Design of a Spacecraft Prototype for Interstellar Journey Using Existing Methods of Propulsion

Wan Muhammad Amir Bin Wan Abd Malik

Universitat Politècnica de Catalunya UPC, Department of Physics, Av. Victor Balaguer 1, Vilanova i la Geltrú, 08800, Spain

Abstract

This work aims to design a spacecraft concept for an interstellar journey that I think would work best. A study on a wide range of different methods of propulsion was made prior to designing the spacecraft prototype. These methods vary from current methods to methods still in the early stages of development. A study on spacecraft design has also been included, ranging from existing spacecraft such as the Saturn V to conceptual spacecraft such as Project Longshot.

I will be using Siemens NX12 software to design my spacecraft model for interstellar travel. I decided to design a multistage rocket, because it is more efficient for the velocity increment. The spacecraft model can be divided into three sections, with different methods of propulsion respectively; lower stage (chemical), upper stage (nuclear fusion) and last stage (solar sail).

The major focus of the design will be on the last stage. The idea for the solar sail depends on the *extendable arms* that are arranged 90° from each other. There are vital features on the *extendable arms* design; *pathways*, *sliders* and *valves*.

The feasibility of the method of propulsion is neglected because we might not have the specific material or technological advancement in the time being. The spacecraft trajectory will not be taken into serious concern as I lack knowledge in that field.

Keywords: *Interstellar journey, Siemens NX12, Chemical propulsion, Nuclear propulsion, Solar sail, IKAROS, Saturn V, TRAPPIST 1-e, Spacecraft prototype*

1. Introduction

Throughout history, we have learned that the progress of human civilization is somewhat linked to transportation. In the 20th century, motor vehicles revolutionized transport. This has led to the rapid growth in land and air vehicles in both war and commercial use. The rocket was the emerging revolution in transportation as they are able to achieve high velocity and cover greater distances. Consequently, aircraft vehicles used in space made us understand more about other planets and solar systems in the universe.

The main purpose of this work is to design a spacecraft prototype that I think I suitable to achieve an interstellar journey, a journey between stars or other planetary systems in a galaxy. As a mechanical engineering student, I will design a spacecraft prototype based on studies regarding different propulsion method and spacecraft design. I will neglect factors that I lack knowledge of.

2. Propulsion methods

In this section, I will discuss the different methods of propulsion ranging from current methods to methods still under development. I will not disregard methods that seem impossible with the current technologies we have. Konstantin Tsiolkovsky (1857 – 1935), a Russian scientist, suggested the rocket as the means of transport for humanity to explore space [1]. A rocket is a device that propels itself into space by emitting a jet of matter as a result of a reaction [1].

The accelerating force of a rocket can be presented by Newton's law, given by:

$$F = \dot{m}v_e \quad \textbf{(1)}$$

Where $\dot{m}$ is the mass flow rate, and v_e is the exhaust velocity.

Meanwhile, the velocity of the rocket is given by:

$$V = v_e \log_e \frac{M_0}{M} \quad \textbf{(2)}$$

Where M_0 is the initial mass or mass at ignition, and M is the current mass of the rocket. This is known as the mass ratio (M_0/M).

2.1 Chemical Propulsion

A chemical engine propulsion method converts the heat generated in the combustion chamber from the burning of the propellants (fuel and oxidizer). This energy is then converted into kinetic energy of the spacecraft. Any chemical reaction that produces heat can be a source of fuel for a chemical engine [1].

- LIQUID PROPELLANT ENGINES

The basic configuration of a liquid propellant engine involves a fuel and oxidizer tank, combustion chamber, nozzle, and a delivery system. With the help of turbo-pumps, the propellant (fuel and oxidizer) are delivered into the injector, which helps convert liquid propellant into small droplets. It is then sprayed into the combustion chamber. Upon contact with the ignitor, the droplet mixture undergoes combustion. The pressure energy of the gas is converted to the kinetic energy of the spacecraft in the nozzle.

On the launch pad, Saturn V consists of three stages. The first stage had five F-1 engines burning liquid oxygen and kerosene; the second stage had five J-2 engines burning liquid oxygen and liquid hydrogen, while the third stage had a single J-2 engine [1].

Oxidant	Fuel	Ratio(4) (O/F)	T_c (K)	Density (mean)	c^* ($\mathrm{m\,s^{-1}}$)	v_e ($\mathrm{m\,s^{-1}}$)
O_2	H_2	4.83	3,251	0.32	2,386	4,550
O_2	RP1(1)	2.77	3,701	1.03	1,783	3,580
F_2	H_2	9.74	4,258	0.52	2,530	4,790
N_2O_4	MMH(2)	2.37	3,398	1.20	1,724	3,420
N_2O_4	N_2H_4 + UDMH(3)	2.15	3,369	1.20	1,731	3,420

(1) RP1 is a hydrocarbon fuel with hydrogen/carbon ratio 1.96, and density 0.81.
(2) MMH is monomethyl hydrazine.
(3) UDMH is unsymmetrical dimethyl hydrazine.
(4) The mixture ratios are optimised for expansion from 6.8 bar to vacuum.

Table 2.1 Combustion temperature and exhaust velocity for different propellants. Source: [1]

2.2 Nuclear propulsion

At the beginning of the twentieth century, the idea of using nuclear energy for rocket propulsion started to emerge. The idea of using nuclear energy for interplanetary voyages become more popular alongside the development of chemical energy.

$$P = \frac{1}{2}\dot{m}v_e^2 \quad \textbf{(3)}$$

P represents the power dissipated in the exhaust stream, while $\dot{m}$ is the mass flow rate assuming for a 100% efficiency.

