Multi-Disciplinary Applications and Practicality of Solar Sails

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The theory and idea of solar sails have been discussed for centuries by scientists such as Johannes Kepler and Maxwell Planck, but the actual practice of utilizing the law of conservation of momentum, general relativity, and photons' momentum for spacecraft propulsion has been a recent engineering development. Solar sails take the properties of photons and extend them to many applications including, but not limited to, expanding Lagrange Points for observing weather and climate patterns, high-latitude communications, deep space travel for interstellar research missions, and halo orbits of various celestial bodies. This paper analyzes those applications by exploring the history of solar sails - both theoretically and practically - while establishing a baseline understanding of the engineering and physical properties of solar sails. This paper will also evaluate the practicality and obstacles of solar sails in those applications. Additional areas where solar sails may be or are already employed will be investigated and potential innovations for solar sail technology will be proposed. The proposed innovations are the keys to new inventions and scientific progress, but they should not overshadow the importance of developing a strong, fundamental understanding of solar sails and their properties. While still in its infancy, the successful employment of solar sails in aerospace engineering is critical to a better understanding of Earth, its inhabitants, and its place within the universe as further exploration of our home and other celestial bodies continues.

I. Nomenclature

a_0	=	characteristic acceleration
A	=	sail area
η	=	sail finite efficiency
P	=	pressure of solar force
σ	=	sail mass-to-area ratio
m_p	=	payload mass
m_s	=	sail mass
m_t	=	combined sail and payload mass

II. Theory and History

The German scientist Johannes Kepler first believed that humans could move among the stars by using solar sails that were like traditional boat sails but were fashioned to be "proper for heavenly air" according to a letter from NASA sent from Mr. Kepler to Galileo Galilei approximately 400 years ago [1]. Since then, a multitude of discoveries and theories have turned the 400-year-old idea into a reality, such as the Law of Conservation of Momentum, the discovery of the photon and its properties (pressure and momentum) by Albert Einstein and Maxwell Planck, and the achievements of the first flight and interplanetary travel.

The idea of the solar sail is conceptually elementary, but the properties of the photon are not. In theory, photons have no mass, but they do have momentum and energy as determined by Arthur Holly Compton in his paper *A Quantum Theory of the Scattering of X-Rays by Light Elements* [2]. This conclusion is additionally supported by the

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findings of Maxwell Planck and Albert Einstein's general theory of relativity. Since photons have both momentum and energy, their collision(s) with other objects transfers a portion of their momentum to the other object, thus raising the other object's overall kinetic energy. Figure 1 is a visual representation of this system.

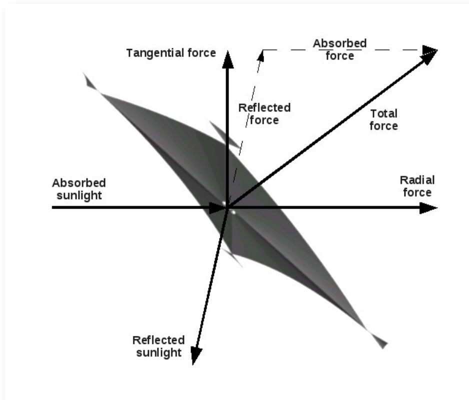

Fig. 1 A simplistic diagram of the forces involved in solar sails [3]**.**

Each photon that hits the sail will transfer energy and momentum into the sail. Individually, each photon would be negligible, but given enough time, surface area, and a consistent stream of photons, the total kinetic energy and momentum of the solar sail will become significant. Additionally, since there is little to nothing to slow down the solar sail, its momentum will continue to build – although at a decreasing rate as the distance from the light source increases. Similarly, to the sails on a boat, one could control the direction of the payload by adjusting the angle of the solar sail relative to the light source to manipulate the direction of the force acting on the sail. This results in a change in the direction of the force being applied to the sail, causing the payload to turn gradually. And, as the sail turns, the amount of its area that remains normal to the light source reduces, decreasing the magnitude of the force accelerating it.

The first attempt to demonstrate this concept was recorded in *Scientific American* in November 2003, which explained that Cosmos 1 (see Figure 2) was to be launched by the Russian Space Agency (Roscosmos) and The Planetary Society [4]. Unfortunately, The Planetary Society reports that Cosmos 1 did not make it to orbit when it launched on June 21st, 2005 [5].

