Reconfiguration of Spacecraft Cluster Based on Distributed Local Information

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(Received 6 September 2020; revised 1 February 2021; accepted 5 February 2021)

Abstract: The reconstruction of spacecraft cluster based on local information and distributed strategy is investigated. Each spacecraft is an intelligent individual that can detect information within a limited range and can determine its behavior based on surrounding information. The objective of the cluster is to achieve the formation reconstruction with minimum fuel consumption. Based on the principle of dual pulse rendezvous maneuver, three target selection strategies are designed for collision avoidance. Strategy-1 determines the target point's attribution according to the target's distance when the target point conflicts and uses a unit pulse to avoid a collision. Strategy-2 changes the collision avoidance behavior. When two spacecraft meet more than once, the strategy switches the target points of the two spacecraft. In Strategy-3, the spacecraft closer to the target has higher priority in target allocation. Strategy-3 also switches the target points when two spacecraft encounter more than once. The three strategies for a given position, different completion times, and random position are compared. Numerical simulations show that all three strategies can accomplish the spacecraft cluster's reconfiguration under the specified requirements. Strategy-3 is better than Strategy-1 in all simulation cases in the sense of less fuel consumption with different completion times and given location, and it is more effective than Strategy-2 in most of the completion time. With a random initial position and given time, Strategy-3 is better than Strategy-1 in about 70% of the cases and more stable.

Key words: spacecraft cluster; formation reconstruction; relative Lambert problem; two-impulse rendezvous; distributed maneuver

CLC number: V44 **Document code:** A **Article ID:** 1005-1120(2021)04-0704-09

0 Introduction

With the development of the information industry, spacecraft gradually becomes miniaturized and low-cost. The cooperation of multiple spacecraft to complete some space missions has become a hotspot in the space field[1]. Some spacecraft cluster plans have been proposed one after another, such as the Defense Advanced Research Projects Agency (DARPA) F6 program, Edison Demonstration of Smallsat Networks (EDSN), Cyclone Global Navigation Satellite System (CYGNSS) Mission, "Tiantuo-3" plan, Magnetospheric Multiscale (MMS) project, European Space Agency (ESA) Cluster Ⅱ plan. In the future, the spacecraft cluster will become the leading force in the field of space applications.

During the flight of the spacecraft, formation reconstruction is one of its key technologies. To adapt to different space missions, it is often necessary to change the formation according to requirements. Formation reconstruction can also be seen as path planning for each spacecraft. It refers to planning the state of the spacecraft based on a norm (time, consumption, etc.) so that each spacecraft can transfer from one state to another. In the process of spacecraft path planning, a fundamental is-

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How to cite this article: YU Binggu, WANG Shuquan. Reconfiguration of spacecraft cluster based on distributed local information[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2021, 38(4): 704-712.

http://dx.doi.org/10.16356/j.1005-1120.2021.04.016

sue is to avoid collisions. How to effectively and quickly avoid collisions is important for spacecraft.

The traditional spacecraft cluster mission is committed through the leader-follower method to achieve formation reconstruction, and the periodic maneuvers to achieve a stable relative motion state of following and leading the spacecraft. However, the increase of spacecraft will bring substantial communication costs and more significant requirements of the main spacecraft for the computing power. Simultaneously, since the leader is in a relatively fixed position, the follower needs to consume more fuel to maintain a fixed configuration, it is essential to construct a distributed spacecraft cluster reconstruction method based on local information.