By combining equation **(1)** and **(3)**, this gives:

$$F = 2\frac{P}{v_e} \quad \textbf{(4)}$$

This shows that the thrust depends on the power dissipated from the nuclear engine and inversely proportional to the exhaust velocity.

- NUCLEAR FISSION PROPULSION

Nuclear fission is the splitting of a large nucleus into smaller fragments to release energy. In principle, the absorption of a neutron in the nucleus is what causes it to split into two nuclei, with a certain amount of energy released.

For a nuclear fission of uranium, two or more neutrons are given off as a result of the fission reaction. Consequently, the neutrons would the interact with other uranium nucleus and cause it to split. Eventually, this will create a chain reaction.

Parameters	NRX XE	NERVA 1	New designs based on NERVA		
Fuel rods	UO_2 beads embedded in graphite	UO_2 beads ZrC coat, embedded in graphite	UC_2 + ZrC + C composite	UC_2 + ZrC all carbide	UC_2 + ZrC + NbC all carbide
Moderator	Graphite	Graphite + ZrH	Graphite + ZrH	Graphite + ZrH	Graphite + ZrH
Reactor vessel	Aluminum	High-strength steel	High-strength steel	High-strength steel	High-strength steel
Pressure (bar)	30	67	67	67	67
Nozzle expansion ratio	100 : 1	500 : 1	500 : 1	500 : 1	500 : 1
I_{sp} (s)	710	890	925	1,020	1,080
Chamber temperature (K)	2,270	2,500	2,700	3,100	3,300
Thrust (kN)	250	334	334	334	334
Reactor power (MW)	1,120	1,520	1,613	1,787	1,877
Engine availability (yr)	1969	1972	?	?	?
Reactor mass (kg)	3,159	5,476	5,853	6,579	?
Nozzle, pumps, etc., mass (kg)	3,225	2,559	2,559	2,624	?
Internal shield mass (kg)	1,316	1,524	1,517	1,517	?
External shield mass (kg)	None	4,537	4,674	4,967	

Table 2.2 Nuclear rocket engine schemes based on NERVA programme. Source: [1]

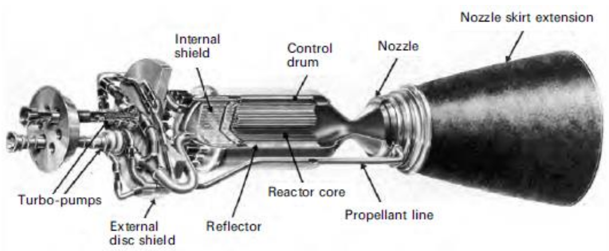


Figure 2.1 Drawing of a NERVA nuclear rocket engine. Source: [1]

2.3 Solar sailing

There are three choices when relying on the Sun as the external fuel source to the spacecraft; particles, fields or photons. In this case, we will focus on the photon energy released by the Sun. Although photon does not have mass, they can still have momentum that can be bombarded to any sail. Therefore, to maximize optimisation, the sail should have high reflectivity and low absorption.

Some aspects to be considered for a solar sail includes the density, which must be light for maximum light pressure. It should also be thin. In addition, the sail area plays an important role to reflect greater number of photons onto the sail. Lastly, the reflectivity of the sail should be as excellent as possible to avoid photon from being absorbed into the material or transmitted through.

The amount of solar radiation flux from the Sun varies with distance according to an inverse square law [2]:

$$S_r \left[\frac{W}{m^2}\right] = \frac{3.04\ x\ 10^{25}}{r^2} \quad \textbf{(5)}$$

The solar radiation flux intensity at Earth's orbit is around 1,400 W/m^2. This value comes by substituting the value at a distance of 1 AU (Astronomical Unit), which is equivalent to 1.496x10^{11} m.

The solar pressure can be expressed as:

$$P_{rad} \left[\frac{N}{m^2}\right] = \frac{1+\mu}{c} S_r \quad \textbf{(6)}$$

Equation **(6)** shows that the solar pressure acting on the sail is influenced by the sail reflectivity, μ and the solar radiation flux, S_r. For a realistic sail, the sail reflectivity should be around 0.8 – 0.9 or equal to unity for a completely reflective surface.

The sail loading, σ or the areal density is given by g/m^2. The mass consist of the entire spacecraft system that includes the sail, payload and other components. The sail loading, σ can be expressed by:

$$\sigma \left[\frac{g}{m^2}\right] = \frac{m}{A} \quad \textbf{(7)}$$

Combining equations **(6)** and **(7)** gives the characteristic acceleration of the sail, a_c:

$$a_c \left[\frac{m}{s^2}\right] = \frac{P_{rad}}{\sigma} \quad \textbf{(8)}$$

An example of a spacecraft using solar sail is the IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun), which was launched by Japan Exploration Agency (JAXA) on 21st May 2010.

The wet mass of the IKAROS is 307 kg attached to a rectangular solar sail that weighs 16 kg with a minimum thickness of 7.5 µm. The deployment mechanism of the sail depends strictly upon the spinning of the spacecraft by centrifugal force.

