TRAJECTORY DESIGN FROM THE EARTH TO THE MOON USING THE MULTI-OBJECTIVE OPTIMIZATION FOR DESTINY MISSION

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Abstract: *Multi-objective evolutionary computation (MOEC) is applied to the mission design for DESTINY mission, whose spacecraft will go to the moon by the ion engine from the large ellipse orbit around the Earth. This approach revealed some important design knowledge such as tradeoff information among minimization of the operation time of ion engine, minimization of the transfer time to the Moon, and minimization of the transit time under 20000 km altitude. This study also shows possibility of simultaneous design of trajectory and spacecraft.*

Keywords: *DESTINY, Mission Design, Multi-objective optimization, Non-dominated solution*

1 Introduction

Recently, the DESTINY (Demonstration and Space Technology for INterplanetary voYage) mission, which will be launched by the third Japanese next-generation solid propellant rocket (Epsilon rocket) around 2017 [1] has been studied in JAXA (Japan Aerospace Exploration Agency). In the DESTINY mission, the spacecraft will go to the moon by the ion engine from the large ellipse orbit around the Earth. Afterward, by using the lunar swing-by, the spacecraft will transfer to the periodic orbit in the vicinity of the Sun- Earth L2 libration point (Halo orbit) as shown in Fig. 1. This study focuses on the transfer trajectories from the Earth to the Moon.

After the spacecraft is put into the elliptical orbit by using the Epsilon rocket, the orbital energy is increased by the high specific ion engine to reach the moon. During this phase, the trajectory of spacecraft is spiral, thus the degradation of the solar array panel arising from going through the radiation region (the Van Allen belt) many times should be reduced. Moreover, the amount of use of propellant (the operation time of ion engine) to increase the apogee altitude should be reduced. Furthermore, the spacecraft should reach the moon in less time. To solve this kind of complicated mission design problem evaluating the multi-objective, in this study we utilize a multi-objective evolutionary computation (MOEC) because the MOEC is robust and make it possible to search for many solutions simultaneously and efficiently with parallel computation.

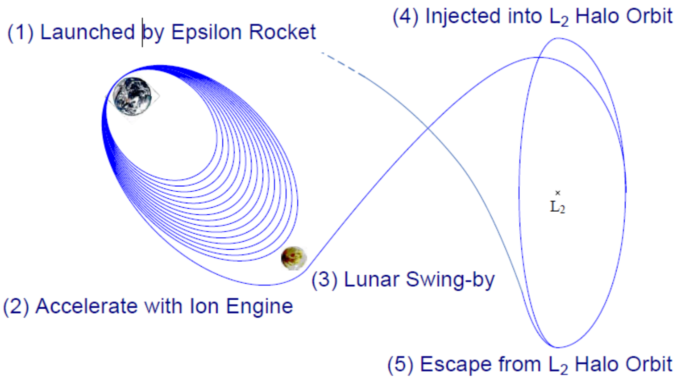


Figure 1. Profile of DESTINY Mission [2]

2. Multi-objective Evolutionary Computation (MOEC)

While a single objective design optimization problem may have a unique optimal solution, a multi-objective design optimization problem has a set of compromised solutions, largely known as Pareto-optimal solutions or non-dominated solutions. Each of these solutions is optimal in the sense that no other solutions in the search space are superior to it when all objectives are considered. Figure 2 shows an example of multi-objective design optimization problems, which minimizes two conflicting objectives f1 and f2. Gray-colored area is feasible region where solutions exist. This problem has innumerable Pareto-optimal (non-dominated) solutions such as solutions A, B, and C on the edge of the feasible region (called Pareto-front). These solutions are optimal in the sense that there is no better solution in both objectives. One cannot say which is better among these Pareto-optimal (non-dominated) solutions because improvement in one objective degrades another.

Multi-objective design exploration [3] (MODE) is a framework to extract essential knowledge of a multi-objective design optimization problem, such as tradeoff information between contradicting objectives and the effect of each design parameter on the objectives. In the framework of MODE, non-dominated solutions are obtained by multi-objective optimization using, for example, a multi-objective evolutionary computation[4], and important design knowledge is then extracted by analyzing objective function and design parameter values of the obtained non-dominated solutions using data mining approaches such as the self-organizing map and scattered plot matrix. Recently, MODE framework has been applied to a wide variety of design optimization problems including multi-disciplinary design of a regional-jet wing[5], aerodynamic design of a flapping airfoil[6], and aerodynamic design of a turbine blade for a rocket engine[7]. In this paper, MOEC is applied to design of the first stage (from launch to the Moon) for the DESTINY mission.

