International Core Journal of Engineering Volume 9 Issue 12, 2023
ISSN: 2414-1895 DOI: 10.6919/ICJE.202312_9(12).0035

Summary of Transfer Orbit Optimization Methods for Low-thrust Engines

Lingyu Han

Qingdao No. 9 Middle School, Qingdao, Shandong, 266012, China

*E-mail: HLYC0424@163.com

Abstract

The optimization of spacecraft transfer orbit under low thrust is a global problem to find a large number of local optimal solutions, and the focus is on the optimal control solution. There are two kinds of optimization methods: global optimization and local optimization, global optimization can be based on genetic algorithm, and local optimization is mainly divided into direct method, indirect method and mixed method. Global optimization: Determine the approximate time point of each stage of the task when the task indicators are approximately optimal. Local optimization: The approximate orbit can be transformed into a low-thrust orbit that meets the constraints. The main performance indexes of this paper are time optimal and fuel optimal, i.e. bang-bang control.

Keywords

Low Thrust; Transfer Orbit; Global Optimization; Local Optimization.

1. Introduction

China has completed the third phase of the lunar exploration project "circling, landing and returning", and successfully launched the "Tiwen 1" satellite in 2020. The white paper "China Space 2021" pointed out that in the next five years, China will continue to carry out the lunar exploration project, launch the "Chang 'e-6", "Chang 'e-7" and "Chang 'e-8" probes, reach the lunar polar region, and build lunar scientific research stations. Deeper exploration of the moon. China will also continue to implement the planetary exploration project, launch asteroid probes, complete near-Earth asteroid sampling, Jupiter system exploration and other key technology research and demonstration of the solar system marginal solar system exploration implementation plan. This indicates that China will continue to push into deep space exploration. To date, the United States National Aeronautics and Space Administration (NASA), the Russian Federal Space Agency (FSA), the European Space Agency (ESA), the Japanese Space Agency (JAXA) and the Indian Space Research Organization (ISRO) have independently conducted deep space exploration activities.

Deep space exploration has been included in the national major science and technology projects, in the future space missions, interplanetary and interstellar exploration will receive more attention. Among them, the total speed increment of the asteroid exploration mission is required to be greater than 8km/s [1], and the traditional chemical propulsion system cannot continue to be used because of its low specific impulse. Therefore, electric propulsion, plasma propulsion and other sustained small thrust propulsion methods will play an increasingly important role. The low-thrust engine has the characteristics of high specific impulse, increased payload of spacecraft, long propulsion time and long service life. At the same time, the small thrust enriches the shape of the deep space exploration orbit and provides more flexibility for the orbit design [2].

The paper is generally based on the Earth-moon and earth-fire transfer in the background, in recent years, the main research is local optimization, global optimization research is few. In the global

Volume 9 Issue 12, 2023
DOI: 10.6919/ICJE.202312_9(12).0035

optimization method, Zhou Zhiyuan et al. put forward the genetic algorithm to search the low thrust interplanetary transfer orbit optimization scheme. According to these three methods of local optimization In the latest study, Xun Pan et al studied the trajectory optimization in the restricted three-body problem, and Kun Peng et al used a guided artificial immune algorithm.

2. Global Optimization

Global optimization determines the approximate time point of each task and focuses on finding the extreme value of the function on the given set when the task index is approximately optimal. The problem that the initial value of the costate variable is difficult to estimate in indirect method can be avoided. Genetic algorithm is introduced below, which can quickly obtain the low-energy interplanetary transfer window consistent with the global search, and the low-thrust orbit control optimization results can not only meet the requirements of the corresponding detection mission, but also provide the terminal state of the detector [3].

2.1 Genetic Algorithm

Zhou Zhiyuan et al. mentioned that genetic algorithm is used in the search optimization of interplanetary transfer window. The process of genetic evolution is realized by keeping the individuals with high fitness, exchanging the individual part of the genes of two paired individuals, and making a small number of individuals have gene mutations. When searching for the target asteroid, the constraint condition is whether the required fuel consumption meets the engineering practice, and the cyclic search evolution converges to the optimal solution. In the optimization of the interplanetary transfer window, the launch date is optimized by genetic algorithm, and after the launch time range is determined, the genetic algorithm randomly generates a population of 100, and the cycle is 50 generations[3].The low-energy interplanetary transfer window consistent with the global search can be quickly obtained, and the low-thrust orbit control optimization results can not only meet the requirements of the corresponding detection mission, but also provide the terminal state of the detector[3].

