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Optimization of Advanced Space Propulsion Technique: Solar Sail

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Abstract

Numerous space missions have been launched since the last lunar mission, including several deep space probes that have been sent to the edges of our solar system. However their journeys have been limited by the power of chemical rocket engines and the amount of rocket fuel that a spacecraft can carry. International space agencies are proposing many methods of transportation that would allow us to go farther, but a manned space mission has yet to go beyond the moon. The most realistic of these space transportation options calls for the replacement of conventional chemical fuels with an inexhaustible natural resource: sunlight. Using the Sun's energy as a way to travel through space could give spacecraft more mobility and versatility during flight—thus opening up new regions of the Solar System for exploration and science. A Solar Sail is a spacecraft propelled by sunlight. Solar sails work by capturing the energy from light particles as they bounce off a reflective surface. Each light particle has momentum, and when it strikes a reflective surface, it imparts that momentum to the reflective sheet. As billions of light particles hit the sheet, they push the sail strongly enough to move a spacecraft. Over time, the solar particles could keep pushing a spaceship faster and faster, allowing it to attain very high speeds. The sails can be as large as football fields, but are 40 to 100 times thinner than a sheet of paper. Inflatable booms provide the sheets with rigidity, and tether the solar sail to the spacecraft. This innovative concept for low-thrust space propulsion works without any propellant and thus provides a wide range of opportunities for high- energy low-cost missions. Offering an efficient way of propulsion, solar sail craft could close a gap in transportation options for highly demanding exploration missions within our solar system and even beyond.

Keywords: *Chemical fuel Exploration, Inflatable booms. propulsion, Solar sail.*

1. INTRODUCTION

It is an accepted phenomenon that the quantum packets of energy which compose Sunlight, that is to say photons, perturb the orbit attitude of spacecraft through conservation of momentum; this perturbation is known as solar radiation pressure (SRP). To be exact, the momentum of the electromagnetic energy from the Sun pushes the spacecraft and from Newton's second law momentum is transferred when the energy strikes and when it is reflected. The concept of solar sailing is thus the use of these quantum packets of energy, i.e. SRP, to propel a spacecraft, potentially providing a continuous acceleration limited only by the lifetime of the sail materials in the space environment. The momentum carried by individual photons is extremely small (McInnes, 1999), thus to provide a suitably large momentum transfer the sail is required to have a large surface area while maintaining as low a mass as possible. Adding the impulse due to incident and reflected photons it is found that the idealised thrust vector is directed normal to the surface of the sail, hence by controlling the orientation of the sail relative to the Sun orbital angular momentum can be gained or reduced. Using momentum change through reflecting such quantum packets of energy the sail slowly but continuously accelerates to accomplish a wide-range of potential missions.

The concept of solar sailing and the physics on which it is based can be traced back to the 17th century. Subsequently, the concept of solar sailing was articulated as an engineering principle in the early 20th century by several authors including the Father of Astronautics, Konstanty Cioákowski along with Fridrikh Tsander and Herman Oberth (Cioákowski, 1921; Tsander, 1924; Oberth, 1923). Following the initial work by Cioákowski, Tsander and Oberth the concept of solar sailing appears to have remained largely dormant for over thirty years. However, as the concept re-emerged in the middle of the 20th century the term Solar Sailing was coined by Richard Garwin in the journal Jet Propulsion (Garwin, 1958). Through the latter half of the 20th century and into the 21st century a significant amount of both theoretical and practical work has been performed, considering the astrodynamics, mission applications and technology requirements of solar sailing.

Early comparisons of solar sailing with chemical and ion propulsion systems showed that solar sails could match or out perform these systems for a range of mission applications, though of course the level of assumed technology status is crucial in such comparisons (MacNeal, 1972). Furthermore, the lack of mission concepts limited such studies to exploration of the fundamental problems and benefits of solar sailing. One of the earliest solar sail mission concepts studied in detail was the NASA Comet Halley mission which required a launch in late 1981 or early 1982 to rendezvous with Comet Halley at its perihelion in the mid-1980's by spiralling towards the Sun and then changing the orbit inclination by almost 180 degree (Wright and Warmke, 1976). Since the NASA Comet Halley mission studies a large number of solar sail mission concepts have been devised and promoted by solar sail proponents. As such, this range of mission applications and concepts enables technology requirements derivation and a technology application pull roadmap to be developed based on the key features of missions which are enabled, or significantly enhance, through solar sail propulsion.

