Many-objective Optimization of Trajectory Design for DESTINY Mission

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Abstract. This work investigates a state of the art many-objective evolutionary algorithm to optimize and analyze the design trajectory of DESTINY, a new deep space exploration mission proposed in JAXA. We present initial results for 4 and 5 objectives formulations of the problem analyzing tradeoffs between objective functions and design variables.

1 Introduction

Recently, the design of low-thrust spacecraft propelled by ion engines has attracted special attention. In this work we optimize the design of the spacecraft trajectory of DESTINY, a deep space exploration mission that will test several new systems using a spacecraft equipped with ultra-lightweight solar panels and propelled by a low-thrust Ion engine. Currently, DESTINY's trajectory to the vicinity of the Moon is defined with up to six objective functions. We use AεSεH[3], a state of the art evolutionary many-objective optimizer, to find Pareto optimal sets of solutions and analyze the tradeoffs between variables and objectives. In this work, we solve problem formulations with four and five objectives. These results will serve to feedback the formulation of the problem and include additional variables, objectives and constraints.

2 The AεSεH Algorithm

Adaptive ε-Sampling and ε-Hood (AεSεH)[3] is an evolutionary many-objective algorithm that applies ε-dominance principles for survival and parent selection. Survival selection applies *ε-sampling* to select randomly non-dominated solutions in the population and eliminate solutions ε-dominated by the samples. Parent selection uses the *ε-hood creation* procedure to cluster solutions in objective space. Here, a randomly sampled solution from the surviving population and its ε-dominated solutions determine the neighborhood. Recombination takes place between two solutions randomly selected within the neighborhood.

The mapping function $\boldsymbol{f}(\boldsymbol{x}) \mapsto^{\epsilon} \boldsymbol{f}^{'}(\boldsymbol{x})$ used in [3] for ε-dominance in ε-sampling truncation and ε-hood creation is additive (ADD) , as follows

$$f_i^{'}(x) = f_i(x) + \varepsilon, \qquad i = 1, 2, \cdots, m \tag{1}$$

This mapping function works well when all objective functions have a similar scale. In this work we investigate three variants of the following mapping function for objective functions of different scale

$$f_i^{'}(x) = f_i(x) + (\varepsilon \times (\max_{y \in P} f_i(y) - g_i)), \qquad i = 1, 2, \cdots, m \tag{2}$$

where g_i is $\min_{y \in P} f_i(y)$ (MIN), $median_{y \in P} f_i(y)$ (MEDIAN), or $quartile1_{y \in P} f_i(y)$ (Q_1) assuming population P is in descending order in the i-th objective.

3 DESTINY Spacecraft Trajectory Design Problem

The DESTINY spacecraft will be launched in an Epsilon rocket, released into a low elliptical orbit, and will start a propagation stage to spiral away from Earth towards the Moon propelled by a low-thrust Ion Engine System (IES). This engine is solar-powered. Thus, it is important to reduce the time under the shadow of the Earth. Also, it must escape as soon as possible from the inner(5,000km) and outter(20,000km) radiation belts surrounding the Earth since radiation can damage the solar panels. **Table 1** and **Table 2** show design variables and objective functions of the problem. In problem formulations with less than 6 objectives $x_5 = 400$ kg.

Table 1. Design variables

x_1: Propagation start date
x_2: Switch date from perigee rising to apogee rising phase
x_3: Range for rising apogee
x_4: Range for rising perigee
x_5: Initial mass of the spacecraft

Table 2. Objective functions

f_1: Time to reach an altitude of 20000km
f_2: Operation time of the Ion Engine System
f_3: Time to reach the Moon
f_4: Maximum eclipse time
f_5: Time to reach an altitude of 5000km
f_6: Initial mass of the spacecraft

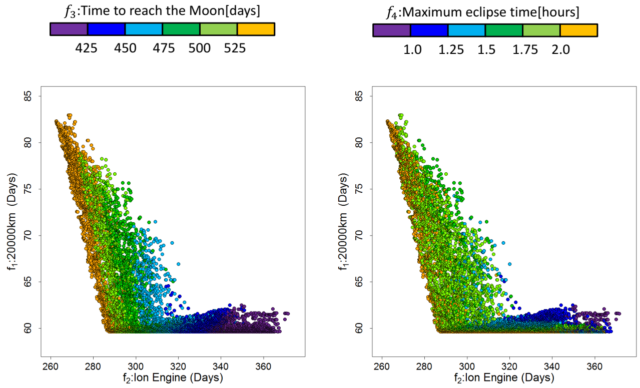
4 Experimental Results and Discussion

In this work NSGA-II and AεSεH use SBX crossover and Polynomial Mutation. Population size is $|P| = 500$, number of generations is 100. Reference neighborhood size for AεSεH is $H_{size}^{Ref} = 20$. We analyze the Pareto optimal set (POS) obtained in 10 runs of the algorithm.