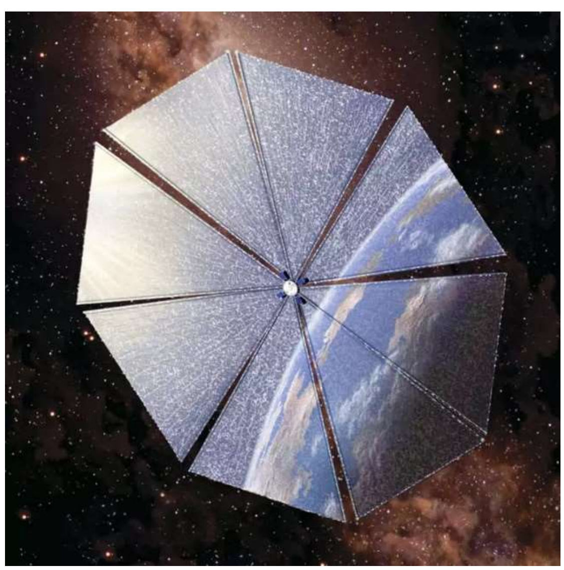

Fig. 2 Artist Rendition of the Cosmos 1 [6]**.**

Five years later, on May 21st, 2010, JAXA (Japan Aerospace Exploration Agency) successfully put the first solar sail into orbit and proved the theoretical properties of solar sail propulsion. According to JAXA, Japan's

IKAROS, or Interplanetary Kite-craft Accelerated by Radiation of the Sun, demonstrated that propulsion from photons transferring their momentum into the satellite could be the main propelling force of an object and the direction of the solar sail could be adjusted manually with assistance from Liquid Crystal Displays (or LCDs) to indicate the best change in direction for the sail relative to the Sun [7].

While JAXA developed and deployed the first solar sail satellite, NASA was not too far behind with its NanoSail-D, which was then followed by the Planetary Society's Lightsail-1. Lightsail-1 was then followed by the University of Illinois Urbana-Champaign's CubeSail, and most recently by NASA's Near-Earth Asteroid Scout (NEA Scout) which was on board November's Artemis 1 launch [8-11]. Figure 3 is a photo of the NEA Scout and gives a more tangible idea of how large solar sails are even for small satellites. This solar sail had an area of 86 square meters, a total (sail and payload) mass of 14kg, and a sail made of an aluminized polymer that looks similar to tin foil and is lighter than a feather [12].

Fig. 3 NEA Scout's Sail at Full Mast Credit to NASA/MSFC/Emmett Given [11].

Unfortunately, a Microsoft News report explains that as of November 21st, 2022, NEA Scout has been quiet since the launch of Artemis 1 [13]. However, solar sails and satellites are just starting to pick up momentum as their benefits in propulsion and mass management finally come to fruition after decades of strenuous effort and engineering achievements.

III. Engineering Aspects

Similar to nearly all other engineering concepts, there exist certain traits of solar sails that give an at-a-glance notion of their expected performance. Among these traits is the "characteristic acceleration", which Dr. McInnes, a professor at the University of Glasgow in the U.K., defines as "the light-pressure-induced acceleration experienced by the solar sail while oriented normal to the Sun at a heliocentric distance of one astronomical unit". Professor McInnes goes further to illustrate some of the mathematical equations governing this "characteristic acceleration", two of which are shown below [14].

$$\boldsymbol{a_0 = \frac{2\eta P}{\sigma_t}} \quad (1)$$

$$\boldsymbol{\sigma_t = \frac{m_t}{A}} \quad (2)$$

Here, a_0 is the characteristic acceleration, P is the pressure exerted on the solar sail by the solar light – 4.56×10^{-6} newtons per square meter (assuming a distance of 1 AU from the Sun) – η is a parameter called "the finite efficiency of the sail" that represents the sail's efficiency with regards to reflecting photons, m_t is the combined mass of the sail and its payload, and A is the area of the sail. Since the total solar sail assembly consists of two primary subassemblies, the solar sail, and its payload, it can be useful to split them apart in the equation to treat them as separate entities. Performing this separation yields the following mathematical relationship, where m_s is the mass of the sail, m_p is the mass of the payload, and A is, once again, the sail area [14].