2. DESIGN OF SAIL

Solar sails of all varieties consist of a large, flimsy sail and some kind of payload that holds such things as antennas, computers, solar panels, guidance sensors, science instruments, cargo containers or crew cabins. For most solar sails, what this boils down to is a small, heavy mass attached to the middle of a huge, lightweight sail. Without any kind of support, when sunlight pushes on the sail, it will collapse and flow around the payload. Two ways people have come up with to stabilize the sail and prevent it are to support the sail in 3 dimensions with a structure or to spin the sail. Both methods work well to hold the sail out flat so it can catch as much sunlight as possible.

2.1 Three Axis stabilized sails

Many solar sail designs use a rigid structure, much like a kite, to hold the sail out to catch sunlight. This is called three axis stabilization, because the structure supports the sail in all three dimensions, or axes, without spinning. The three dimensions come from the two dimensions that lie within the surface of the sail, and the third dimension that is perpendicular to the sail.

Attaching the outer edges of the sail to stiff booms that meet at the center of the sail is a good way to prevent collapse in the plane of the sail. The next problem is to prevent these booms from collapsing in the third dimension, like an umbrella being folded.

2.2 Booms

If booms alone are to support a solar sail, they must act as columns and as beams. As columns, the booms prevent the sail from collapsing inward towards the center. As beams, the beams are stiff and fixed at the center, like a diving board, to prevent the sail from folding up like an umbrella. Here are some examples of solar sails that are stabilized in this manner.

2.3 Booms, Masts and Stays

Using a combination of booms, masts and stays, a 3-axis stabilized solar sail can be made lighter, at the cost of the complexity. By supporting the booms with masts and stays, they only need to act as columns, and not as beams. The masts are set perpendicular to the booms and stays connect between the booms to each other and to the masts. The booms can be made lighter because the stays and masts prevents the sail from folding up. This kind of structure is similar to a very tall radio antenna that is supported by cables. The following picture give some example of solar sails with this kind of structure.

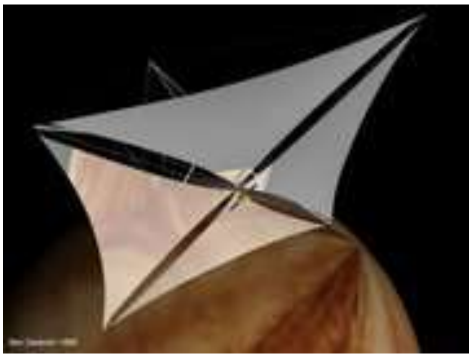

Figure: 1. Booms, mast and stays

2.4 Spin stabilized sails

Spinning a solar sail pulls the sail material out tight and flat so it doesn't collapse when sunlight pushes on it. This is called centripetal acceleration, and is the same effect that prevents water from flowing out of a bucket that is being swung in a circle. Because the sail material itself is very lightweight, it needs to be reinforced with tension lines to carry most of the loads caused by spinning. This results in a sail that needs very little heavy structure, because tension lines are much lighter than the booms used in 3 axis supported sails. Thus, spinning sails have potential for being lighter and faster.

2.5 Circular sails

Circular sails are large, spinning disks supported only by lightweight tension lines to carry loads except at the center, where a structure is needed to carry loads between the payload, control system, and sail. The following sail is controlled by allowing sail panels to move outwards so sunlight pushes off centre to turn the sail

Figure: 2. Spinning disk sail

2.6 Heliogyros

The heliogyro was a design considered by the Jet Propulsion Laboratory for a mission to Hailey's Comet. The sail consists of several very long (twelve vanes, seven km in length in the JPL design) vanes extending from a central hub. The vanes are deployed by rollers by spinning the craft. The centripetal force pulls the sails outwards, unrolling them. The vehicle continues to spin in order to keep the vanes tight. It steers by tilting the vanes, which redirects the solar pressure.

