Solar Sailing

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1 Introduction

Today's space age encompasses many forms of spacecraft propulsion. All of which rely on a power source and a reaction mass that is accelerated into what is know as exhaust. This produces the thrust required on the vehicle to perform a certain maneuver or mission. Most of the common forms of space propulsion involve an on-board energy source along with stored reaction mass. Both of these things greatly affect the overall system mass. This translates to increased launch costs.

A novel idea that would rid the burden of an on-board energy source and stored reaction mass is solar sailing. Using the sun as its energy source and photons as its reaction mass, this propulsion system can provide constant acceleration with a duration based *not* on finite reaction mass, but on the lifetime of its sail alone.

2 History

The fundamental ideas of solar sailing date back to the late 19th century. The Scottish physicist James Clerk Maxwell theorized the existence of light pressure in 1873. It wasn't until 1900 that the Russian physicist Peter Lebedew experimentally measured this pressure. It was not seriously thought of as a form of propulsion until the 1920's when Konstantin Tsiolkovsky and his co-worker, Fridreickh Tsander, wrote of '*using tremendous mirrors of very thin sheets'* to propel.

After the spark of interest in the 1920's, the idea was relatively dormant until the American, Carl Wiley, published an article in May of 1951 discussing the feasibility of solar sailing. An important idea by Wiley was the ability of the sail to spiral towards the Sun, called *tacking.*

A number of other studies were conducted into the 1960's. The basic principles were well understood, but the engineering feat of actually deploying these sails with surface areas on the magnitude of a couple square kilometers was very difficult. During this time, many science fiction authors coined the idea of using sails to propel through the universe, which in turn, gave rise to even more public interest. While these studies all validated the benefits of using solar sails, there was no specific mission at the time to drive more analysis.

3 Solar Sailing Fundamentals

While it is commonly thought that solar sails use solar *wind*, they in fact use solar radiation pressure. Solar wind consists of charged particles streaming from the Sun, while solar radiation pressure is created by solar radiation acting on an object. The force seen by solar wind creates only 0.1% of force produced by solar radiation pressure.

3.1 Solar Radiation Pressure

As mentioned above, solar radiation pressure is created when radiation from the Sun acts on an object. To gain a better understanding of this, the light from the Sun can be thought of as in the form of packets of energy or photons. This way, it is easier to visualize how light can apply a force. These photons from the Sun impact the solar sail and transfer momentum. This is the basic principle of solar sailing.

Using quantum mechanics, the pressure seen on the sail due to solar radiation in the form of photons can be calculated. From Planck's law, the momentum of a single photon is as follows,

$$p = \frac{hv}{c} \tag{1}$$

Where,

h = Planck's constant
v = frequency of photon
c = speed of light

To find the pressure exerted on a body from this momentum, an energy flux (*W)* must be found.

$$W = W_E \left(\frac{R_E}{r} \right)^2 \tag{2}$$

Where,

W_E *= energy flux measured at 1AU (~1368* $Js^{-1}m^{-2}$*)*
R_E *= distance between the Sun and Earth*
r = distance between the Sun and point of interest

Pressure on a surface can be defined as momentum (*p)* transported per unit time *(t)*, per unit area *(A)*,

$$P = \frac{1}{A} \left(\frac{\Delta p}{\Delta t} \right) \tag{3}$$

Substituting $\Delta E = WA\Delta t$ into Equation 3,

$$P = \frac{W}{c} \tag{4}$$

Using Equation 4, it can be found that the pressure exerted on a sail at 1AU is 9.12 N/km^2. The amount of solar radiation pressure acting on the sail will decrease by the inverse square as it travels away from the Sun. This will become more important when addressing orbital dynamics when using such a propulsion system.

3.2 Force on Sail

There are two forces that act on a sail during the impact of a photon. First, there is the force of the impact that transferred momentum, then there is a reacting force that reflects the photon. For simplicity, it was assumed that the sail was a perfect reflector in the following equations. The figure below shows the decomposition of the total force.

