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# Introduction: Solar Sail Propulsion: Demonstration of a System

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THE AIAA is proud to present this special edition of the *Journal of Spacecraft and Rockets* focused on recent advancements in solar sail technology. NASA's In-Space Propulsion Technology Program, the ESA, the DLR, and others have invested in technologies with the potential to revolutionize the robotic exploration of deep space. For robotic exploration and science missions, increased efficiencies of future propulsion systems are critical elements needed to reduce overall life-cycle costs and, in some cases, enable missions previously considered impossible.

Solar sail propulsion uses sunlight to propel vehicles through space, using momentum exchange between solar photons and the sailcraft. The reflective surface of the sailcraft is constructed from lightweight, reflective material with many designs, using a metallized polymer film.

Derivations of photon pressure have been presented by numerous authors [1–3]. To summarize these derivations, it can be stated that the pressure from photon momentum transfer, on a surface perpendicular to the solar radiative energy flux, is given by

$$P = W/c \tag{1}$$

where $P$ is the photon pressure exerted on a surface, $W$ is the energy flux across the surface, and $c$ is the speed of light. For an idealized sailcraft surface that is a perfectly flat reflector, identical forces, per unit area, are exerted by the momentum transferred to the surface by the reflected photons and the incident photons. The corresponding total solar pressure is given as

$$P = 2W/c \tag{2}$$

The force a surface experiences due to the incident radiation is given by

$$\bar{F}_i = PA\cos\alpha\hat{u}_i \tag{3}$$

where $A$ is the total solar sail reflective surface area, and $\alpha$ is the angle between the incident solar radiation and the reflective surface normal. This force is directed in the incident-radiation ($u_i$) direction. In contrast, the force the surface experiences due to the reflection of the radiation is given by

$$\bar{F}_r = PA\sin\alpha\hat{u}_r = -PA\cos\alpha\hat{u}_r \tag{4}$$

in the reflected radiation ($u_r$) direction. Using the identity

$$\hat{u}_i - \hat{u}_r = 2(\cos\alpha)^2\hat{\imath} \tag{5}$$

the total force vector for an ideal sail is described as

$$F_{\text{tot}} = 2PA(\cos\alpha)^2\hat{\imath} \tag{6}$$

and is directed normal to the reflective surface.

The actual force magnitude decreases when the nonideal characteristics of a realistic sail (nonperfect reflection, wrinkles, billow, and so on) are taken into account, and the resultant force vector is offset from the normal direction. In the vicinity of the Earth, the total force exerted on a 1 $m^2$ ideal surface perpendicular to the sun is approximately $9 \times 10^{-6}$ $N$ (nine micro-Newtons). Notice that the energy flux, and thus the solar radiation pressure, varies inversely with the square of the distance from the sun.

The force generated by reflection of the sun's radiation represents a sailcraft's thrust. The net force on a sailcraft surface is generally perpendicular to its reflective surface. Desired orbital maneuvers are conducted by pointing this thrust vector in a particular direction to alter the sailcraft's velocity vector in such a way as to effect a desired change in this velocity ($\Delta v$) over a given period of (sometimes considerable) time.

By tilting the sail surface such that the reflecting surface is no longer perpendicular to the incident radiation, the thrust vector will have a component that is along the sailcraft's trajectory as well as a perpendicular component. This perpendicular component enables the sailcraft to make inclination changes and well as spiral in–spiral out trajectories.

This unique ability to generate thrust has made solar sail propulsion the subject of study for a variety of missions. Solar sail technology offers the potential to provide cost effective, renewable propulsion that enables longer on-station operation, increased scientific payload mass fraction, and access to previously inaccessible orbits (e.g., non-Keplerian, high solar latitudes).

Sailcraft designers have been challenged with developing lightweight materials and structures, and with integrating guidance, navigation, and control systems that use these first principles of photon pressure. This issue of the solar sail special edition concentrates on the development and maturation of modeling and simulation tools applicable for the design and analysis of sailcraft technology. The second issue of the solar sail special edition will focus on various mission architectures, new materials, and environmental effects on sailcraft and sailcraft materials. These special editions on solar sail technology capture specific technology advancements, from both the United States and international communities. We, the editors, hope you enjoy this special edition on solar sail technology.

## Acknowledgments

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## References

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