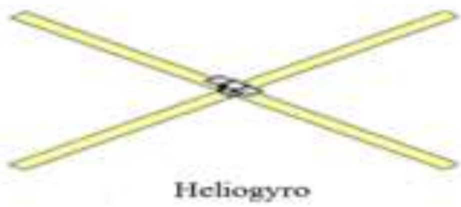

Figure: 3. Heliogyro

3. DESIGN CALCULATIONS

3.1 Calculation of intensity

To find intensity, we must know the power of the source and the area over which it is acting. Since the sun emits light in all directions, the area is equal to that of sphere which equals $4\pi r^2$.

I =solar luminosity/$4\pi r^2$

For Earth,

Solar luminosity = 3.846×10^{26} W

Earth's orbit radius r = 1.496×10^{11} m

$$= \frac{3.846 \times 10^{26}}{4\pi(1.496 \times 10^{11})^2}$$

= 1367.528005 W/m^2

I = 1367.528005 W/m^2

Fraction of incident light (R) is found by the following equation:

$$R = I \exp\left(\frac{-4\pi\eta kd}{\lambda}\right)$$

Where,

R = Fraction of incident light

I = light intensity

η = refraction coefficient

K = absorption coefficient

d = metal thickness

λ = wavelength

For λ= 5 µm, coefficient η = 6.7, K = 5.61

$$=1367.528005 \times exp\left(\frac{-4\pi\times 6.7\times 5.61\times 10\times 10^{-9}}{5\times 10^{-6}}\right)$$

R = 531.7086 W/m^2

For Mars,

Solar luminosity = 3.846×10^{26} W

Mars orbit radius r = 2.2792×10^{11} m

$$= \frac{3.846 \times 10^{26}}{4\pi(2.2792 \times 10^{11})^2}$$

= 589.1617499 W/m^2

I = 589.1617499 W/m^2

Fraction of incident light (R) is found by the following equation:

$$R = I \exp\left(\frac{-4\pi\eta kd}{\lambda}\right)$$

Where,

R = Fraction of incident light

I = light intensity

η = refraction coefficient

K = absorption coefficient

d = metal thickness

λ = wavelength

For λ= 5 µm, coefficient η = 6.7, K = 5.61

$$=589.1617499 \times exp\left(\frac{-4\pi\times 6.7\times 5.61\times 10\times 10^{-9}}{5\times 10^{-6}}\right)$$

R = 229.0720125 W/m^2

3.2 Calculation of weight

The weight of the sail is computed using the equation:

$$W = \rho S d$$

Where,

W = sail weight (mass) in kg

ρ = 2700 kg/m^3 is the density of aluminium

S = sail area (m^2) [considering sail of 30 m long]

d = sail thickness (m)

$W = 2700 \times (30 \times 30) \times (10 \times 10^{-9})$

W = 0.0243 kg

3.3 Calculation of force

Force on a solar sail can be computed by the following equation:

$$F = \frac{2RSAsin^2\theta}{c} = 9.113 \times 10^{-6} \times \frac{RA}{D^2} \times sin^2\theta$$

Where,

F =Thrust

R = fraction of incident light

D = distance from Sun in AU

S = solar flux in W/m^2

c = speed of light

A = Sail area in m^2

θ = Sail tilt angle

For Earth,

The largest proposed solar sail (Sunjammer) is having dimensions of 38 by 38 m. Thus we have considered solar sail having dimensions of 30 by 30 m.

