Space Propulsion

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1. Abstract

Humanity is always expanding and exploring. There are current plans to put humans on mars. Space Propulsion is how humanity travels through space. This report provides an overview of certain space propulsion technologies, Rocket Combustion Engines and Solar Sails. Included are discussions of green propellant and the Green Propellant Infusion Mission, and an analysis of Solar Sails for Low Earth Orbit.

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3. Executive Summary

This project discusses space exploration and propulsion. Space Propulsion is how humanity travels through space. Specifically, this project focuses on Rocket Combustion Engines and Solar Sails.

First, it is important to understand the Rocket Equation and the physics of how rockets move. Rocket engines use expelled propellant to generate thrust. This propellant is often Hydrazine or Hydrazine derivatives. Hydrazine is toxic which has presented many safety concerns. NASA's Green Propellant Infusion Mission (GPIM) is researching safer propellants. This project also discusses the most recent GPIM propellant.

Solar Sails use solar radiation pressure to generate thrust. This project first discusses solar radiation pressure, solar radiation flux, and photon interactions. Then this project discusses solar sails themselves. The main difficulty of using solar sails is how the force produced is only in the direction away from the sun. This can be difficult when looking at satellites in Low Earth Orbit. This project discusses using a solar sail ignoring this difficulty.

4. Introduction

Space has always been an enticing subject and destination. Since early rockets, transportation to and from space has been an integral aspect of space exploration. Early struggles and achievements surrounding space were being able to reach space itself. Only recently have important goals been focused on what humans can do in space.

NASA's current Artemis program is a good summary of the general societal goals for space exploration. Current plans are to send humans back to the moon, specifically focusing on diversifying who has been on the moon. Additionally, NASA is looking at creating a lunar base camp. This will be both for a habitat for astronauts and an outpost for a further trip to Mars [28]. Man-less missions have been even further. Most recently, the James Webb Space Telescope launched and is currently studying the furthest corners of the universe [2]. The furthest man-made object from earth is the Voyager 1 space probe [41].

Space research has been beneficial for humanity. Many popular technologies were able to be developed due to space exploration. One of the most obvious and direct examples is satellite technology. Society largely relies on satellites for daily life. Being able to communicate across the world is due to satellites. Satellites are also able to collect data on the environment, being important in the study of climate change.

Climate change and resource availability have been large issues. These have largely impacted space transportation. Research into new methods and safer resources for space transportation has become important. Advancements in propulsion technology require consideration of how these technologies will affect our planet, our health, and society.

Past projects have looked at Lunar and Martian base camps as well as usable resources found outside of earth. This project will focus on getting to these places. This project will explore and evaluate both current and hypothetical space propulsion technologies. This project will discuss both currently used technology and solar sails. This project will also focus on the feasibility of these methods.

5. Rocket Engines

The most used propulsion method is combustion rocket engines. These use strong chemical reactions to create pressure on and expel propellant to create thrust. This method was used since early rocketry and is tested and known as very reliable and powerful. However, propellants used in rocket engines can be very toxic and dangerous to both humans and machinery, which has motivated many to research new, less toxic propellants.

5.1 Rocket Equation

The force of the expelled propellant results in a force on the rocket in the opposite direction due to Newton's third law. The movement of a rocket can be found using Newton's second law,

$$\vec{F} = \frac{d\vec{p}}{dt} \tag{1}$$

This says that a force F is equal to the time derivative of momentum, p.

A rocket can be considered a closed system, meaning no external forces.

With this, equation 1 can be rewritten as

$$0 = \frac{d\vec{p}}{dt} \tag{2}$$

Which implies that momentum is conserved.