The current research on the reconstruction of distributed spacecraft clusters is mainly based on adaptive control and consistency theory. On this basis, the control model under specific scenarios is added. The current research on the reconstruction of distributed spacecraft clusters is mainly based on adaptive control and consistency theory. On this basis, the control model under specific scenarios is added. Ren[2] designed a cooperative control algorithm for spacecraft to maintain formation and synchronized attitude based on the theory of consensus algorithm. Zhang et al.[3] created a distributed collaborative control method based on the second-order consensus algorithm. Multiple spacecraft are controlled through information topology so that the formation of spacecraft can be maintained and the formation of overall maneuvering can be achieved. Zhang and Duan[4] designed an algorithm to realize distributed satellites' formation and described the relationship between the algorithm and the spacecraft's information transmission structure. Dang[5] conducted an in-depth study on cluster flight boundedness and gave theoretical derivations on cluster spacecraft flight conditions and how to achieve specific cooperation for cluster spacecraft systems. The formation provides a theoretical basis. Jing et al.[6] aimed at the problem that aviation cluster operations can form specific formations and maintain formation stability. In some cluster system consistency theory and graph theory, both single and multiple tasks are simultaneously performed on the cluster. After analyses, a related consistency control model was finally established, and stability was analyzed. However, the method based on the adaptive control and consistency theory has a disadvantage that as the scale of the spacecraft cluster system continues to expand, the control method's calculation is more complicated and cumbersome, which is no longer suitable for the control of large-scale distributed spacecraft clusters.

For the rendezvous or transfer of spacecraft, continuous thrust is used to control the spacecraft to reach the target position in many traditional scenarios[7]. Still, the fuel consumption should be minimized. For this reason, this paper designs dual-pulse-based distributed spacecraft cluster reconstruction strategies. They can finally make the entire spacecraft cluster complete the cluster reconstruction without collisions. Numerical simulation results show that the methods can complete formation reconstruction and optimize the fuel consumption.

1 Problem Description and Modeling

1.1 Problem description

In a spacecraft cluster, each spacecraft is an independent individual that can detect information within a specific range around it. Given the target position of the spacecraft cluster, it can be completed at a specified time without collisions. The target configuration of the spacecraft cluster reaches the designated position. Fig.1 shows the relative motion coordinate system of the spacecraft with O as the origin, $\boldsymbol{r}_0(t)$ as the initial position, and $\boldsymbol{r}(t)$ as the end position. Applying a pulse can transfer the spacecraft from the initial position to the end position.

First, the target position of the spacecraft cluster is given. Under the condition that each spacecraft is uncertain of its target position, a simple initial allocation strategy is designed so that each spacecraft has its target point. To save fuel, the relative Lambert problem[8] is used. After each spacecraft initial-

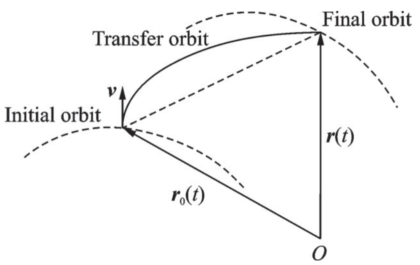


Fig.1 Scene graph of Lambert problem

ly selects the target point, with the initial state, target state (including position and velocity), and the given transition time, the pulses applied at the initial time and the end time can be calculated so that the spacecraft can reach its target point[9]. On this basis, since each spacecraft does not know the target point selection status of other spacecraft, it needs to be adjusted in real-time when the spacecraft finds the target point conflicts during the transfer process. According to the current state, the relative Lambert problem is resolved for the spacecraft that has adjusted the target point. Besides, it is necessary to avoid collisions between the spacecraft, to establish the corresponding dynamic control model, and to use the finite pulse to realize the spacecraft reconstruction task.

1.2 Dynamic analysis model

The Lambert problem is a classic two-point boundary problem in astrodynamics. This paper uses its basic theory to complete the reconstruction of the spacecraft cluster. In the near-circular orbit's relative dynamics model, through the double-pulse rendezvous maneuver principle, given the initial state, end state, and time, the analytical solution of relative motion can be obtained and used to control each spacecraft and complete path planning.

In the relative dynamics of the near-circular orbit, the following assumptions are made[10]:

(1) The earth and the spacecraft are regarded as two mutually attracting mass points;

(2) Spacecraft movement does not consider attitude control;

(3) The orbit of the spacecraft is a near-circular orbit, with an eccentricity of zero or very small;

(4) The distance between spacecraft is much smaller than their orbital radius.