Area of sail = 30× 30 = 900 m^2

$$F = 9.113 \times 10^{-6} \times \frac{531.7086}{1^2} \times 900 \times sin^2 45°$$

F= 2.180457 N

For Mars,

Area of sail = 30× 30 = 900 m^2

$$F = 9.113 \times 10^{-6} \times \frac{229.072}{1.524^2} \times 900 \times sin^2 45°$$

F= 0.40446 N

3.4 Acceleration of the spaceship

The acceleration, a, of a spaceship can be found using the equationas described

$$a = P_0 S \left(\frac{1 - \frac{R}{I}}{M - W} \right)$$

P_0 = Light Pressure

S = sail area

M= useful mass (of the ship without sail) [kg]

If we take solar radiation pressure for 88% reflection at 1 AU, it is about $P_0 = 8 \times 10^{-6}$ N/m^2.

Acceleration from Earth,

$$a = 8 \times 10^{-6} \times (900) \left(\frac{1 - \frac{531.7086}{1367.528005}}{1000 - 0.0243} \right)$$

a = 4.400674745×10^{-6} m/s^2

Acceleration from Mars,

The solar radiation pressure at 1.524 AU is

$P_0 = 3.91 \times 10^{-6}$ N/m^2.

$$a = 3.91 \times 10^{-6} \times (900) \left(\frac{1 - \frac{229.0720125}{589.1617499}}{1000 - 0.0243} \right)$$

$a = 2.1508296 \times 10^{-6}$ m/s^2

3.5 Graphical Variations

The following graphs interprets the thrust developed in Solar Sail on Earth and Mars with the respective change in the tilt angle. The tilt angle is varied from 1° to 90° and thrust developed by the sail is calculated by using the above mentioned formulas.

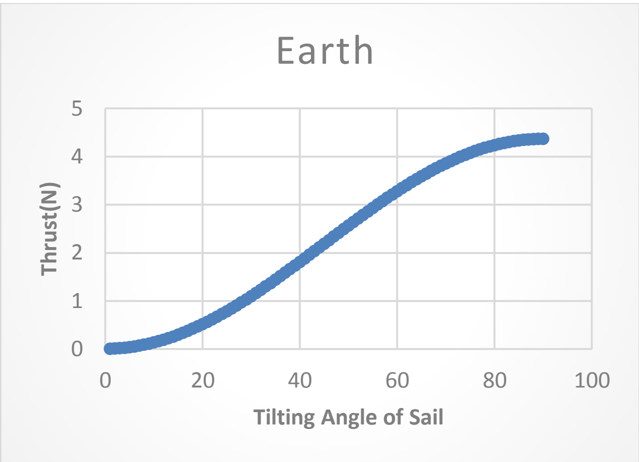

Figure: 4.Variation between thrust and tilting angle launched from Earth

The figure 4 shows the thrust developed for the change in tilt angle for the solar sail launched from Earth.

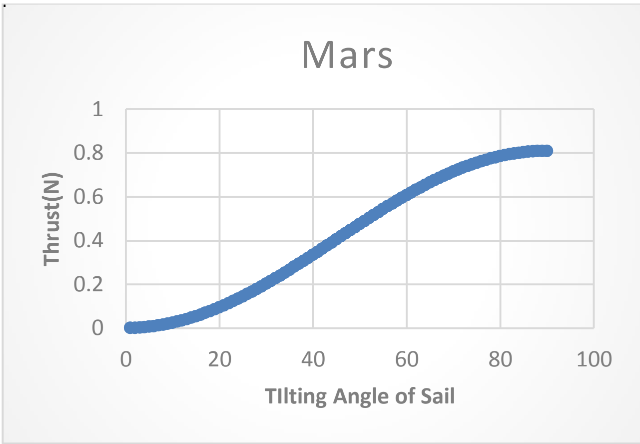

Figure: 5.Variation between thrust and tilting angle launched from Earth to Mars

The figure 5 shows the thrust developed for the change in tilt angle in solar sail moving towards Mars.