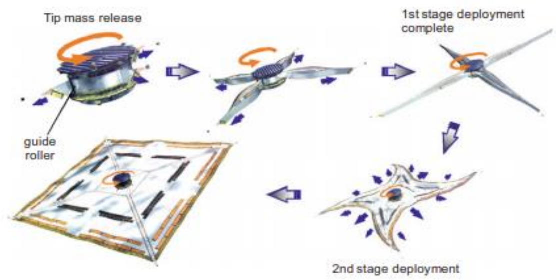


Figure 2.3 IKAROS solar sail deployment. Source: [4]

The deployment mechanism can be separated into two phases. Firstly, extend the sail to a cross shape. The next phase is to enlarge the cross shape to a flat rectangular shape by unlatching four guide rollers.

In addition to that, IKAROS has a reflective control device (RCD). The function is to change the optical reflectance by controlling ON/OFF. This ultimately allows the spacecraft to change its spin axis without any fuel consumption [3].

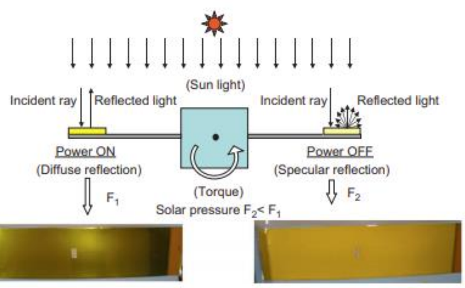


Figure 2.4 Reflective control device (RCD) concept operation. Source: [3]

3. Previous FYP work

We will have a look at previous final year projects or studies done by other students regarding interstellar travel.

Muhammad Nur Ikram Bin Imran, *"Design of Solar Sailing Prototype for Interstellar Journey"*, TFG, June 2020

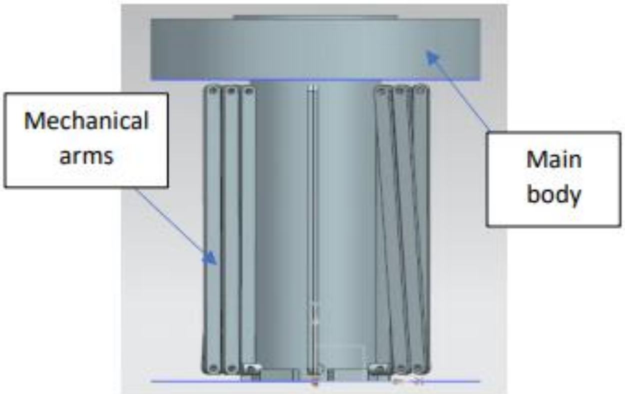


Figure 3.1 Solar sail prototype by Muhammad Nur Ikram. Source: [5]

Based on his work, the idea behind his design is the foldable mechanical arms that expand when deployed while unfurling the sail material. The arms are attached in a zigzag pattern and the material chosen is Kapton with a thickness of 7 µm.

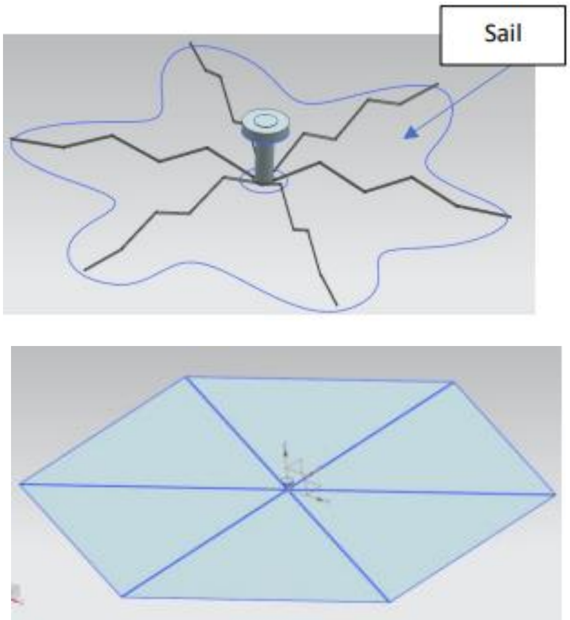


Figure 3.2 Fully deployed solar sail of Muhammad Nur Ikram's concept design. Source: [5]

Josep Pinyol Escala, *"Prototip de veles solars impulsades per laser per al viatge interestal.lar"*, TFG, February 2020

The author's idea is to use a laser emitting a monochrome light in a particular wavelength to propel the sail. Another focus in this work is the geometry of the sail. The author states that a 20% less length structure is required for a square sail than a circular sail for the same reflective area. This would amount to a 20% less mass structure for a square sail than a circular sail.

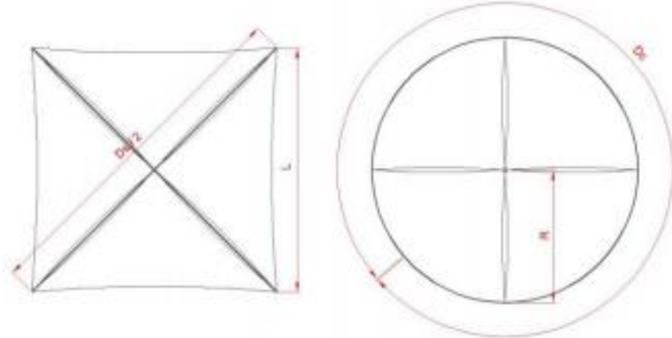


Figure 3.2 Comparison between circular and square-shaped sail. Source: [6]

The material chosen for the sail is aluminium with a layer of Kapton. On the other hand, carbon fibre is selected for other structures.