Consider a rocket at time t=0 and at t= Δt. At t=0, the rocket will have its total mass, m_0, and an initial velocity, v_0. During flight, the mass decreases as the propellant is expelled. At t=Δt, the rocket will have a mass of $m=m_0 - \Delta m$, and a velocity of $v=v_0 + \Delta v$. The propellant at t=Δt has a mass of Δm and a velocity of v_u. These can be used to find the momentum at both times.

$$\vec{p}_0 = m_0\overrightarrow{v_0} \tag{3}$$

$$\vec{p}\Delta t = (m_0 - m)(v_0 + v) + mv_u \tag{4}$$

As momentum is conserved, these can be set as equal and solved for Δv.

$$m_0 v_0 = (m_0 - m)(v_0 + v) + m v_u \tag{5}$$

$$m_0 v_0 = m_0 v_0 + m_0 \Delta v - \Delta m \Delta v + \Delta m v_u \tag{6}$$

$$\Delta v (m_0 - m) = \Delta m (v_0 - v_u) \tag{7}$$

Here we can use $m=m_0 - \Delta m$ as this is describing mass at time $t=\Delta t$.

$$m \Delta v = \Delta m (v_0 - v_u) \tag{8}$$

The velocity of the propellant, v_u is from a stationary reference frame, but if we consider the velocity in the frame of the rocket, the velocity can be given by $v_0-v_u=v_e$.

$$m \Delta v = \Delta m v_e \tag{9}$$

Dividing by Δt and letting Δt go to 0 gives

$$m \frac{dv}{dt} = v_e \frac{dm}{dt} \tag{10}$$

This can be integrated over our time difference. The mass changes over time, as propellant mass is lost. Assume v_e is constant and can be taken out of the integral.

$$\int_0^{\Delta t} \int_{v(0)}^{v(\Delta t)} dv dt = v_e \int_0^{\Delta t} \int_{m(0)}^{m(\Delta t)} \frac{dm}{m} dt \tag{11}$$

$$\Delta v = v_e \ln\left(\frac{m_0}{m_0 - \Delta m}\right) \tag{12}$$

Equation 13 is also known as the rocket equation. Δv is the total impulse given to the rocket. This dictates the rocket's change in velocity.

5.2 Launching Rockets to Space

To get to low earth orbit, a rocket needs to go against the force of gravity and the atmospheric pressure. To be in a stable low earth orbit, the centrifugal force of a rocket needs to be equivalent to the force of gravity on the rocket. The force of gravity and the centrifugal force are given by equations 13 and 14 respectively.

$$\overrightarrow{F_g} = -\frac{GMm}{r^2}\hat{r} \tag{13}$$

$$\overrightarrow{F_c} = \frac{mv^2}{r}\hat{r} \tag{14}$$

In these equations, G is the gravitational constant, M is the mass of the earth, m is the mass of the rocket, r is the distance from the center of the earth to the rocket, and v is the velocity of the rocket. To stay in orbit, total force in the r-direction should be zero.

$$0 = \frac{mv^2}{r} - \frac{GMm}{r^2} \tag{15}$$

$$v^2 = \frac{GM}{r} \tag{16}$$

Equation 16 gives the needed velocity to be in a stable orbit at a distance r from the center of the earth. Low earth orbit is not universally defined, but in general describes an orbit within ~3000 km above earth's surface.

Say a rocket will need to be in a stable orbit at 1000 km above earth's surface. Here, r = the radius of the earth + the desired height. The radius of the earth is 6371 km, so r = 7371 km. G is the gravitational constant, which is $6.674 \times 10^{-11}\ \frac{Nm^2}{kg}$. M is the mass of the earth, $5.972 \times 10^{24} kg$. Using these numbers in equation 16 gives a velocity v of $7.35\frac{km}{s}$. Assuming the rocket starts from rest, this v = Δv.

V_e is based on the rocket engine design and the type of propellant. v_e can also be defined as specific impulse multiplied by acceleration due to gravity. Specific impulse measures the total impulse produced per unit propellant.

Throughout the flight, the propellant mass decreases, so $\frac{m_{initial}}{m_{propellant}}$ goes to 1. As mass decreases, so does Δv, given a constant v_e. Ideally, this ratio should stay constant throughout the flight.

It is impossible for a rocket to continuously lose structural mass as it loses propellant mass, but it is possible to get close using stages. Almost every spacecraft put into space today uses multi-stage launch devices.

5.3 Rocket Engine Fuel

The main type of propellant used both in history and today is hypergolic propellant. This describes a combination of a fuel and an oxidizer that will strongly react when they come into contact with each other. These can be described as bipropellants, as the propellant has two components. This is ideal because the engine will not need any additional ignition system. There are many fuels and oxidizers that can be and have been used. The most common combination used today is hydrazine for fuel and dinitrogen tetroxide for oxidizer [29].

