbital para un viaje interestelar utilizando velas solares [15]

The authors Marc Rocas Alonso and Adrià Méndez Heredero in June 2016, have developed a project to study the feasibility to travel between International Space Station (ISS) to Alpha Centauri through solar sailing. They investigate on how does the length of the interstellar journey will vary the orbital's mechanics and dynamics behavior.

Prototip de veles solars impulsades per làser per al viatge interestel·lar [16]

This is also a Solar Sailing Prototype project made by the author Josep Pinyol Escala. The author mainly focusses on studying the reachable velocity of the spacecraft and the material for the sail. And at the end of the study, the author creates a virtual mission to the extrasolar planet Proxima b, to test the feasibility of the prototype designed.

3.1.4.2 First Successful Solar Sailing Projects

Kite-craft Accelerated by Radiation Of the Sun or its acronyms IKAROS is the first spacecraft that use solar sail in history. It is a Japanese spacecraft aboard (operated by JAXA) on H-IIA rocket on May 2010 along with other small spacecrafts [17].

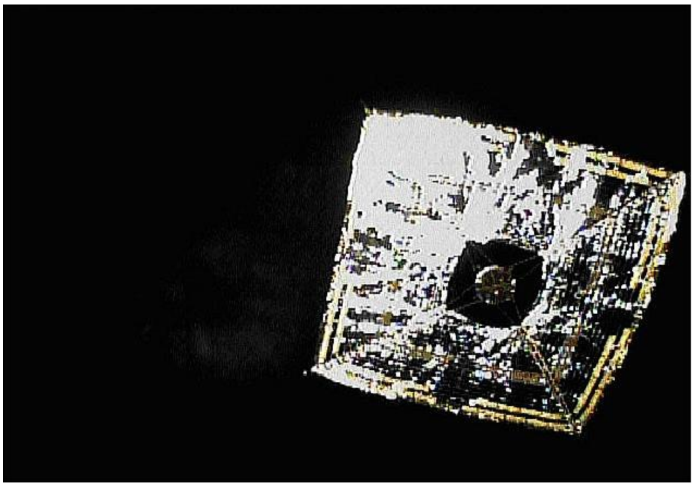

Figure 6: Image of fully deployed IKAROS [18]

The main objectives for the deployment of the IKAROS is to prove the technology that the spacecraft can control the big thin solar membrane. Also, in this mission, the physicists are trying to prove that they can control the altitude of the spacecraft by using the 80 liquid crystal panels that has been installed in it [19]. To maximise the outcome, other missions also have been added to this project, such as studying the Gamma-Ray bursts, solar wind, and cosmic dust [20].

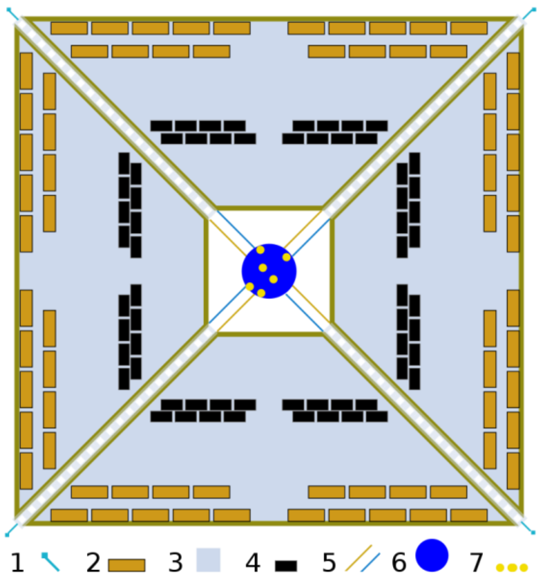

Figure 7:Schematic diagram of IKAROS spacecraft [21]

1. Tip mass 0.5 kg, 1 of 4.
2. Liquid crystal device, 1 of 80.
3. Membrane 7.5 µm thick, 20 metres on the diagonal.
4. Solar cells 25 µm thick.
5. Tethers.
6. Main body.
7. Instruments

Figure 7 is the detailed schematic view of the IKAROS spacecraft. The membrane originally folded or rolled into a cylinder shaped before it has been fully deployed through centrifugal knowledge. A full complete cycle of deployment is explained in the next figure.

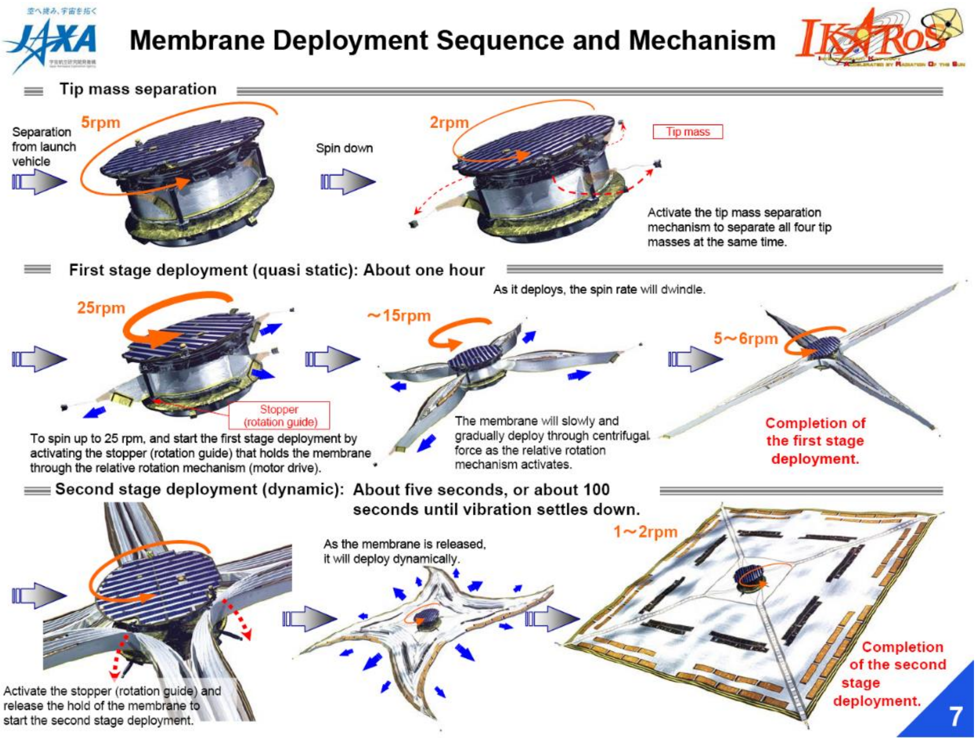

Figure 8: Deployment stages of IKAROS spacecraft [21]

3.2 Comparison of Space Propulsion Methods

Here is a complete table for each propulsion earlier to ease the process of listing advantages and disadvantages. The maximum velocity also tabulated as a reference for the next part.

Propulsion Methods	Maximum Velocity (m/s)	Advantages	Disadvantages
Bussard Ramjet	100 000	Hydrogens' atoms in outer space is the main fuel for the spacecraft	The low intensity of hydrogens atom in space
Antimatter Rocket	32 186 880	The highest velocity compared to other propulsion's methods, resulting a much lower time consuming for travel	The cost of manufacture of the antimatter is extremely high for a small amount of it.
Ion Thruster	11 500	A simple ionizing and neutralizing of a neutral gas which is a non-pollutant to the space.	A relatively slow of velocity, will not functioning well to travel a far distant planet or galaxy
Solar Sailing	29 933 798 (9.97% speed of light)	Unlimited resources of renewable energy (sunlight)	The complex characteristic of materials for the reflective layer

Table 1: Summary of comparison propulsion methods [Own Source]

As we can see from simplified table above about the advantages and disadvantages for each types of propulsion. Based on this table I can clearly see the idea that can be implemented into the project and at the same time minding the limitation to make it more realistic. This includes the spacecraft design, deployment phases and the materials chosen in compliance of the limiting factors that exist.

4. Physics of Solar Sailing

The main principle of designing a solar sailing spacecraft is to maximise the flat reflective surface area with as minimum of total mass as possible. This characteristic is a main properties of a solar sailing spacecraft need to have as it will increase number of photons that bounce and hit the reflective part.

4.1 Calculations

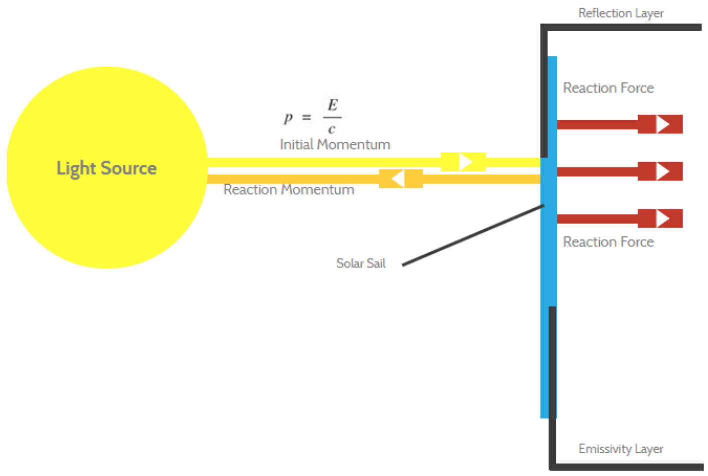

Figure 9:Diagrams of reflecting light on Solar Sail (case 1) [13]

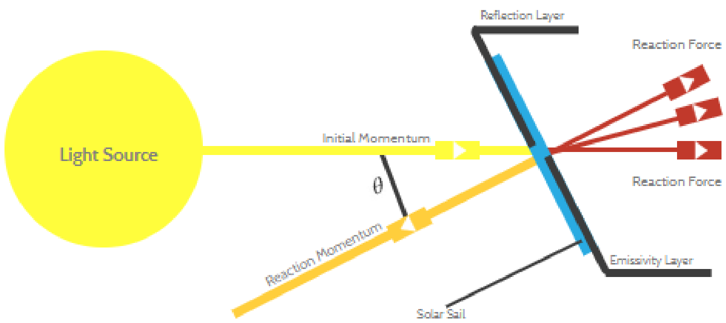

Figure 10:Diagrams of reflecting light on Solar Sail (case 2) [13]

Momentum is the key factor of functionality of a solar sailing. As the stream of photons from the sun hit the membrane (reflective layer or sail), a force is applied towards the spacecraft and moves forward. Theoretically, the photons itself has very small mass, or basically zero, but the momentum is still produced because this photon bombarded the layer with a high velocity.