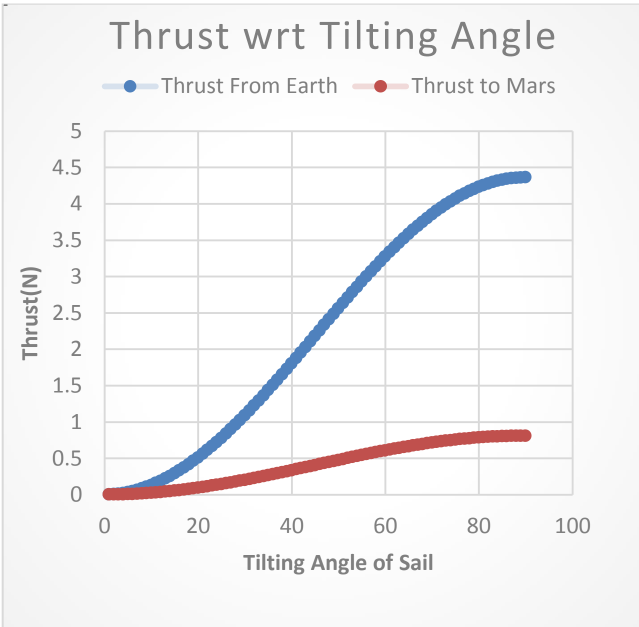

Figure: 6.Contrast in thrust developed on the two planets

The figure 6 shows the difference in the amount of thrust developed in the solar sail by changing the tilt angle. It can be easily visualised from the graphs that a larger amount of thrust is developed in the solar sail when it is launched from earth. It is because of the large amount of incident light which the sail receives from the sun due to the closeness of the planet earth from the sun as compared to mars.

4. SOLAR SAIL MATERIALS

While solar sails have been designed before (NASA's had a solar sail program back in the 1970s), materials available until the last decade or so were much too heavy to design a practical solar sailing vehicle. Besides being lightweight, the material must be highly reflective and able to tolerate extreme temperatures. The giant sails being tested by NASA today are made of very lightweight, reflective material that is upwards of 100 times thinner than an average sheet of stationery. This "aluminized, temperature-resistant material" is called **CP-1**. Another organization that is developing solar sail technology, the Planetary Society (a private, non-profit group based in Pasadena, California), supports the *1*, which Cosmos boasts solar sails that are made of aluminum-reinforced Mylar and are approximately one fourth the thickness of a one-ply plastic trash bag.

The reflective nature of the sails is key. As photons (light particles) bounce off the reflective material, they gently push the sail along by transferring momentum to the sail. Because there are so many photons from sunlight, and because they are constantly hitting the sail, there is a constant pressure (force per unit area) exerted on the sail that produces a constant acceleration of the spacecraft. Although the force on a solar-sail spacecraft is less than a conventional chemical rocket, such as the space shuttle, the solar-sail spacecraft constantly accelerates over time and achieves a greater velocity.

Figure: 7.A four-quadrant solar sail system created by NASA's solar sail propulsion team at the Marshall Space Flight Center in Huntsville, Ala., and its industry partner, L'Garde, Inc. sits fully deployed in a 100-foot-diameter vacuum chamber at NASA's Glenn Research Center.

4.1 Metallic Materials

The material developed for the Drexler solar sail was a thin aluminum film with a baseline thickness of 0.1 micrometers, to be fabricated by vapor deposition in a space-based system. Drexler used a similar process to prepare films on the ground. As anticipated, these films demonstrated adequate strength and robustness for handling in the laboratory and for use in space, but not for folding, launch, and deployment.

The most common material in current designs is aluminized 2µm Kapton film. It resists the heat of a pass close to the Sun and still remains reasonably strong. The aluminium reflecting film is on the Sun side. The sails of *Cosmos 1* were made of aluminized PET film (Mylar).

In addition to aluminium, there are a no. of other candidate light sail materials. A particularly attractive candidate material is Niobium, a highly reflective metal commonly used in various industrial processes. Although the bulk density of niobium is 8.85 g/cm^3 compared to the 2.7 g/cm^3 of aluminium, it has significantly higher melting point at 2741 K allowing a higher thermally limited acceleration.

4.2 Non-Metallic Materials

The present invention describes the use of graphene in solar sail applications, specifically as a lighter weight alternative to the Mylar support. Use of graphene is expected to reduce the total weight of the solar sail by ≈90%, while also conferring superior strength, thermal conductivity, and stability to the structure.