$$\sigma_t = \sigma_s + \sigma_p = \frac{m_s + m_p}{A} \tag{3}$$

Plugging equation 2 into equation 1 – shown below in equation 4 – illustrates that the characteristic acceleration of a solar sail is *directly proportional* to its area and *inversely proportional* to its total mass. Of course, this is in line with general intuition; when the photons collide with the sail, the law of conservation of momentum states that a portion of their momentum should be transferred into the sail. This will cause a change in the velocity of the sail; and the greater the sail's area, the greater this change will be. Conversely, the heavier the sail, the smaller its change in velocity [14].

$$a_0 = \frac{2\eta PA}{m_s + m_p} \tag{4}$$

Frequently, the sail's mass-to-area ratio is referred to as the "sail-assembly loading", notably because when designing a sail, it's simpler to think about maximizing this "sail-assembly loading" rather than trying to optimize the mass while simultaneously optimizing the area as independent variables. In equation 2, this is represented by the σ_s term. Resultingly, given the mass of the sail m_s, its characteristic acceleration a_0, its finite efficiency η – which, according to Professor McInnes, is "typically around 0.85" – and the pressure exerted on the solar sail by the barrage of photons *P*, it's possible to calculate the maximum possible payload mass m_p the sail can support via equation 5 below [14].

$$m_p = A\left(\frac{2\eta P}{a_0} + \sigma_s\right) \tag{5}$$

Similarly, equation 1 can be used to derive the total mass of a solar sail and its payload, given a required characteristic acceleration – shown below in equation 6. And since the total mass is simply the summation of the sail mass and the mass of its payload, deriving its total mass along with its payload mass from equation 5 allows for the mass of the sail to be calculated by subtracting the payload mass from the total mass – shown in equation 7 – and for the maximum payload mass to be calculated as illustrated by equation 8.

$$m_t = \frac{2\eta PA}{a_0} \tag{6}$$

$$m_s = m_t - m_p \tag{7}$$

$$m_p = m_t - m_s \tag{8}$$

Of these, perhaps the most important is equation 8, allowing for the calculation of the greatest possible payload mass that a given sail can undertake given the mission requirements. The sail's dimensions will determine its characteristic acceleration as shown in equation 1, the result from which, once again in combination with the sail's dimensions, can then be used to determine the maximum total mass of the sail-payload assembly. Then, simple subtraction of the sail mass from the total sail-payload mass yields the maximum payload mass, which will determine a multitude of aspects of the mission, such as the amount of scientific data that can be collected, the duration for which the mission can run, and even the operational agility of the sail. All these factors come into play at the commencement of a mission design and having the ability to alter these characteristics of the sail becomes crucial for tailoring the sail's operability to the specific scientific and operational needs of the mission.

IV. Practicality and Applications

A. Lagrange Points

With regards to Newtonian physics, a Lagrange point is a point in space where the gravitational pulls of separate celestial bodies "cancel out". In other words, a spacecraft – one that does not have/include a solar sail – positioned at one of these locations will tend to stay in place. However, it is crucial to remember that typical spacecraft do not *constantly* have a force acting on them. For this reason, solar sails are unique: the barrage of photons from the Sun – or any star for that matter – is unrelenting. In the words of Professor McInnes, "the solar sail adds an extra force to the dynamics" of the situation, which allows the sails to "artificially displace" these points of dynamic equilibrium, creating unique pseudo-Lagrange points [14].

Resultingly, unlike traditional spacecraft which are limited to the conventional five Lagrange points for a two-body system, solar sails can, theoretically, have an infinite number of pseudo-Lagrange points, which collectively may be better referred to as a 'Lagrange surface' or a 'Lagrange disk'. This creates a world of possibilities in terms of the ways solar sails can be used for missions for which traditional self-propelled spacecraft could not be feasibly considered. As an example, "the National Oceanic and Atmospheric Administration is interested in using sails to station satellites above Earth's poles" [15]. In these locations, the combined gravitational forces of the Earth and the Sun try to bring a satellite back into the Earth-Sun orbital plane, but the force of the solar light acting on the solar sail can be used to counteract this and maintain the satellite's extreme latitude. A satellite positioned in such a remote location – relative to other satellites – would be essential for scientific observations such as "monitor[ing] the poorly understood polar climate, [and] watch[ing] the moon and auroras around the clock", as well as less-than-scientific, but nonetheless important aspects such as "provid[ing] a phone link to researchers at the South Pole" [15].