By dividing photon or flux energy (E) with speed of light (c), we will obtain the momentum (p). This calculation only taken into account if we neglect the effect of the reflectivity that photons caused [22].

$$p = \frac{E}{c} \qquad (1)$$

To understand the further calculations of this solar sail, we need to familiarize with the term of Solar Radiation. It is a radiant energy emitted by the sun resulting from nuclear fusion reaction that creates electromagnetic energy. At 1 AU, total solar radiation is $4.56\text{x}10^{-6}$ N/m^2 [23]. By finite efficiency ŋ of the sail, we could calculate the acceleration of a sail through the formula below.

$$a_0 = \frac{2ŋP}{\sigma} \qquad (2)$$

The sail loading, σ, is the average mass per unit area of the spacecraft.

From Tsiolkovsky's equation [24]:

$$\Delta V = I_{sp} g_0 \ln\left(\frac{m_1}{m_2}\right) \qquad (3)$$

I_{sp} = Specific Impulse, a total impulse produced per fuel consumed (N.s/kg)

m_1 = sum of mass of the sail and the payload (kg)

m_2 = mass of payload (kg)

As Rieber claimed in his journal [22], solar sails have an infinite specific impulse. This infinite condition on valid with infinite mission duration. This solar sail normally sends to the orbit with a payload, hence only the solar sail with mass lower than the mass of chemical that are needed to complete the mission (sending payload to orbit) would be considered a good option.

$$I_{sp} \sim \frac{a_0 T}{g_0} \ln\left(\frac{m_1}{m_2}\right)^{-1} \qquad (4)$$

To calculate the specific impulse, equation above is the approximation that we can use with T as the mission duration. This is because, as the solar sail would not always being pointed to the sun, we could not find the exact value of this impulse.

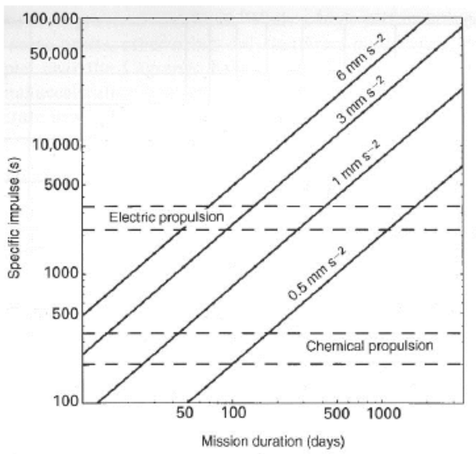

Figure 11:I_{sp} vs Mission Duration for different types of propulsions [22]

Based on the graph above, it is the relation of Specific Impulse (s) against mission duration for a few accelerations of solar sails. Take into account that in this graph, a payload of 1/3 is assumed. As we can see, electric propulsion results in higher specific impulse than chemical propulsion. This also means that the amount of days needed for electric propulsion to approach certain acceleration is lower compare the chemical one.

In calculating the solar sail pressure, we must derive the equations from two different field, quantum description and electromagnetic description.

From Planck's Law:

$$E = hv \qquad (5)$$

While special relativity concludes:

$$E^2 = m^2c^4 + p^2c^2 \qquad (6)$$

As we know that the mass of photon is 0, this brings an equation:

$$E^2 = p^2c^2 \qquad (7)$$

By doing simultaneous equation of (5) and (6):

$$p = \frac{hv}{c} \qquad (8)$$

With two data of solar luminosity, L_s and distance of the sun and the earth, R_E, we can calculate W_E or energy flux of earth.

$$W_E = \frac{L_s}{(R_E)^2} \qquad (9)$$

Since the orbit is in helicoidal shape, we could scale the equation (8) to a heliocentric and finally find the value of the total energy.

$$W = W_E \frac{{R_E}^2}{r} \qquad (10)$$

$$E = WA\Delta t \qquad (11)$$

Finally, with this, we could find the value for the original equation of momentum as in the figure 9.

Apart from the equation derived above, there is a principle that takes a major effect on the amount pressure obtain from the sun, which is The Solar Radiation Pressure. This phenomenon is common when dealing with sun especially when a body, a satellite or a spacecraft is close to the sun. The smaller the body of a spacecraft, the greater its effect on itself [25].

4.2 Non-Ideal Solar Sailing

A perfect solar sail could never be achieved. This is because there are few limiting external factors that affects its efficiency [22]:

- **Reflectivity**

The cause of reflectivity is because the sail is not fully flat or maybe wrinkle. As this happen, the photons can never fully reflect and some of them is absorbed by the sail film in result of heating it up.

- **Heating of sail**

In space, the only cooling method is radiation [26]. As the sail heated up, the photons absorbed will be emitted on both front and back side. This resulting in the momentum primarily acquired from the bombardment of photons which cause the momentum to slow down a little bit.

- **Pressure of Solar Wind**

The existence of coronal holes [27] causes the solar wind in space exist. Even though the value is very small it does contribute to the drawback of becoming a perfect solar sail.

- **Atmospheric Drag**

Finally, the atmospheric drag. It is a force acting opposite to the relative motion of an object [28]. Frequent collision of gas molecule with the satellite results in atmospheric drag at orbital altitude. This reduces the altitude of that particular satellite or solar sail spacecraft particularly.

Magnitude	Types of pressure
10^{-17} Pa	Pressure in outer space in intergalactic voids
10^{-15} Pa	Pressure in outer space between stars in the Milky Way
10^{-12} Pa	Lowest pressure obtained in laboratory condition
10^{-11} Pa	Atmosphere at Moon at lunar day
10^{-10} Pa	Atmosphere at Mercury
10^{-9} Pa	Vacuum expected in the beam pipe of Large Hadron Collider
	Approximate solar wind pressure at Earth’s distance from the sun
10^{-8} Pa	Pressure inside a vacuum chamber for laser cooling atom (magneto-optical trap)
	Atmospheric pressure in low Earth’s orbit, around 500 km altitude

Table 2: Order magnitudes of different pressure [29]

5. Existing Design

Before proceeding into the designing of the prototype, I must study the current models that have been realized by the engineers including its components involved. I will study three different models thoroughly before making a final decision of characteristic.

5.1 VOLNA Spacecraft (COSMOS 1 Project) [21 June 2005]

Figure 12: COSMOS Solar Sail 1 Project [30]

If we take a look at the actual VOLNA Solar Sail Spacecraft, basically it is like a launching rocket (14-metre-long with 1.8 metre of diameter) [31] from the earth directly to the outer earth (using liquid propellant). The only actual solar sailing compartment is inside the tip of the rocket. After passes the stages of launching, only then the solar sail parts deployed to the space [32].

This spacecraft inflated its 8 sail blades attached out until it is fully stretched. With the thickness of 5 µm of Aluminized-reinforced PET film (MPET), it will be stretched to 15 m long in result of making a total surface area of 600 m^2 [33].

Refer to figure 13 on next page for a clear explanation on how does the deployment takes place.

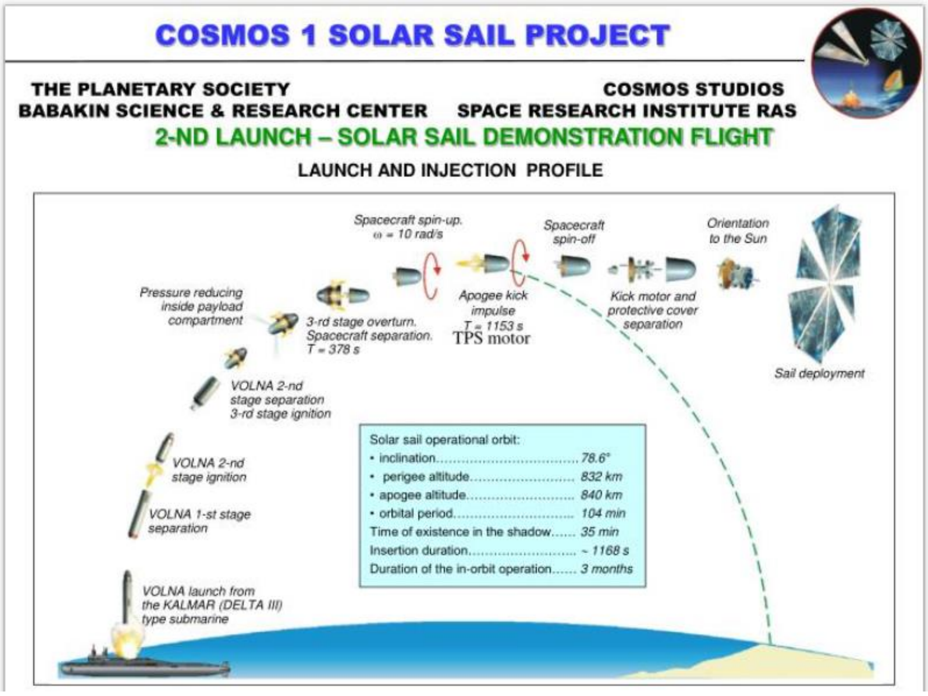

Figure 13: Deployment stages of COSMOS 1 Project [32]

For the particular solar sail design, it consists of camera, antennas, sun sensor, solar array, the sail, and ultimately the attitude control thruster. For every single item installed in this spacecraft, they all have their main function to the success of the mission. The highlight of this design is the attitude control thruster. It is a component that works as momentum wheels or known as reaction wheels.

