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Adaptive surrogate model-based fast path planning for spacecraft formation reconfiguration on libration point orbits

Haijun Peng [a,*], Wei Wang [b]

[a] Department of Engineering Mechanics, State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian, 116024, China
[b] Department of Engineering Mechanics, Tsinghua University, Beijing, 100084, China

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ABSTRACT

This work considers the optimization of fast path planning for spacecraft formation reconfiguration on libration point orbits. An adaptive surrogate model is proposed for solving the above optimization problem in abnormal conditions and/or emergency cases. First, a multi-layer optimization problem is established. In the outer loop of the multi-layer optimization, the nonlinear optimal control problem, taken as a dynamic optimization, is solved to obtain the optimal transfer paths of all spacecraft in the formation. In the inner loop of the multi-layer optimization, the parameter optimization problem, taken as a static optimization, is solved to obtain the states of all the spacecraft within the maximized area of the spacecraft formation. Then, an adaptive surrogate model is proposed. Because the multi-layer optimization problem is typically time-consuming and computationally expensive, the adaptive surrogate model is constructed using data drawn from the multi-layer optimization model and provides a fast approximation of the objective at new design points. Therefore, the adaptive surrogate model is feasible and cheap for spacecraft formation reconfiguration. Finally, numerical simulations show that the adaptive surrogate-based parameter optimization has advantages over the direct global optimization method. The accuracy, efficiency and robustness of the proposed adaptive surrogate model have also been compared between the different types of surrogate models.

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1. Introduction

The exploration of deep space, especially of a libration point space environment, is an important research topic that has attracted much attention in recent years [1–10]. These positions are ideal for searching for habitable terrestrial exoplanets or situating a set of interferometer space telescopes or midway refueling space stations for large missions. Deep space formation flying technology is essential to meet the increasing demand for deep space exploration. Thus far, both spacecraft formation keeping and reconfiguration, potential applications that involve spacecraft formations flying on the libration points, have attracted great interest for formation control strategies in a multibody regime.

Various strategies and approaches have been proposed for the reconfiguration of the spacecraft formation on libration point orbits. Reference [5] gives comparisons among the optimal nonlinear control, geometric control, linear quadratic regulators, and input state feedback linearization. Reference [6] proposes a finite element method for solving for optimal control and applies it to spacecraft formation reconfiguration in a libration point regime of the sun–earth system. Reference [7] develops a technique based on generating functions for designing spacecraft formation reconfiguration in Hill three-body dynamics. Reference [8] presents an efficient parameter optimization algorithm for collision-free energy sub-optimal path planning of spacecraft flying in formation in deep space. Based on the characterization of requirements and constraints, different algorithms for centralized optimal formation planning and coordination have been developed in reference [9]. Reference [10] employs a finite-dimensional parameter optimization method for spacecraft formation reconfiguration guidance.

Although the literature cited above has emphasized the problem of spacecraft formation reconfiguration near libration point orbits, particularly in path planning, avoiding collisions and balancing energy, etc., all the reconfiguration missions are planned based on known information in normal circumstances and can be evaluated off-line before the actual implementation of the spacecraft formation reconfiguration mission. However, an engine failure or other mechanical defect on a certain spacecraft in the formation will arise in abnormal conditions and/or emergency cases. In these extreme cases, all the information for the spacecraft cannot be obtained in advance, and primary fast path planning for

* Corresponding author.
E-mail address: hjpeng@dlut.edu.cn (H. Peng).

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spacecraft formation reconfiguration is particularly important for the follow-up normal missions. Therefore, the development of fast path planning for spacecraft formation reconfiguration in case of emergency is an active area of research.

From the point of view of dynamics and control, there are two primary scientific problems to be solved before the actual implementation of spacecraft formation reconfiguration: (1) the scientific objective of the spacecraft formation; i.e., the new form taken by the spacecraft formation, based on the present state and number of spacecraft; (2) with the new form taken by the spacecraft formation known, the path planning for the spacecraft formation reconfiguration. Regarding the first scientific problem, the parameter optimization method is usually employed to plan the new geometric configurations and to obtain the new states of the spacecraft in their new formation. In the second scientific problem, the nonlinear optimal control method is always used to design the optimal transfer paths of all spacecraft from the failure formation to the new formation. It is essentially a coupling system between the first and the second scientific problems, and neither of the above problems can be solved alone. This leads to complex nonlinear optimization problems, in which computational efficiency is a determining factor for successful implementation of spacecraft formation reconfiguration in extreme cases.

Gradient-based methods and intelligent algorithms are usually employed to solve the above complex nonlinear optimizations problems. However, the gradient-based methods have a high efficiency but will obtain locally optimal results [11]. Moreover, the optimization problem proposed in this paper has strongly implicit relationship between the design variables and the objective function, so the analytic gradient information cannot be obtained from the above complex nonlinear optimization. The intelligent algorithms are convenient to implement and can obtain globally optimal results. However, they require thousands of function evaluations [12], and this process may require unacceptable computational cost.