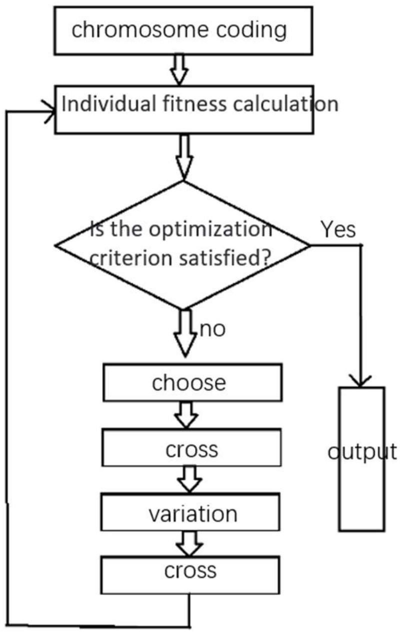

Figure 1. Genetic algorithm process.

3. Local Optimization

For a problem in a given situation, a decision is better than a decision that solves part of the problem. The direct, indirect and mixed methods are described below. The direct method is not sensitive to the

ISSN: 2414-1895 DOI: 10.6919/ICJE.202312_9(12).0035

initial value, but the calculation amount increases greatly with the increase of the calculation precision, and it is easy to precocious and converge to the local optimal solution. The indirect method can guarantee the local optimality of the obtained solution, and the calculation accuracy is high, but the initial value is difficult to estimate and the convergence radius is small. The hybrid method combines the direct method and the indirect method, and the calculation amount is smaller than the direct method, and the convergence is better than the indirect method [4].

3.1 Direct Method

The direct method is essentially a discrete idea and a nonlinear programming method. First, state variables and control variables are discretized, then the optimal control problem is transformed into a nonlinear programming problem, and the discrete parameters are solved directly. The available solutions include pseudo-spectral method, shooting method, direct transformation method, differential inclusion method, SOCS algorithm, etc.

3.1.1. Pseudo-spectral Method

Li Xun et al. studied the optimization scheme of interplanetary low thrust orbit based on pseudo-spectral method, used simulated annealing method to search the initial reference orbit, and then used twice pseudo-spectral method to optimize [5]. Zhu Qiang et al. studied the optimization of the multi-gravitational field trajectory with low thrust, established a multi-gravitational field dynamic model, and used Radau pseudo-spectrum method for optimization calculation. The pseudo-spectral method has a wide convergence domain and is insensitive to initial values[2].

3.1.2. Based on the Initial Pulse Value

Wang Xusheng et al. studied the optimization of small thrust transfer based on initial pulse value, established the optimization model by direct method, and proposed a combined optimization algorithm based on particle swarm optimization and sequential quadratic programming.

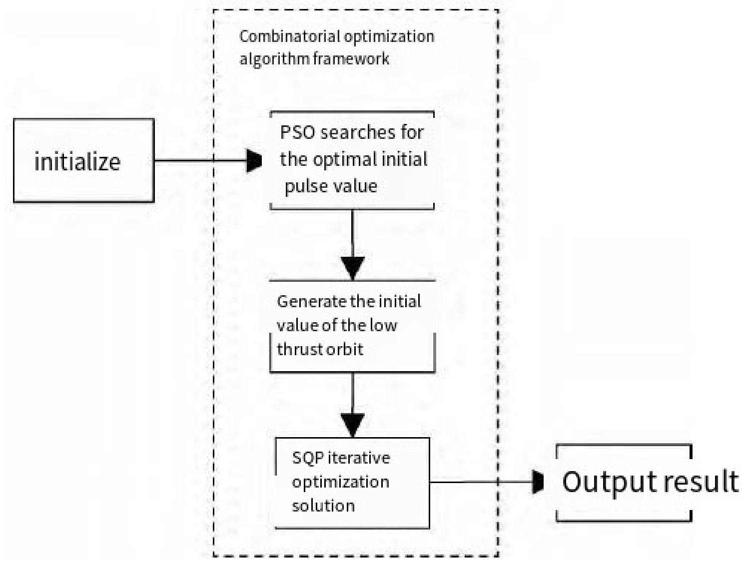

Figure 2. Combinatorial optimization algorithm framework.

3.2 Indirect Method

The indirect method uses the maximum principle, introduces Hamiltonian function and adjoint variables, transforms the optimal control problem into a two-point boundary value problem, and obtains the optimal orbit by solving it.