Hydrazine formally refers to a molecule of the composition N2H4. Hydrazine can also refer to hydrazine derivatives, chemical compounds based on N2H4 where at least one hydrogen is replaced with a hydrocarbon. Hydrazine is also often used alone as a monopropellant. Dinitrogen tetroxide, N2O4, is very common as an oxidizer. This is hypergolic to many different fuels, including hydrazine and hydrazine derivatives [29].

5.4 Use of Rocket Engines During Missions

As hypergolic propellants have been used for some time, they are known to be reliable and fast. The reactions of hypergolic propellants are so rapid that any ignition delay is essentially obsolete [35]. Hydrazine and Dinitrogen Tetroxide are both liquids at room temperature and are easy to store with proper handling [29].

The James Webb Space Telescope (JWST) can be looked at as an example of how rocket engines are used on spacecraft and during missions. The JWST’s spacecraft bus uses both bipropellant and monopropellant thrusters. Hydrazine is used as propellant along with Dinitrogen Tetroxide as the bipropellant. The spacecraft bus originally contained enough propellant to last over 20 years. The bipropellant thrusters are used for orbital correction. JWST has a slow orbit decay. These thrusters are used about every 21 days. The monopropellant thrusters are used for attitude control and orientation [22].

5.5 Dangers of hypergolic propellants

While discussing rocket fuel, it is important to acknowledge the dangers and safety concerns of hypergolic propellant. The nature of combustion engines suggests that the propellant used will be hard to handle. Hypergolic propellants are good for rockets because of their quick reactivity, but this also translates to a large amount of safety precautions when handling the spacecraft and propellant. If not properly handled, there is a possibility of creating this reaction outside of the designated combustion chamber. This can very easily damage the rest of the structure as well as any humans close enough [29].

Part of this concern includes ensuring the safety of the workers when building or handling the propellant and spacecraft. Most propellants used are highly toxic to the human body, are possibly carcinogenic, and are corrosive. Even alone, the fuels and the oxidizers are not safe for humans [29].

There have recently been efforts to find a propellant that is less toxic but is still as efficient or more efficient. For example, NASA's Green Propellant Infusion Mission was created to research green propellants, propellants that are not as toxic as current fuels. A propellant they are focusing on is called Advanced Spacecraft Energetic Non-Toxic (ASCENT). ASCENT is a mixture of hydroxyl ammonium nitrate and water. This propellant is less toxic than hydrazine due to its high solubility and high stability. This is not only beneficial to those working with the propellant, but is also beneficial for NASA, as lowered toxicity decreases the need for certain restrictions associated with hydrazine. The decreased restrictions can save NASA money.

Not only is ASCENT less toxic, but it is more efficient. This was tested both in 2019 and 2022. In 2019, the ASCENT test was one of many technologies tested in the US Department of Defense's Space Test Program 2. This was launched on SpaceX's Falcon Heavy Rocket and was successfully tested for about a year [31]. ASCENT was further tested during NASA's Lunar Flashlight mission. ASCENT was used as the main source of propulsion. It was found that ASCENT has a 5% greater specific impulse and 45% greater density [3].

6. Solar Sails

Solar sails use solar radiation on large reflective membranes to create thrust. This is done by using the momentum of photons in solar radiation to push the sail in accordance with Newton's 3rd law. This is a technology that is currently being used and tested. Solar sails as propulsion are enticing because, unlike rocket engines, solar sails are propellant-less. They still have limits other than propellant. A solar sail cannot produce thrust towards the sun.

6.1 Solar Radiation

Solar radiation describes the flow of photons emitted by the sun. Light will exert a force on any body it encounters. The relationship between energy, E, momentum, p, and mass, m, is given by equation 17, with c being the speed of light.

$$E^2 = (mc^2)^2 + (pc)^2 \tag{17}$$

Considering photons have no rest mass, this equation can be simplified to

$$E = pc \tag{18}$$

Considering Newton's 2nd law, equation 1, the force, F, can be found by taking the time derivative of equation 18, which gives

$$\frac{dE}{dt} = Fc \tag{19}$$

The time derivative of energy gives power. Power per unit area, dA, gives the flux, Φ. Expressing equation 19 in terms of flux results in

$$\Phi dA = Fc \tag{20}$$

Therefore, the maximum force from solar radiation is

$$F = \frac{\Phi}{c} dA \tag{21}$$

6.2 Energy from stars

To find the flux of photons from the sun, it is important to understand the light energy given off by the sun.

