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A fast multi-objective optimization design method for emergency libration point orbits transfer between the Sun–Earth and the Earth–Moon systems

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ABSTRACT

This paper considers the emergency trajectory design mission of libration point orbit transfer between the Sun–Earth system and the Earth–Moon system. In order to balance the two indexes of transfer time and fuel consumption, Halo orbits and their invariant manifolds in the circular restricted three body problem (CRTBP) are combined with low thrust in the bicircular restricted four body problem (BRFBP) to design the transfer trajectories. A fast multi-objective optimization method based on surrogate model which is greatly needed especially for emergency transfer missions is proposed to overcome the low-efficacy of original evolutionary multi-objective optimization methods. The advantages of the Sun–Earth manifolds, the Earth–Moon manifolds and the optimal control method are fully considered. In the part of numerical simulations, several simple problems with analytical solutions are first employed to validate the proposed fast optimization algorithm, then the proposed method is compared with NSGA-II for the same multi-objective transfer problem. Numerical results show that the fast optimization method chooses the expected samples and has a much higher efficiency than direct multi-objective optimization. The significance of the Sun–Earth manifolds and the Earth–Moon manifolds are considered. Several cases show the complicated relationship between transfer time and fuel consumption.

1. Introduction

With the developing of aerospace technology, the exploration of deep space attracts more researchers than ever before. Besides, most studies focus on the significant values of libration points and their periodic orbits. The libration points and their periodic orbits are the ideal positions for space telescopes and deep space explorers. For the sake of the fundamental advantages of the space around libration points, the positions of libration points and their orbits are ideal positions for space telescopes. Moreover, if there are hetroclinic orbits, invariant manifolds associated with libration point orbits can connect different libration points and their orbits. So there be free fuel consumption for transferring in theory, i.e., the explorer satellites can achieve long travel nearly without fuel consumption.

In recent years, low-cost libration orbit transfer attracts much attention [1–12]. The low-cost orbit transfer based on the restricted four-body model is implemented in the Earth–Moon system in reference [1]. Howell and Kakoi [2] use invariant manifolds to study low-cost transfer trajectory between the Sun–Earth and the Earth–Moon systems. The dynamic characteristics of the complex bielliptic four body problem is studied in reference [4]. Pseudo-stable manifold is considered in reference [5] to contain the effect of the forth body, and then the transfer trajectory is determined using the low-thrust and the pseudo-stable manifold. Based on the multi-objective genetic algorithm and calculus-of-variations-based low-thrust trajectory optimization, reference [6] designs the transfer trajectory between the Earth–Mars and the Earth–Mercury systems. Canalias and Masdemont [7] use the coupled restricted three body model and the JPL ephemeris for analyzing the natural transfer orbits between the Sun–Earth and the Sun–Moon systems. Besides, many researches [3,5,7] focus on the Poincare sections to find free fuel consumption transfer trajectory, and almost no control is used in these missions. But it appears that there is no such ideal mission in practical aerospace engineering. Meantime it is usually time-consuming for such free fuel consumption mission. So, the balance between the transfer time and the fuel consumption must be considered in most cases.

Since the two indexes of transfer time and fuel consumption are usually conflicted, many researches are devoted to obtain the

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Nomenclature

x, y, z	Cartesian coordinates	D
D	Normalized unit	
m_1, m_2, m_3	The mass of the Sun, the Earth and the Moon	kg
α	The angle between the lunar line of nodes and the x-axis	
β	The angle between the Moon and the lunar line of nodes	
i	The oblique angle between the rotation plane of Sun–Earth and Earth–Moon systems	
$\vec{r}_1, \vec{r}_2, \vec{r}_3, \vec{r}_4$	Vectors of the Sun, the Earth, the Moon and the spacecraft	
d_{se}, d_{em}	The distance between the Sun and the Earth, Earth and the Moon	km
D_{se}, D_{em}	The normalized distance between the Sun and the Earth, Earth and the Moon	
Δt	The total flight time, day	
Δv	The total fuel consumption	m/s
$\boldsymbol{u}(t)$	The control vector	m/s^2
V^S, V^U	The eigenvector of stable and unstable manifolds	
$\varepsilon(\boldsymbol{x})$	The error function	
$R(\boldsymbol{x}^{(i)}, \boldsymbol{x}^{(j)}, \boldsymbol{\theta})$	The basis function	
F_i	The Pareto fitness function value of the ith design point	

