

Sundiving solar sails for fast space exploration

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Abstract. Spacecraft with solar sails, if sent to the Sun's vicinity, can achieve high heliocentric velocities—up to tens AU per year. This opens prospects for fast missions to various destinations in the Solar system and beyond: asteroids, distant planets, heliopause, solar gravitational lens' focus, etc. This work reviews the concept of the so-called Sundivers with respect to its real capabilities, scientific potential, and implementation challenges.

Introduction

Solar sails have been investigated since the 20th century for both Solar System and interstellar exploration. To the best of the authors' knowledge, the earliest scientific introduction of interstellar travel using solar sails appeared in the work of [1]. In the paper it was suggested to employ Earth-based lasers to propel a sailcraft up to 99% of the speed of light. Later, studies [2, 3, 4] put forward the idea of harnessing a natural radiation source—the Sun—to drive a sailcraft onto an interstellar path. One proposal was to send a sailcraft in a heliocentric orbit with a low perihelion and deploy the solar sail right at the perihelion in order to achieve substantial acceleration. This is the core idea of what is today known as *Sundiver*¹.

A Sundiver trajectory is a fast solar sailing trajectory in which a solar sailing spacecraft executes a close solar flyby to transition into a high-energy hyperbolic trajectory, exploiting both the Oberth effect and the strong solar radiation pressure. As interest in exploring the interstellar medium and the distant reaches of the Solar System grows, Sundiver trajectories are gaining increased relevance. It was demonstrated recently that realistic small spacecraft outfitted with solar sails have a variety of potential scientific uses, including those requiring Sundiver trajectories [5]. That paper highlighted a broad range of possibilities, spanning heliophysics and

¹The term can refer to a concept, or to a mission, or to a spacecraft, or to a trajectory, etc., depending on the context.

planetary science investigations, astrophysics applications, the solar gravitational lens focus mission, and more.

In this work we discuss: potential applications of Sunidver trajectories, development status and some engineering aspects, dynamical aspects—especially we pay attention to the maximum achievable velocities,—and current challenges.

1. Equations of motion and solar sail model

Throughout the work we consider a scenario when a solar sailing spacecraft (sailcraft) orbits the Sun, no other objects are involved. The motion of the spacecraft is modelled within the perturbed two-body framework:

$$\ddot{\mathbf{r}} = -\frac{\mu\mathbf{r}}{r^3} + \mathbf{a}_s$$

Here $\mathbf{r}$ is a radius vector from Sun to the spacecraft, μ is the Sun's gravitational parameter, and $\mathbf{a}_s$ is acceleration induced by the sail. To study orbital motion the sail is assumed to be flat specularly reflecting, with $\mathbf{a}_s$ given by

$$\mathbf{a}_s = a_c \left(\frac{1 AU}{r} \right)^2 \cos^2 \alpha_{\mathbf{n}} \mathbf{n}$$

Here a_c is the sailcraft's characteristic acceleration², $\mathbf{n}$ is a unit vector perpendicular to the sail's surface and directed away from the Sun (backside's unit normal vector), and $\alpha_{\mathbf{n}} = \alpha_{\mathbf{n}}(\mathbf{r}, \mathbf{n})$ is the angle between $\mathbf{r}$ and $\mathbf{n}$ called *the cone angle*. Vector $\mathbf{n}$ is considered as a control parameter when studying orbital motion, with only restriction $\alpha_{\mathbf{n}} \in [0, \pi/2]$ (so as to keep the backside in shadow).

When studying angular motion, the sailcraft is assumed to have the "Sunvane" architecture [5], i.e. a centrally truss hosting payload with six independent vanes attached to it (see Fig. 1). The vanes are assumed to have two limited degrees of freedom that will be used in practice to trim the sails and control angular motion. The sailcraft's mass is constituted by truss' mass that is constant, vanes' canvas mass that is proportional to the square of the vanes' size, and vanes support structure's mass that is a linear function of the vanes' size. Then, the area-to-mass ration of the sailcraft is

$$A/m = \frac{6 \cdot (R^2 - R_0^2) \sin 30^\circ}{m_{pl} + 6 \cdot [\sigma_{sq} (R^2 - R_0^2) \sin 30^\circ + \rho_{lin} R]}$$

where R is the size of a single vane, $R_0 \approx 0.5m$ is a size of a technical gap, σ_{sq} is the total surface density of everything that scales as R^2 , ρ_{lin} is the total linear density of everything that scales as R , m_{pl} is the payload mass, and $\sin 30^\circ$ appears from geometry. Based on [5], we assume $\sigma_{sq} \approx 3.55 g/m^2$ and $\rho_{lin} \approx 110.87 g/m^2$.