3.2.1. Homotopy Method

Pan Xun et al. studied the small thrust propulsion transfer orbit design based on the homotopy three-body problem. In the limited three-body problem model of the Earth-moon system, aiming at the bang-bang control problem of optimal fuel, the homotopy parameters were introduced to construct a new performance index, the optimal control law was obtained by using the pseudo-arc length method, and finally the most transfer orbit was obtained. They also studied the optimization of low thrust transfer orbit of Earth-moon L2 point based on homotopy method. In order to optimize the time and maintain the maximum thrust, the optimization problem was first transformed into a two-point boundary value problem, and then the homotopy function was constructed to solve the optimal orbit by pseudo-arc length method.

3.3 Mixing Method

The hybrid method adopts the optimal control law of indirect method, and then optimizes other adjoint variables. The costate is introduced in the hybrid method, which can obtain smooth control and increase the radius of convergence without solving the two-point boundary value problem.

3.3.1 Artificial Immune Algorithm

Peng Kun et al. studied the hybrid design method of earth-fire transfer orbit, and established a two-dimensional polar coordinate dynamics model. The optimal control law of the low-thrust engine is determined by the maximum principle, and then the guided artificial immune algorithm is used to optimize the solution. Anran et al. studied the optimal design of the Earth-moon L2 point transfer orbit based on invariant manifolds. In this paper, a concatenated coordinate system conversion method between invariant manifolds and the rising stage was established to complete the transfer stage design, in which a hybrid method was used to solve the minimum performance index by a suitable nonlinear programming algorithm.

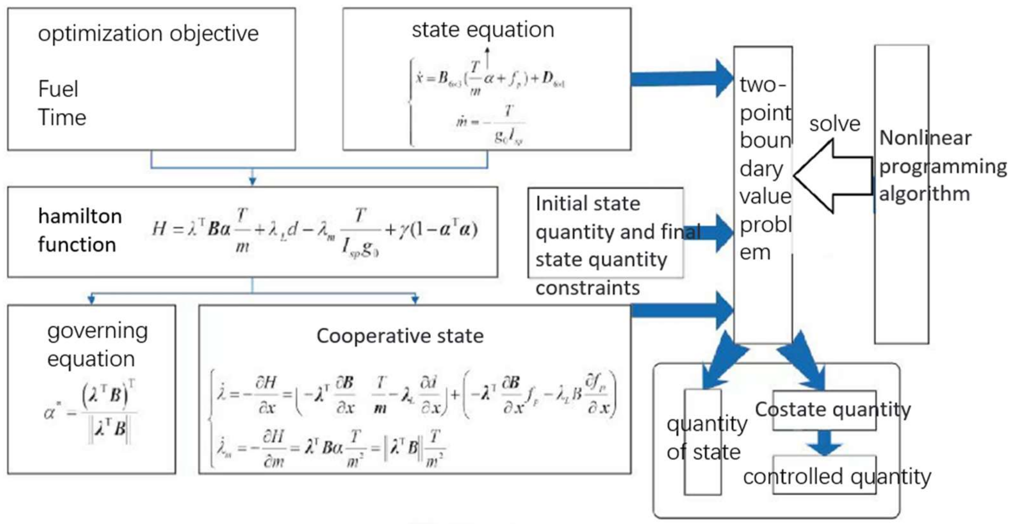

Figure 3. Nonlinear programing algorithm.

4. Summary and Prospect

Deep space exploration has been included in the national major science and technology projects, in the future space missions, interplanetary and interstellar exploration will receive more attention, so the low thrust transfer orbit design optimization methods are more and more, and the update speed is fast.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202312_9(12).0035

References

[1] Wang X., Wang W & Peng Y. (2019). Based on the small thrust of the initial value of pulse transfer orbit optimization research. Shanghai aerospace (01), 54-59.

[2] Zhu Q, Shao Z & Song Z. (2018). Design and optimization of multi-gravitational orbit with low thrust. Control Theory and Applications (06),741-750.

[3] Zhou Z, Liu Y, Tan T & Tian L.(2016). Low thrust interplanetary transfer orbit design and control optimization method based on genetic algorithm. Shanghai Aerospace (01),38-41+49.

[4] Peng K, Zeng H, Tian L & Hou Z. (2020). Hybrid design method of Earth-Mars transfer orbit for low-thrust spacecraft. Space Return and Remote Sensing (01),10-17.

[5] Li X, Han C, Li J & Zhang X. (2019). Optimal design of interplanetary low-thrust orbit based on pseudo-spectral method. Computer Simulation (07),29-33.