optimal transfer trajectories using multi-objective optimization algorithm. Reference [1] uses multi-objective genetic algorithm to obtain the Pareto frontier for choosing the optimal trajectories in the restricted four-body problem. Efficient low-energy trajectories are obtained in reference [13] by using low-thrust, and variational optimal control is used to improve the results. A hybrid optimization method which combines a multi-objective genetic algorithm and a calculus-of-variation-based low-thrust trajectory optimization is proposed in reference [6] for obtaining the optimal transfer trajectories between the Earth–Mars and the Earth–Mercury systems. In all these papers, the powerful but time consuming intelligence algorithms are used. It is acceptable for regular missions that can be off-line designed. But in some emergency missions like SOHO mission [14] which is once lost and saved by scientists, the transfer trajectory can only be on-line designed. For the potential more emergency missions, the time cost for traditional intelligence algorithms is probably unacceptable. Meantime, these urgent transfer missions truly exist when the spacecraft meets emergency incidents or temporary missions. For example, in pursuit and capture missions [15–18], when a spacecraft needs to pursue or intercept an objective spacecraft that flies in other orbits, the transfer maneuver opportunity is significant. In the near future, some space stations or telescopes may locate on halo orbits of the Sun–Earth/Earth–Moon systems. If a telescope works failure, it is necessary to send a new spacecraft to repair it rapidly. When the nearest spacecraft locates on Earth–Moon halo orbits, the urgent transfer orbit is needed to be designed for rescuing the failure telescope. Besides, if astronauts are trapped in the station, and they will face a variety of crisis situations, the urgent transfer trajectory design problem is also very important for astronauts' safety. For these missions, short transfer time is necessary, meantime, ideal transfer trajectory just appears in certain period of libration point orbits. Therefore, the spacecraft may miss this important time due to the low efficiency of finding optimal transfer trajectory. For these reasons, the efficiency for on-line designing optimal transfer trajectory has significant value. Furthermore, according to the point of view in the reference [18], the use of an efficient design tool can enable significant time savings when performing trajectory design over long propagation times, trajectory optimization using massive grid searches, or trade space exploration for exercises in rapid mission design. Based on the above analysis, the main concern of this paper is to find a fast multi-objective design method for transfer trajectory. Besides, a popular tool for constructing the fast optimization method is surrogate model [19–24]. Thus, an adaptive surrogate model based multi-objective optimization method is proposed in this paper.

The recent researches using surrogate models for constructing optimization algorithms are introduced. Surrogate models which are combined with multi-objective optimization algorithm are proposed in reference [20]. Also in reference [20], the values of multi-objective functions in other design regions are applied with a large value to obtain more accurate results in Pareto region. Similarly, an efficient global optimization based surrogate model which chooses the region of low objective function value is developed in multi-objective optimization algorithm in reference [21]. Reference [22] adds the optimal points of surrogate models to the multi-objective model for obtaining an adaptive multi-objective optimization method. In the field of spacecraft trajectory design, the usage of surrogate models is not wide. Reference [23] proposes an adaptive method that updates the sampling points in approximate Pareto frontier for optimizing the shape of airfoil sections. Peng et al. [8,24] employ the optimal control method and surrogate model to study the problem of spacecraft rendezvous and fast path planning of spacecraft formation reconfiguration on libration point orbits.

In conclusion, only a few researches mention surrogate model in aerospace field and few papers employ surrogate models for systematic multi-object optimization design in aerospace field. Therefore, this paper proposes a systematic and efficient fast optimization method based on surrogate models for emergency trajectory design mission.

2. Multi-objective libration point orbit transfer strategy

The multi-objective transfer mission chosen in this paper is a pursuit and/or capture problem that one spacecraft from the Earth–Moon system transfers to pursuit and/or capture another spacecraft or space station in the Sun–Earth system. The dynamical equations which are used to obtain the Halo orbits and manifolds are first introduced. Then, the CRBFP equations which are used in optimal control method are introduced. Finally, a multi-objective optimization model of libration point orbit transfer is established based on the combination of low thrust and invariant manifolds.

2.1. *Dynamical equation*

2.1.1. *The circular restricted three body problem*

The well-known CRTBP is considered in this paper to obtain Halo orbits and their invariant manifolds around the libration points in the Sun–Earth and the Earth–Moon systems. There are two massive bodies and one spacecraft in the CRTBP model, and we first assume that the two massive bodies rotate along their barycenter with a constant angular velocity. Besides, the motions of two massive bodies cannot be affected by the spacecraft. If the original point of the coordinate is set at the barycenter of the massive bodies, then the x-axis extends from the original point to the smaller massive body, meanwhile, the y-axis is normal to the x-axis in the rotate plane of two massive bodies. Finally, the z-axis