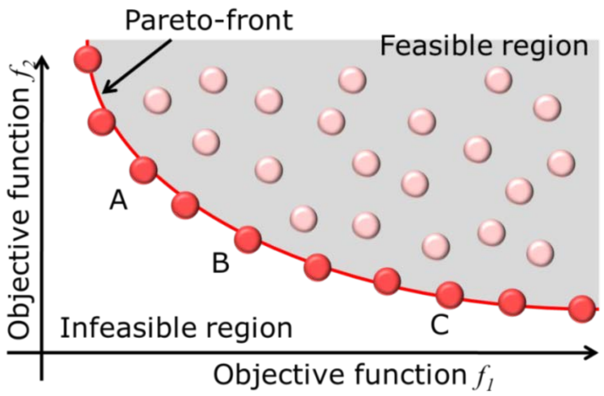


Figure 2. The Concept of Pareto-Optimality [8]

3. Setup for Multi-Objective Optimization Problem

3-1. Assumption

Here, the first stage of the trajectory for the DESTINY mission is designed. The launcher is assumed to be the third Japanese next-generation solid propellant rocket (Epsilon rocket) equipped with an upper stage, and spacecraft is put into the high elliptical orbit (see Table 1). The initial mass of the spacecraft is assumed to be 350 kg. The property of the ion engine (IES) is shown in Table 2. The accelerated direction with IES is tangential to the velocity of spacecraft. Concerning the dynamical mode, the ephemeris of the Earth, Moon and Sun are used in this study.

Table 1: Initial Orbit

Perigee altitude	150 km
Apogee altitude	290000 km
Longitude of ascending node	25 degree
Inclination	32 degree
Argument of perigee	124 degree
Mean anomaly	5 degree

Table 2: Property of the Ion Engine (IES)

Thrust	40 mN
Isp	3800 second

For the stop condition of the orbit propagation, when spacecraft approaches the Moon within 20000 km or the distance between the geocentric and the ascending/descending node becomes greater than 380000 km, the propagation is stopped. (The lunar encounter is not considered in this study)

3-2. Formulation of Design Multi-objective Optimization Problem

The objective functions, design parameters, and the IES constrains of the multi-objective optimization problem are as follows.

3-2-1. Objective function

1) Minimization of the transit time less than 20000 km altitude (h2e4km)
2) Minimization of the use of the ion engine (IES)
3) Minimization of the transfer time to the Moon (TOF)

The first objective means to minimize the degradation of the solar array panel. The second one is equivalent to the maximization of the payload weight.

3-2-2. Design parameter

a) Start date/time (2017/1/1 ~ 2018/1/1)
b) Range of the use of the IES for perigee up, 180 $\pm$(180-ϕ) deg (ϕ : 0 ~ 180 deg)
c) Range of the use of the IES for apogee up, 0 $\pm\theta$ deg (θ : 0 ~ 180 deg)
d) Change time switching control from the perigee-up to the apogee-up (90 ~ 365 day)

In this simulation, the launch date is selected between January 1, 2017 and January 1, 2018 because the third epsilon rocket is likely to be launched around that time. For the IES control, we would like to confirm where is the efficient range in a round of orbit for use the ion engine to increase perigee and apogee. Here, the range is defined using the true anomaly (see Fig. 3). Concerning the parameter (d), spacecraft should pass through the Van Allen belt as soon as possible to avoid degradation of solar array panel. Thus, the operation devotes to increase the perigee altitude first, and then concentrates on increasing of the apogee altitude after given parameter time (d).

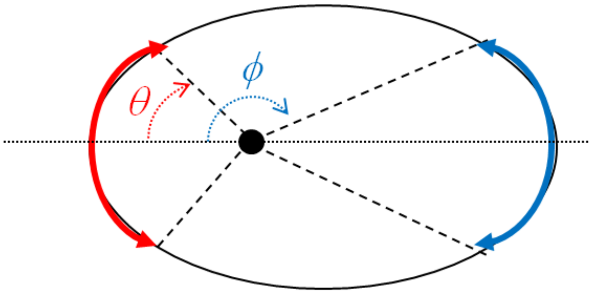


Figure 3. Definition of Range of True Anomaly for Perigee/Apogee Up

3-2-3. Constraint for use of IES

i) For a first month from launch
ii) Eclipse
iii) Duration of small solar incident to y-plane of spacecraft, α (0 ~ 90 deg)
iv) Duration of small solar incident to z-plane of spacecraft, β (0 ~ 90 deg)

In the DESTINY mission, the large-scale ion engine is used, thus a lot of power is needed for IES operation. Under the above-mentioned constraints, the IES is unusable (see Fig. 4). Duration of small power generation is not considered in this study.

