H^2-Reversal Trajectory: a New Mission Application for High-Performance Solar Sails

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ABSTRACT

The aim of this paper is to quantify the performance of a flat solar sail to perform a double angular momentum reversal manoeuver and produce a new class of two-dimensional non-Keplerian orbits. The problem is addressed in an optimal formulation and using a parametric approach. Two main difficulties must be properly taken into account. On one side the sail must perform a rapid reorientation maneuver when it approaches the Sun. It is shown by simulation that this assumption is reasonable. In second place the corresponding trajectories require high performance solar sails, that is, sails with a characteristic acceleration greater than $3\,\mathrm{mm/s^2}$. Such a value, although well beyond the currently available sail performance, is comparable (or even lower) to that required by the original H-reversal maneuvers.

1 INTRODUCTION

The use of propellantless propulsion systems, like a solar sail, is known to be particularly attractive for those missions requiring large changes in orbital energy. In fact the theoretical availability of a low propulsive thrust for an unlimited time period, makes accessible a class of missions that would be otherwise unfeasible through conventional propulsion systems (either chemical or electrical).

An important practical example is constituted by missions that use the motion reversal [1] to achieve an exotic non-Keplerian trajectory. The "H-reversal" concept was introduced by Giovanni Vulpetti in 1996 [2, 3] for a mission towards the boundary of the Solar System. Until now, the "H-reversal" mode has been proposed only occasionally in Solar System escape trajectories, as an alternative to the well known Sun gravity assist maneuver introduced by Sauer [4].

In this paper a reappraisal of the H-reversal concept is proposed to produce of a new class of two-dimensional non-Keplerian orbits. In particular, a closed trajectory in the ecliptic plane, which does not contain the Sun (the primary focus), can be obtained with the aid of a double reversal manoeuver. Accordingly, the corresponding orbit will be referred to as H^2-reversal trajectory (H2RT).

These new orbits exhibit some interesting characteristics, like, for example, a synchronicity with the Earth's orbit. They also guarantee near-heliostationary conditions on the two aphelion points. As such, H2RTs are well suited for investigating various deep space characteristics or for an in-situ analysis of the interstellar dust.

2 TRAJECTORY DESIGN

In the context of solar sail based trajectories a non-Keplerian orbit usually corresponds to a closed trajectory, often of circular shape, whose orbital plane does not pass through the primary focus (such a trajectory is referred to as displaced orbit [5]), or whose orbital period does not obey Kepler's third law. Non-Keplerian orbits guarantee feasible solutions to a class of unusual mission scenarios. In particular, these orbits are well suited for scientific missions characterized by onerous requirements in terms of ΔV demand, such as the study of the Sun's polar regions [5, 6, 7] or the generation of artificial Lagrange points [8, 9].

The fundamental idea of a H2RT is to look for a closed trajectory, with a prescribed orbital period and belonging to the ecliptic plane, that does not contain the Sun. Such a trajectory, other than demonstrating the potentialities offered by a solar sail in the fulfilment of high energy orbits, was conceived as a possible application of the H-reversal concept originally proposed by Vulpetti [2, 3]. In addition, a H2RT presents some interesting features that will be now further investigated.