4. Our solar system and beyond

4.1 Earth

Before achieving interstellar travel, let us first understand the requirement to fully escape Earth's gravitational influence. Combining the centripetal force and the gravitational force gives:

$$\frac{mv^2}{r} = \frac{GM_{\oplus}m}{r^2} \quad \textbf{(9)}$$

Where $M_{\oplus}$ is the central mass (mass of Earth), m is the orbiting mass (spacecraft), orbital radius r, velocity of rotation v, and gravitational constant G.

To reach circular orbital velocity:

$$v_{circ} = \sqrt{\frac{GM_{\oplus}}{r_o}} \quad \textbf{(10)}$$

Substitute the values of Earth's mass (5.975×10^{24} kg), gravitational constant, G (6.67×10^{-11} N/kg^{2}m^2) together with the mean radius of the Earth, 6,371 km into equation **(10)**. This gives a value of 7.9 km/s to reach a circular orbit.

Meanwhile, the escape velocity or the minimum velocity needed to leave Earth's gravitational field is greater by a factor of $\sqrt{2}$ than the circular orbital velocity. A spacecraft has to accelerate to a velocity of 11.2 km/s to entirely escape the Earth's orbit [1]. The escape velocity can be expressed as:

$$V_{esc} = \sqrt{\frac{2GM_{\oplus}}{r_o}} \qquad \textbf{(11)}$$

Object	Mass (Earth = 1)	Mass (kg)	Equatorial radius (km)	v_{circ} (km/s)	v_{esc} (km/s)
Sun	3.3×10^5	1.989×10^{30}	6.959×10^5	437	618
Mercury	0.055	3.302×10^{23}	2,439	3	4.3
Venus	0.815	4.869×10^{24}	6,052	7.3	10.4
Earth	1.0	5.974×10^{24}	6,378	7.9	11.2
Moon	0.012	7.348×10^{22}	1,738	1.7	2.4
Mars	0.107	6.419×10^{23}	3,397	3.6	5
Jupiter	317.83	1.899×10^{27}	71,492	42.1	59.5
Saturn	95.16	5.685×10^{26}	60,268	25.1	35.5
Uranus	14.5	8.662×10^{25}	25,559	15.0	21.3
Neptune	17.204	1.028×10^{26}	24,764	16.6	23.5
Pluto	0.002	1.3×10^{22}	1,150	0.87	1.3

Figure 4.1 Circular orbital velocity and escape velocity for different solar system bodies. Source: [2]

4.2 Possible destinations

In this section, I made a study on the possible destinations for my conceptual spacecraft to head to.

__Exoplanets__

Exoplanets are planets that orbit around other stars. They come in a variety of sizes, from gas giants to rocky planets. The four main category type of an exoplanet are:

- Gas giant

A large planet mainly composed of Helium and/or hydrogen, can be bigger than Jupiter and much closer in size to their stars. Gas giants nearer to their stars are called 'hot Jupiters' [7].

- Neptunian

They are similar in size to Neptune or Uranus in our solar system [8]. Neptunian exoplanets may have a mixture of rocky interiors with heavier metals at their cores, and typically have hydrogen and helium dominated atmospheres.

- Super-Earth

Super-Earth exoplanets are larger than Earth, but lighter than Neptune and Uranus. They can be made of gas, rock or a combination of both [9]. Exoplanets at the upper limit of the Super-Earth size limit is known as mini-Neptunes.

- Terrestrial

Terrestrial planets are planets with a size similar or smaller to Earth. They are planets composed of rock, silicate, water and/or carbon. Terrestrial planets have a bulk composition that is dominated by rock or iron, and a solid or liquid surface [10].

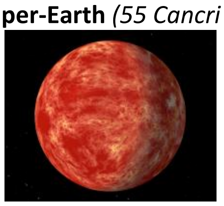
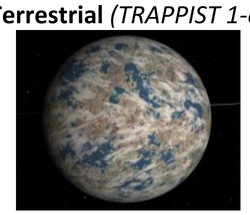
Destination	Characteristics
Gas Giant *(51 pegasi b)* 	-46% mass of Jupiter -50 light years from Earth
Neptunian *(Kepler-1655 b)* 	-has a mass 5 times of Earth -696 light years from Earth
Super-Earth *(55 Cancri e)* 	-hottest side of planet is nearly 2,700 K and the coolest is 1,400 K. -41 light years from Earth
Terrestrial *(TRAPPIST 1-e)* 	-believed to have liquid water on its surface -41 light years from Earth

Table 4.1 Comparison of exoplanets. Source: own

After a brief study and comparison between different exoplanets, the destination chosen for my conceptual spacecraft prototype is *TRAPPIST 1-e*. This is because the amount of radiation it receives from its star is the most similar to Earth, and it is believed to have liquid water on its surface.

