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Interplanetary parking method and its applications ☆

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A B S T R A C T

In this study, we propose a flexible orbit design method that enables anytime launch of a deep-space explorer. Based on the Electric Delta-V Earth Gravity Assist (EDV-EGA) scheme, (Kawaguchi, 2001, 2002) [1,2] the proposed interplanetary parking method enables the explorer to make an Earth return orbit at an arbitrary time-of-flight by connecting to the minimum energy transfer orbit to destination. While the time-of-flight of the transfer orbit is fixed, the Earth return orbit with the arbitrary time-of-flight significantly alleviates the severe launch window constraint in interplanetary missions. We offer two case examples of applications of this method. The first is the dual launch of a Mars explorer with a geostationary transfer orbit (GTO) mission payload. The second is a dual launch of Mars and Venus explorers by a single launch vehicle. In the first case, we assume that a small Mars explorer is dual launched into a GTO for a secondary payload. With this assumption, the secondary payload cannot choose a desirable launch epoch for itself because the launch window to Mars is very narrow and opens only every 2 years. Moreover, the GTO, whose orbital period is approximately 10 h, repeatedly passes through the Van Allen belt wherein the radiation level is very high. Hence, the explorer has to escape from the GTO as soon as possible. However, our proposed interplanetary parking method enables the explorer to reach the destination within the limits of a practical mass resource, regardless of the Earth departure epoch. In the second case, the explorers traveling to different destinations, i.e., Mars and Venus, are dual launched by a single launch vehicle, and they fly to each destination via an interplanetary parking orbit. Our proposed method will widen the scope of opportunity for interplanetary missions.
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1. Introduction

When an interplanetary mission such as a Mars exploration mission is designed, the launch window is severely constrained. A Hohmann transfer orbit, a minimum energy transfer orbit, is one option; however, the opportunity for a Hohmann transfer comes only every synodic period, i.e., every 2 years in the Earth-to-Mars transfer case. Moreover, the required launch energy, C_3, which is the square of the V-infinity at Earth departure, steeply increases as the departure epoch moves from the Hohmann transfer injection point, as shown in Fig. 1, which is the "pork-chop" plot of the C_3 departure energies. Practically speaking, the launch window for Mars missions is approximately 1 or 2 weeks every 2 years.

Considering these circumstances, this study introduces a new type of orbit design method for flexible deep-space exploration, utilizing dual launch opportunities. The

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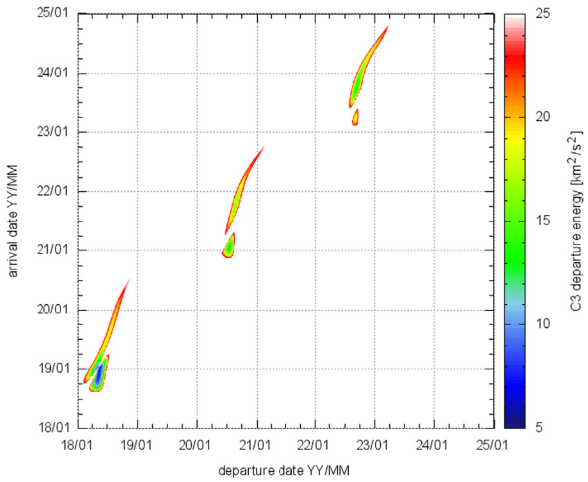

Fig. 1. C_3 departure energies for Mars from 2018 to 2024.

