Multi-objective design optimization of DESTINY$^+$ spiral trajectory in consideration of the diversity of launch date and time

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DESTINY$^+$ is a small-sized high-performance deep space vehicle proposed by ISAS/JAXA. To accomplish the mission, it is necessary to optimize the spiral trajectory of DESTINY$^+$ to minimize the time of flight, to minimize the fuel consumption and to minimize the maximum eclipse period. In this study, multiobjective design optimization of the spiral trajectory was conducted by using multiobjective Evolutionary Algorithms to improve the performance while expanding the launch date and time. The present results and problems are discussed in the paper.

打ち上げ日時の多様性を考慮した DESTINY$^+$スパイラル軌道の多目的設計最適化

DESTINY$^+$は，JAXA が開発を進める深宇宙探査技術実証機である．ミッションを達成するためには，DESTINY$^+$が地球から月までのフェーズでスパイラル軌道を最適化する必要がある.本研究では,進化アルゴリズムを使用してスパイラル軌道の多目的設計最適化を実施し,DESTINY$^+$打ち上げ日時の拡大を目指した．現在の結果と問題点について示す.

1. Introduction

DESTINY$^+$ is “Demonstration and Experiment of Space Technology for INterplanetary voYage, Phaethon fLyby and dUSt analysis.” A mission of DESTINY$^+$ is to explore the asteroid Phaethon by launching a small satellite by Epsilon rocket. Table 1 shows Mission profile of DESTINY$^+$ [1]. In the first phase, DESTINY$^+$ is injected into an extended elliptical orbit launched by the Epsilon rocket. The second phase is many revolution transfers (spiral trajectory) to raise the apogee altitude to the lunar trajectory nearby. In the third phase, DESTINY$^+$ escapes out of the Earth sphere of influence by the multiple lunar swingby toward the asteroid Phaethon. In the interplanetary cruise, DESTINY$^+$ gets transferred to the asteroid Phaethon for flyby observation. After that, DESTINY$^+$ is planned to head for another asteroid as the extended mission [2].

In this study, it is assumed that the launch period of DESTINY$^+$ will be from April 1, 2024 to March 31, 2025, and performed the design optimization of spiral trajectory. Table 2 shows Design parameters, Constraints and Objective function of Evolutionary Algorithms used in this study [3]. In the previous DESYINY$^+$ trajectory design, the launch date and time candidates are limited to around 0 to 9 o'clock in October to December 2024 when design optimization of the spiral trajectory is conducted. The reason is that the existing multiobjective Evolutionary Algorithms [4,5] consider the diversity in the objective function space, but not in the design variable space. Thus, it is difficult to obtain a variety of the launch date and time candidates (the design variable space). However, when the range of launch date and time were divided into months to reduce the design variable space, it was found that many solutions existed in April-May 2024, which was difficult to be obtained in the one-year range. It is not realistic to conduct many optimizations by dividing the design space because it takes too much time. Since the launch date and time may be changed due to the development status of DESYINY$^+$ or weather conditions, it is needed to obtain a wide range of the launch date and time candidates to increase the flexibility of DESTINY$^+$ operation. Therefore, in this study, the crossover and mutation parameters of the multiobjective Evolutionary Algorithms are changed for the optimization problem of DESTINY$^+$ trajectory design. The purpose of this study is to investigate the effect of each parameter on the diversity of the resulting solution in the design variable space in terms of the launch date and time.

Table 1. Mission profile of DESTINY$^+$

	Phase
1	Orbit injection into an extended elliptical orbit launched by the Epsilon rocket
2	Many revolution transfers by low thrust propulsion system to the lunar orbit nearby
3	Connect to the transfer trajectory for Asteroid Phaethon by using the moon swing-by
4	Transfer to Asteroid Phaeton
5	Flyby observation of Phaethon

Table 2. Design parameters, Constraints and Objective function

<table>
<tr><td>Design parameter (32)</td><td>

- Launch date
- Launch time

Ion engine injection on the node

<table>
<tr><td>node</td><td>Ion engine</td><td>Thrust parameter</td></tr>
<tr><td>1-6</td><td>All thrust
[Initial trajectory]</td><td></td></tr>
<tr><td>7-16</td><td>Thrust
and
coasting</td><td>● $\Delta L_{p,i}$ = angular distance of the thrust arc near the perigee on the i^{th} node.
● $\Delta L_{a,i}$ = angular distance of the thrust arc near the apogee on the i^{th} node.
● η_i = offset angle is the thrust profile.
10 nodes × ($\Delta L_{p,i}$, $\Delta L_{a,i}$, η_i) = 30</td></tr>
</table>