5. Design and 3D model

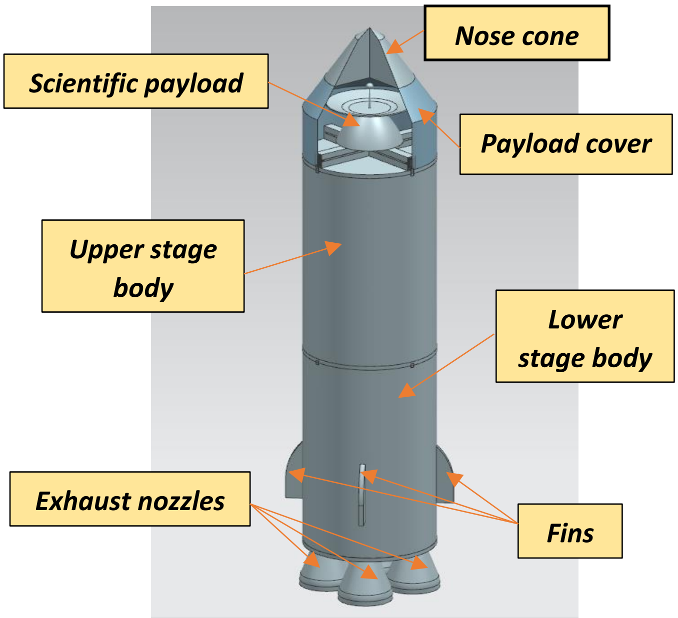


Figure 5.1 Overall 3D model of the spacecraft concept. Source: own.

The idea behind this design is a multi-stage rocket with different methods of propulsion. Since the mass of propellant heavily influences a rocket's mass, a multi-stage rocket is able to remove any unnecessary weight such as empty tanks, engine, etc., once the propellant is exhausted. In doing so, the acceleration of the spacecraft will be greater as the overall mass of the spacecraft decreases with time.

The velocity increment of a rocket with two or more stages can be shown by:

$$V = v_e log_e R_1 + v_e log_e R_2 \qquad \textbf{(12)}$$

Where v_e is the exhaust velocity and *R* is the mass ratio of each stage.

For the design section, I will not go into detail, such as designing the engine or the delivery systems. Instead, I will choose a method of propulsion for each stage and will briefly explain the conceptual spacecraft design.

The spacecraft concept can be divided into three sections; lower stage, upper stage and last stage. The main focus will be on the last stage, in which the scientific payload will head towards the exoplanet, *TRAPPIST 1-e*.

5.1 Lower stage

The lower stage body frame design is a cylindrical hollow body with holes at the base to fit in the exhaust nozzles. In this particular stage, the exhaust nozzles are made to be short to minimize expansion, especially in the lower stages of flight, where the atmospheric pressure is the greatest [1]. Meanwhile, the fins attached to the body frame help to reduce any form of drag acting on the spacecraft.

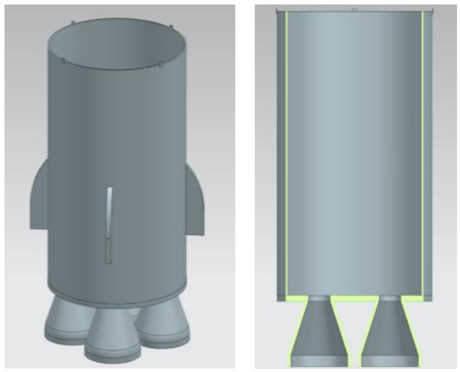


Figure 5.2 Lower stage body frame with exhaust nozzles and fins attached. Source: own

Before deciding on the material, a study has been made between two main material used on a rocket body frame, titanium and aluminium.

Properties	Aluminium	Titanium
Density (g/cm³)	2.70	4.506
Melting point (K)	933.47 (660.32 °C)	1941 (1668 °C)
Boiling point (K)	2743 (2470 °C)	3560 (3287 °C)
Young's modulus (GPa)	70	116

Table 5.1 Physical property comparison between aluminium and titanium. Source: Wikipedia

In conclusion, the material chosen for the body frame is titanium since it has the ability to withstand greater temperatures despite being twice as dense.

The method of propulsion chosen for this stage is chemical propulsion – liquid propellant engine with a propellant choice of liquid oxygen and liquid hydrogen. Referring back to table 2.1, liquid oxygen and hydrogen could generate an exhaust velocity of 4,550 m/s.

The main focus of the lower stage is to generate a thrust greater than the total mass of spacecraft at lift-off rather than gaining enough velocity. Equation **(1)** shows that the thrust depends on the mass flow rate, $\dot{m}$ and the exhaust velocity, v_e. Therefore, the bigger the mass flow rate, the greater the thrust generated by the engine.

5.2 Upper stage

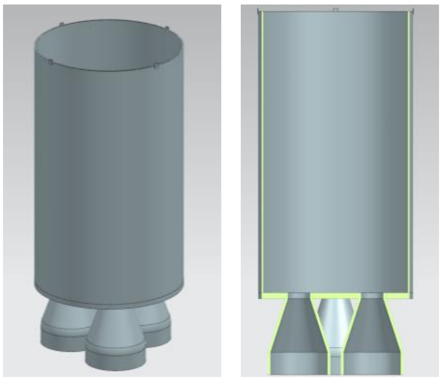


Figure 5.3 Upper stage body frame with exhaust nozzles attached. Source: own

The upper stage is somewhat similar to the lower stage in which it is made up of titanium. It is also a hollow cylindrical body with holes at the base to fit in the nozzles. One significant difference is that the nozzles for the upper stage are designed to be long with a suitable expansion ratio. The best way to optimize the rocket engine in space is to expand the nozzle as much as possible [1].

The propulsion method chosen in this stage is nuclear fission propulsion. The maximum exhaust velocity in theory for a nuclear fission propulsion is 8,7000 m/s.