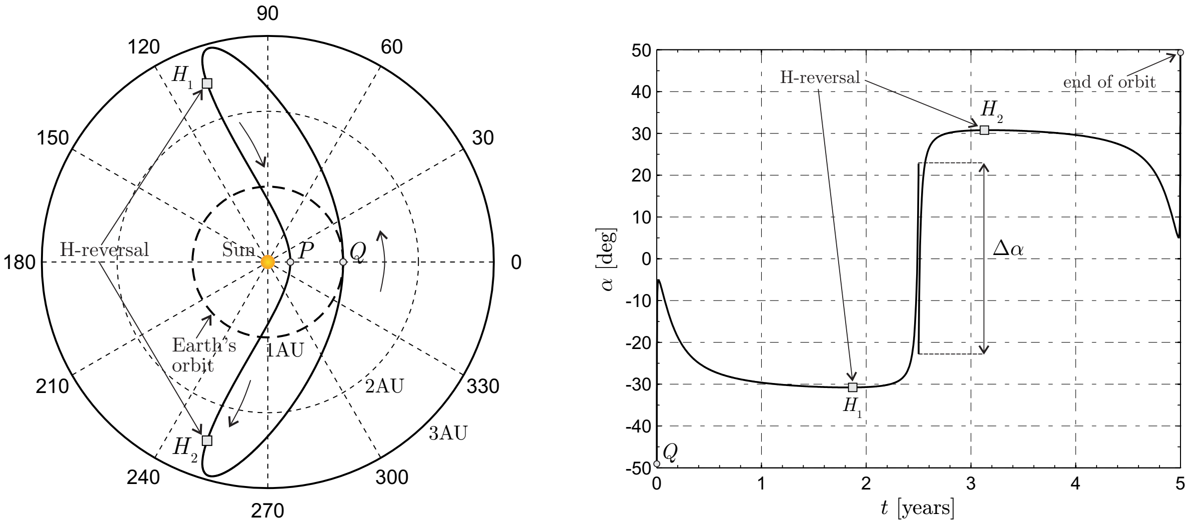
2.1 H2RT Properties

Consider a flat solar sail [10] whose motion belongs to the ecliptic plane. Two force models are considered, an ideal (perfectly reflecting) model and an optical model with no degradation effect [11]. The force coefficients for the optical model are chosen in accordance to Ref. [10]. The orientation of the sail, and so the force vector, is described through the cone angle α, that is, the angle between the sun-line and the direction of the sail acceleration.

The solar sail characteristic acceleration $a_\oplus$ that produces a H2RT is the output of a suitable optimization process. More precisely, $a_\oplus$ is the minimum characteristic acceleration necessary to accomplish a non-Keplerian trajectory subject to the following assumptions/constraints, see Fig. 1(a). 1) The trajectory belongs to the ecliptic plane, 2) its orbital period is prescribed and equal to Δt, 3) it is tangent at Q to the Earth's heliocentric orbit (which, by assumption, is circular with radius $1\,\mathrm{AU}$), 4) its perihelion P is at a (given) distance r_P from the Sun, 5) the absolute sailcraft velocity at both P and Q coincides with the local circular velocity, and 6) the trajectory is symmetric with respect to the segment PQ, whose prolongation passes through the Sun's center-of-mass. Some of the above assumptions, such as, for example, the previous 3, 5 and 6, are somewhat arbitrary and can be removed without affecting the H2RT concept. In particular, assumptions 3 and 5 correspond to a H2RT at the end of an Earth's escape maneuver with zero hyperbolic excess velocity. If the assumption 5 regarding the velocity at Q is relaxed, the new mission scenario corresponds to an escape phase with a nonzero hyperbolic excess velocity calculated with respect to the Earth. If, instead, the assumption 5 regarding the velocity P is relaxed, the optimization process converges to the optimal value of the circumferential sailcraft velocity at P (recall that the radial velocity component at perihelion is zero by definition). Finally note that assumption 6 is useful to simplify the trajectory analysis. In fact, the problem symmetry allows one to optimize only one half of the trajectory and, therefore, to substantially reduce the simulation effort.