Figure 14: The Momentum Wheel is an innovative flywheel/bearing arrangement that allows the entire rotating system to be balanced after it is assembled [34].

As we can see in figure 14, this reaction wheels are important to a spacecraft because they provide attitude control authority and stability for the spacecraft [34].The way it operates is to convert angular momentum from the spacecraft to the wheels and vice versa to move the spacecraft to the desired direction.

The weight total of the spacecraft is 100kg with solar sail area around 600m^2 (made of PET film or mylar). The calculated speed of this spacecraft shows that in a day it would reach 45 m/s and will reach 44 704 m/s in time frame of 3 years. However, this spacecraft was lost due to failure of launching and never reached the orbit [35] [36].

5.2 LightSail-1 (formerly known as NanoSail-D) [20 May 2015]

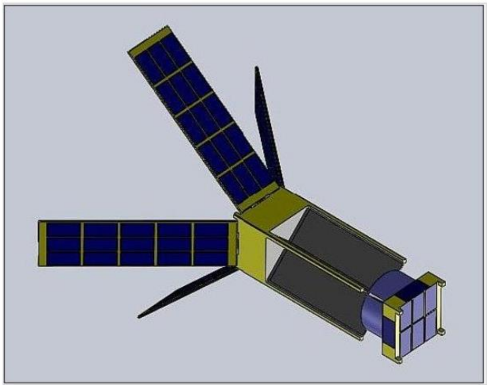

Figure 15: Schematic view of the lightsail satellite [37]

Unlike the Volna spacecraft, this spacecraft only weighs 4.5kg. With the design of 3 CubeSat (or triple CubeSat) and the size of 340mm x 100mm x 100mm, it consists of solar panels, two 2Mpixel cameras mounted at the end of solar panels, 4 sun sensors, 6 ultra-tiny accelerometers with the function of direct measuring of light-force, and several others including a momentum wheel for attitude control [37].

The solar sail itself does have a thickness 4.5 µm of mylar material, aluminized and rip-stop protection. However, since the CubeSat itself is very small, the maximum solar sail surface area is around is 32m^2 only [38], far lower than the previous VOLNA. That clarifies the 'Nano' term in its name.

There are 4 modes of ADCS (Attitude Determination and Control Subsystem) used in this solar sail [36]:

1) B-dot detumble (use magnetometers only as its sensors)
2) Momentum wheel turn-on
3) Sun-pointing
4) Orbit Raising (thrust on/thrust off)

The nominal momentum for the solar sail is 0.060 kg.m/s with an angular velocity of 2.5 rpm. As there is no propulsion for the solar sail to travel from earth to space, it needs a ride from other space mission, as in this case Falcon 1. Unluckily, this project also having a failure due to the rocket [39].

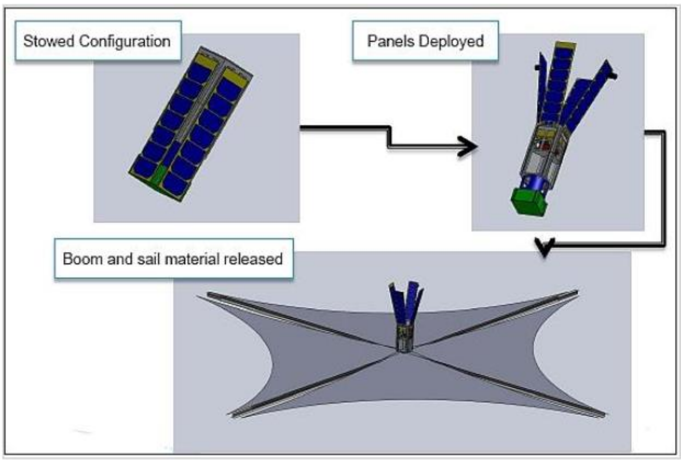

Figure 16: Schematic view of deployment sequence LightSail-1 [37]

5.3 IKAROS [20 May 2010]

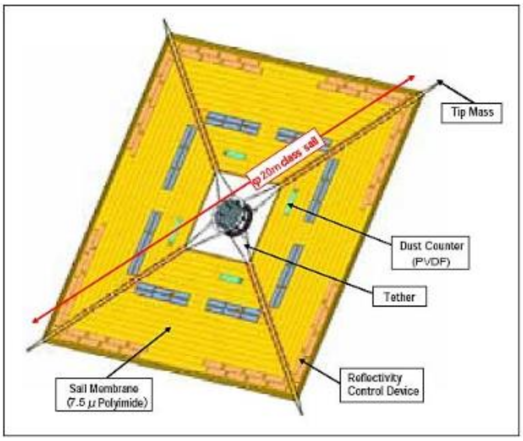

Figure 17:IKAROS components [18]

IKAROS is no different from the LightSail-1 as it is made to explore new solar sail technique by the use of a lightweight and ultra-thin material for its sail. By riding the H-2A rocket [39], a diagonal of 20m kite shaped of solar sail is deployed to the space through centrifugal principle as there is no rigid support in the structure itself. The sail membrane is made of from polymer group, a Polyimide (or known as Kapton), with 7.5µm of thickness, and also layered with 80nm of evaporated aluminium. All the materials chose and coating, instead of having a light mass, it leads to a very high resistance to thermal, mechanical, and chemical reaction [41].

Parameter	Satellite body structure	Sail membrane
Shape	Cylinder	Square
Size	(Ø 1.5 x 0.4) m	(14 x 14)
Mass	55 kg	14 kg + 2kg (tip masses)
Material	Al7075, Al6061, CFRP, SUS304	Polyimide
Total mass spacecraft	307 kg wet mass, (dry mass = 293 kg)	

Table 3: Specification of IKAROS [18]

The study shows, it is an ideal solar sail to use spin-type solar sail as its deployment mechanism, however, there are some disadvantages to this method. Because of the various flexibility of the membrane, an impulsive torque input causes the oscillatory motion in the membrane. In addition, the whenever the sails need to be steered to certain direction, a large angular momentum is needed, hence the propellant consumption is very high and could affect the lifetime of the spinning sail. Apart from the energy consumed, the 'sticking' of the sail could may occur if it is folded is incorrect [42].Lastly, the lower magnitude of spinning rate also will result into counter spin or worse not spinning at all [43].

However, it also has its advantages. The spacecraft is resistance towards the external disturbance torque caused by sail deformation as it is averaged during its spin motion. This makes the attitude behaviour is in safe condition. Plus, it could detect automatically the sun's direction.

5.4 Comparison Solar Sails

In reference of the study in previous part, we are able to determine each characteristic of 2 different types of solar sail. Here is the summary of previous study.

Aspect	VOLNA	LightSail-1	IKAROS
Mass	100 kg	4.5 kg	55 kg
Size of Capsule	(14 x 1.8) m	(0.34 x 0.1 x 0.1) m	(1.6 x 0.8) m
Area of Solar Sail	600 m^2	32 m^2	196 m^2
Solar Sail Material	Mylar	Mylar	Polyimide with coating evaporated aluminium
Momentum Wheel	Yes	Yes	No
Ride other space mission	No, Volna use its own propulsion.	Yes, Falcon 1	Yes, H-2A

Table 4: Comparison of Different Solar Sails [Own Source]

We can notice here that the sail material is always be taken from a polymer, either mylar or Polyimide (Kapton). The reason of why these 2 materials has been chosen as the material's sail because their high tensile strength. Besides, the stability properties at a large range of temperature is a boost factor. Kapton is remain stable at temperature ranging from -273 to +400 °C while Mylar's range is about -70 to +180 ºC [44]. Since IKAROS is the latest solar sail invented among the other two, VOLNA and LightSail1, it uses Kapton as its sail material instead of Mylar.

6. Solar Sail Designs

In this section, I will introduce sketches of ideas for the protype design based on what I have studied earlier. After doing the comparison and evaluation of each sketches, a final prototype to develop will be selected and precisely draw in a chosen drawing application. Each planes' design will be presented in Appendix section for detailed view of the dimensions of the spacecraft prototype.

6.1 Pre-Design

For the first part, I will design 2 sketches of solar sail prototypes. Next, I will point out the main properties and characteristics for each sketch along with the function for each element.

6.1.1 Design 1

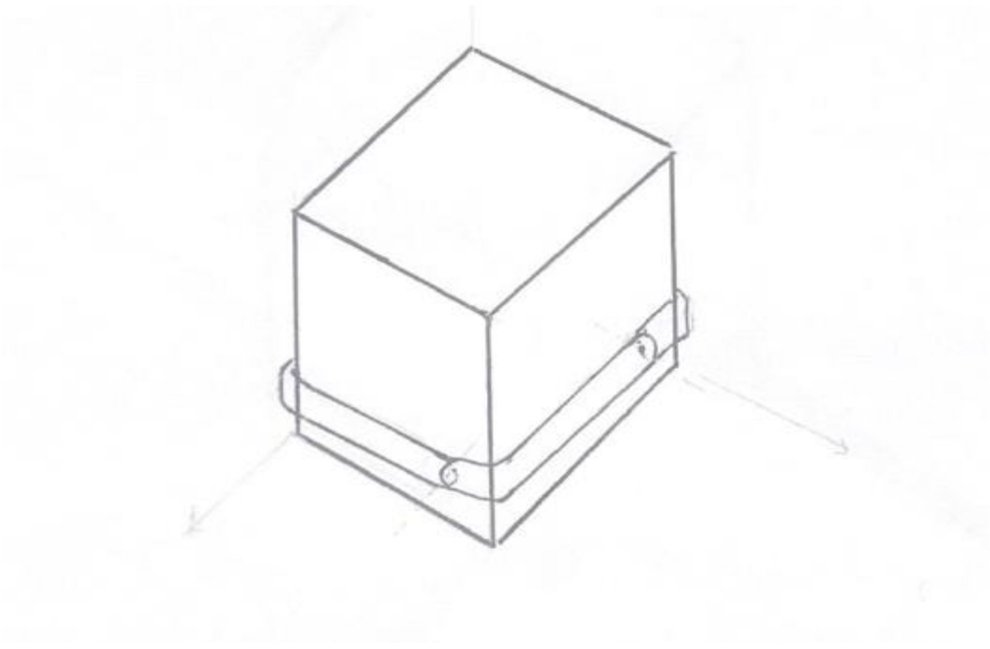

Figure 18: Sketches of Design 1[Own Source]

Figure 18 shows a sketch that is inspired from the IKAROS spacecraft. It uses the physics concept of centrifugal force and motors to deploy it sails. There are four identical sails that are rolled by 4 different motors installed in the 40kg cube. With cubic dimensions of 2.5 m on each side, this space craft can hold 4 sail's membranes with surface area of 56.25m each (total surface area 225m^2). At start, the main cubic body is wrapped with the rolled sails as in the figure 18.