First, **Table 3** shows the C-metric values between AεSεH(Q_1) and the other mapping functions. Results by NSGA-II are also included for reference. In **Table 3** A stands for AεSεH(Q_1) and B for NSGA-II, AεSεH(ADD), AεSεH(MEDIAN) or AεSεH(MIN). From **Table 3** note that C(A,B) > than C(B,A) for almost all combinations of algorithm and number of objectives. That is AεSεH with the Q1 mapping function for ε-dominance produces solutions with better convergence characteristics compared to the other scaling functions and to NSGA-II.

Table 3. C-metric, A: AεSεH(Q_1)

B	4 objectives		5 objectives		6 objectives	
	C(A,B)	C(B,A)	C(A,B)	C(B,A)	C(A,B)	C(B,A)
NSGA-II	44.7	7.7	56.9	2.46	53.2	0.949
ADD	23.6	14.7	23.5	6.89	9.68	4.74
MEDIAN	29.6	13.7	23.0	14.7	9.93	7.49
MIN	25.6	19.7	20.5	11.8	6.97	8.50

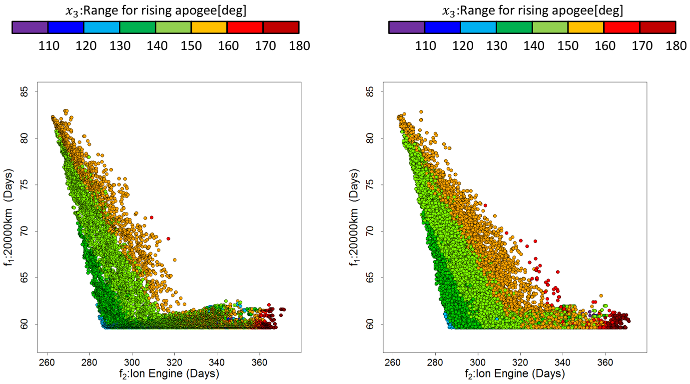


(a)Colored by f_3 (b)Colored by f_4

Fig. 1. Results by AεSεH(Q_1) plane $f_2 - f_1$, 4 objectives

In the following we focus our analysis using results by AεSεH(Q_1). **Fig.1** (a) and (b) show POS on the plane f_1-f_2 for a 4 objective formulation of the problem, coloring solutions according to their value in function f_3 and f_4, respectively. From **Fig.1** (a) note that in order to reduce the time to reach the Moon (f_3) the operation time of the Ion Engine must be increased (f_2). In addition, note that it is possible to reduce f_2 and still have many solutions in the range of 60 to 80 days to reach an altitude of 20,000km (f_1) and leave the outer radiation belt. However, from **Fig.1** (b) note that the eclipse time (f_4) for solutions in that region becomes larger as f_2 reduces. In this problem, solutions with a maximum eclipse time of 1.5 hours are desired to avoid larger batteries. From **Fig.1** (b) note that there are not many solutions within this desirable range.

Fig.2 (a) and (b) show POS on the plane $f_1 - f_2$, coloring solutions according to their value in variable x_3 range for rising apogee, for 4 and 5 objectives problem formulations, respectively. Comparing **Fig.2** (a) and (b) it can be seen a more clear but similar distribution of solutions for the 5 objective problem. Thus, the addition of the time to reach an altitude of 5000km to leave the inner radiation belt(f_5) as evaluation function allows to find good alternative for f_5 without affecting other variables or objectives.



(a)4 objective(Q_1) (b)5 objective(Q_1)

Fig. 2. Results by AεSεH(Q_1), plane f_2-f_1, colored by x_3

5 Conclusions

This work used the many-objective AεSεH evolutionary algorithm to find solutions for the trajectory design problem of JAXA's DESTINY mission. Three mapping functions that consider the different scales of the objective functions were tried to compute ε-dominance in AεSεH. Using the C-metric, we verified in 4, 5 and 6 objectives problem formulations that all the new mapping functions work better than the additive function that assumes the same scale for all objectives. Also, we presented an initial analyzes of the Pareto optimal sets of solutions found. Particularly, in the 4 objectives problem formulation we analyzed the trade-off between the objectives that measure the time to reach the Moon, the time to leave Earth's outer radiation belt, the operation time of the Ion Engine, and the eclipse time. Also, we verify that adding f_5 to leave earlier the Earth's inner (5000km) radiation belt does not affect other objectives.

As future works, we would like to continue our analysis with the 6 objective problem formulation, where mass of the spacecraft also is subject to optimization. In addition, we would also like to constraint our search to areas where more solutions with an eclipse time of less that 1.5h can be found.

References

1. M. Nakamiya, A. Oyama, M. Bando, C. Hirose, S. Campangnola, and Y. Kawakatsu, "Trajectory Design from the Earth to the Moon using the Multi-objective Optimization for DESTINY Mission", in *23rd International Symposium on Space Flight Dynamics (ISSFD ' 2012)*, Pasadena, California, USA, 2012.
2. A. Lopez, A. Oyama, K. Fujii, "Space Trajectory Design: Analysis of a Real-World Many-Objective Optimization Problem", *proc. CEC 2013*, pp.2809-2816, 2013
3. H. Aguirre, A.Oyama and Ktanaka, "Adaptive ε-Sampling and ε-Hood for Evolutionary Many-Objective Optimization", *proc. EMO 2013,* LNCS, vol. 7811, pp.322-336, 2013.