⇒Launch date + Launch time + 30 =32 (Design parameter)</td></tr>
<tr><td>Constraint (2)</td><td>1. The perigee altitude is 100km or more (do not plunge into the atmosphere).
2. The differences between point of intersection distance and terminal condition (= apogee altitude) with final orbit and the moon's path side are less than 0.1km.</td></tr>
<tr><td>Objective function (3)</td><td>1. To minimize the time of flight
2. To minimize the fuel consumption
3. To minimize the maximum eclipse period</td></tr>
</table>

2. Method

Trajectory design using a multiobjective Evolutionary Algorithm is considered because of multiobjective design optimization problem. In this study, CHEETAH/R and iSPM (interactive Scatter Plot Matrix) developed by ISAS are used [6]. CHEETAH/R is the tool for design exploration by multiobjective optimization calculations. iSPM is the tool for analyzing optimal solutions by visualizing multidimensional data. As a propagator to be executed in the multiobjective optimization for orbit integration, FABLE [7,8] by the averaging method is used. Table 3 shows the crossover and mutation of Evolutionary Algorithms [9]. In this study, it is used that SBX as crossover and Polynomial Mutation as mutation. Figures 1 and 2 show probability density of crossover and mutation [10,11]. The distribution index of crossover η_C has a direct effect in controlling the spread of offspring solutions. When η_C is small, the offspring are more likely to be generated far from the parent. Therefore, it is expected to search for various launch dates by calculating with a smaller η_C. On the other hand, the distribution index of mutation η_m is the parameter related to maintaining diversity in the population. η_m is that polynomial probability distribution is used to perturb solutions in a parent's vicinity. If η_m is large, the value of the disturbance added to the design variable of the child tends to be small. Thus, it is expected to search for a wide range of launch dates by increasing η_m. Table 4 shows default parameter values for CHEETAH/R.

Table 3. Crossover and mutation parameter

Crossover [SBX]	Crossover rate P_C	Probability of crossover
	The distribution index η_C	The spread of the offspring solutions with respect to the parent solutions
Mutation [PM]	Mutation rate P_m	Probability of mutation
	The distribution index η_m	Polynomial probability distribution to perturb solutions in a parent's vicinity

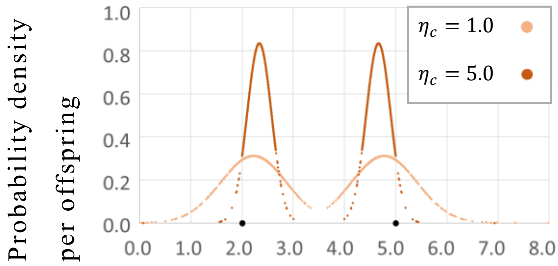


Fig. 1 The probability density function for creating offspring under an SBX-η_c operator

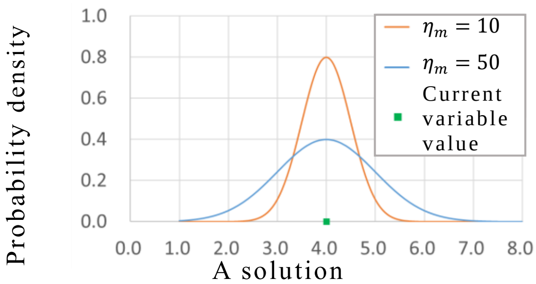


Fig. 2 The probability density function of creating a mutated child solution using polynomial mutation operator

Table 4. Parameter values for CHEETAH/R under reference condition

Population size		400
Number of generations		100
Crossover [SBX]	Rate P_c	1.0
	The distribution index η_c	5.0
Mutation [PM]	Rate P_m	1/32
	The distribution index η_m	10

3. Results

Feasible solutions that satisfy the constraints are obtained by performing evolutionary computations. The maximum eclipse time is desired to be within 1.5 hours to design the trajectory of DESTINY$^+$. Therefore, the solutions with the maximum eclipse time within 1.5 hours are extracted from feasible solutions and are called "Preferred solution" in this study.

The optimization was firstly conducted under the conditions in Table 4, and Preferred solutions are plotted in Fig. 3. Figure 4 shows an example of the calculated orbit design. From Fig. 3, it can be seen that Preferred solutions are biased around 0 to 9 o'clock in October to December 2024 for the reference calculation conditions. The distribution indices of crossover and mutations are changed to obtain a wide range of launch date and time over one-year period. Figure 5 shows results for the reference calculation conditions (η_c =5.0, η_m =10). Figure 6 shows results for η_c =1.0, η_m =10, and Fig. 7 shows results for η_c =5.0, η_m=50.

From Fig. 6, it can be seen that the diversity of launch date and time can be obtained when η_c of SBX is small. However, when compared in the objective function space, the improvement of objective functions is degraded. From Fig. 7, it is observed that the diversity of launch date is accomplished when η_m of Polynomial Mutation is large. Additionally, there does not seem to be a significant effect on the search in objective function space.