The main body has 4 circular holes in total at the lower right side. These holes are designed to hold the 4 motors that are purposely added for deployment phase. Next, from the figure 19 below, we could observe that each motor that installed inside the main body is mounted with a rolled sail. Inside the rolled sail, a special material of polymer with flexible characteristic (bendable) is used. This is important for the spacecraft as it gives some weight to the sail, so that the centrifugal force can successfully worked. On top of the cube, an antenna and 2 cameras have been installed for controlling and monitoring purposes.

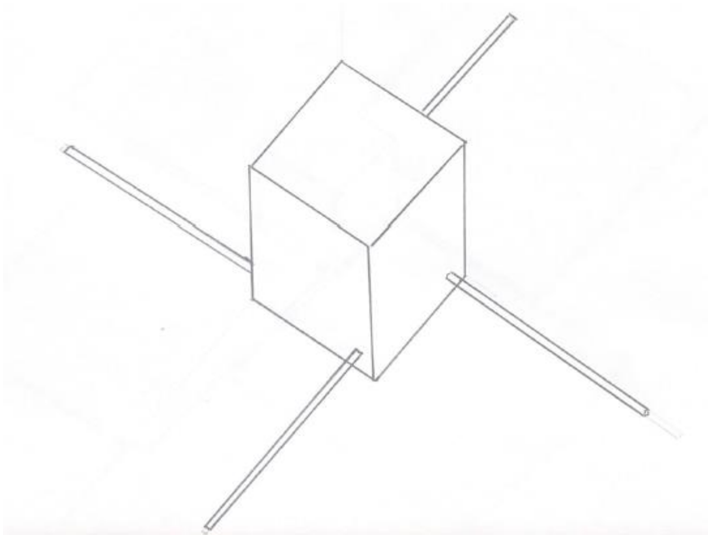

Figure 19: First deployment stage [Own Source]

To fully deploy the sails, there are 2 steps that must be followed. Firstly, as mentioned, by using centrifugal force concept, the cubic body will start spinning slowly along the vertical axis (as in the picture) and as result all 4 rolled sails will be straightened perpendicularly to the body. After that, 4 small motors installed in the body are triggered and start to fully unroll the sails as in figure 20.

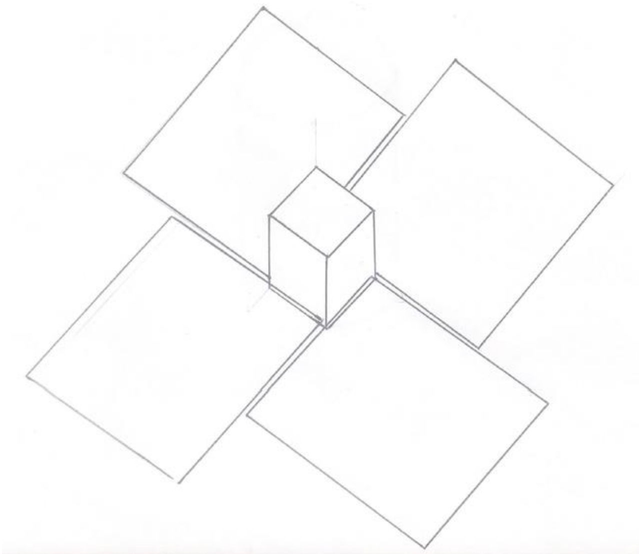

Figure 20: Fully deployed design 1 [Own Source]

6.1.2 Design 2

Figure 21: Main body with cover on [Own Source]

For this second sketch, some characteristic from VOLNA model has been implemented. The main body of this space craft, with the weight of 35kg, is cylindric shape with a cover on lower part of it as illustrated in figure 21. The dimensions of the cylinder are 2m for diameter and 3m for the length.

From the next figure 22, a sketch of the sail when the cover is removed is showed. If we removed the cover, 6 sets of 'mechanical arms' are visible. These main components bars made of carbon fibre, are attached in zigzag structure to the body. As for the sail, it is folded inside the bottom of the main body and at the same time it is also attached at the tip of the arms. The other features for this spacecraft are solar panel, 2 cameras, and 2 momentum wheels.

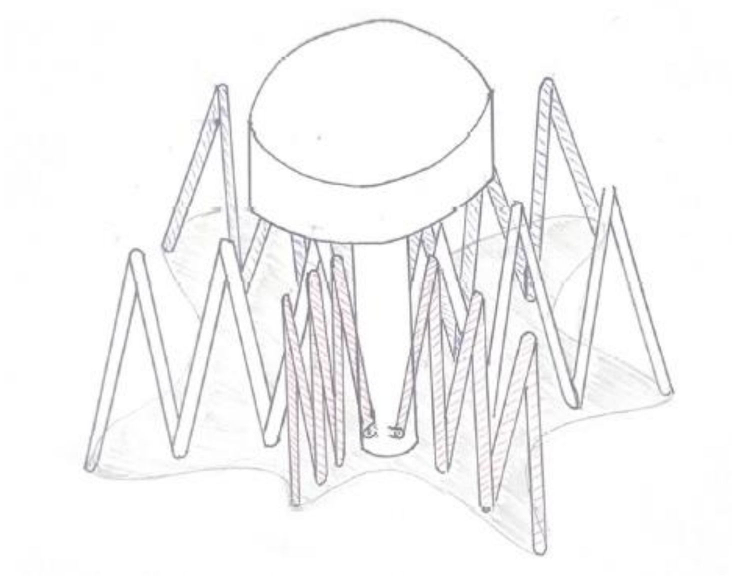

Figure 22: It shows the mechanical arms in deploying state [Own Source]

For deployment steps, the cylindric capsule will detached its cover into the space. After that, the 6 arms attached to the body will slowly straightened along with the sails until the hexagon shape is obtained with total surface area of $800m^2$.as shown in figure 23.

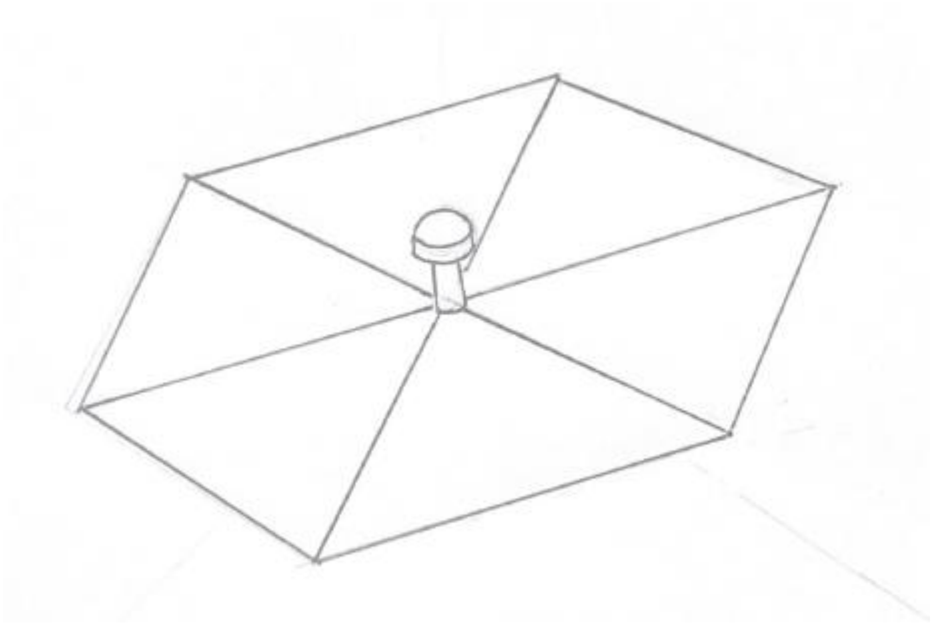

Figure 23: Fully deployed of Design 2

6.1.3 Comparison of Design

	Design 1	Design 2
Main Body	Cube	Cylinder (Hollow for sail storage)
Deployment Method	Centrifugal Force	Mechanical Carbon Fibre Arms
Sail's Material	Kapton	Kapton
Storage place for the sail	Rolled and wrapped around the cube	Folded inside the cylinder main body
Motor	Has 4 motors. Used to unroll the sails	Has 1 main medium sized motors inside the main cylinder body that control all six arms
Solar Panel	No	Yes.
Momentum wheel	No. The spacecraft use the centrifugal force to maintain the spin and keep the sail stretched.	2 wheels installed. Easy navigating and change of direction if needed.

Table 5: Comparison of designs [Own Source]

From the tabulated data, we can see there are few different characteristics for each design.