Graphene-metal sandwich structures are prepared from bilayer graphene through metal deposition methods. Through this route, chromium/graphene/aluminium hybrid materials can be generated to serve as a potential alternative to the chromium/Mylar/aluminium structures used in conventional solar sails. Graphene is envisioned as an attractive alternative in this application due to its light weight, atomic layer thickness, and exceptional strength.

4.2 Benefits and features

- Lighter weight alternative to convention solar sails
- Controlled assembly of graphene-metal sandwich structures
- Enables use of thicker metal films in solar sails without overall weight

There has been some theoretical speculation about using molecular manufacturing techniques to create advanced, strong, hyper-light sail material, based on nano tubes mesh weaves, where the weave "spaces" are less than half the wavelength of light impinging on the sail. While such materials have so far only been produced in laboratory conditions, and the means for manufacturing such material on an industrial scale are not yet available, such materials could mass less than 0.1 g/m²,making them lighter than any current sail material by a factor of at least 30. For comparison, 5 micrometre thick Mylar sail material mass 7 g/m², aluminized Kapton films have a mass as much as 12 g/m², and Energy Science Laboratories' new carbon fibre material masses 3 g/m².

5. RECENT ADVANCED DEVELOPMENTS

5.1 Integrated Software Tools

A set of integrated simulation tools are developed to predict the trajectory, manoeuvres, and propulsive performance of a solar sail during a representative flight profile. The tools were designed to be integrated into an optimal guidance and navigational control (GNC) subsystem on a future flight mission. The tools incorporated the following analytical models:

- Solar radiation pressure acting on the sail as a function of sail orientation and distance from the Sun.
- Disturbance forces acting on the sail such as gravitational torques and thermal deformation of the support structure.
- Orbital mechanics.
- Sail structural dynamics.
- Attitude control system dynamics.
- Navigational sensors.

5.2 Optical Diagnostic System

The overall objective for this task was the development of an Optical Diagnostic System (ODS) to Technology Readiness Level (TRL) 6 for a solar sail. Possible requirements for the ODS included observation of the sail deployment and monitoring of the health and integrity of the sail during and after deployment. After solar sail deployment, the ODS would be available to provide shape and vibration measurements adequate to infer the stress state of the solar sail by aid of computational structural models, which could then feed real time into a closed loop spacecraft GNC system.

It was determined that continuous real-time integration with the guidance system was not necessary due to the quasi-steady-state nature of solar sail operations. In addition, studies showed the relative insensitivity of the thrust vector magnitude and direction to sail billow. The conceptual design process identified a number of significant challenges to on-orbit photogrammetric including significant weight, power, and data requirements for instruments and support structures for camera clusters, achieving sufficient image contrast, integrating targets into the sail membrane, and considerable software development needs. The concept development activities were conducted in parallel with the development of the ground test capability for the solar sail demonstrator hardware. A developmental test of an L'Garde inflatable boom in a thermal vacuum chamber at NASA Goddard Space Flight Center, as well as tests on smaller sail quadrants, provided an opportunity to familiarize researchers with cameras, analytical tools, and test operations.

6. RESULTS AND DISCUSSION

A solar sail of 30 m long was considered made up of thin aluminium sheet having a mass density of 2700kg/m^3 and the calculations were done on it and the following were the outcomes:

Tilting angle of sail = 45°

I_{Earth} = 1367.52 W/ m2

I_{Mars} = 589.161 W/ m2

R_{Earth} = 531.708 W/m2

R_{Mars} = 229.0720 W/m2

W = 0.0243 kg

F_{Earth} = 2.18046 N

F_{Mars} = 0.40446 N

$a_{Earth}= 4.4006 \times 10^{-6} m/s^2$

$a_{Mars}= 2.1508296 \times 10^{-6} m/s^2$

7. CONCLUSION

The intent of this paper is to show that present technology allows construction of sail craft capable of carrying substantial payloads on deep space missions.

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