Under these assumptions, the dynamic analysis model for spacecraft i can be expressed as

$$\begin{cases} \boldsymbol{r}_i(t)=\boldsymbol{\Phi}_{rr}(t)\,\boldsymbol{r}_{i0}+\boldsymbol{\Phi}_{rv}(t)\,\boldsymbol{v}_{i0} \\ \boldsymbol{v}_i(t)=\boldsymbol{\Phi}_{vr}(t)\,\boldsymbol{r}_{i0}+\boldsymbol{\Phi}_{vv}(t)\,\boldsymbol{v}_{i0} \end{cases} \tag{1}$$

where $\boldsymbol{r}_i(t)$ is the relative position of spacecraft i and $\boldsymbol{r}_i(t)=[x_i(t), y_i(t), z_i(t)]^{\mathrm{T}}$, $\boldsymbol{v}_i(t)$ the relative speed of spacecraft i, $\boldsymbol{r}_{i0}$ the initial position of spacecraft i, and $\boldsymbol{v}_{i0}$ the initial speed of spacecraft i. The C-W matrix is

$$\boldsymbol{\Phi}_{rr}(t)=\begin{bmatrix} 4-3\cos(nt) & 0 & 0 \\ 6(\sin(nt)-nt) & 1 & 0 \\ 0 & 0 & \cos(nt) \end{bmatrix} \tag{2}$$

$$\boldsymbol{\Phi}_{rv}(t)=\frac{1}{n}\begin{bmatrix} \sin(nt) & 2(1-\cos(nt)) & 0 \\ 2(\cos(nt)-1) & (4\sin(nt)-3nt) & 0 \\ 0 & 0 & \sin(nt) \end{bmatrix} \tag{3}$$

$$\boldsymbol{\Phi}_{vr}(t)=\begin{bmatrix} 3n\sin(nt) & 0 & 0 \\ 6n(\cos(nt)-1) & 0 & 0 \\ 0 & 0 & -n\sin(nt) \end{bmatrix} \tag{4}$$

$$\boldsymbol{\Phi}_{vv}(t)=\begin{bmatrix} \cos(nt) & 2\sin(nt) & 0 \\ -2\sin(nt) & 4\cos(nt)-3 & 0 \\ 0 & 0 & \cos(nt) \end{bmatrix} \tag{5}$$

where n is the angular velocity of the spacecraft i. At the time $t=0^-$, the position vector $\boldsymbol{r}_{i0}$ and velocity vector $\boldsymbol{v}_{i0}^-$ of the spacecraft i in the relative coordinate system is known. Perform a pulse maneuver at the time $t=0$, and change the speed to $\boldsymbol{v}_{i0}^+$ instantly at $t=0^+$ so that the spacecraft can accurately reach the target position $\boldsymbol{r}_i(t_f)$ of spacecraft i at the specified time t_f.

$$\boldsymbol{r}_i(t_f)=\boldsymbol{\Phi}_{rr}(t_f)\boldsymbol{r}_{i0}+\boldsymbol{\Phi}_{rv}(t_f)\boldsymbol{v}_{i0}^+ \tag{6}$$

From Eq.(6), the speed of the spacecraft at the time $t=0^+$ can be calculated by

$$\boldsymbol{v}_{i0}^+=\boldsymbol{\Phi}_{rv}^{-1}(t_f)\boldsymbol{r}_i(t_f)-\boldsymbol{\Phi}_{rv}^{-1}(t_f)\boldsymbol{\Phi}_{rr}(t_f)\boldsymbol{r}_{i0} \tag{7}$$

The first pulse applied of spacecraft i is

$$\boldsymbol{v}_{i1}=\boldsymbol{v}_{i0}^+-\boldsymbol{v}_{i0}^- \tag{8}$$

Substituting into Eq.(1), the speed at the end position of spacecraft i can be calculated.