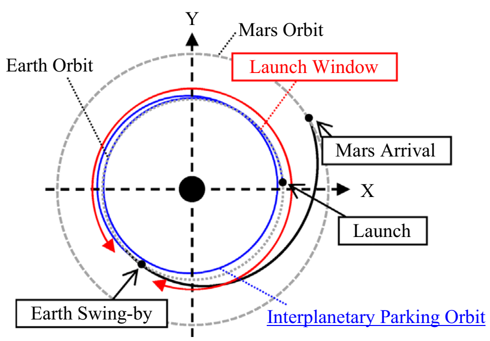

Fig. 2. Diagram of interplanetary parking method. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

proposed method, known as the interplanetary parking method, enables anytime launch of deep-space explorers. The basic concept of the interplanetary parking method is the Electric Delta-V Earth Gravity Assist (EDV-EGA) scheme, [1,2] which was demonstrated by the Japanese asteroid explorer Hayabusa [4,10]. The major objective of this method is to design an EDV-EGA trajectory with an arbitrary time-of-flight, which serves to widen the launch window. Fig. 2 shows an orbital diagram of this concept. The blue orbit in the figure is the interplanetary parking orbit, and the red line shows the expanded launch window associated with this method.

To demonstrate our proposed method, in this study, we describe two dual launch simulations. First is the dual launch of a Mars explorer with a geostationary transfer orbit (GTO) mission payload. Second is the dual launch of Mars and Venus explorers.

In the former case, we assume that a Mars explorer is dual launched into a GTO together with a primary payload. Then a delta-V is applied at the perigee of the GTO, which injects the explorer into an interplanetary orbit whose orbital energy, C_3, is almost zero. After escaping the Earth, the on-board electric propulsion system accelerates the explorer to increase the V-infinity at the Earth re-encounter point, which enables the explorer to inject itself into a transfer orbit to Mars after the Earth swing-by. In this scenario, the secondary payload, i.e., the explorer, cannot choose a desirable launch epoch; however, our proposed method enables the explorer to transfer to Mars via an interplanetary parking orbit.

In the second case, explorers traveling to different deep-space destinations, i.e., Mars and Venus, are dual launched by a single launch vehicle. While the launch windows to Mars and Venus are different, the interplanetary parking method sends each explorer to its destination via interplanetary parking orbits.

The interplanetary parking method will enhance the flexibility of deep-space mission designs.

2. Interplanetary parking method

2.1. Theory

The basic idea of the interplanetary parking method is expressed by the following simple equation:

$$t_{DEP} = t_{SB} - T_{PARK} \tag{1}$$

where t_{SB} is the Earth swing-by epoch to be injected into the transfer orbit to the destination, t_{DEP} is the Earth departure epoch, and T_{PARK} is the time-of-flight during the interplanetary parking orbit. As Eq. (1) indicates, the variation of T_{PARK} determines the width of the t_{DEP} variation, which is the launch window.

The theory of the interplanetary parking method begins with Hill's equation, which describes the relative motion around a circular orbit, as shown in the following:

$$\begin{aligned} &\ddot{x} - 2n\dot{y} - 3n^2 x = a_x \\ &\ddot{y} + 2n\dot{x} = a_y \end{aligned} \tag{2}$$

where a_x and a_y are the components of the acceleration vector in the Hill coordinate, and n is the mean motion of Earth. For simplicity, here we discuss only in-plane motion. Note that the spacecraft departs from Earth, i.e., the origin of the Hill coordinate. Hence, $x_0 = y_0 = 0$.

The objective of the interplanetary parking method is to find a control law of the acceleration vector, wherein the spacecraft returns to Earth after the designated time-of-flight, T_{PARK}. Assuming that the acceleration vector rotates at some rate k, starting from an initial phase angle θ_0, the acceleration vector may be described as follows:

$$\begin{aligned} &a_x = a\ \cos(\theta_0 - kt) \\ &a_y = a\ \sin(\theta_0 - kt) \end{aligned} \tag{3}$$

where a is the magnitude of the acceleration and t is the time from Earth departure.

To solve the in-homogenous, second-order differential equations in Eq. (2), we use a Laplace transform. The Laplace transform of a function $f(t)$ is defined as follows:

$$F(s) = L(f(t)) = \int_0^\infty e^{-st} f(t)dt \tag{4}$$

where s is a complex number. The results of the Laplace transform of Eq. (2) are described as the follows;

$$\begin{aligned} &L(x) = P_1 + P_2 + P_3 + P_4 \\ &L(y) = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6 \end{aligned} \tag{5}$$

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