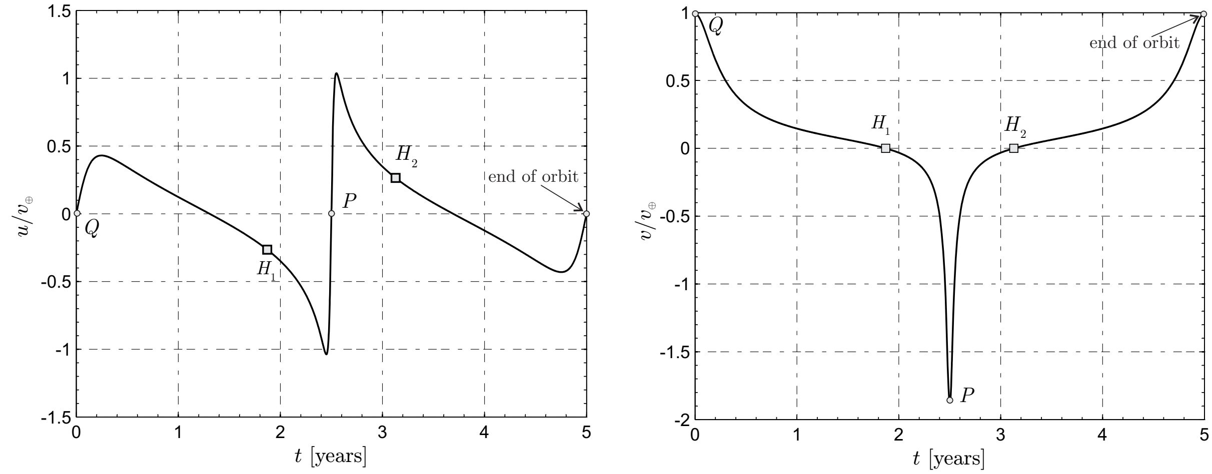
Figure 1(a), which represents a typical H2RT, shows the two points H_1 and H_2 where the sign variation of the angular momentum (that is, the H-reversal) takes place. Note that, due to the previous two-dimensional trajectory assumption, the sailcraft circumferential velocity is equal to zero at both H_1 and H_2. The trajectory part between Q and H_1 looks like that found by Vulpetti in Ref. [2]. However, unlike the approach in Ref. [2], in which the cone angle was maintained constant, in this study α is varied and is chosen to minimize the characteristic acceleration necessary to fulfil the trajectory (recall that according to assumption 2 the flight time Δt is given). The problem of minimizing $a_\oplus$ has been solved using an indirect approach, following the methodology described in Ref. [12].

The time variation of $\alpha \in [-\pi/2,\, \pi/2]$ is shown in Fig. 1(b). Apart from the (obvious) symmetry in the function $\alpha = \alpha(t)$, Fig. 1(b) shows a discontinuity in the cone angle at $t = \Delta t/2$, that is, at perihelion. Such a discontinuity, with a magnitude equal to $\Delta\alpha$, is due to the fact that the link between the two half trajectories



(a) Sailcraft optimal trajectory.

(b) Sail cone angle α vs. time t.



(c) Radial velocity u vs. time t.

(d) Circumferential velocity v vs. time t.

Figure 1: H^2-reversal trajectory for a flat solar sail with an optical force model, aphelion radius $r_P = 0.3\,\mathrm{AU}$, orbital period $\Delta t = 5\,\mathrm{years}$, and a characteristic acceleration $a_\oplus = 3.708\,\mathrm{mm/s^2}$.

is obtained by enforcing the continuity of both spacecraft position (in terms of distance r and anomaly θ) and velocity components (radial u and circumferential v). Because the control variable α directly affects the radial and circumferential acceleration, the presence of a discontinuity in the cone angle could in principle imply a corresponding discontinuity in $\dot{u}$ and $\dot{v}$ at perihelion. This is confirmed by Figs. 1(c) and 1(d), in which the two velocity components are shown in dimensionless form by dividing their value by Earth's orbital velocity $v_\oplus \triangleq \sqrt{\mu_\odot / r_\oplus} \simeq 29.785\,\mathrm{km/s}$, where $\mu_\odot$ is the Sun's gravitational parameter.