Motivated by the requirements for high computational efficiency for spacecraft formation reconfiguration in extreme cases, an efficient adaptive surrogate model-based fast path planning strategy for spacecraft formation reconfiguration on libration orbits will be investigated in this paper. Surrogate-based optimization (SBO) is an important and efficient way to quickly access the optimal results [13]. Because the surrogate model uses an explicit and approximate expression to replace the true complex model, the optimization based on the surrogate model has a very high efficiency. As a result, SBO has been shown to be an effective approach for the design of computationally expensive models, such as many optimizations in aerospace systems [14–16]. In this paper, for the first scientific problem, the present geometric configuration of spacecraft can be measured in abnormal conditions and/or emergency cases. The desired new geometric configuration of spacecraft should be designed according to the requirement of different space mission. One requirement of these different space mission is to obtain high-resolution for deep space explorations and studies of outer space. In particular, a larger area that is surrounded by the spacecraft formation can obtain a higher resolution. Thus, maximum area of the spacecraft formation under some geometric constraint should be a key objective. For the second scientific problem, the fuel consumption should be minimized in path planning for spacecraft formation reconfiguration. Sufficient remaining fuel is a prerequisite for the follow-up normal missions. Based on the above analysis, a multi-layer optimization model is first formalized for the fast spacecraft formation reconfiguration problem. Then, the adaptive surrogate model is proposed for fast solving of the above multi-layer optimization problem. Finally, the numerical simulations are implemented to test the effectiveness of the proposed fast path planning strategy for the spacecraft formation reconfiguration problems.

The paper is organized as follows: in section 2, a brief review of spacecraft formation reconfiguration is introduced, including the dynamic model and the nonlinear optimal control problem. In section 3, the programming and design of the fast spacecraft formation reconfiguration problem is taken as a multi-layer optimization problem. An adaptive surrogate model is proposed for solving the multi-layer optimization problem in section 4. In section 5, the accuracy, efficiency and robustness of the proposed adaptive surrogate model are verified through the numerical simulations of spacecraft formation reconfiguration.

2. Background

In this section, we shall give a brief introduction to some basic knowledge used for constructing fast path planning models for spacecraft formation reconfiguration on libration point orbits. First, the dynamic model for the spacecraft formation will be introduced. Then, the path planning problem of spacecraft formation reconfiguration will be formulated as a nonlinear optimal control problem.

2.1. Dynamic model

The primary concern in this paper is the spacecraft formation reconfiguration problem on libration point orbits in the sun–earth system. Therefore, the circular restricted three-body problem (CRTBP) model is used to construct the dynamical equations for the spacecraft formation reconfiguration problem. In the CRTBP model, there are two massive bodies (i.e., the sun and the earth) and a spacecraft. The sun and the earth are assumed to be in circular orbit around the barycenter of the sun–earth system because their masses are far larger than that of the spacecraft and the motion of the two primary bodies is not affected by the spacecraft. Because we mainly discuss the orbits around the second libration (L_2) point, we set the origin of the reference coordinate system at the L_2 point. The x vector of the reference coordinate is extended from the sun to the earth, the y vector is normal to the x vector and in the rotation plane, and the z vector complies with the rule of right-handed frames. Furthermore, continuous low thrust (typically electrically powered spacecraft propulsion) has been developed and employed as a novel propulsion system for deep space exploration in recent years. The present study also employs continuous low thrust for spacecraft formation reconfiguration.

Therefore, according to the above assumptions and statements, we can obtain the controlled dynamic equations for the ith spacecraft in the following dimensionless form [1]:

$$\ddot{x}^i - 2\dot{y}^i - x^i = -\frac{(1-\mu)(x^i+1+1/\gamma)}{\gamma^3 d_1^3} - \frac{\mu(x^i+1)}{\gamma^3 d_2^3} + \frac{1-\mu+\gamma}{\gamma} + u_x^i \tag{1}$$

$$\ddot{y}^i + 2\dot{x}^i - y^i = -\frac{(1-\mu)y^i}{\gamma^3 d_1^3} - \frac{\mu y^i}{\gamma^3 d_2^3} + u_y^i \tag{2}$$

$$\ddot{z}^i = -\frac{(1-\mu)y^i}{\gamma^3 d_1^3} - \frac{\mu z^i}{\gamma^3 d_2^3} + u_z^i \tag{3}$$

where the dot represents the time derivative in the rotating frame, $i = 1, 2, \cdots, n$, n is the number of spacecraft in the geometric formation, μ is the ratio of the earth's mass to the sum of the masses of both the earth and the sun,

$$d_1 = \sqrt{(x^i+1+1/\gamma)^2 + (y^i)^2 + (z^i)^2},$$

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