$$\boldsymbol{v}_i(t_f)^-=\boldsymbol{\Phi}_{vr}(t_f)\boldsymbol{r}_{i0}+\boldsymbol{\Phi}_{vv}(t_f)\boldsymbol{\Phi}_{rv}^{-1}(t_f)\boldsymbol{r}_i(t_f)-\boldsymbol{\Phi}_{vv}(t_f)\boldsymbol{\Phi}_{rv}^{-1}(t_f)\boldsymbol{\Phi}_{rr}(t_f)\boldsymbol{r}_{i0} \tag{9}$$

The last pulse applied is

$$\boldsymbol{v}_{i2}=\boldsymbol{v}_i(t_f)^+-\boldsymbol{v}_i(t_f)^- \tag{10}$$

Each spacecraft applies the initial pulse and the termination pulse according to Eqs.(7, 9). When the two spacecraft i and j detect that a collision is about to occur, they apply unit pulses in opposite directions to the two spacecraft and then perform the above planning.

$$\mathrm{pulse}_i = \frac{\boldsymbol{p}_i - \boldsymbol{p}_j}{\left|\boldsymbol{p}_i - \boldsymbol{p}_j\right|} \tag{11}$$

where pulse_i is the unit pulse applied to spacecraft i, the size is 1 m/s, and the direction is from spacecraft j to spacecraft i. $\boldsymbol{p}_i$ and $\boldsymbol{p}_j$ are the relative positions.

2 Cluster Reconstruction Strategy

The task allocation is an essential issue in multi-agent systems in the field of distributed artificial intelligence, that is, how to allocate appropriate tasks to appropriate agents to obtain better overall performance[11]. In the reconstruction task for the distributed spacecraft cluster, each spacecraft is an independent agent, interacting with other spacecraft around it. Each spacecraft determines its behavior according to the optimization goal expected by the entire cluster, and finally, it makes the whole cluster reach the goal status.

This article assumes that the position and target point information of the spacecraft can be shared with other spacecraft within its communication range. According to the control equation, the spacecraft can complete the formation reconfiguration while ensuring that the spacecraft avoid collisions during the transfer process.

2.1 Initialization

At the time $t=0^-$, each spacecraft's position vector $\boldsymbol{r}_0$ and velocity vector $\boldsymbol{v}_0^-$ in the relative coordinate system is known, where $\boldsymbol{v}_0^- = (0,0,0)^{\mathrm{T}}$ is for each spacecraft. At the initial time, each spacecraft selects the closest target point. According to the position of the target point and the reconstruction time, the initial pulse of each spacecraft can be calculated by Eq.(3) so that the spacecraft can reach the target position at the specified time.

$$\boldsymbol{v}_0 = \boldsymbol{\Phi}_{rv}^{-1}(t_f)\boldsymbol{r}(t_f) - \boldsymbol{\Phi}_{rv}^{-1}(t_f)\boldsymbol{\Phi}_{rr}(t_f)\boldsymbol{r}_0 \tag{12}$$

2.2 Target selection and collision prevention

During the spacecraft cluster transfer process, each spacecraft does not know the entire spacecraft clusters' information and can only exchange information with other spacecraft within the communication range. The spacecraft needs to solve target point conflicts during the reconstruction process and avoid collision. Three strategies can be used to accomplish the above goals.

2.2.1 Strategy-1

The initial target point is the closest, and the first pulse is applied according to the principle of double-pulse rendezvous maneuver. As shown in Fig.2, when the distance between two spacecraft is less than the communication threshold, the spacecraft can exchange information (including the selected target point and current position). Set a fixed threshold $f_{\mathrm{fix\_flag}}$. If the spacecraft can communicate, select the same target point and the closer spacecraft is smaller than $f_{\mathrm{fix\_flag}}$, and restore this target point as the target point of the spacecraft. Other spacecraft that also want to reach this target point change the target point. The spacecraft that changes the target point uses the current position $\boldsymbol{r}_1$ and current speed $\boldsymbol{v}_1$ as the position and speed corresponding to the initial state of the double pulse rendezvous maneuver, and re-planning, apply pulse

$$\boldsymbol{v} = \boldsymbol{\Phi}_{rv}^{-1}(t_f)\boldsymbol{r}(t_f) - \boldsymbol{\Phi}_{rv}^{-1}(t_f)\boldsymbol{\Phi}_{rr}(t_f)\boldsymbol{r}_1 - \boldsymbol{v}_1 \tag{13}$$

If the distance between the two space craft is not less than the fixed target threshold, the target point is allocated to the spacecraft further away, and the closer ones select the sub-optimal solution. Under both circumstances, the principle of double-pulse rendezvous maneuver is used to plan and apply pulses.