B. Practical Structures of Solar Sails

Solar sails offer deep space exploration at rates beyond any current mission by utilizing the sail's gradual acceleration. To maximize the acceleration that the sail experiences, the sail's area must be maximized while also considering how the sail's mass affects the satellite's characteristic acceleration. For a mission similar to New Horizons, a 465 kg total payload equipped with a sail with an area of approximately 2875m^2 would produce a characteristic acceleration of 0.046 mm/s^2 [16]. Figure 4 is a reference model that demonstrates the size relationship between the sail and satellite, where the payload is at the intersection of the beams and the outer grey area is the sail.

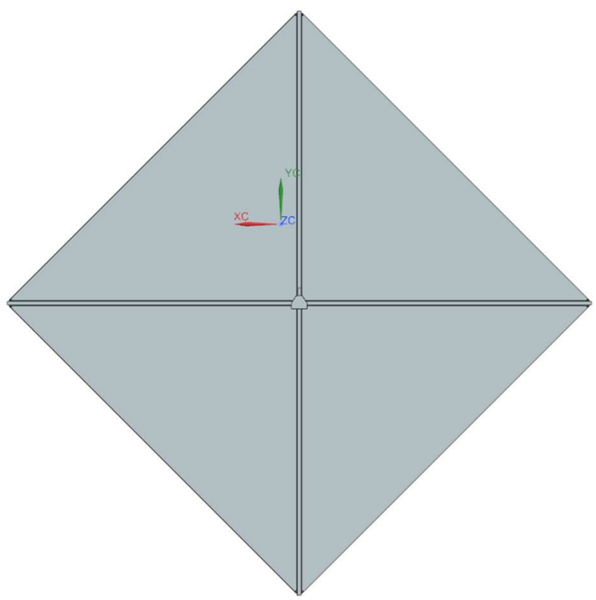

Fig. 4 The size relationship between a 465 kg payload and the sail necessary for a characteristic acceleration of 0.046 mm/s^2.

The above model is the most typical sail structure consisting of four support beams extending from the payload with the solar sail tethered to the supports so that as the supports expand from the center, the sail unfolds from inside the satellite. This sail structure is essentially two-dimensional and is currently the most popular structure for solar sails, but this design ignores the possibility of an inflatable three-dimensional structure that may be more efficient and yield greater results. One such design is proposed by Dr. Gregory Matloff from the New York City College of Technology, and he proposed a "parachute" design with the payload on the sunward side of the sail with cables extending from the payload to the sail. This structure choice takes advantage of a three-dimensional sail that increases the surface area for photon impacts, but as Dr. Matloff explains the mass of the cables increases exponentially as the payload mass increases and the temperature of the payload on the sunward side of the sail could cause some issues for temperature sensitive instruments [17].

One additional possibility is a monolithic Gossamer structure – a fillable ultra-lightweight structure – with four quadrants with a similar support and deployment equipment to a flat sail that would inflate with a gas (e.g., hydrogen) once the sail reaches full mast. The low-density gas would fill the inside of the sail to increase the volume and surface area for photon collisions. This increase in surface area allows for two design possibilities: either a flat sail design with the extra area once the sail is fully inflated or a plan for the same area as the flat sail but using less material and adding an inflation system with storage for the sail's fill gas. The mass penalty for the additional systems remains to be investigated but is not anticipated to be a critical issue. Since the area of one section of Figure 4 is less than the surface area of that section inflated, less material would be needed to achieve the same area. However, a Gossamer structure has additional considerations due to the nature of the structure. A few of those considerations include the tensile strength of the sail's material, connecting and bonding the sail to itself, its filling system, the support beams, and how the chosen gas would diffuse and behave inside the structure [18]. A couple of materials are discussed in the next section that are effective candidates for the structures detailed in this section.

C. Micro Impacts and Sail Materials

When considering deep space exploration, it is critical to also consider the long-term endurance and qualities of the sail's materials that will be used and understand the performance of those materials over time. Tensile strength is critical for any chosen design as the solar pressure will apply stress and strain to the sail while impacts from micrometeorites will wear on the sail over time and cause changes to the sail's structural integrity. Impermeability is also a necessary consideration for a Gossamer structure that will be inflated; the melting point of the sail's material should be considered if a near pass of the Sun is to be made for a gravity/acceleration assist. One such material that is currently being used on NASA's NEA Scout is an aluminized polyimide resin that, according to NASA Technical Reports from 2017, is about 3 microns thick with a sail area of $86m^2$ [16]. This material is not currently being used for a three-dimensional sail such as that discussed in the section above, but its mass and density are notable as the polyimide resin sail is extraordinarily light and thin. A large sail made of this material would have a small mass and could be effectively transported if proper precautions are taken concerning its low tensile strength.