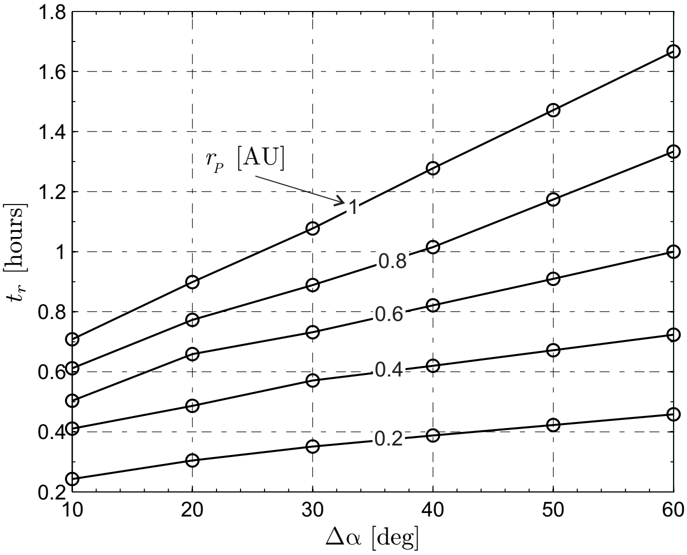
2.2 Near-Perihelion Sail attitude manoeuver

The discontinuity $\Delta\alpha$ of the cone angle at the orbital perihelion (see Fig. 1(b)) corresponds to a rapid solar sail reorientation maneuver that must be performed in a finite time interval. It is important to simulate the feasibility of such a maneuver in order to verify the assumption of nearly-impulsive maneuver.

The attitude control of a solar sail is a very demanding task for missions in which the sail orientation must be largely varied in a short time using the solar radiation pressure only. Many different concepts for attitude control actuators have been studied in the literature [13, 14] for different mission types. In case of high performance applications, the sliding masses concept seems to be the most attractive solution. Accordingly, this kind of actuator was assumed in the simulations. It consists of two ballast masses moving along the booms of a square solar sail, that are used to change the position of the composite center of mass of the system with respect to the sail center of pressure. The attitude dynamics of such a system was studied in detail by Wie and Murphy [15] to which the interested reader is referred.

The selection and design of the control system is a key point to obtain a high sail performance during the reorientation maneuvers. In this paper, a two degrees of freedom approach, which combines a feed-forward and a feedback part, has been adopted. Such a solution is able to manage the fast response of the feed-forward control system with the feedback ability of rejecting unpredicted disturbances. Further details about the controller's architecture can be found in Ref. [16]. In addition, such an approach allows one to completely characterize the system behavior under the effects of disturbances in the feedback section, while the desired behavior is entirely described in the feed-forward part of the controller.

Under the assumption of ideal force model and no offset between the center of pressure and the geometrical center of the sail's reflective area, the numerical simulations have shown that it is possible to accomplish a $\Delta\alpha = 60\,\mathrm{deg}$ around the direction of the incoming radiation at a distance of $0.2\,\mathrm{AU}$ in about $t_r \simeq 27.5$ minutes. This value is consistent with the assumption of instantaneous maneuver, which was made during the trajectory optimization. Figure 2 shows the characteristic times of reorientation maneuvers as a function of different distances from the Sun. As expected, the smaller the maneuver amplitude, the shorter is the time needed to complete the reorientation. In addition, the maneuver time clearly decreases when the reorientation is closer to the Sun.