Stellar radiative power, also called Luminosity, can be found using the Stefan-Boltzmann law. Luminosity, L, depends on the radius, R, and temperature, T, of a star. The Stefan-Boltzmann constant, σ_{SB}, is equal to $5.67 * 10^{-8}\ \frac{W}{m^2K^4}$. The emissivity of the star, ε, is the effectiveness of a body to emit energy, the amount of energy emitted. This can range from 0 to 1. An emissivity of 1 represents a black body, a perfect emitter.

$$L = 4\pi R^2 \varepsilon \sigma_{SB} T^4 \tag{22}$$

Solar Luminosity, or solar radiative power, is $3.83 * 10^{26}\ W$. The flux from the sun at a distance r can be found using equation 23. As this shows, the maximum flux, and maximum force, decreases as the distance from the sun increases.

$$\Phi(r) = \frac{L}{4\pi r^2} \tag{23}$$

At a distance of 1 au the flux is $1361.8\ \frac{W}{m^2}$.

6.3 Photon Interaction

The radiation force on a sail depends on the interactions between the photons and the surface of the sail. Photons introduce force when they are reflected or absorbed by the sail.

Man-made material that either perfectly reflects or absorbs photons is currently difficult to make. All sails are subject to both force due to photon reflection and force due to photon absorption.

There are two types of reflection, specular and diffusive. Specular reflection is where light is reflected at a definite angle. This is due to a smooth reflective surface and is commonly seen in mirrors. An incident photon approaches the surface at an angle. This photon will then be reflected at an angle equal to the incident angle. The incident and reflected angle are symmetric upon the axis normal to the reflective surface. Both incidence and reflection introduce a force on the surface. The resulting force has no component parallel to the reflective surface, as they are symmetric. To find this resulting force, the incident and reflective force must be found in the direction normal to the surface. The normal vector is given by **n**. If the incident photon has an angle θ with respect to the normal vector, the force component in this direction is Fcosθ**n**. The photon will be reflected at an angle θ, and the force component in this direction is Fcosθ**n**. The resulting force is then given by

$$\vec{F} = 2Fcos(\theta)\hat{n} \tag{24}$$

Diffusive reflection is when reflected radiation is scattered, and so does not have a definite reflected angle. This is seen when a surface is not perfectly smooth. Similar to specular, diffusive reflection force is due to both the incident photon and the reflected photon. The force from the incident photon is the same as in specular reflection, but the force from the reflected radiation is the sum of all reflected photons, as there are many different possible reflection angles. The sum of the force due to reflection is less than the force due to the incidence because of the variation of reflection angles. Diffusive reflection provides less force in the normal direction than specular reflection.

Upon absorption, the photon momentum will transfer as already described. This will be in the direction of the incident photon, and the resulting force will have a magnitude given by equation 21. When considering the force with respect to the surface, the force will have a component parallel to the surface and normal to the surface. When absorbed, another type of light interaction needs to be considered: emissivity. After the light is absorbed, the energy of the sail is changed, so the dynamics will slightly change too. Force due to emission is less than the force due to absorption and will also have components parallel and normal to the surface. Therefore, force due to absorption and emission is less than force due to reflection.

When designing and choosing sail materials, surfaces that are more reflective than absorptive are optimal, as this will result in the most force. As a result, most sails used today are 90% reflective. The maximum force on the sail is when all photons are specularly reflected.

$$F_{max} = 2\frac{\Phi}{c}\cos(\theta)dA \tag{25}$$

6.4 Design of sail

The important and universal property of solar sails is the fact that the surfaces are reflective. Other properties will affect the efficiency of the sail, as they affect the amount of radiation on the sail. This includes shape, interference with space debris, deformation (thermal and physical), and any additional mass and structures.