If the distance between the two spacecraft is less than the fixed target threshold, to prevent collisions, the instantaneous unit pulse shown in Eq.(11) is applied to the two spacecraft. At that moment, the state is taken as the initial state, using the principle of double-pulse rendezvous maneuver to reinitialize, recalculate, and plan.

2.2.2 Strategy-2

The method of target allocation is the same as

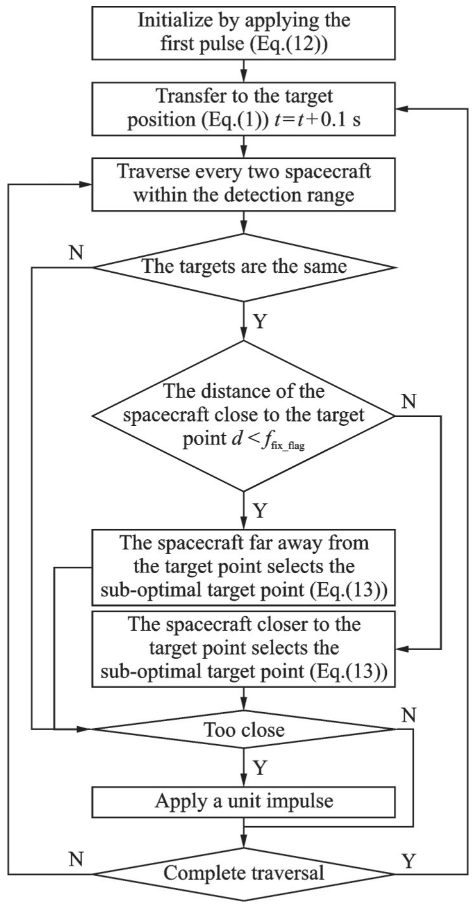


Fig.2 Flowchart of Strategy-1 to reselect target

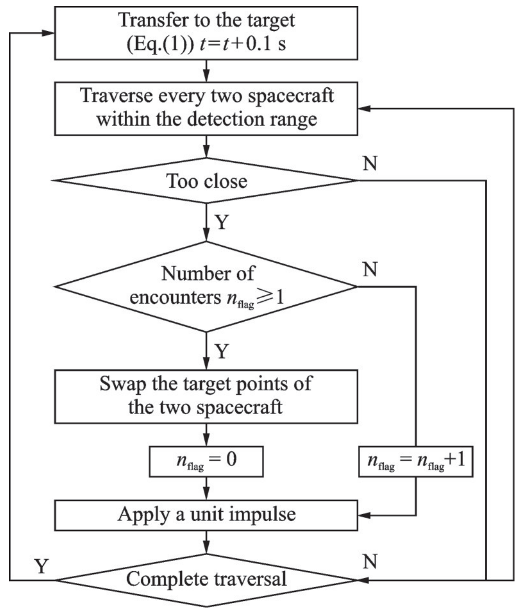


Fig.3 Flowchart of Strategy-2 to avoid a collision

Strategy-1. Before applying the initial pulse, each spacecraft checks whether the spacecraft within its communication range conflicts with its target point. If there is a conflict, the target point is assigned to a distant spacecraft.

A measure taken by two spacecraft to avoid a collision is defined as one encounter. In the link to avoid a collision, as shown in Fig.3, n_{flag} is used to record the number of encounters between the two spacecraft. If two spacecraft encounter more than once, exchange the two spacecraft's target points, reset the number of meetings, and apply pulses in the opposite direction to prevent collisions. After running for a while, take the exchanged goal as the endpoint, and re-plan with the state at that moment as the starting state. If there are no multiple encounters, follow the Strategy-1 to prevent collisions.