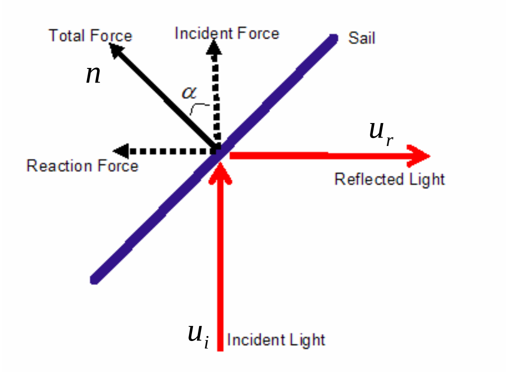

Figure 1. Force action on solar sail

As Figure 1 shows, there is an incident force and a reaction force. The magnitude of these forces alone relies on the pitch angle (α) of the sail and the distance from the Sun. This ultimately affects the acceleration of the spacecraft because Force = Mass * Acceleration. By utilizing the pitch angle to your advantage, the spacecraft can be steered just like a sailboat using the wind on the sea.

Using Figure 1 and the vector identity $\boldsymbol{u}_i - \boldsymbol{u}_r = 2(\boldsymbol{u}_i \cdot \boldsymbol{n})\boldsymbol{n}$, the total force exerted on the sail is now,

$$f = \frac{2AW_E}{c}\left(\frac{R_E}{r}\right)^2 (u_i \bullet n)^2 n \tag{5}$$

To find the acceleration of any spacecraft wielding solar sails, we can use the sail loading (mass per unit area) constant $\sigma = m/A$.

$$a = \frac{2W_E}{c}\frac{1}{\sigma}\left(\frac{R_E}{r}\right)^2 \left(\cos^2 \alpha\right) n \tag{6}$$

4 Orbital Dynamics

A wide range of maneuvers and orbits can be achieved by using solar sails. Virtually any part of the solar system can be reached using a series of proper maneuvers. Rotating the sails to obtain the correct direction and magnitude of acceleration is key. This section will describe the types of maneuvers possible and how to use them to reach or stay in the desired orbit.

4.1 Maneuvers

There are three basic types of maneuvers in solar sailing. They are *reaching*, *running*, and *tacking*. All of these movements can be used during a single orbit to maintain the correct altitude. An illustration of all three is seen below.

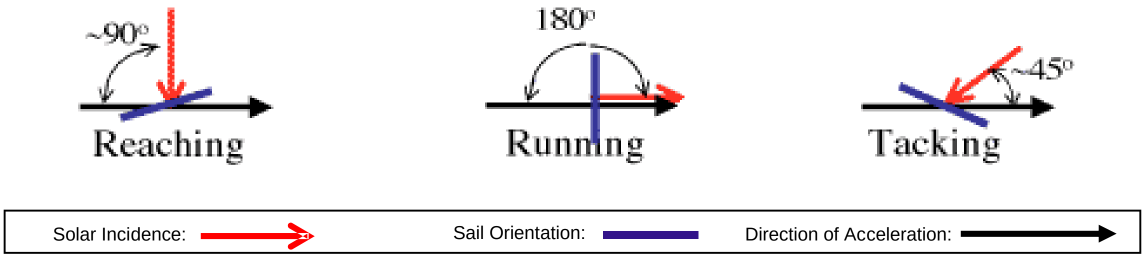

Figure 2. Sail Maneuvers[*]

Reaching is when the spacecraft is accelerating in directions near tangential to the incident light. This is when the reaction force is greater than the incident force. It requires pitch angles of close to 90^0.

Running is when the spacecraft is accelerated in the same direction the light is traveling. This occurs when the pitch angle is 0^0.

Tacking is a counter-intuitive movement where the spacecraft is propelled towards the light. It can be thought of as *sailing against the wind.* This is possible when the pitch angles are negative. This, in turn, slows the spacecraft down. If it is in a *sun-centered* orbit, the spacecraft will fall into a spiraling orbit towards the Sun.

4.2 Types of Orbits

Most conventional orbits can be achieved with solar sails as long as the system has the ability to be steered, which involves changing the pitch angle with respect to the Sun. By altering the pitch angle, the force vector can be directed in any orientation within 90^0 of the incident light. This can be accomplished by actively rotating the sail, or passively by adding small tip vanes. Tip vanes are smaller sails located in strategic locations where they are actively rotated to induce a moment on the sail. As a result, the inclination of the orbit can also be changed. The sail also provides continuous acceleration, which is not commonly seen in other conventional propulsion systems. Because of this, spiral orbits are easiest to maintain in a sun-centered orbit. The idea of maintaining a planet-centered orbit will also be explored.