Another contender, while not readily available in the desired form and the necessary preparations are complex, offers many advantages: graphene. Dr. Gregory Matloff explains the versatility and efficiency of graphene in his 2012 paper "*Graphene, the Ultimate Interstellar Solar Sail Material?*" of using a "pure graphene monolayer" as the main material of the sail itself. With the specifics Matloff sets out in his analysis, graphene's tensile strength and impermeability to gases make it the "ideal" candidate for an inflatable sail as its tensile strength is "200x that of steel", gasses cannot easily diffuse through it, and layering graphene levels increases its reflectivity [19]. This will be especially useful for holding the seams of the sail together while simultaneously protecting the sail from damage from any micro-meteorites that the sail may collide with as it moves through the atmosphere, space, or any other medium. Furthermore, researchers at the University of Minnesota estimate that graphene's melting point is approximately between 4000K and 6000K, allowing for a solar sail to make a near pass at the Sun safely for a gravity assist [20]. Finally, diffusion is especially important if a large sail needs to be inflated for a Gossamer sail. With these qualities, graphene outperforms its competitors like beryllium and polyimide resin because of its diffusion qualities, tensile strength, and high melting point, but is hindered by its necessary preparations.

D. Asteroid Rendezvous and Space Transports

Thanks to the self-propelling and reusable nature of solar sails, they also offer themselves nicely for missions where there is a multitude of unique destinations, or similarly, where several destinations are going to be approached multiple times each. As Robert L. Staehle notes in the *Journal of the Washington Academy of Sciences*, a solar sail could "move from one asteroid to another in an open-ended survey," thus singly accomplishing a mission that "would require many [spacecraft] using conventional propulsion." Since asteroids are particularly difficult celestial bodies to study using typical spacecraft, solar sails provide a unique opportunity to overcome this barrier. And not terribly unlike the concept of studying asteroids, the idea of using solar sails as interplanetary cargo vessels arise. These "Clipper Ships of Space," as Mr. Staehle calls them, would be rather humungous compared to sails used in the past, measuring in the order of miles on each side. However, since a sail of this magnitude would be used as a transport, it will only need to encounter a planet's atmosphere once, (Earth's upon launch\deployment), since the rest of its life will essentially involve serving as an Earth-Mars shuttle. Mr. Staehle goes further, saying that a sail of "nearly two miles on a side" could take a modern-day eighteen-wheeler load from Earth to Mars in about the same amount of time as a

United States single-term presidential administration, and, provided it was empty, it could return to Earth in about half that time [21].

E. Waste Disposal

On a slightly different, but relevant note lies the problem of waste disposal; specifically, the type of waste that poses a particular threat to the environment: nuclear. Since the era of the second world war, nuclear energy has been harnessed for both constructive and destructive purposes. But regardless of its use, the fact cannot be avoided that nuclear fission tends to produce a large amount of radioactive nuclear waste. In the most extreme cases, this waste needs to be isolated from the biosphere for one hundred millennia (or longer). And as Mr. Staehle points out, "methods of geologic disposal have been proposed," but many have concerns regarding the permanence of the "isolation from groundwater or other elements" of the environment using this method. With a solar sail, a sample of nuclear waste can be disposed of in several ways: moving the waste to another, less desired-for-habitation celestial body, "incineration by the Sun" if taken close enough to the solar surface (although this could pose the challenge of designing a sail capable of withstanding *extreme* solar radiation and temperatures), or flat-out expulsion from the Solar system. Any of these methods of disposal will prevent any negative effects that the waste could yield on the Earth's biosphere from coming to fruition. And the sooner waste is managed in this manner, the more mitigated any negative effects the waste has already yielded will be [21].

F. Halo Orbits

A halo orbit by nature is an orbit situated around a celestial body's poles, which when looked upon from afar, resembles a halo on an angel. The practicality of maintaining a halo orbit around the Sun, or other celestial bodies, offers the greatest efficiency when data collection and communication are involved. A satellite trajectory of this type eliminates all blackout periods that may emerge when a probe or satellite is blocked by a celestial object that intersects its direct connection with the receiver(s). Using this type of orbit, problems that may arise during the blackout period can be identified and corrected immediately unlike current missions. This can make the difference between a mission's success and failure. Additionally, there will be a constant connection between the satellite and its receiver, Earth, or another satellite in a relay, which will avoid blackouts in data transmission.