² $a_c := \eta \cdot P(1 AU) \cdot A/m$ where $\eta \in [1, 2]$ is the effectiveness coefficient, $P(1 AU)$ is SRP at one astronomical unit, A is the sail's area, and m is the total spacecraft's mass.



FIGURE 1. A scale model of a Sunvane sailcraft built at LGarde, Inc. Tustin, CA, USA shown on display at the Xplore, Inc. facility in Redmond, WA, in March 2023 [5].

2. Main results

Using a backwards-in-time propagation technique, described in [6], we determined hyperbolic excess velocities that a sailcraft can achieve depending on the flight distance and the characteristic acceleration (see Fig. 2). This data shows that the minimal required a_c for entering a hyperbolic trajectory is 0.8 mm/s^2 ($A/m \approx 95 \text{ m}^2/\text{kg}$) if r_π is limited to 50 solar radii and 0.32 mm/s^2 ($A/m \approx 38 \text{ m}^2/\text{kg}$) if r_π is limited to 20 solar radii.

Considering the "Sunvane" architecture, the numbers above correspond to the size of the vanes of $R \approx 57 \text{ m}$ and $R \approx 26.5 \text{ m}$ respectively, with payload weighting $m_{pl} = 30 \text{ kg}$. These sizes lead to inertia tensors that are of orders of $1 \cdot 10^5 \text{ kg m}^2$ and $6 \cdot 10^3 \text{ kg m}^2$ respectively. Knowing the inertia tensor, we can estimate the magnitude of control torques required to perform the Sundiver maneuver. As shown in [6], angular acceleration can be estimated as $\varepsilon = 20 \text{ marcsec/s}^2$, therefore the maximum required torque is $1 \cdot 10^5 \text{ kg m}^2 \times 20 \text{ marcsec/s}^2 \approx 0.56 \text{ N m}$. However, this estimate does not account for any disturbances that can be caused by vanes disalignment, meanwhile one 57-m vane creates a torque (relative to the connection point) of 0.32 N m at $r = 1 \text{ AU}$ and 37.4 N m at $r = 20$ solar radii. Clearly, no fly-wheel can compensate a 37.4 N m torque, therefore an adaptive and robust control algorithm will be required to orchestrate the sails so as to minimize misalignments and disturbance torques.

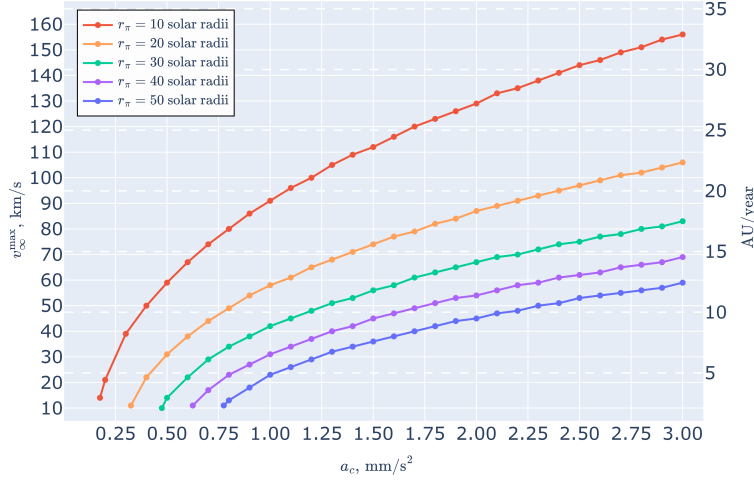


FIGURE 2. Maximum achievable hyperbolic excess velocity as a function of the solar sail's characteristic acceleration for specific values of the hyperbola's pericenter distance. The initial aphelion distance is limited to Earth's orbit [6].

Conclusion

Sundiver concept provides great scientific prospects and poses great engineering challenges. To get v_{∞} of at least 5 AU/year it requires characteristic acceleration of at least 1 mm/s^2 , with 0.8 mm/s^2 being the minimal characteristic acceleration required to enter a hyperbola ($r_{\pi} \approx 50$ solar radii). However, 0.8 mm/s^2 corresponds to the sail's radius of approximately 57 m , which leads to enormous inertia tensor ($\sim 10^5 \text{ kg m}^2$) and external torques ($\sim 10^1 \text{ N m}$). Therefore, implementing such a mission means not only building a gigantic lightweight structure, but also developing a robust algorithm to precisely control the sails so as to ensure a required angular motion.

References

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