4.2.1 Sun-Centered

When a spacecraft is in a sun-centered orbit, the vehicle can be assumed to be under the influence of only the Sun. This is the type of orbit in which all the planets of our solar system posses. In this orbit, the sail will either propel the spacecraft towards or away from the sun. Figure 3 shows an illustration of this.

[*] Photo courtesy of NASA, solarsail.jpl.nasa.gov

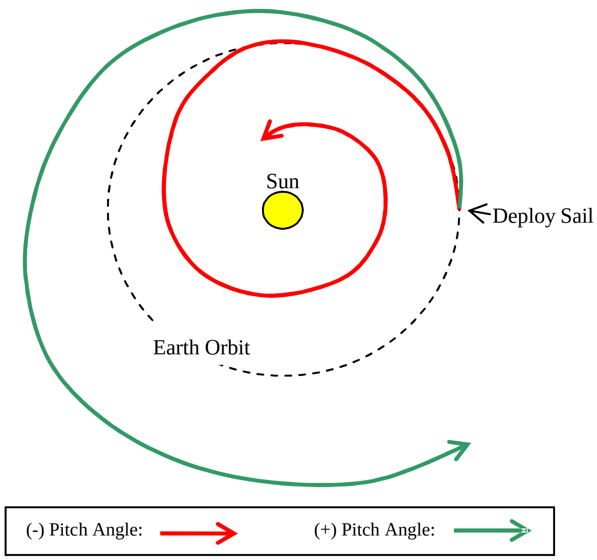

Figure 3. Sun-Centered Spiral Orbits

In order to spiral towards the sun, the sail must have a negative pitch angle. By doing this, there will be some component of the resulting force vector in the opposite direction of motion. This, in a sense, slows the spacecraft down drawing it closer to the Sun. This is also characterized as *tacking*, which was defined earlier.

The other possible orbit is to spiral away from the Sun. This is done by maintaining a positive pitch angle relative to the incident light.

It should be noted that with the use of steering, the spacecraft can fall into many other trajectories. They include elliptical, circular, rectilinear, and even escape orbits.

4.2.2 Planet-Centered

Spacecraft using solar sails can also easily stay in a planet-centered orbit. To do this, a variety of simply steering maneuvers are utilized. However, orbiting a planet also presents a few more challenges than orbiting the Sun. Problems unique to planet-centered orbits include atmospheric drag at low altitudes because of the massive sail area, and only negligible energy can be gained when the sail is moving directly towards the Sun or while in eclipse. To overcome these issues, the spacecraft can fly at high altitude polar orbits, but it is not the most efficient trajectory, especially when an escape of the planet's gravity is necessary.

The most sophisticated way to keep a spacecraft in the desired planet-centered orbit is to use *orbit rate steering.* This is a process in which the sail will continually be rotating at one half of the orbital rate. Figure 4 shows the orientation of the sail during the orbit.