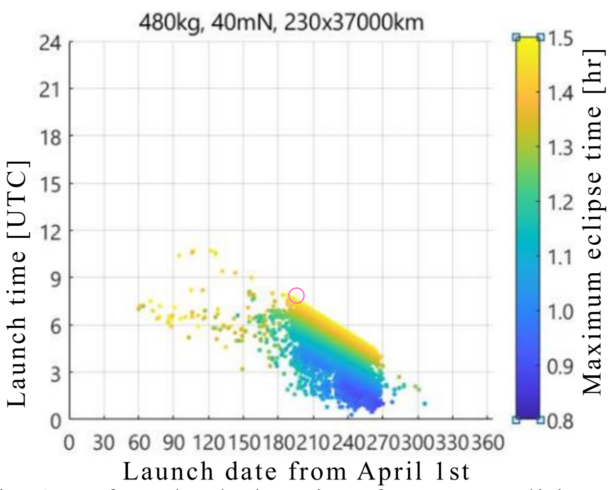


Fig. 3 Preferred solutions in reference condition

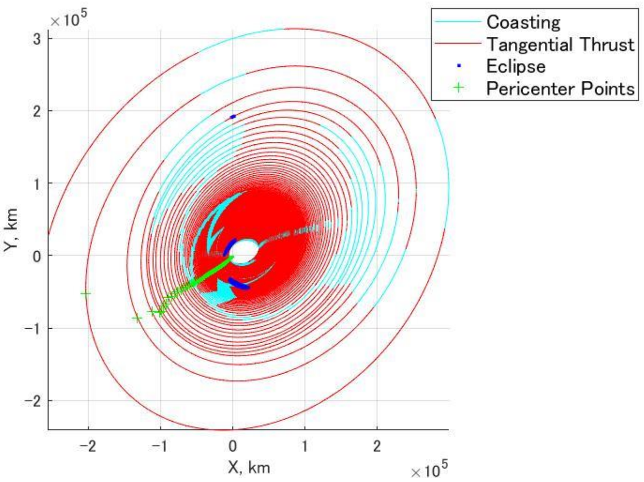
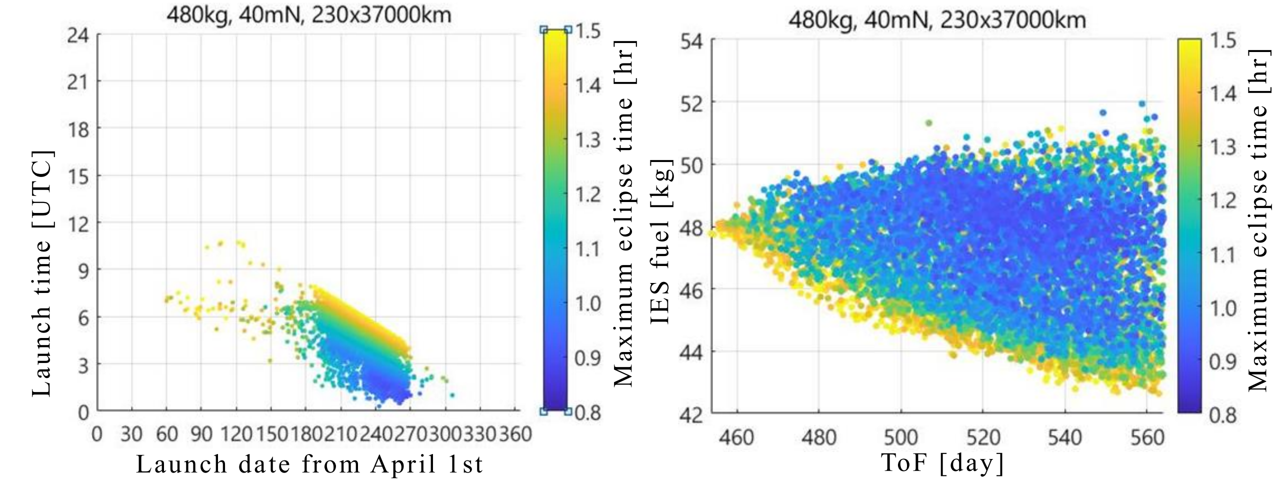
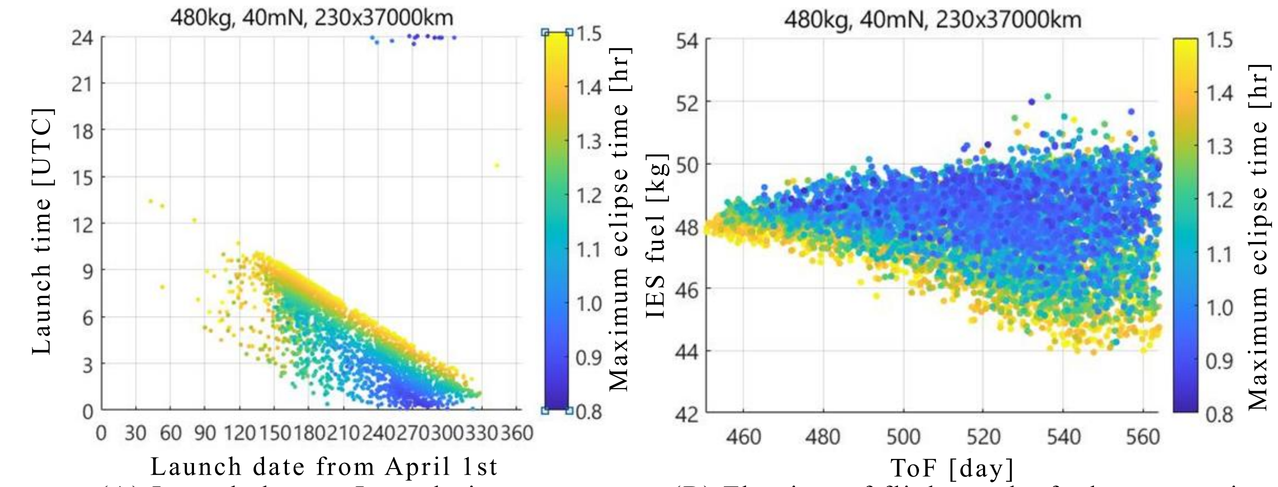