2.2.3 Strategy-3

When two spacecraft target points within the communication range conflict, the target is assigned to the closest target point in the transfer process. The spacecraft that is farther away selects the secondary advantage and re-plans according to the principle of double-pulse rendezvous. As shown in Fig.4, the other stages are the same as Strategy-2.

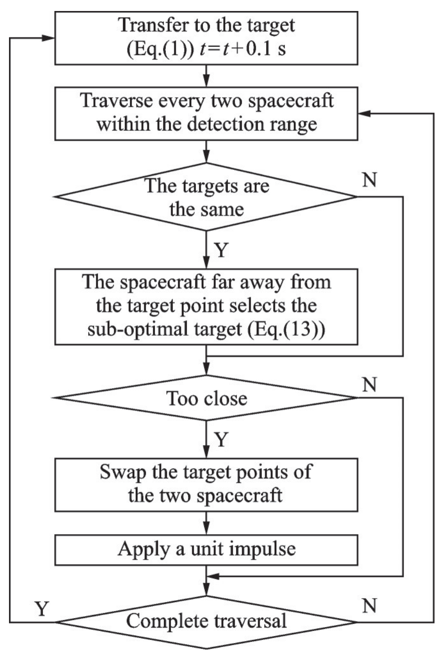


Fig.4 Flowchart of Strategy-3 to restructure the formation

2.3 Terminated pulse

According to the double-pulse rendezvous maneuver principle, each spacecraft arrives at the target point simultaneously. At this time, the last pulse is applied to complete the formation reconstruction. When the spacecraft terminates, the relative speed is 0, then the last applied pulse is determined by Eq.(5) and can be obtained as

$$\boldsymbol{v}(t_f)=\boldsymbol{\Phi}_{vv}(t_f)\boldsymbol{\Phi}_{rv}^{-1}(t_f)\boldsymbol{\Phi}_{rr}(t_f)\boldsymbol{r}_0-\boldsymbol{\Phi}_{vr}(t_f)\boldsymbol{r}_0+\boldsymbol{\Phi}_{vv}(t_f)\boldsymbol{\Phi}_{rv}^{-1}(t_f)\boldsymbol{r}(t_f) \tag{14}$$

3 Simulation

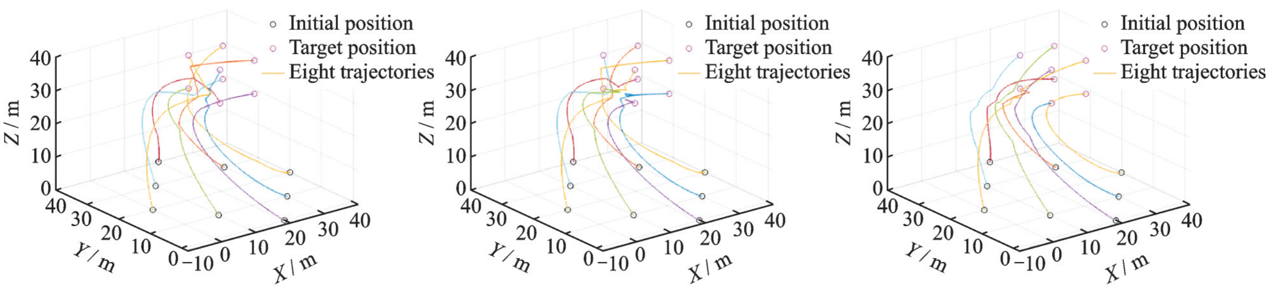
The Runge-Kutta method[12] is used to approximate the differential expression for simulation, and the simulation environment is commercial software.

3.1 Given target location

Assuming that the spacecraft cluster performs formation reconstruction tasks at an orbital altitude of 2 000 km, and the communication range is 8 m. The spacecraft can exchange information with spacecraft within 8 m of its own. If the distance is less than 2 m, measures are taken to prevent collisions and the target configuration is set to be completed in 2 000 s. The size of the applied pulse represents the size of fuel consumption. Eight spacecraft are selected, and the target position of the spacecraft cluster is given.