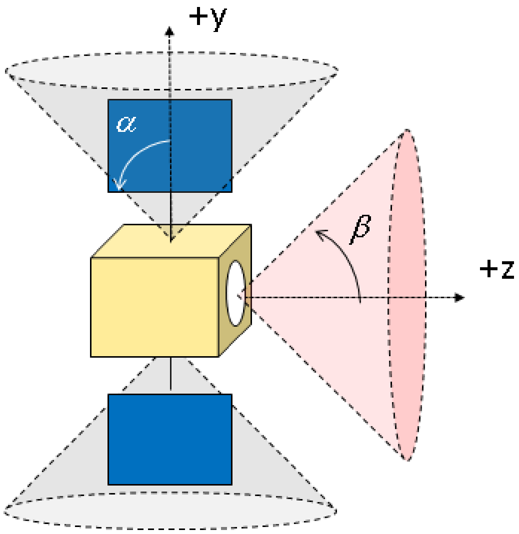


Figure 4. Constraint for Use of IES

4. Simulation Results

Multi-objective evolutionary computation (MOEC) was applied to solve the trajectory design optimization problem for DESTINY mission. The test case and parameters of MOEC are shown in Tables 3 and 4. Using a Core i7 computer (2.93 GHz), the computational time was about 39 hours. Moreover, the number of non-dominated solutions is 137 in the case of TOF < 1.5 years.

Figure 5 shows the scattar plot matrix of the objectives and design parameters with correlation coefficient in the case that the TOF is less than 550 days.Red point indicates the non-dominated solution, and blue point means the dominated solution.The figure revealed feasible design space. For instance, for the relation between the IES operation time and the TOF, the non-dominated solutions evolved in the direction of lower left. Moreover, the minimum values of the objectives were obtained; Transit time below 20000 km: is 1400 hours, the IES operation time is about 6900 hours and the time of flight is about 410 days. This figure also shows sensitivity of each design parameter to each design objective. For example, the true anomaly denoting the range for perigee up was distributed around 0 degree (namely, the IES was almost operated) maybe because of decreasing the transit time less than 20000 km.

Table 3: Test case

Solar incident angle, α	60 degree
Solar incident angle, β	0 degree

Table 4: MOEC parameters

Algorism	NSGA－II
Seed of pseudo random number	0.1
Number of island	1
Number of thread	8
Population size	300
Number of generation	200
Crossover probability	1.0
Mutation probability	0.05
Index of crossover distribution	5
Mutation distribution	10