The size and shape of the sail gives the surface area. The force is given per unit area, so the more surface area the sail has, the more force will be acted on it.

The acceleration of a sail depends on the amount of mass on the sail. This includes any structural support and any mission dependent machines. The sail loading parameter, σ, describes the relationship between total mass and the surface area of a sail. A small sail loading parameter translates into a large characteristic acceleration.

Sails and sail support can be structured in different ways. One style is using rigid supports, with the sail being connected to the supports at different points. This can make it easier to control the sail and adjust the tension but does reduce overall flexibility.

A spin sail uses centrifugal forces to deploy the sail and keep it in place. Similar to the spin sail is the Heliogyro sail. This is made of multiple thin strips of sail material, like helicopter blades.

Deformation includes any wrinkles, folding, or shadows. These will affect the amount of radiation on the sail, changing the effective surface area [11].

6.5 Steering & movement of sails

The characteristic acceleration of a sail is defined as the acceleration of a sail orthogonal to solar radiation and at a distance of 1 au from the sun. The characteristic acceleration is equal to the force per unit area divided by the sail loading parameter. Solar sails have a continuous acceleration, are continuously thrusted, and so can reach large delta v values.

The attitude of a sail describes the orientation of the sail. For sails with controllable support structures, simply adjusting different sections of the sail is used for attitude control. This can include changing the surface area in a section and changing the direction of a certain section.

Another method is adding movable control masses that change the center of mass [11].

6.6 Challenges with sails

Solar sails are not limited by propellant mass, but by the durability of the sail. This can be preferred for longer missions where the amount of propellant will not be enough. Additionally, there are some limits due to the source of thrust being solar radiation. Force from solar sails can only be in the direction away from the sun, so if any force is needed in the direction of the sun, a solar sail will be worse. Solar sails always undergo acceleration due to radiation pressure, but this is not a constant acceleration. Solar flux decreases as the distance from the sun decreases, so as the sail gets further and further from the sun, the instantaneous force on that sail decreases.

6.7 IKAROS

Japan Aerospace Exploration Agency's (JAXA) Interplanetary Kite-craft Accelerated by Radiation Of the Sun, or IKAROS, was the first to use sailing as the primary propulsion method. This was launched in 2010. The craft was designed as a spin sail. The sail was square and had a total surface area of $196\ mm^2$. The sail was made of polyamide resin $0.0075\ mm$ thick. After deployment, the sail had an initial thrust of $1.12\ mN$. After six months of operation, the sail had accumulated over $100\ \frac{m}{s}$velocity. In addition to testing solar sailing as a propulsion method, IKAROS's objectives included testing the use of generating solar power using solar cells to power the additional ion propulsion engines [39].

6.8 Sails and Satellites

Sails can be useful even when the spacecraft's primary propulsion method is not solar sails. Considering the increasing amount of space debris in LEO, many groups are making efforts in preventing their spacecraft from becoming space debris once dormant. This can be achieved using de-orbit sails. When designing and building spacecraft, small sails are included so that once done, they can be deployed and bring the craft back to earth.

Another possible application is to use sails to do the opposite, keeping the satellite in orbit. For satellites in low earth orbit, both gravity and atmospheric drag forces are present. Periodically throughout their orbit, satellites must perform adjustments to counteract the impact drag has on the satellite's orbit.

In considering solar sails as a propulsion method, there are many ways that this can be beneficial. The largest benefit is how solar sails can be used until the sail is worn out. Using combustion engines requires chemical propellant. The lifetime of these engines depends on the initial amount of propellant. Eventually, the propellant will run out, and the engines are unusable, but with sails, if there is a good maintenance system for the sail, the satellite can be propelled indefinitely.

There are a few difficulties regarding solar sail propulsion for low earth orbits. Solar sails do not produce thrust in the direction of the sun, and so will only be useful for half the orbit. There are two keyways this can be remedied. Using an additional propulsion method for the half without the sail is a good idea. This can be done with any propulsion method, but what I would suggest is one similar to what IKAROS had, solar cells collecting solar energy to power ion thrusters., which will be discussed later.