Take note that the material mentioned for the mechanical arms is carbon fibre. This material is

But the material of each design is the same, a Kapton. This is because, as we studied earlier, it is the highest tensile strength among other light materials such mylar.

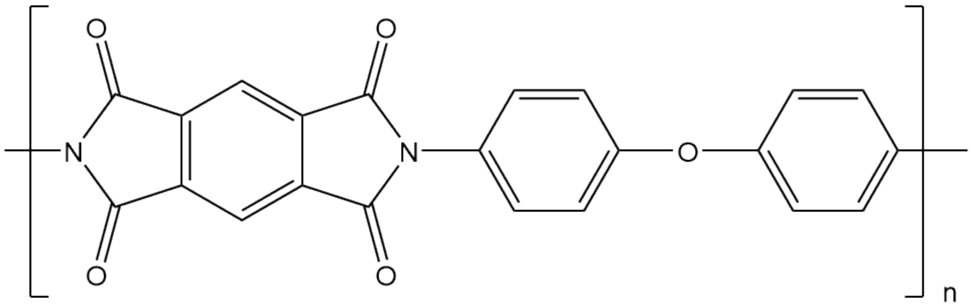

Figure 24: Structural formula of polymer Kapton (Polyimide) [45] [46]

This polyimide is made from imide group. In general, the intermolecular structure is strong for this material because the polymer chains itself. As result, an incredible strong in mechanical and thermal properties is produced. At high temperature of (400-500) °C, this polymer is stable and that what makes this material a good choice for our sail [45]. Apart from the mechanical properties, it also has an excellent electrical performance as in table below.

Electrical Performances	
Dielectric Constant	3.1 – 3.55
Dielectric Strength	(22 – 27.6) V/m
Dissipation Factor	(18 – 40) x 10^{-4}
Volume Resistivity	(14 – 18) x10^{13} Ω.m

Table 6 : Electrical characteristic of Kapton (Polyimide) [47]

For design 1, I choose to make use of centrifugal force idea to deploy the sail. Then, I add an improvement through motors to unrolled the sail. But for the second design, I use the mechanicals arms to deploy the sail. All these arms are controlled by 1 single motor which is placed inside the main cylinder body. To choose between these 2 designs, I must line out the advantages and disadvantages for each of them.

In term of motors, the first design use 3 extra motors compare to the other one. In general, the consumptions of energy gained from the photon will be used for this purpose will be much higher and as a result will reduce the capability of our main objective which is sailing. Although we can simply install rechargeable battery inside the main body, still it does not lower the consumption of energy by this cause.

The next comparison we can use see is how does the sail stored. For first design, the sails are rolled by motors and then wrapped along the cube main body, while the second design is folded inside the cylinder main body with also attached at the end of the mechanical arms. As we can see, the second design will not have a complication to fully stretch and maintain the hexagon sail shape. But the first design simply relies on rotation of the main body to keep the sails stretched. If the spacecraft fail to keep rotating, this will be a problem to the sails themselves. Furthermore, each sail is easily twisted and cannot be deployed as it is wrapped onto each other at the moment of the launch.

Lastly, the influencing factor will be the existence of momentum wheels. As studied in previous part, it is very important to a spacecraft having a momentum wheels as it works as a handle for it. It can easily manoeuvre the space craft to desired direction.

Based on the explanations above, clearly the best design of prototype will be the second. The design has advantages in many aspects compared to the first one and much more practical to be applied on our solar sail prototype for this interstellar journey.

6.2 Final Design (NX12)

For reader information, a drawing application NX12 is chosen for this project. It is an application for drawing any sketches as 3D or 2D before doing any further analysis such as tensions, thermal and many other advanced features [46].

Full view of design:

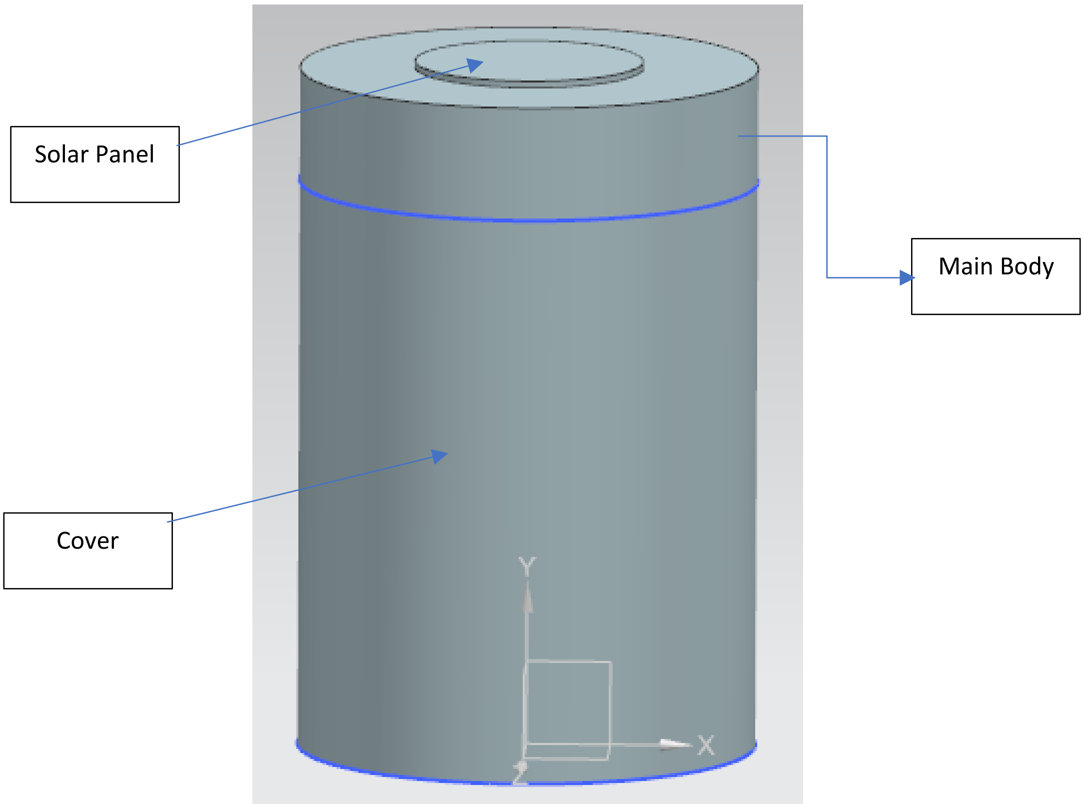

Figure 25:Isometric view of design [Own Source]

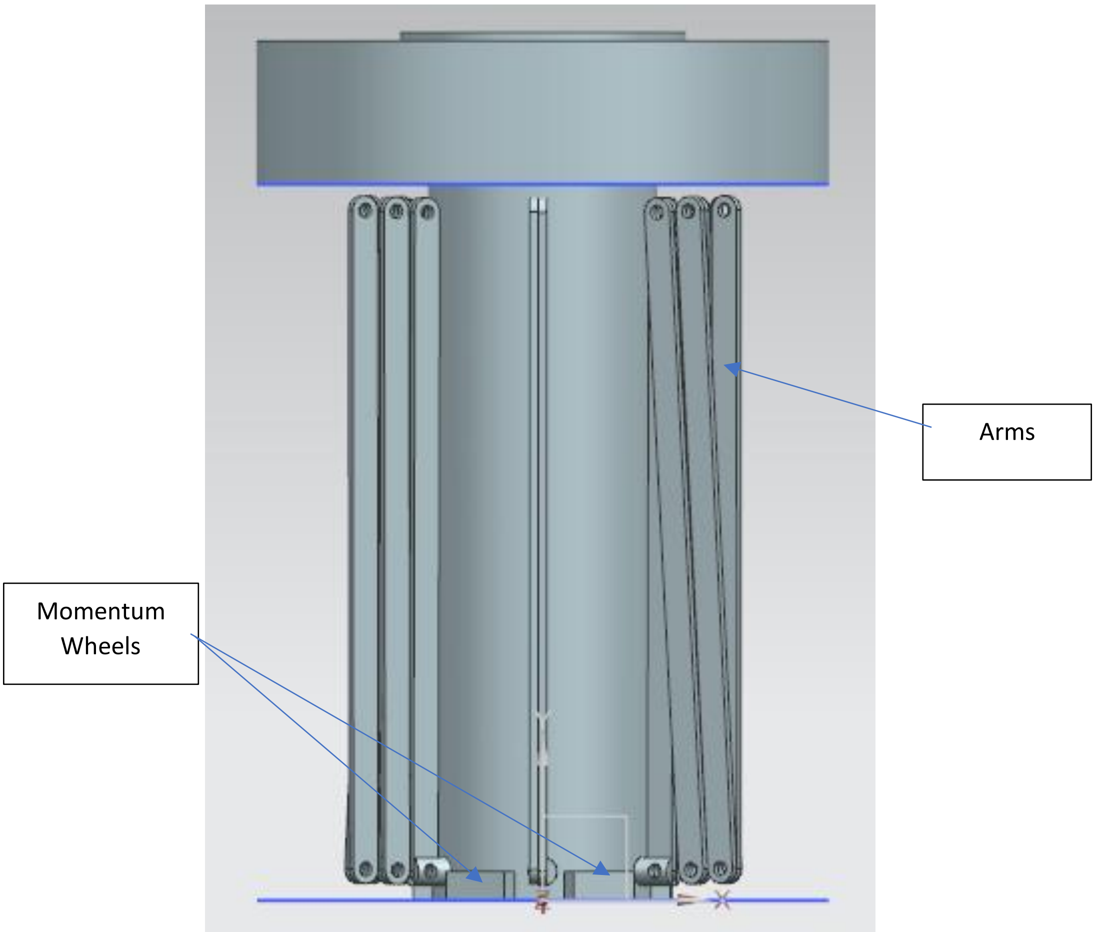

Figure 26:Side view without cover [Own Source]

The major components of the design are the main body, the mechanical carbon-reinforced arms, and the sail itself. As we can see in figure 25, there is a cover that wrapped around the main body. This cover will be removed into the space. After that, the 6 pairs of mechanical arms are slowly extending themselves along with the attached sail that have been stored inside the main body.