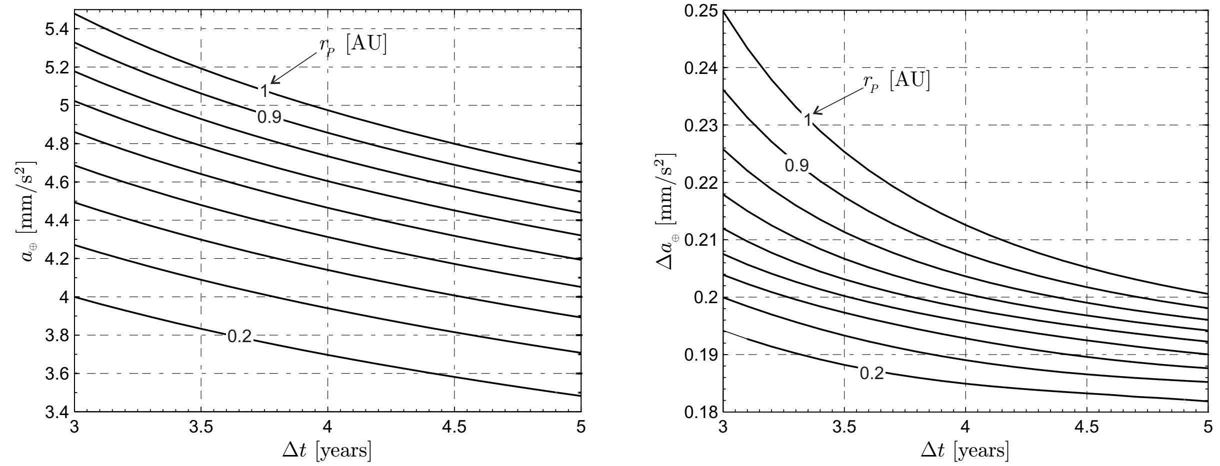


Geometry	
Sail size	40 m
Boom length	28 m
Sail area	1200 m^2
Masses	
Sail mass	6 kg
Boom tip mass (each)	1 kg
Booms mass	7 kg
Central assembly	8 kg
ACS	3 kg
Payload	7 kg
Bus mass	150 kg
Total mass	185 kg
Principal Inertia	
Ix (roll)	4340 kg m^2
Iy (pitch)	2171 kg m^2
Iz (yaw)	2171 kg m^2

Figure 2: Near-Perihelion Attitude maneuver performance (sailcraft data from Ref. [15]).

2.3 Parametric study

A family of different H2RTs has been obtained by varying the perihelion radius in the range $r_P \in [0.2,\ 1]\,\mathrm{AU}$ and the orbital period in the range $\Delta t \in [3,\ 5]\,\mathrm{years}$ using either an ideal or an optical force model. The minimum value of $a_\oplus$ as a function of the two above parameters is shown in Fig. 3(a) for a solar sail with an optical force model. A H2RT requires the use of a high performance solar sail, that is, greater than $3.5\,\mathrm{mm/s^2}$. These values are in line with the performance requirements obtained by Vulpetti during his studies of H-reversal trajectories [2, 3]. An ideal solar sail requires a slightly lower performance, but the



(a) Characteristic acceleration as a function of r_P and Δt for a sailcraft with an optical force model.

(b) Variation (decrease) in $a_\oplus$ passing from an optical to an ideal force model.

Figure 3: Tradeoff performance study for different orbital periods.

decrease of characteristic acceleration necessary for the mission does not exceed $0.25\,\mathrm{mm/s^2}$, as shown in Fig. 3(b).

3 CONCLUSIONS

A new concept of non-Keplerian orbits with double angular momentum reversal has been introduced and discussed. Assuming that the orbital period is given along with the perihelion distance, and that the trajectory is symmetrically shaped with respect to the Sun-perihelion line, the minimum value of the characteristic acceleration necessary to complete the trajectory was found by solving an optimal control problem. The H^2-reversal trajectories exhibit a "bean-like" shape. Is has been shown that the sail is required to perform a nearly instantaneous reorientation maneuver at perihelion. The simulations prove that such a reorientation may take place in a few dozen minutes. In addition, the H^2-reversal trajectories require high performance solar sails, that is, sails with a characteristic acceleration greater than $3\,\mathrm{mm/s^2}$. Such a value, although well beyond the currently available sail performance, is comparable (or even lower) to that required by the original H-reversal maneuvers. Accordingly, this new class of trajectories represents an intriguing perspective for a future employment of high performance solar sails.

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