Using equation **(12)**, the velocity increment for the conceptual spacecraft design is:

$$V = 4{,}550 log_e R_1 + 8{,}700 log_e R_2$$

With the right mass ratio for each stage, the rocket should gain enough velocity to escape the Earth's orbit as discussed in chapter 4.1.

5.3 Last stage

As for the last stage, the payload design will be focused more since it will be destined for *TRAPPIST 1-e*. The majority of the conceptual spacecraft trajectory will be neglected in this section.

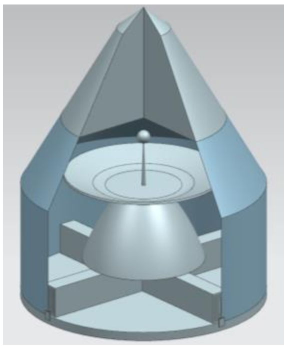


Figure 5.4 The scientific payload inside its cover and the nose cone of the rocket. Source: own

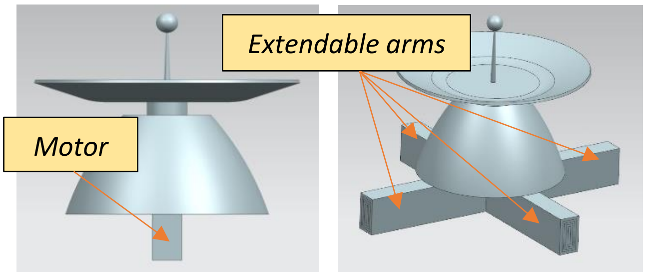


Figure 5.5 3D model of the scientific payload. Source: own

The concept behind the design is based on Muhammad Nur Ikram's work on solar sailing [5]. The mechanical arms on his spacecraft design were foldable, allowing it to save space. However, in my approach, I added features onto the *extendable arms* that would help provide more stability and rigidity to the sail.

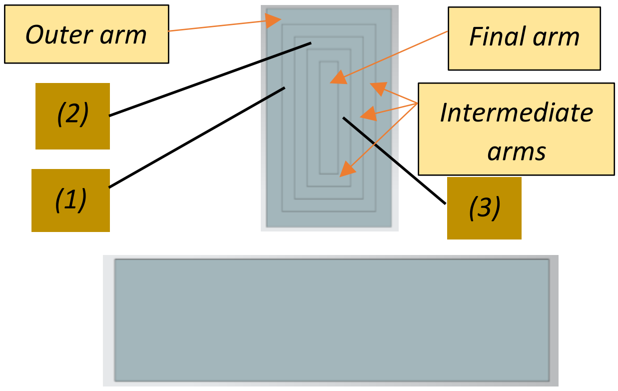


Figure 5.6 Front and side view of an *extendable arm*. Source: own

The deployment mechanism of the *extendable arms* depend on three key features; *pathways*, *sliders* and *valves*. The features on the *outer arm*, *intermediate arms* and *final arm* are different from one another.

- *Outer arm*

The *outer arm* is designed to be stationary and is connected to the motor on the payload. It is a rectangular hollow body with *pathways* and *valves* incorporated on the interior walls. The *pathways* allow the *intermediate arm (1)* to slide along it while the *valves* lock the *sliders* in place. This is to avoid the arms from moving backwards.

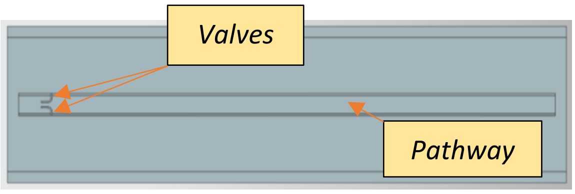


Figure 5.7 Interior wall of the *outer arm*. Source: own

- *Intermediate arms (1, 2 and 3)*

The three intermediate arms are designed with the same features but different hollow rectangular dimensions. *Sliders* are attached on the exterior walls, and it has features similar to the *outer arm* on the interior walls of the *intermediate arms*. The *sliders* would guide the movement of arms during the deployment of the sail.

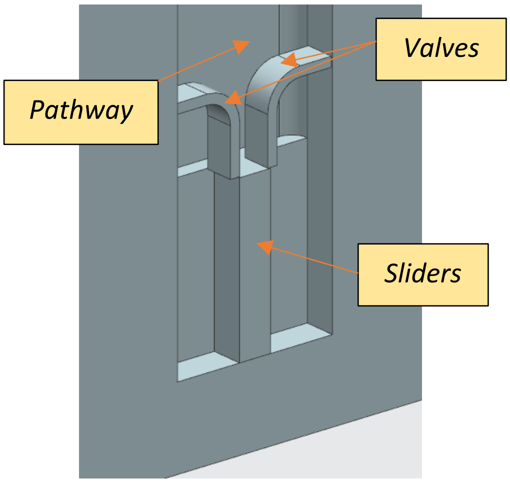


Figure 5.8 Inside view of the *sliders* and *valves* mechanism passing through the *pathway*. Source: own

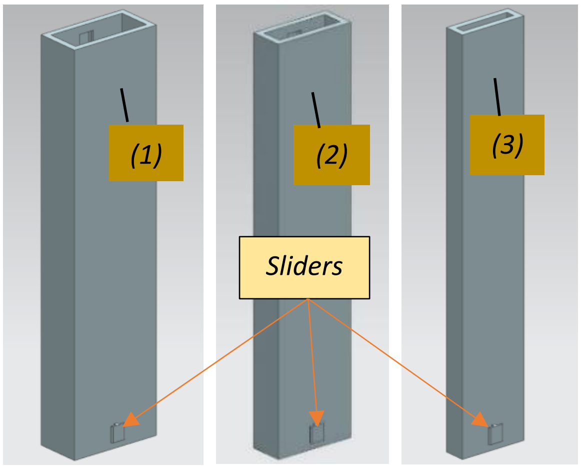


Figure 5.9 Design of the three *intermediate arms*. Source: own

- *Final arm*

The final arm is designed to a solid rectangular body with *sliders* attached to the exterior walls. The sliders will move along the *pathways* of the *intermediate arm (3)*.