The applications of a halo orbit allow for a satellite, positioned via solar sail(s), to be situated at the poles of the Sun, thus providing a connected system that can be accessed from any orbiting body in our solar system. The applications of halo orbits are discussed by Angel Jorba et al. in their 2016 paper "*Dynamics, Geometry and Solar Sails"* where halo orbits "can keep permanent communications with the Earth while it has continuous coverage of the Sun" [22]. The implementation of solar sails onto such a satellite offers the ease of maintaining a halo orbit without the need to consume chemical propellant. This greatly simplifies satellite construction and reduces its overall weight. The mass saved could then be allocated to more data collection instrumentation or a larger solar sail.

Furthermore, halo orbits are not limited to usage around the Sun. Positioning a satellite and maintaining a halo orbit with a solar sail expands the overall capability of a communications satellite to maintain a constant flow of data. A recent example was seen in the recent completion of the Artemis mission; when the Orion capsule crossed to the dark side of the Moon, all forms of communication were lost since there was no way to properly relay the information around to Earth. But, by having a satellite positioned at either pole of the Moon and using solar sails to adjust the orbit by either increasing or decreasing the radius of the orbit, blackout periods will no longer be a concern as data could be relayed from the capsule to the satellite and then to Earth. This type of orbit will be employed on the upcoming NASA CAPSTONE mission. The specific name behind the orbit chosen for the CAPSTONE mission is a near rectilinear halo orbit [23]. The benefit behind the orbit is a stable trajectory that requires very little correction over time. If solar sails were to take the place of chemical propellants, less mass would be dedicated to the propulsion systems that deal with trajectory correction. Another benefit lies in the service life of solar sails, which use the environment they are situated in and do not consume any fuel. The inclusion of solar sails onto a satellite or spacecraft offers a chance to test new orbit patterns that were previously thought to be impossible due to their nature of needing constant correction. Those corrections require aggressive fuel consumption and make current long-term missions impossible.

G. Vehicle life

Since solar sails are independent of the need to consume propellants, the service life of the satellite being used expands over the capabilities of current satellites, which eventually run out of their propellants entirely and lose all ability to adjust, resulting in the loss of the vehicle [22]. The flexibility in the design of a solar sail allows for energy production, in the form of incorporated solar panels in the sail, to power the craft. The ability to have the sail as the main form of propulsion and energy production opens the door to new design possibilities. Traditional satellites such as Voyager 1 or Cassini implemented a Radioisotope Thermoelectric Generator (RTG) to provide power for the vehicle. Although there are benefits to the RTG setup, being extraordinarily reliable in their construction, the added mass as well as their inefficiency in producing electrical energy prohibit wide use for smaller satellites. Their conversion from heat to electrical energy is mainly found to be in the efficiency "range of between 5 to 9%" [24]. With the advancements in solar panel technology, modern solar panels that are used for space missions are about three times more efficient than RTG's. Even on the consumer scale, solar panels prove to be a reliable method of producing electrical energy. Though since more funding and research are poured into space, non-commercial solar panels reach a higher degree of efficiency. "These panels can reach up to around 34% efficiency vs. the 15-20% that most commercial solar panels can reach" [25]. It must be noted that solar panels have been implemented on solar sails before, most notably the IKAROS satellite, which was launched on May 21, 2010. The novelty of incorporating solar panels onto the solar sail itself proved to be a major success where it was "confirmed that it produced power using thin film solar cells" [7]. With real-world examples that exhibit success such as IKAROS, it opens the door to solar sails as a new form of propulsion and electrical generation.

H. Pseudo Radar/Mirror Dish

Solar sails operate primarily through photons; however, high-energy waves can be used as an alternative means of obtaining propulsion. As it is known, a photon is redirected once it collides with the sail, and depending on the angle, can be adjusted to bounce off in a specific direction. The same principle is seen in radar and radio technology with the need to use a dish to direct energy waves. Hypothetically, a solar sail can serve the same purpose. Since solar sails can reflect the highest charged energy wave, they would be able to tolerate the concentrated burst from an emitter that is attached to the craft. With this in mind, the momentum of the sail can be changed with the implementation of high-powered radio transmitting devices. Having a transmitter oriented towards a specific point or area on the sail hypothetically allows for a controlled method of accelerating the satellite. If this is the case, the satellite construction can be simplified further and lighter as the need to fit and carry a satellite dish is eliminated. Mechanisms for manipulating the sail to reflect a signal towards a specific direction or angle would have to be researched. The benefits that would emerge from a configuration as described before would open the door to a larger payload capability since numerous areas that previously took up the mass of the craft would no longer be needed. On top of that, the space saved from the listed design concept makes the construction even more compact and smaller. The sail would not only function as the primary form of propulsion but would also double its role as an integral component of communication equipment.