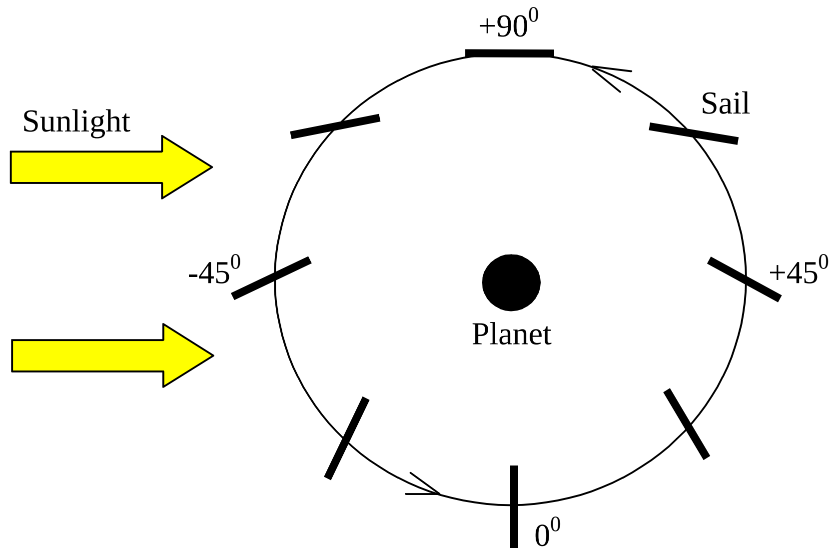

Figure 4. Orbit Rate Steering

This steering allows the sail to continually raise the orbital altitude as it is subject to degradation. This basically uses the sails to perform orbital maintenance to ensure the spacecraft stays in the desired orbit. This is most noted in the angles chosen throughout the orbit. When the spacecraft is closest to the Sun, it has a negative pitch angle. As stated earlier, negative pitch angles draw the spacecraft closer to the light source. This, in effect, raises the orbit.

5 Solar Sail Design

Now that the fundamental groundwork has been laid, an overview of various solar sail design options will be given. Sail configuration and material are the two main design parameters. For the purpose of this paper, other considerations, such as sail control, will not be discussed, but should be taken into account. The design of these components directly impact the mass, lifetime, reflectivity, packageability, and deployment of the sail.

5.1 Configuration

The sail configuration plays a major role in how the sail will be packaged, deployed, and the method of which it maintains a flat, reflective surface. There are three configurations commonly studied. They are the *square, heliogyro,* and *spinning disk.* All three have unique advantages and disadvantages. The three types of configurations that will be discussed are shown in Figure 5.

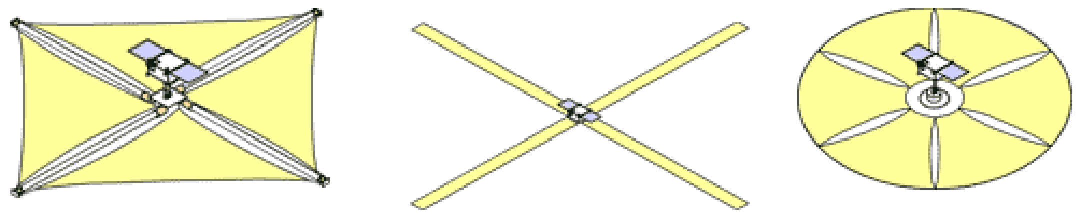

Figure 5. Solar Sail Configurations[†]

The optimum square sail design consists of four deployable spars from the central hub. These spars will keep the sail material in very high tension to provide a flat surface for reflection. A draw-back for this design is the difficulty in deploying and packaging the spars. Deployment requires a series of operations which increases the risk of failure. The mass of the spars can also prove to be quite large as there is little room for bending, which would cause a non-uniform sail surface.

The next configuration seen in Figure 5 is the heliogyro. This design uses spin-induced tension. The long blades are attached to a central hub as in the square sail. As the blades slowly rotate, a flat surface is created. A unique design feature is that the individual blades can be pitched which would induce passive rotation. This is attractive due to the mass associated with on-board power sources. Heliogyros are also relatively easy to pack and deploy. However, the long blades are subject to bending and may require stiffeners.

The spinning disk sail has a number of advantages. This configuration also uses rotation as a means of tension across the film similar to the heliogyro. Though, the spinning disk has a continuous sail film as seen in Figure 5. To induce the passive rotation, torques can be applied to the central mass represented by the central hub. A distinctive feature of the spinning disk is that it can also passively deploy by using the rotation.

The ultimate choice of sail configuration is dependent on the specific mission requirements. Such things to keep in mind are the acceleration and maximum sail turn rate. The reliability, cost, and structural mass of the particular sails also have great influence.

5.2 Material

Sail material is of utmost importance when thinking of ways to minimize the mass of the enormous sail. Many technologies are available. However, a super light sail would have to encompass new materials such as carbon-nanotubes, which are still in development. When these technologies have finally been proven, the feasibility of solar sails will grow exponentially.

[†] Photo courtesy of wikipedia.com

In deciding on a material for the sail, it must be thought of in two parts. First, the sail substrate must be chosen. This is the material that allows the sail to be handled and packaged. Next, a coating must be applied to the substrate to give the sail its reflective properties. Recent studies have found that materials like an Aluminum mesh would serve the purpose of both a substrate and a reflective surface. However, this type of material is still too fragile to be used alone.