Figure 27 shows the arms are in extending mode.

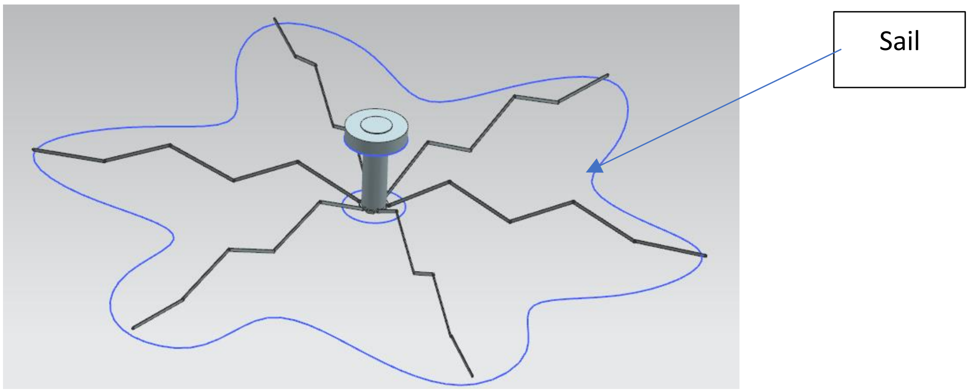

Figure 27:Deploying stage with the solar sail attached at the arms [Own Source]

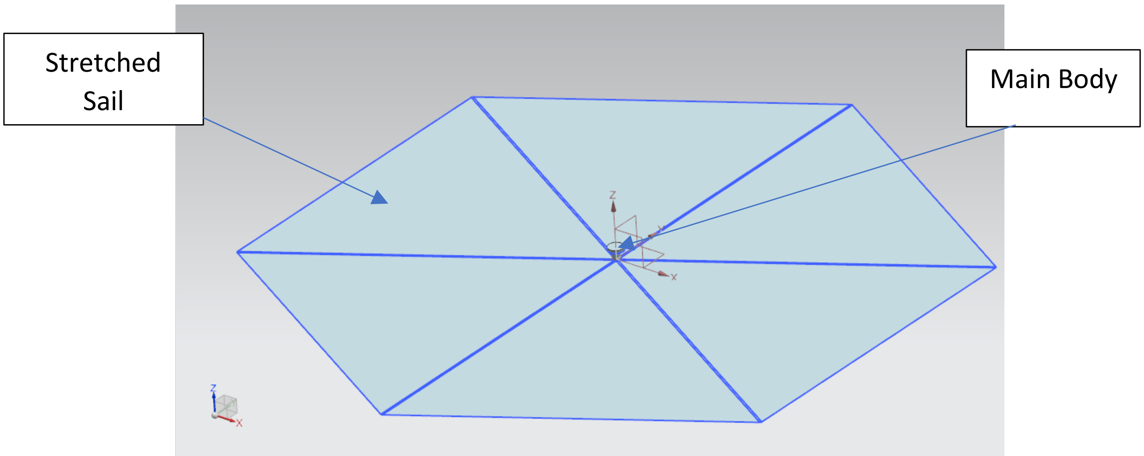

Figure 28: Fully Deployed Solar Sail [Own Source]

These arms will keep extending until the sail fully stretched and able to fully functional as in figure 28. This fully deployed sail has its own solar panel installed on top of the main body. It functions as to store some energy from the sun and can be used to run some electronics circuit in the main body such as cameras and the momentum wheels. This extra feature is an additional and optional for the designer to consider if ever this prototype is acceptable in the future.

6.3 Characteristics and Components

In this part, I will list all the main characteristics of the designed spacecraft including its components.

Main Body (Compartment Storing)	A hollow cylinder for compartment storage (folded sail)
Material of the Sail	Kapton
Total Weight	35 kg
Dimensions	Ø 2m x 3m
Area of the Sail	340 m^2
Thickness of the Sail	7 µm
Methods Deployment	By 6 mechanical Arms (folded)
Material of 'Arms'	Ultrahigh molecular weight polyethylene (UHMWPE) Carbon fibre
Camera	2 cameras installed inside the body (hidden)
Momentum Wheel	2 Wheels Installed
Solar Panel	1 Spiral Solar Panel on top of the main body
Rechargeable Battery	1 pair. The purpose is to power the circuit inside the main body for the camera and other electrical circuit.

Table 7: Characteristic finalized for the final design [Own Source]

As mention earlier, this design is customized from original COSMOS 1 project. There are few modifications made in my design. Firstly, it is dependable on other rocket of space mission because it does not have main propulsion for sending the spacecraft to outer space, same method as LightSail 1 and IKAROS. Hence, a smaller total weight is designed (compare to Volna) to increase efficiency of the rocket for original mission. To achieve this much lower weight of spacecraft, an alternative of using Ultrahigh Molecular Weight Polyethylene (UHMWPE) with reinforced carbon fibre for the arms is the crucial factor.

UHMWPE is a material that is effective in shielding against galactic cosmic ray and another solar energetic particle [47]. At the same time, it is also having an excellent mechanical and physical properties despite his low density of 0.945g/cm^3 [48].

As we compared, the design that I introduced in this prototype has a rigid arms structure. This feature is added because to ensure there is no billowing of the sail itself. In the first part of the study, if the sail wrinkled, the benefit of momentum from the photon cannot be fully maximised.

In the same time, a beneficial feature such momentum wheels are maintained in the design. Also, the materials of Kapton which originally implemented from IKAROS spacecraft is used in the sail as we discussed before.

Although there are no significant changes made in the design, but in term of efficiency and feasibility, the small changes do help the spacecraft to maximise the outcome of the solar sail.

6.4 Summary of selected design and the other original spacecrafts

The table 8 below shows tabulated characteristics of different spacecrafts including the design selected on previous part.

Design	**Selected Design 2**	**VOLNA**	**IKAROS**
Main body	A hollow cylinder	Bullet	Solid cylinder
Material of the sail	Polyimide	Aluminized-reinforced PET film (MPET).	Polyimide
Total weight	35 kg	100 kg	71 kg
Dimension	Ø 2m x 3m	Ø 1.8m x 14m	Ø1.5m x 0.4m
Area of the sail	340 m^2	600 m^2	196 m^2
Thickness of the sail	7 µm	5 µm	7.5 µm
Methods deployment	By 6 mechanical Arms (folded)	Inflating 8 structural tubes of solar sail blades	Using concept of centrifugal force
Material of Support	UHMWPE	N/A	N/A
Momentum wheels	2 wheels installed	1 wheel installed	N/A

Table 8: Comparison selected design with other spacecrafts [Own Source]

From the summarize table 8, we could see that some characteristics from these 2 existing designs are maintained in our prototype such as material Polyimide and the momentum wheels. These characteristics are studied thoroughly to ensure the best selections of components is used in the prototype.

Also, a complete different of characteristic is invented in the spacecraft, the sets of mechanical arms. This ultralightweight material is chosen to decrease greatly the weight of the space craft and the same time to avoid billowing or wrinkle on the sail as stated earlier.

7. Conclusion

The project in general is the study of crucial characteristics and properties to be implanted into the prototype design. With the help of previous successful ideas and models of solar sail spacecraft, it does give myself some improvement to add in my design. The conclusion of characteristics is written as follows:

1. In the prototype, I have designed a rigid structure of 'mechanical arms' made from an ultralight material UHMWPE carbon fibre. The reason for this structure is to prevent the sail from billowing to maximise momentum produced from photons that is reflected on the sail. On the other hand, the selection of material for this rigid structure is made from a low-density material as to minimise the weight and increase the efficiency the spacecraft itself. From table 8, we can see that the actual designs VOLNA and IKAROS, did not have this rigid structure installed. This gives a flaw in the solar sailing due to lost of energy obtained (due to some wrinkles occurred on sail) from bombarded photons.

2. This spacecraft can hold a foldable sail with area of 340 m^2 inside the main body. Instead of wrapping the sail around the main body as in IKAROS, I prefer to fold them in the inside (bottom of the body). This is because there is always a chance for the sail to not well deployed when in space as it is tied to itself. To reduce this risk, I design the prototype by folding them in the inside and attached it at the end of the mechanical arms. This is a solution that can be approached to ensure the deployment of the sail no matter in what situation as long as the mechanicals arms straighten.

3. Using the high-quality solar sail, made from Kapton material, as it is the lightest and the highest tensile strength in its category. Additional characteristic such as ability to stay stable for a large range of temperature will be a good thing as to avoid excessive radiation malfunction as its cooling process.

4. The existence of momentum wheel is crucial for a spacecraft as to manoeuvre the direction to the desired path. So, this feature is also added for excellent navigation of spacecraft.

5. The added solar panel on the prototype is and extra credit for the solar sail as it can help run the small circuits such cameras installed for monitoring purposes.

8. Recommendation

There are few recommendations that I can point out to continue with this project.

1. Study a possible target planet to perform the interstellar journey using this solar sail spacecraft. This includes the speed, the time consumed and acceleration maximum able to achieve.

2. A further discussion on the radiation of the sun and external possible drawbacks that can affect solar sail such coronal holes can be elaborated more in the next study.