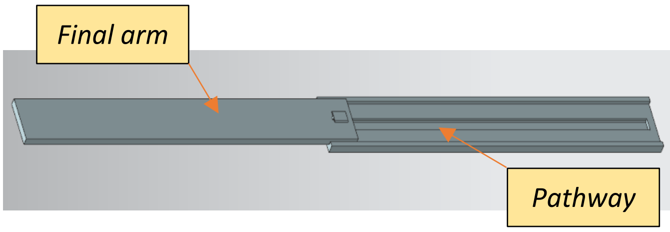


Figure 5.10 View of *final arm* extension. Source: own

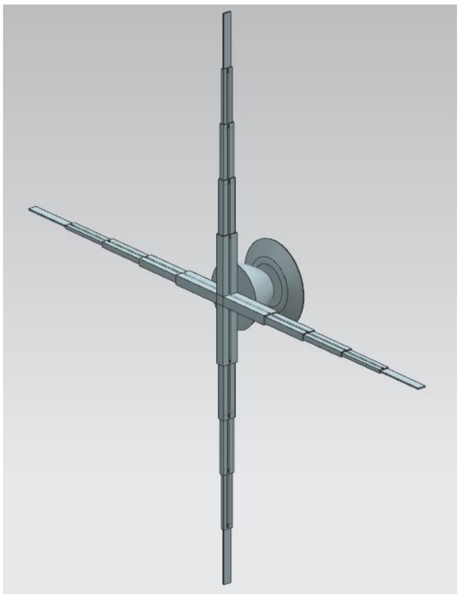


Figure 5.11 All four *extendable arms* fully deployed. Source: own

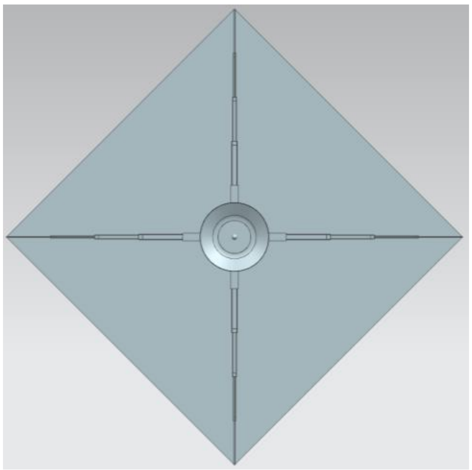


Figure 5.12 Fully deployed *extendable arms* with sail. Source: own

The square sail is adapted from Josep Pinyol Escala's work. He explains how a square-shaped sail would require 20% less length structure than a circular sail [6]. This would ultimately result in a 20% less mass of the structure for the same reflective area.

To summarize, the payload's characteristic and components can be shown as follows:

Main body	Curved cylindrical body
Dimensions	Ø 1.4 m x 1.5 m, with a 4.5 m curvature
Sail material	Kapton and aluminium bilayer
Sail thickness	10 μm
Sail area	≈ 280 m² (square)
Method of deployment	Extendable arms
Material of arms	UHM type carbon fibre
Antenna	Placed on top of payload for navigation

Table 5.2 Characteristic and components of the scientific payload. Source: own

The idea is to place the payload as close as possible to the Sun, in this case, the orbit of Venus. This relates to the solar radiation flux intensity, equation **(5)**, which is inversely proportional to the squared distance. Venus has an orbit with a semi-major axis of 0.72 AU [11].

At a distance of 0.72 AU, the solar radiation received by the payload can be calculated:

(1 AU = 1.496x10^{11} m)

$$S_r = \frac{3.04\ x\ 10^{25}}{(0.72\ AU)^2}\ X\ \frac{(1\ AU)^2}{(1.496x10^{11}\ m)^2} = 2{,}620\ \text{W/m}^2$$

For a realistic value of 0.9 for the reflectivity of the sail μ, the solar pressure can be calculated using equation **(6)**:

$$P_{rad} = \frac{1+0.9}{c} S_r = 16.6\ x\ 10^{-6}\ \text{N/m}^2$$

The characteristic acceleration a_c of the payload is:

$$a_c = \frac{A}{m}\ x\ P_{rad} = \frac{280}{m}\ x\ (16.6\ x\ 10^{-6})$$

Assuming for a sail loading (σ) value of 0.1, the characteristic acceleration of the spacecraft prototype can be calculated using equation **(8)**:

$$a_c = \frac{P_{rad}}{\sigma} = 1.66x10^{-4}\ \text{m/s}^2$$

Neglecting any space drag such as cosmic radiation and solar wind, and assuming for a simple linear trajectory, the approximate time taken for the payload to reach a destination can be calculated by:

$$S = vt \qquad \textbf{(13)}$$

$$S = ut + \frac{1}{2}at^2 \qquad \textbf{(14)}$$

Where *S*: displacement, *v*: velocity (rocket), *t*: time taken, *u*: initial velocity (= 0), *a*: acceleration