For this method, the solar sail force must always be equal to the drag force. Assuming the sail is always in a direction normal to the sun, the force in the direction away from the earth is

$$F = \frac{L\eta}{2\pi c d^2} A \tag{26}$$

Here, d is the distance from the sun. As the satellite will be in low earth orbit, d can be equal to the distance from the sun to the earth. This is $1.496 * 10^{11}\ m$. The efficiency of the sail, η, is 90%.

Drag force depends on the drag coefficient, C, the velocity of the object, v, and the atmospheric density, ρ.

$$F = \frac{1}{2} C \rho v^2 \tag{27}$$

The atmospheric density can also be given as

$$\rho = \rho_0 e^{-\frac{R-R_0}{H}} \tag{28}$$

Where R_o is the radius of the earth, H is equal to 88.667 km, R is the altitude of interest from the center of the earth, and ρ_o is the atmospheric density at sea level, 1.2227 kg/m^3. Substituting this into the drag force equation gives

$$F = \frac{1}{2} C \rho_0 v^2 e^{-\frac{R-R_0}{H}} \tag{29}$$

To always compensate for drag, the satellite must be given an amount of force equal to the drag force. If a solar sail was viable for the entire orbit, these forces are related in the following equation.

$$\frac{L\eta}{2\pi c d^2} A = \frac{1}{2} C \rho_0 v^2 e^{-\frac{R-R_0}{H}} \tag{30}$$

Considering a satellite orbiting at a distance R=1000 km above the surface of the earth, the needed velocity to stay in orbit is found using equation 17. At this distance, the needed velocity would be 7.35 km/s. Assuming a sail with 90% efficiency propels this satellite constantly, the needed surface area, A, of the sail is

$$A = C\frac{\rho_0 v^2 c\pi d^2}{L\eta}e^{-\frac{R-R_0}{H}} \tag{31}$$

$$A = 5.1 * 10^7 C \tag{32}$$

The drag coefficient depends on the geometry of the object and will generally be very small. Using these assumptions, the surface area of a sail needed can be seen in the graph. For a drag coefficient $1 * 10^{-8}$ of the needed surface area would be very close to $0.5\ m^2$.

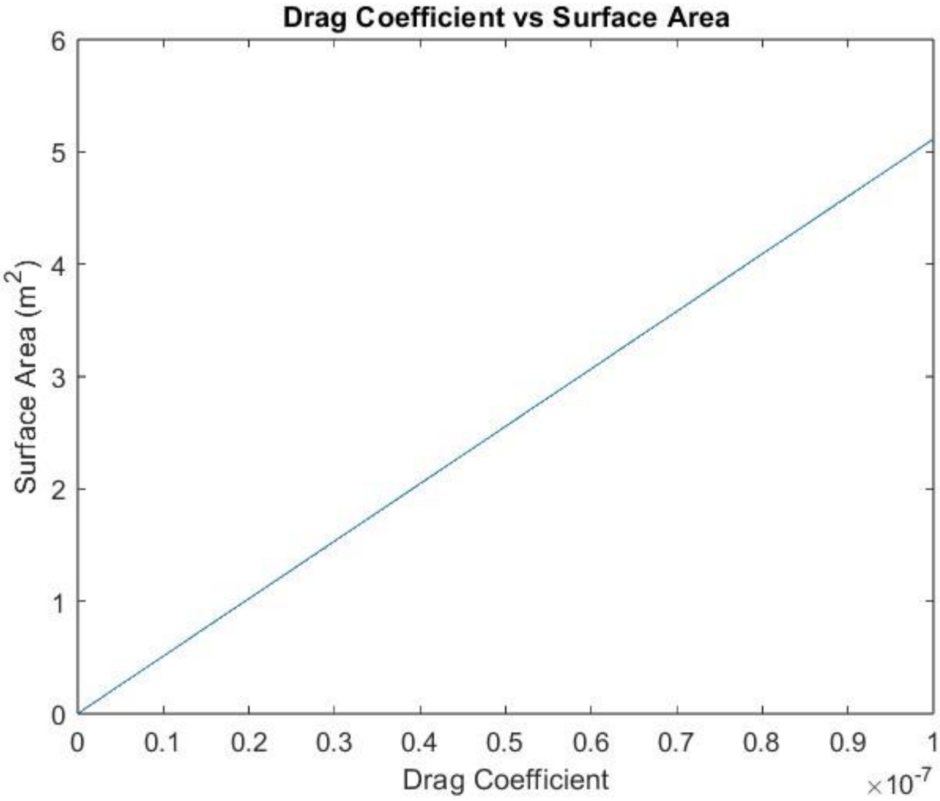

Figure 1: Surface area of a solar sail depending on the drag coefficient. Created through MATLAB, see Appendix A