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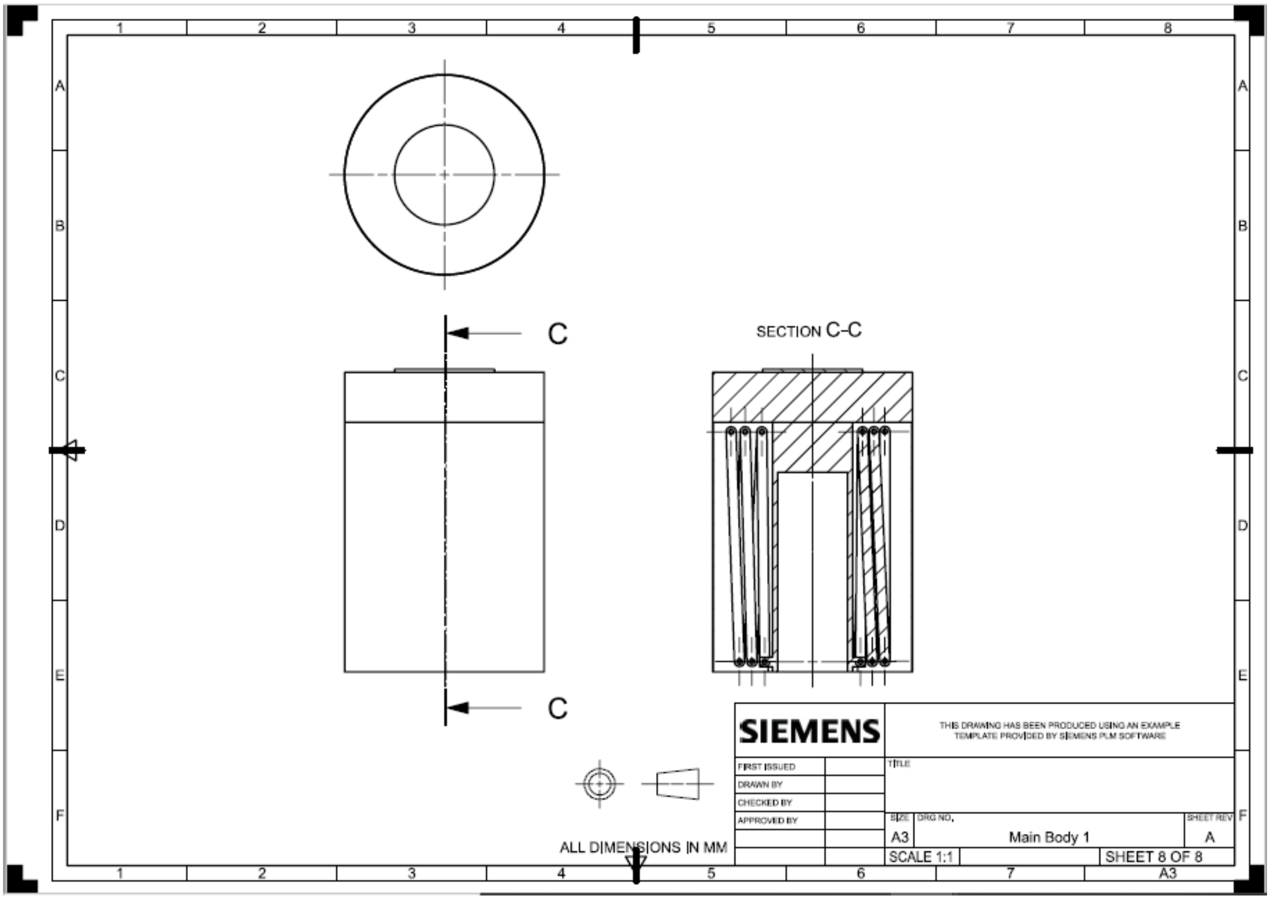
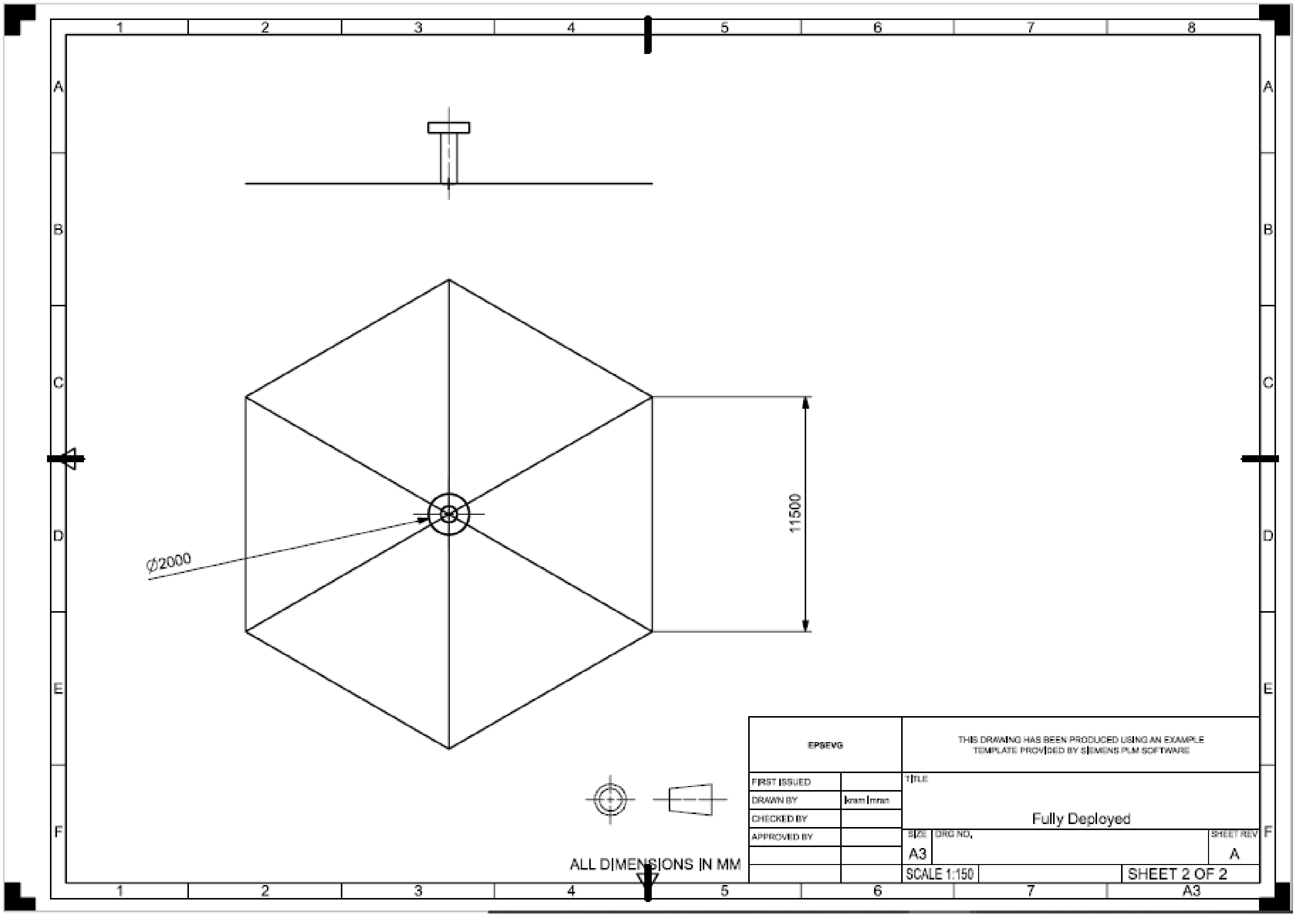
Appendix - Planes

Assembled (Undeployed):



Assembled (Fully Deployed)



Component:

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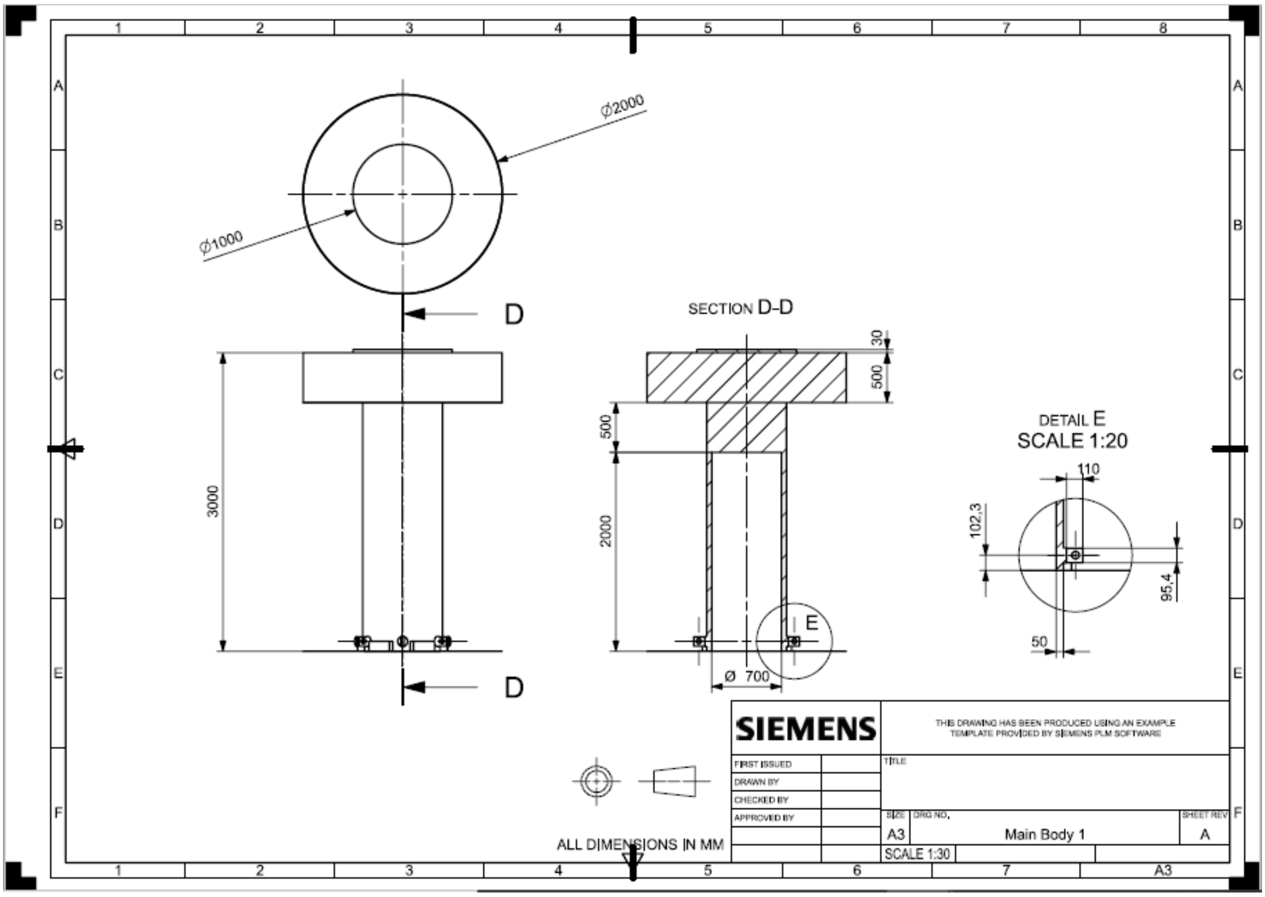
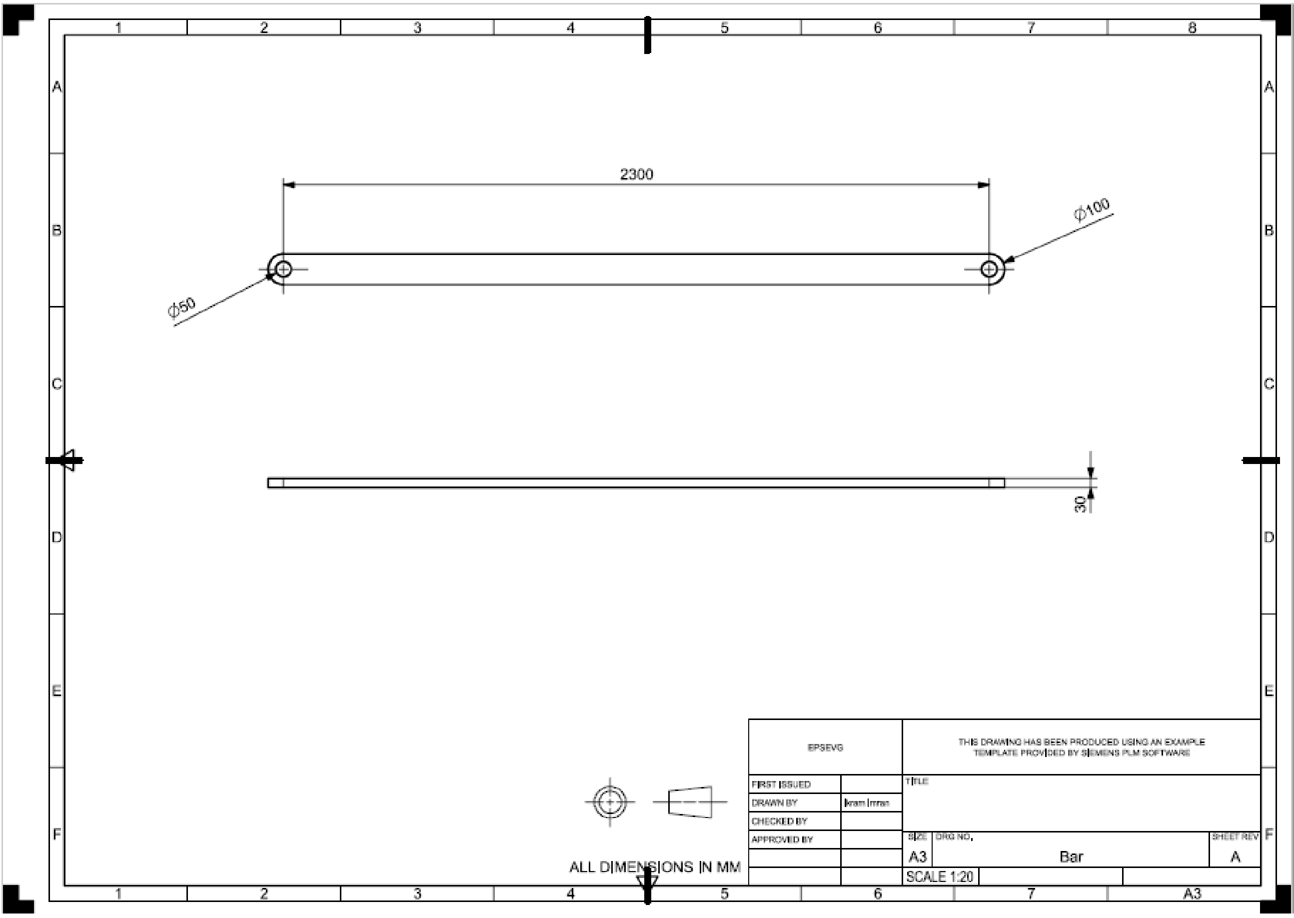


2. Bar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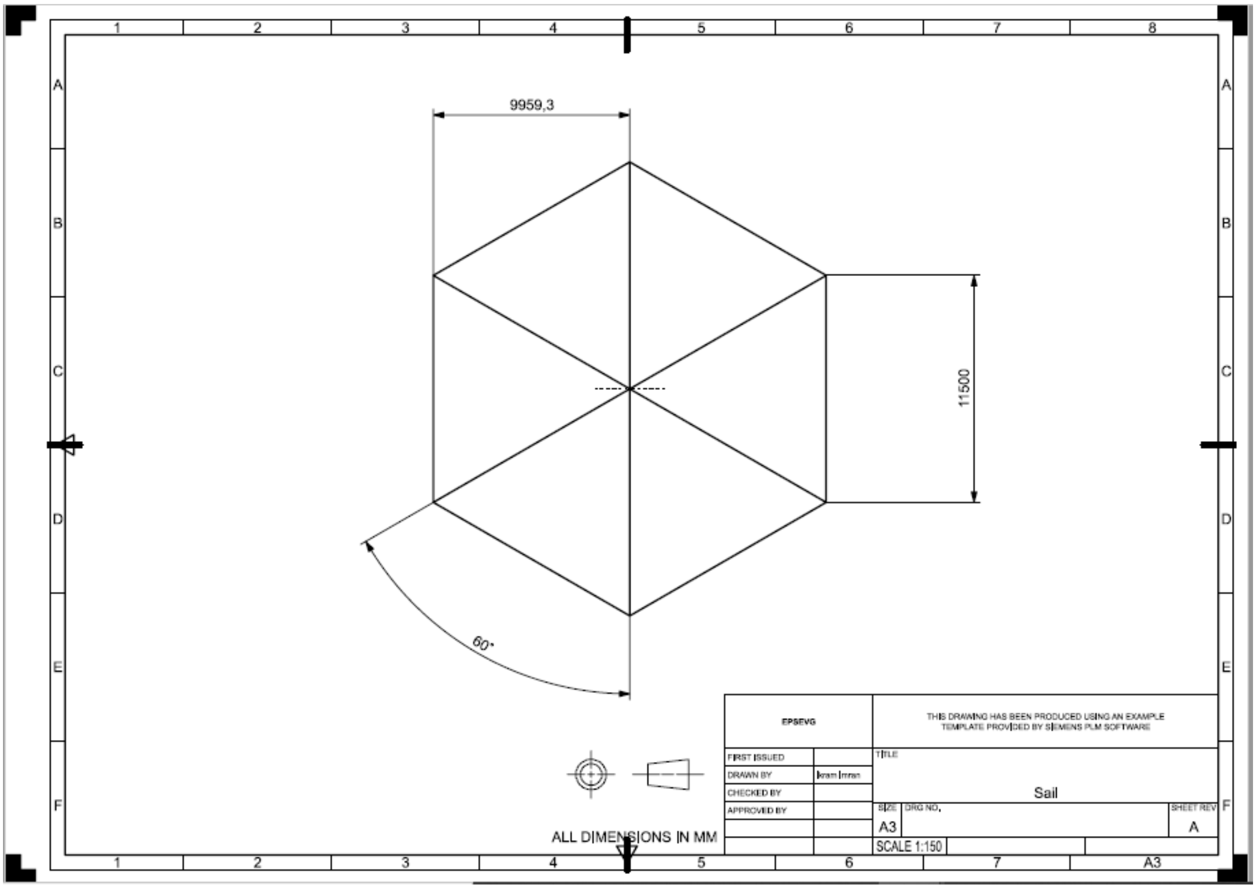
Ø100
Ø50
30
ALL DIMENSIONS IN MM
EPSEVG
THIS DRAWING HAS BEEN PRODUCED USING AN EXAMPLE TEMPLATE PROVIDED BY SIEMENS PLM SOFTWARE
FIRST ISSUED
DRAWN BY
Ikram Imran
CHECKED BY
APPROVED BY
TITLE
SIZE
DRG NO.
SHEET REV
A3
Bar
A
SCALE 1:20

3. Sail


9959,3
11500
60°
ALL DIMENSIONS IN MM
EPSEVG
THIS DRAWING HAS BEEN PRODUCED USING AN EXAMPLE TEMPLATE PROVIDED BY SIEMENS PLM SOFTWARE
FIRST ISSUED
DRAWN BY
Ikram Imran
CHECKED BY
APPROVED BY
TITLE
Sail
SIZE
DRG NO.
SHEET REV
A3
A
SCALE 1:150
A3