For example, the approximate time taken to reach Neptune from the orbit of Venus can be calculated using equation **(14)**. *S* is substituted with the difference in distance between the orbit of Venus and Neptune, 29.38 AU.

$$t = \sqrt{\frac{2S}{a}} = \sqrt{\frac{2(29.38)(1.496x10^{11})}{1.66x10^{-4}}}$$

$$t = 2.301x10^8\ \text{s} \approx 7.3\ \text{years}$$

Assuming the spacecraft prototype accelerates to a velocity of 12,000 m/s by the end of the upper stage, the approximate time for the spacecraft to reach the orbit of Venus can be calculated using equation **(13)**. The displacement is the difference in distance between the Earth and Venus's orbit, 0.28 AU.

$$t = \frac{S}{v} = \frac{0.28(1.496x10^{11})}{12{,}000}$$

$$t = 3.49x10^{6}\ \text{s} \approx 40\ \text{days}$$

Destination	Estimated time taken
TRAPPIST 1-e	2170 years
Neptune	7.3 years
Kuiper Belt (outer boundary)	9.45 years
Oort Cloud (inner limit)	60.2 years
Orbit of Venus	40 days

Table 5.3 Summary of estimated time taken for the spacecraft prototype to reach exoplanet *TRAPPIST 1-e*, Neptune, Kuiper Belt, Oort Cloud and orbit of Venus. Source: own

The approximate times calculated in Table 5.3 are based on assumptions that include; 0.9 sail reflectivity (μ) and 0.1 sail loading (σ) that would lead to a characteristic acceleration, a_c of $1.66x10^{-4}$ m/s^2. Meanwhile, the reflective area of the sail is based on the design of the *extendable arm* that could extend up to 11.9 m, with an initial length of 2.5 m.

The design, characteristics and components of the spacecraft for all stages is based on my approach to achieve interstellar journey. Table 5.4 shows the summary on the three stages of the conceptual spacecraft.

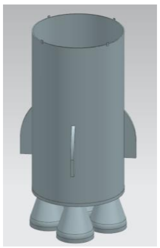
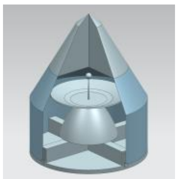
STAGES	DESCRIPTION
LOWER STAGE 	-body frame is made up of titanium -explosive bolts mounted to detach itself from the upper stage -fins on the side to reduce drag in the lower stage -exhaust nozzles are short to minimize expansion -chemical propulsion – liquid propellant engine (liquid oxygen and liquid hydrogen) -exhaust velocity: 4,550 m/s
UPPER STAGE 	-body frame is made up of titanium -explosive bolts mounted to detach itself from the last stage -exhaust nozzles are long to maximize expansion -nuclear propulsion – nuclear fission. -exhaust velocity: 8,700 m/s
LAST STAGE 	-explosive bolts mounted to remove the payload cover safely without damaging the payload -nose cone is to reduce drag in the lower stage -solar sail propulsion -sail area of around 280 m^2 (square) -*extendable arms* designed to deploy sail (UHM-type carbon fibre)

Table 5.4 Summary of the three stages of the conceptual spacecraft design. Source: own

6. Conclusion

Referring back to the objectives of this work, I did a study on different methods of propulsion. The study ranges from current propulsion methods to other methods that are still under development.

I also did a study on existing spacecraft designs and ones still in concept. This helped me have a better understanding of the performance and the features of the spacecraft.

Besides that, I made a concise comparison between the different methods of propulsion. This helped me understand the pros and cons of each method before deciding which would work best for each stage.

A brief study on our solar system and beyond were made. The aim is to understand the requirement to leave Earth before setting flight for interstellar travel. I also chose a destination for my conceptual design, *TRAPPIST 1-e*, after studying neighbouring stars and exoplanets.

My approach to achieve interstellar travel is by using a multistage rocket, with different methods of propulsion; lower stage (chemical), upper stage (nuclear fission) and last stage (solar sail). Two materials were compared, aluminium and titanium, before being chosen for the body frame of the upper and lower stages.

For the last stage of flight, by solar sail, my approach is influenced by Muhammad Nur Ikram and Josep Pinyol Escala's work on interstellar travel. The *extendable arms* design was adapted from the mechanical arms on Muhammad Nur Ikram's spacecraft concept, while the square sail is adapted from Josep Pinyol Escala's work.

The *extendable arms* are made of UHM-type carbon fibre, while the sail material is a combination of Kapton and aluminium bilayer.

Variation in flight trajectories will not be discussed in detail, but my approach only involves the payload leaving the Earth's orbit and entering the orbit of Venus before making a deep space trajectory headed for its destination, *TRAPPIST 1-e.*

In conclusion, I fulfilled all the objectives of this work. I hope further studies regarding this work can be done to improve the design or the method of propulsion.

Recommendations

I would like to give some recommendations of future work as a continuation of this project.

i. Calculate the mass of engine and propellant needed for the lower and upper stage of flight.
ii. Study regarding the flight trajectories and the requirements needed for the spacecraft to be injected into the orbit of Venus.
iii. Additional components to be installed onto the payload that would help its interstellar flight.
iv. Improvements on the sail and its mechanism, which includes the unfurling of sail and a material for better reflection of photons.

These recommendations may help improve the conceptual spacecraft prototype in terms of its efficiency or design.

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