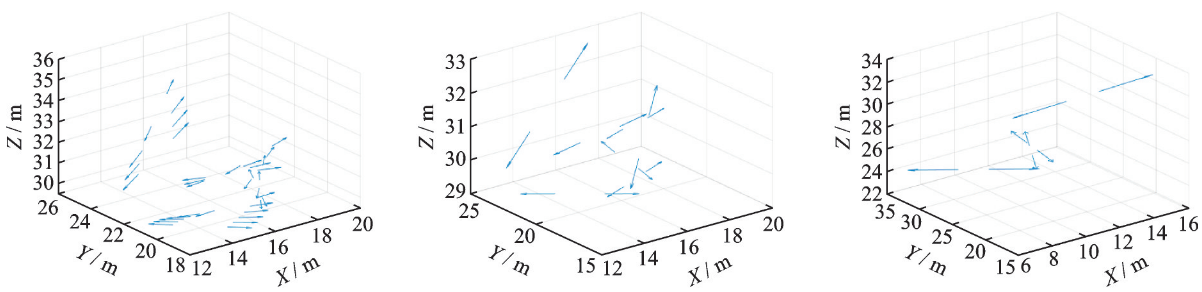
Under the same conditions as mentioned above, setting the fixed threshold in Strategy-1 to 2 m, all three strategies can meet the requirements, and the running trajectory is shown in Fig.5.

The situations preventing the collision pulse application in these three strategies are shown in Fig.6.



(a) Strategy-1 (b) Strategy-2 (c) Strategy-3

Fig.5 Trajectories of three strategies



(a) Strategy-1 (b) Strategy-2 (c) Strategy-3

Fig.6 Pulse to avoid collisions of three strategies

The magnitude of the pulse is used to indicate fuel consumption. The results are shown in Table 1. It can be seen that under the above initial conditions, the use of Strategy-3 achieves the best results.

Table 1 Comparison of the results of three strategies

Strategy	Fuel consumption/ ($\mathrm{m \cdot s^{-1}}$)	Number of pulses to avoid collision
Strategy-1	6.954 698 054 633 933	36
Strategy-2	3.563 159 922 123 792	14
Strategy-3	1.930 819 721 423 483	8

3.2 Different completion time

The three performance conditions are tested separately for different completion times by taking a value every 10 s from 1 000 s to 2 500 s. The other parameters are the same as in Section 3.1. The result comparison is shown in Fig.7.

For different completion times, the performance of Strategy-1 is much worse than those of Strategy-2 and Strategy-3. Not only the fuel consumption but also the fluctuation under different

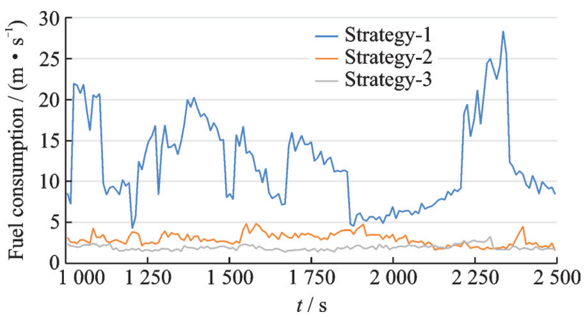


Fig.7 Comparison of fuel consumption with different strategies at different time

time are large. For Strategy-2 and Strategy-3, in most cases, the fuel consumption of Strategy-3 is lower than Strategy-2; and for different completion times, the total fuel consumption fluctuates little.

3.3 Random location

The time is 2 000 s. Points are randomly picked in a cube with a side length of 20, and the distance between the target points is not less than 4. The starting point cube center is (20, 20, 0), and the ending cube center is (20, 20, 80). The 1 000 sets of data are randomly taken and Strategy-1 and Strategy-3 are used for numerical simulation.