5.2.1 Substrates

Important properties of a good substrate include heat resistance and strength. The material must be able to withstand high temperatures for missions close to the Sun and must maintain strength as it will be in high tension throughout its lifetime. While possessing these traits, the substrate must also be as light as possible. Table 1 shows a few top choices for substrates.

Table 1. Substrate Properties‡

	Bulk density (gcm^{-3})	Tensile strength (Nm^{-2})	Tensile modulus (Nm^{-2})	Surface density (gm^{-2})			UV life
				1μm	3μm	5μm	
Kapton	1.42	1.72×10^8	2.96×10^9	1.42	4.26	7.10	Good
Kylar	1.38	1.72×10^8	3.79×10^9	1.38	4.14	6.90	Low
Lexan	1.20	6.89×10^8	2.07×10^9	1.20	3.60	6.00	Poor

Of the three choices above, Kapton is thought of as the optimum. It provides good overall lifetime, is highly resistant to radiation, and can also maintain its physical properties over extreme temperatures.

5.2.2 Coatings

Properties of good coatings include high reflectivity, high melting point, and low density. The melting point requirement is mission specific, meaning not all used coatings need to have extremely high melting points. This reflective coating also acts as a means of passive thermal control to prolong the lifetime of the sail. Table 2 summarizes the properties of a few coatings.

Table 2. Coating Properties‡

	Bulk density (gcm^{-3})	Surface density (gm^{-2})			Melting point (K)
		1μm	3μm	5μm	
Aluminum	2.70	0.27	0.81	1.35	933
Lithium	0.53	0.05	0.16	0.27	453
Silver	10.5	1.05	3.15	5.25	1234

‡ Table taken from McInnes.

Silver has a very high melting point, but it is very dense compared to the other choices. However, if a mission was to take a spacecraft to an orbit close to the Sun, this may be the best option. Lithium is very light, but has a relatively low melting point. Of these choices, Aluminum coating seems the optimum with a low density and fairly high melting point of 933 K. Again, the choice of coating is very mission dependent.

6 Future Applications

There are many future missions that would greatly benefit from using solar sails versus the conventional propulsion systems used today. Missions that require orbits close to the Sun, stationary over planet poles, or cargo transport could all be optimized by eliminating the need for on-board propellant mass. Essentially, solar sails make for an optimum choice concerning missions with high energy or long duration requirements. Also, to surmount the inverse square loss of solar radiation pressure for mission traveling away from the Sun, laser driven light sails have been investigated.

6.1 Inner Solar System

Solar sails become a very attractive form of propulsion especially for Sun research missions. Being close to the Sun provides more than enough energy to keep the spacecraft in a desired orbit. These missions would, although, be limited by the lifetime of the sail material which would face quicker degradation so close to the Sun.

While located above a pole of a planet, the sail could also provide a constant force equal to the gravitational force of the planet. This would keep the spacecraft stationary. For clarification, when the sail is located at the pole of the planet, it will never be subject to an intense eclipse seen in other orbits around a planet. This, once again, could be used in missions specific to studying the pole of a particular planet.

Also worth mentioning are the benefits of using this propulsion for cargo transport. Specifically, this could be useful in manned missions to Mars. Equipment, habitats, tanks, etc. could be launched an ample time before the crew and taken to Mars using solar sails.

6.2 Laser Driven

For this type of technology, the energy source is a laser and not the Sun as previously discussed. Laser driven light sails are only efficient for very high energy missions. These include rapid outer solar system and interstellar missions. Each Gigawatt of laser power produces only 6.7 Newtons of force on the sail.

The main advantage to using laser driven light sails is that the power source or laser can be fixed and maintained somewhere in the solar system, while the only components needed to be accelerated include the sail and the attached payload.

7 Conclusions

While the science behind solar sailing has been established, the engineering behind fulfilling its requirements remains young. Functional objectives such as packaging and deployment still need a lot of research. The benefits from this technology is hard to overlook. The future feasibility of solar sails lies in the development of advanced materials that can provide the opportunity for extremely light, strong sails.

In order for the technology of sailing through space to really excel, there must be a specific mission or need to really drive its development. Once this happens, it won't be long before we're traveling through space just as early explorers adventured onto the unknown sea.

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