This will vary at different orbital radii but does not depend on mass. Drag force has an exponential relationship with orbital radius and is only notable at altitudes less than 8000 km. At these altitudes, the drag force is small enough to be negligible.

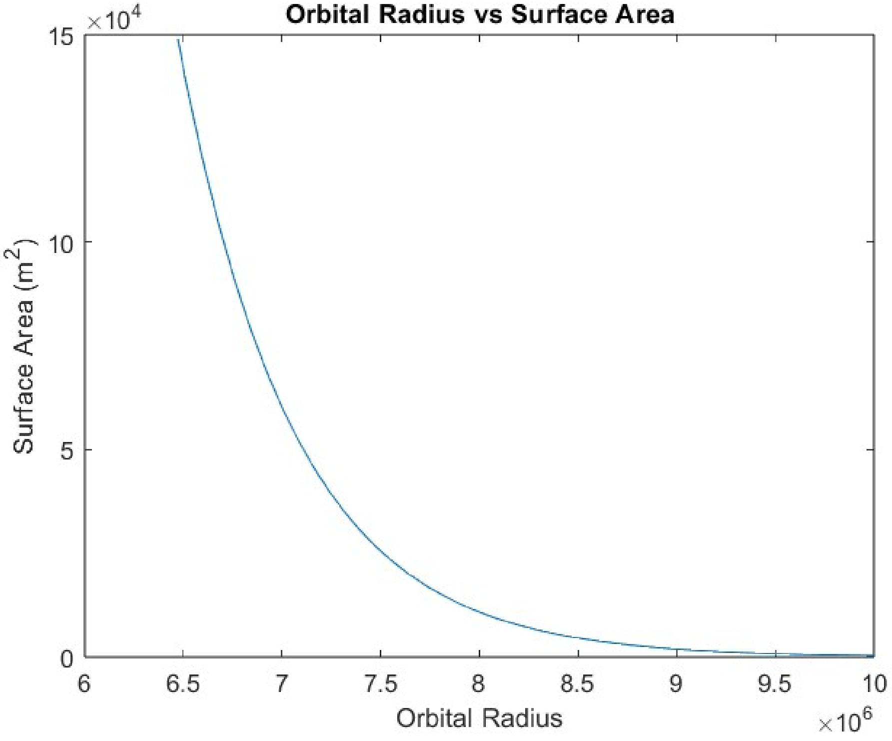

Figure 2: Surface area of a solar sail depending on radius of the orbit. Created through MATLAB, see Appendix B

If solar sail is the only method of propulsion for a satellite, the sail needs to accommodate for the entire orbit. For this, the satellite gains velocity from the sail for the first half of the orbit, then loses velocity during the second half when the sail force is not usable. The initial and final velocities over one orbit must be the same to keep the satellite in low earth orbit. This is a lot more complex. During the half of the orbit where the needed total acceleration has a component towards the sun, we can assume that the sail is positioned so that no force due to the solar sail is produced.

The total force in the r direction, considering the center of the earth as the origin, will always include gravity and centrifugal force. Similarly, the total force in the theta direction will always include drag due to the atmosphere.

$$F_r = \frac{mv^2}{r} - \frac{GmM}{r^2} \tag{33}$$

$$F_\theta = -\frac{1}{2}C\rho v^2 \tag{34}$$

The force due to the solar sail will have both an r and theta component. To find the total force for the half of the orbit where solar sail force is valid, the solar sail force components must be included.

$$\Sigma F_r = \frac{mv^2}{r} - \frac{GmM}{r^2} + \frac{L\eta A}{2c\pi d^2}\sin(\theta) \tag{35}$$

$$\Sigma F_\theta = -\frac{1}{2}C\rho v^2 + \frac{L\eta A}{2c\pi d^2}\cos(\theta) \tag{36}$$

7. Conclusion

Space exploration has become easier to accomplish. A large part of this is due to the many advancements in space propulsion technology. Every propulsion method has its advantages and disadvantages. Each method has certain missions, or parts of missions, where it would be best. Using a variety of methods can be beneficial.

