HELIOGYRO ORBITAL CONTROL AUTHORITY

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Abstract: *Solar sailing is an elegant form of space propulsion that reflects solar photons to produce thrust. Different sail configurations exist, including a traditional flat sail (either square- or disc-shaped) and a heliogyro, which divides the sail membrane into a number of long, slender blades, analogous to a helicopter rotor. The magnitude and direction of the induced thrust force depends on the sail's attitude with respect to the Sun, i.e., on the cone angle. At each cone angle, a flat sail can only generate force of particular magnitude and direction, while this paper demonstrates that a heliogyro can arbitrarily reduce the magnitude of the thrust vector through the additional control of pitching the blades. This gives the heliogyro more force control authority, which is exploited in this paper for orbital control. A linear-quadratic regulator feedback controller is used to quantify the maximum error in the injection state vector of a solar sail halo orbit from which the nominal orbit can still be recovered. The conclusion is that an order of magnitude larger error in position and velocity can be accommodated, demonstrating superior capabilities of the heliogyro over a flat sail for orbital control.*

Keywords: *heliogyro, solar sail, halo orbit, orbital control*

1. Introduction

As a propellant-less form of propulsion, solar sailing has great potential for large-ΔV and long-duration missions and has recently been demonstrated in space with the IKAROS and NanoSail-D2 missions. While both missions employed a flat solar sail, renewed interest exists in the heliogyro concept [1], which allows greater thrust accelerations as sail shape is spin-flattened rather than through a mechanical structure. Significant research has been conducted regarding the blade dynamics, stability and control [2] and the heliogyro's attitude control moment authority [3], but much remains to be explored in its orbital control capabilities. This paper therefore investigates the heliogyro's force capabilities and exploits these for orbital control of solar sail displaced halo orbits. These orbits are positioned sunward of the Sun-Earth L_1-point point to increase warning times of solar storms [4].

2. Heliogyro force capabilities

The force induced by a solar sail varies with its distance to the Sun squared and its attitude with respect to the Sun by the cosine squared of the sun angle α (cone angle) to account for the angle of incident sunlight and the apparent sail area seen by the Sun. Furthermore, the sail's performance can be expressed through the lightness number, β, which is a function of the ratio of sail area to spacecraft mass. In this paper a value of $\beta = 0.0363$ is assumed, based on the expected performance of relatively mature flat sail technology designed for the Sunjammer mission [4]. Note that, due to the reduced sail system mass, a near-term value for a similarly mature heliogyro-type sail would be approximately $\beta = 0.08$ [1].

For a traditional flat solar sail at 1 AU distance, the achievable forces along the Sun line, F_s, and perpendicular to it, F_l, describe a "bubble-shaped" curve as shown in Figure 1a. As the heliogyro has the additional control of pitching the blades, e.g. in a collective, cyclic, or half-p manner [3], the achievable (F_s,F_l)-combinations are not constrained to the neighborhood of the surface of the bubble, but can instead take on any value within the bubble. This is demonstrated in Figure 1b, which shows contours of equal pitch amplitude for a collective pitch profile.

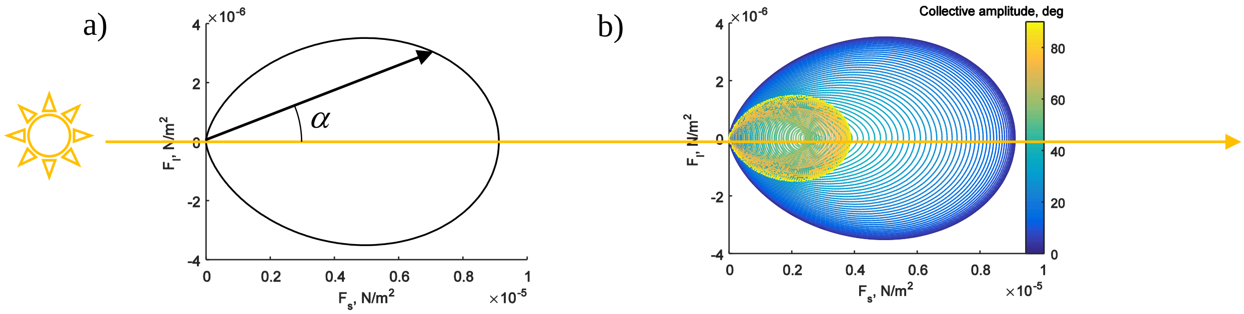

Figure 1 Solar sail "force bubble". a) Flat solar sail. b) Heliogyro with collective profile.

3. Heliogyro orbital control authority

The results in Figure 1 show that a heliogyro has a highly-variable lightness number, allowing it to scale the solar sail force between zero and that of an equivalent-area flat solar sail. This is exploited in this paper for orbital control. Figure 2 shows the results of an LQR feedback controller to correct for injection errors into a solar sail displaced Sun-Earth L_1 halo orbit using the sail attitude as control parameters, adding the lightness number as extra control in case of the heliogyro for which an upper limit of $\beta = 0.04$ is imposed. The dynamics are those of the circular restricted three-body problem and the in- and out-of-plane amplitudes of the halo orbit are 1,473,872 and 444,236 km, respectively, in order to fit around a 5 deg solar exclusion zone around the Sun-Earth line [4].

The injection error is applied in the direction of the unstable eigenvectors and the correction is considered successful if (after 5 orbital revolutions) the error in position and velocity is smaller than 75,000 km and 15 m/s, respectively. (Similar "correctability" metrics have been used [5], and will be considered in the final version of this paper). Details for the case represented by the black marker in Figure 2b are given in plots c and d, showing how the lightness number settles around the nominal value of 0.0363 and how the orbit is recovered. It is clear from these initial results that the heliogyro can correct for significantly larger injection errors in position and velocity than a flat sail (about an order of magnitude in Fig. 2).

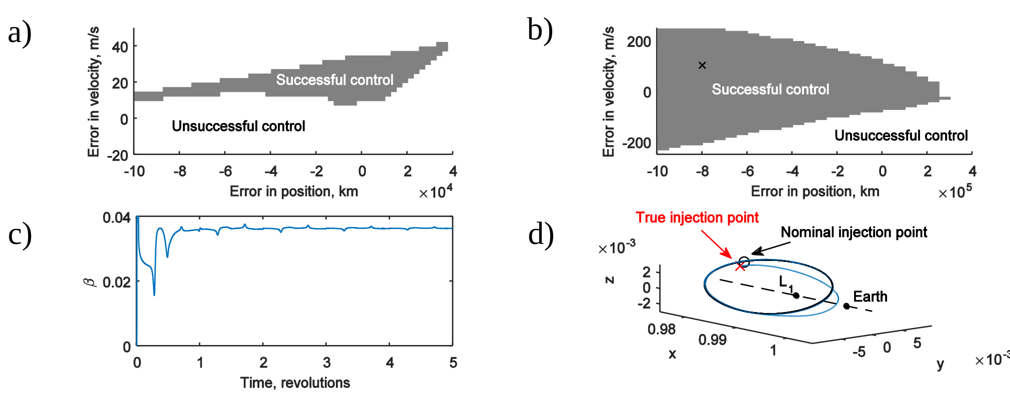

Figure 2 Solar sail halo orbit orbital control. a-b) Recoverable injection error for a flat sail (a) and heliogyro (b). c-d) Detailed results for black marker in plot b).

References

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