Fault-Tolerant Low-Thrust Trajectory Optimization with Arbitrary Number of Thrusters and Target Celestial Bodies

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Keyword: Trajectory Design, Fault Tolerance, Backup Trajectory, Dynamic Programming

This paper presents a method to design robust trajectories against the possible faults of low-thrust engines. Recently, increasing number of space probes with low-thrust engines have been launched. Due to the insufficient reliability of low-thrust propulsion system, however, almost all probes with ion engines have experienced the failure of engines. Conventional methods to design the low-thrust trajectory have pursued fuel minimum solution to only one target celestial body, which does not necessarily mean the maximization of mission achievement. On the other hand, if a space probe considers a secondary candidate and intelligently modifies the trajectory in case of engines failure, it can escape from reducing the possibility of mission accomplishment. Figure 1 indicates the concept of this research. If a space probe takes into account secondary candidates and adopts a magenta trajectory, it can maintain the possibility of mission accomplishment by adopting backup trajectories in case of engines failure. Based on this concept, this paper has an objective to propose a trajectory design method with backup trajectories considering possible faults of low-thrust engines.

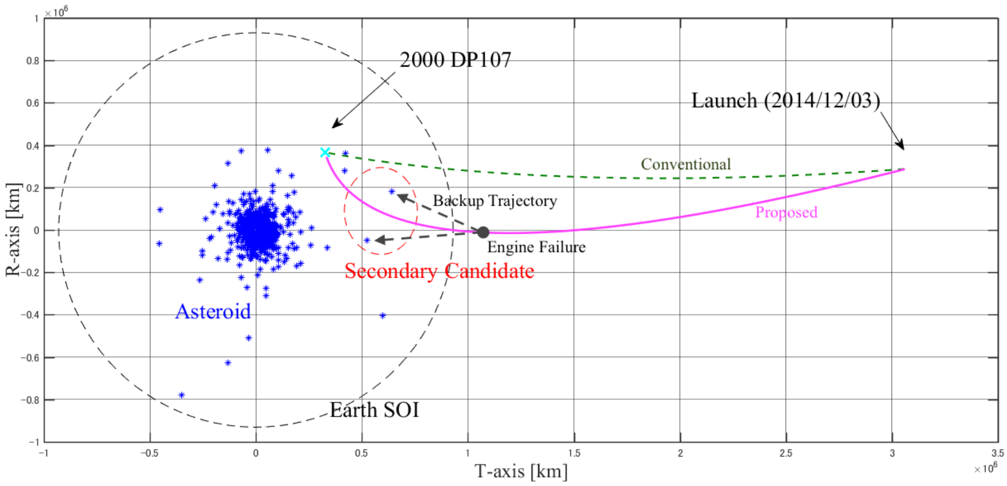

Fig. 1 Concept of this research

In this research, the objective function is defined as *expected scientific gain* as follows:

$$J_k(\boldsymbol{x}_k, \boldsymbol{n}_k, \boldsymbol{u}_{k:N-1}) = \sum_{j=1}^{m} w^j \Pr[\boldsymbol{r}_N = \boldsymbol{r}^j] \quad (1)$$

, where k is a stage number, $\boldsymbol{x}_k$ is state vector, $\boldsymbol{n}_k$ is the number of normal (unbroken) engines, and $\boldsymbol{u}_{k:N-1}$ is control input from state k to stage $N-1$. Thus, $\Pr[\boldsymbol{r}_N = \boldsymbol{r}^j]$ is the possibility to reach j-th candidate. In addition, m is the number of candidate to consider, and w^j is the exploration worth of j-th candidate. This objective function enables us to consider multiple target celestial bodies and directly optimize primary objective of space missions. Despite the fact this objective function seems to be incompatible with conventional one, theoretical analysis can prove that the objective function does never conflict conventional objective function (i.e. fuel consumption). And we formulate the problem of optimizing this objective function and search an optimal solution by a proposed method. Resulting method, sampling based Dynamic Programming (DP) algorithm, can efficiently explore nearly optimal solution by applying the Bellman's principle of optimality. Finally, the numerical simulation demonstrated that a proposed method improves the mission achievement using real deep space exploration scenario.