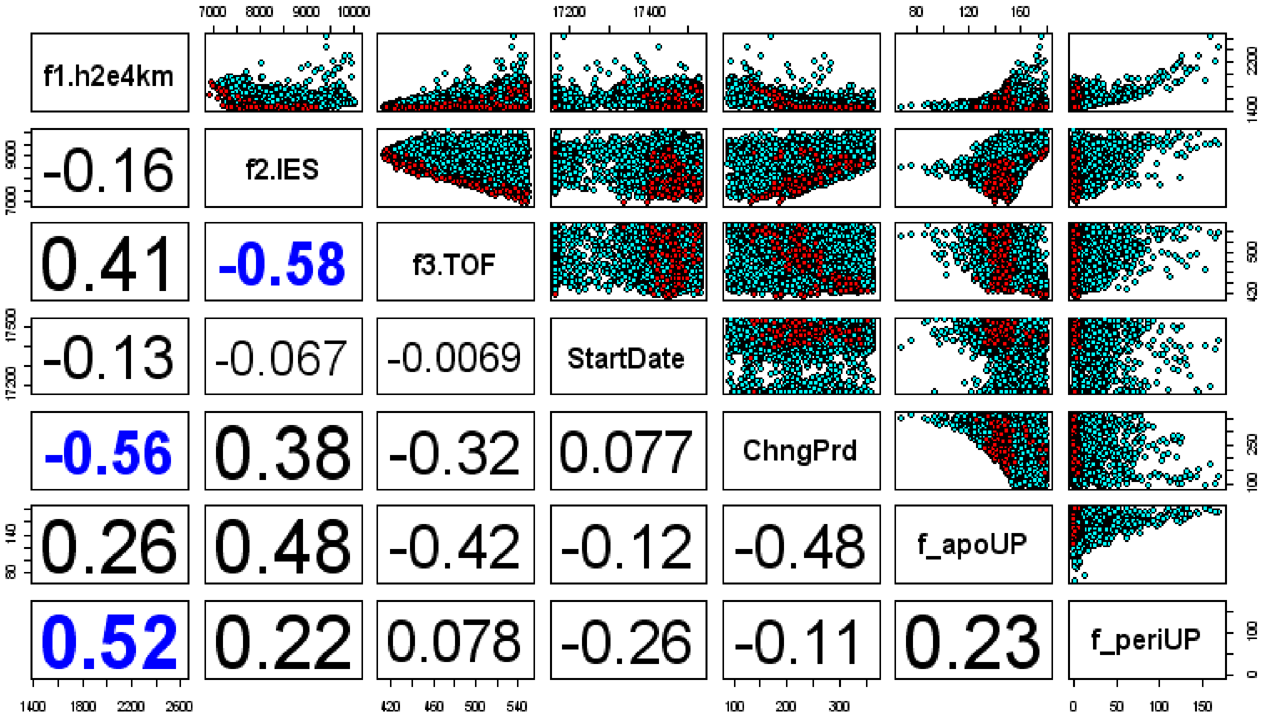
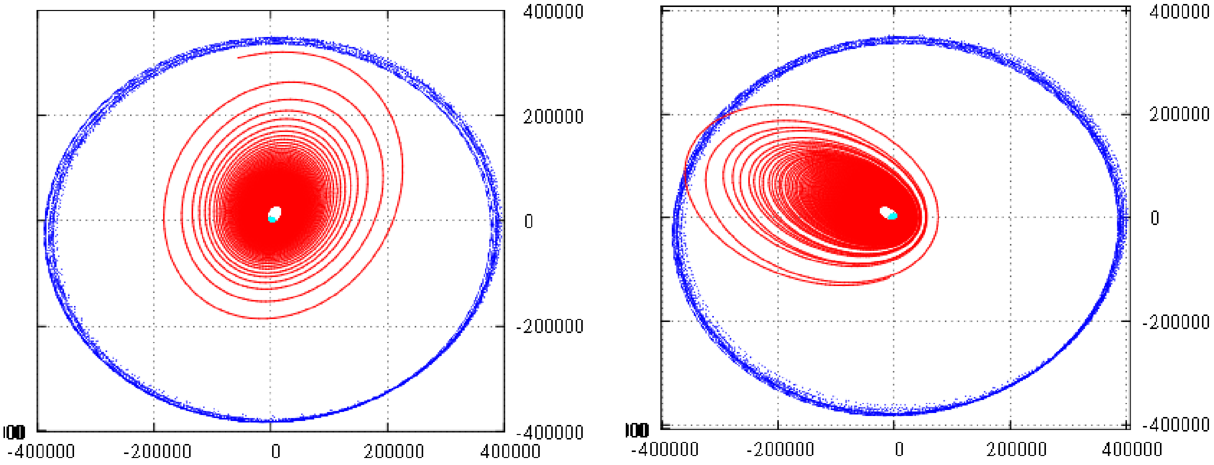


Figure 5. Scatter Plot Matrix of non-dominated solutions with Correlation Coefficients, extracting results on the condition that the TOF 550 days

Figure 6 shows the example trajectories in the geocentric equatorial plane for the minimum and maximum TOF cases, and Tables 5 and 6 show the input design parameters and results of objectives for these cases. The operation time of IES for minimum TOF case was about 1600 hours longer than that for the maximum TOF case. Thus, the revolution around the Earth decreased, and the TOF is shorter until reaching the stop condition of the propagation.



(a) Minimum TOF case (b) Maximum TOF case

Figure 6. Example Trajectories

Table 5: Example of Design parameters

	Minimum TOF case	Maximum TOF case
Start Date	2017/10/10 04:39:10	2017/12/27 04:39:42
Range for Peri UP	180 ± 175.1 deg ($\phi = 4.9$)	180 ± 179.6 deg ($\phi = 0.4$)
Range for Apo UP	0 ± 178.2 deg ($\theta = 178.2$)	0 ± 133.4 deg ($\theta = 133.4$)
Change period	231.2 days	226.0 days

Table 6: Example of Objectives

	Minimum TOF case	Maximum TOF case
Time below 20000km	1463 hours	1445 hours
IES oeration time	8971 hours	7315 hours
TOF	412.6 days	549.6 days
Revolution around Earth	486 times	528 times

6. Conclusions

The Multi-objective evolutionary Computation (MOEC) was applied to the trajectory design for DESTINY mission. This approach revealed some important design knowledge such as tradeoff information among minimization of the time of flight, minimization of the transit time under the Van Allen belt, and the minimization of the IES operation time. This study also showed possibility of simultaneous design of trajectory and spacecraft under MOEC framework.

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