Fig.4 An example of the calculated orbit design



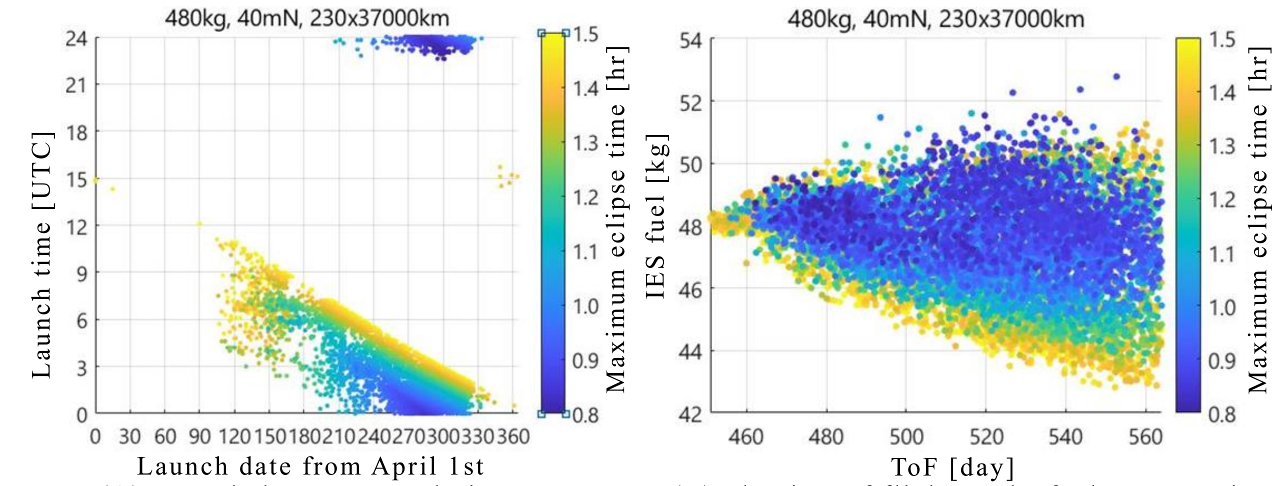
(A) Launch date vs Launch time (Same as Fig. 3) (B) The time of flight vs the fuel consumption of electric propulsion

Fig.5 Results for the reference calculation conditions (η_c =5.0, η_m=10).



(A) Launch date vs Launch time (B) The time of flight vs the fuel consumption of electric propulsion

Fig.6 Results for η_c =1.0, η_m=10



(A) Launch date vs Launch time (B) The time of flight vs the fuel consumption of electric propulsion

Fig.7 Results for η_c =5.0, η_m=50

4. Conclusions

Multiobjective design optimization of the spiral trajectory is conducted by using Evolutionary Algorithms. For the optimization problem of DESTINY$^+$ trajectory design, it is investigated the effect of the parameters of the multiobjective Evolutionary Algorithms on the diversity of solutions in the design variable space (the launch date and time). Through this study, it is found that it is difficult to obtain sufficient diversity in the launch date by simply changing the distribution index of crossover and mutation. It is necessary to review the handling of the objective function and constraints, and consider the method suitable for DESTINY$^+$.

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