A possible application of using a solar sail as a surface to bounce off high-powered energy waves that originate from the craft itself is in replacing Reaction Control Systems (RCS). Modern spacecraft utilize Reaction Control Systems to adjust attitude and make small corrections to trajectory. During the service life of a spacecraft, there are numerous attitude adjustments that are executed, and with time, the carried propellant is depleted, the principal issue of RCS systems. Solar sails can replicate the functionality of RCS through a transmitter on the satellite. By regulating the intensity of the transmitter, precise bursts of energy waves can be sent out to impact the solar sail and change the attitude of the craft. With regards to the concept, this means that all propulsion and attitude control can be done without propellant indefinitely. This potentially expands the range of operations a satellite can have given the lack of a necessity for chemical propellant and appropriate care in avoiding possible debris, and with the idea that thousands of bursts of high beam energy will be directed to the solar sails, it would be important to consider possible degradation over time as the materials would fatigue. More research needs to be done on this concept as it is new and untested.

I. CubeSats

Upon looking at smaller-scale applications, CubeSats greatly benefit from the use of solar sails. The main concern regarding CubeSats lies in the expected lifetime of the craft. Dangers posed by atmospheric drag only hinder the ability to maintain a constant orbit around Earth. Other issues, such as running out of chemical propellants for attitude adjustment have been ongoing concerns about the sustainability of the craft long-term. Although reaction wheels are used as a solution to attitude adjustment, they add a layer of weight and more components to the satellite. The application of solar sails reduces CubeSats' construction weight and complexity. It also indefinitely provides both attitude and orbit control without the need to dedicate alternative subsystems to keep the craft in a specified trajectory. As such, the integration of solar sails in the construction of CubeSats offers a solution towards expanding the satellite's service life and operational ability by increasing the radius of orbit around Earth. According to Ceriotti et al. (2014), "...realistic architectures appear likely to have the capability to raise the orbit of CubeSat-class spacecraft above this altitude by several tens of kilometers per year" (p.21). With such a development, CubeSats can adopt a greater scale of usability, performing duties on a larger scale of time compared to other satellites that lack the implementation of solar sails to continuously adjust their orbit [26]. At this scale, every component matters, therefore with the ability to simplify construction as well as reduce the mass of a CubeSat, the implementation of solar sails is a major economical step upwards.

V. Conclusion

Solar sails, although not necessarily a novel concept, have only recently begun their transition from the drawing board to the real world. However, an extended maturation period for such an unorthodox idea is not necessarily a detracting feature, as it gave time for opportunities to work out any imperfections in the theory that could impact mission capabilities. And it arguably paid off. Advancements in the understanding of astrophysics have opened greater possibilities for the types of missions that solar sails can serve, the least of which include asteroid rendezvous and interplanetary cargo transports. And with the ability of sails to artificially displace Lagrange points using the force of solar radiation, the possibility and efficacy of communication with higher latitudes are greater than ever, which has only become more important with the Earth at its highest human population ever. Of course, fewer of these advancements would have been made without the growth in materials science and engineering that has occurred most vigorously in recent decades. The possibility of creating increasingly thinner sails without compromising tensile strength ensues the feasibility of using solar sails for a wider variety of missions, such as observing the solar surface from closer proximity or exploring in greater detail the depths of the outer solar system and interstellar space. And as the relevant science and technology continues to evolve, so will the possible applications. Space agencies such as NASA have already begun using solar sails as propulsion for CubeSats to conduct miniature zero-gravity experiments. Considering this, there is no reason for a future in which package delivery services utilizing solar sails for interplanetary transportation could not exist. Or perhaps, one day, a large collection of solar sails will be used to systematically block parts of sunlight and other solar radiation to cool the Earth or gain better control of agricultural yields. The point is that, with solar sails, the sky is not even close to the limit.

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