Combustion rocket engines have been used for decades. They are reliable and powerful. They can produce large levels of thrust and are great for both leaving earth's atmosphere and in space. There are sustainability issues surrounding popular propellants as they are toxic and corrosive. This creates large and expensive safety issues during construction for both workers and the rocket's structure itself. NASA's GPIM has been researching green propellants that are less toxic and corrosive yet still as powerful. Combustion rocket engines are and will always be used for some portions of space exploration. What can and will change is the propellant being used.

Solar sails are relatively new and promising. The main benefit is that the lifetime for a solar sail is longer than rocket engines as there is no propellant used. Solar sails provide a small but continuous force. This force is limited to only in a direction away from the sun. Therefore, the types of missions these would be most beneficial for are interplanetary travel and fly-bys. In 2010, JAXA's IKAROS mission first successfully tested using a solar sail as the main propulsion method. Since then, there have been more missions using solar sails as well as more research into how sails can be used, such as deorbiting satellites.

This project only scratches the surface of the knowledge and possible research of space propulsion. Future projects could perhaps dive deeper into any of these propulsion methods or look at even more methods. Future IQPs could focus on the new green propellants. This project did not have the time to fully analyze using solar sails for satellites and how the limits of direction of thrust affect this.

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9. Appendix A: Matlab calculations for drag coefficient vs surface area

```
clear all
close all

%This uses equation 31 to plot the needed surface area to compensate for drag

r=1000e3;
%Desired altitude in meters
R=r+6371e3
%orbital radius in meters
R_km=R*10^-3;
%orbital radius in kilometers
G=6.67e-11; %Gravitational constant
M=5.972e24; %Mass of earth in kilograms
v=sqrt(G*M/R); %required velocity in meters per second


c=0:.0000000001:0.0000001;
sa=surf(c,v,.9,R);
%Considers drag coefficents in the magnitude of 10^-10

figure
plot(c,sa)
title('Drag Coefficient vs Surface Area')
xlabel('Drag Coefficient')
ylabel('Surface Area (m^2)')


function sa=surf(c,v,eff,r)
%find needed surface area using equation 31
    p=1.2227; %atmospheric density at sea level
    ls=3e8; %speed of light meters per seconds squared
    W=3.83e26; %Luminosity of the sun in watts
    R0=6371e3; %Radius of earth
    H=88.667e3;
    d=1.496e11; %Distance between earth and sun in meters
    T=pi*c*p*ls*(d^2)*v^2;
    B=W*eff;
    E=exp(-(r-R0)/H);
    sa=(T*E)/B
end
```

10. Appendix B: Matlab calculations for orbital radius vs surface area

```
clear all

close all

%This gives the relationship between the desired orbital radius and the
%needed surface area
i=1;
for r=linspace(6471e3,7000e3)
    sa=surf(0.9,r)
    sap(i)=sa
    i=i+1;
end

rr=linspace(6471e3,10000e3);
figure
plot(rr,sap)
title('Orbital Radius vs Surface Area')
xlabel('Orbital Radius')
ylabel('Surface Area (m^2)')



function sa=surf(eff,r)
    p=1.2227; %atmospheric density at sea level
    ls=3e8; %speed of light (m/s)
    W=3.83e26; %Luminosity of the sun, Watts
    R0=6371e3; %radius of earth, meters
    H=88.667e3;
    G=6.67e-11; %gravitational constant
    d=1.496e11; %distance between earth and sun, meters
    C=10^-7; %drag coefficient
    M=5.972e24; %mass of earth
    T=C*p*ls*pi*G*M*(d^2)
    B=W*r*eff
    E=exp(-(r-R0)/H)
    sa=(T*E)/B;
end
```