The average fuel consumption of Strategy-1 is 3.957 455 817 m/s. The standard deviation is 2.888 691 55 m/s, the maximum is 23.243 214 13 m/s, and the minimum is 0.964 501 382 m/s.

The average fuel consumption of Strategy-3 is 2.222 695 449 m/s. The standard deviation is 0.707 993 186 m/s, the maximum is 6.392 273 402 m/s, and the minimum is 1.104 730 549 m/s.

According to these 1 000 sets of fuel consumption data, the corresponding histogram and corresponding standard curves for fuel consumption segments are drawn (Figs.8, 9).

It can be obtained from the comparison of Fig.8 and Fig.9 and the related data for different randomly generated locations, Strategy-3 is used for reconstruction. The fuel consumption fluctuates little. The data are relatively concentrated, and the maximum value is less than the fuel consumed by Strategy-1.

In the 1 000 sets of data in this test, there are 697 sets of data whose fuel consumption for Strategy-3 is lower than that for Strategy-1, and the maximum reduction is 21.129 640 6 m/s. The fuel consumption of the remaining 303 groups of data increases. The maximum increase is 3.113 395 942 m/s, which means that in 70% of the cases, using Strategy-3 is better than Strategy-1, and the increase in fuel consumption will not be large under bad conditions. The first 100 sets of data are selected to draw a line graph for comparison, as shown in Fig.10.

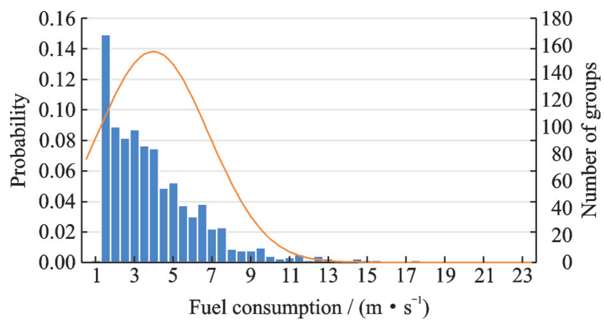


Fig.8 Random location fuel consumption histogram of Strategy-1

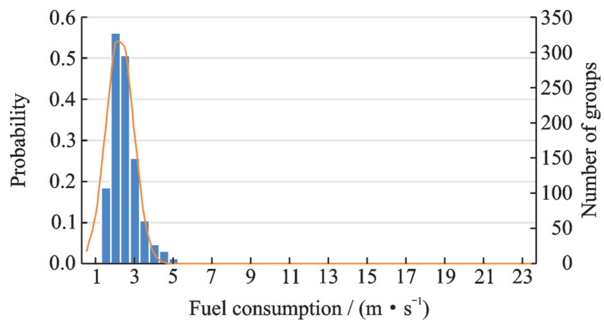


Fig.9 Random location fuel consumption histogram of Strategy-3

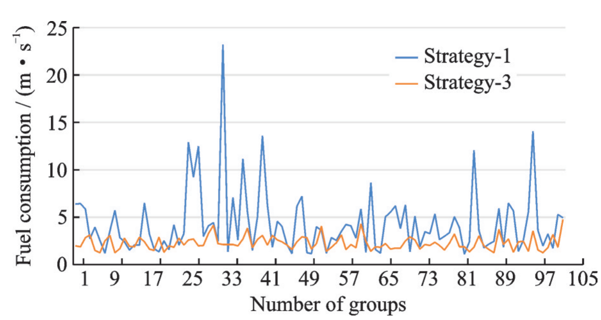


Fig.10 Comparison of fuel consumption between Strategy-1 and Strategy-3 at random locations

3.4 Multiple spacecraft

The number of spacecraft is expanded to 42 for numerical simulation. The parameters are set as follows: The reconstruction time is 2 500 s; the spacecraft communication range is 15 m; the distance to take collision measures is 2 m; and the fixed threshold in target allocation is 2 m. The three strategies can achieve formation reconfiguration. Strategy-1 has a total fuel consumption of 151.390 645 883 709 1 m/s, and the number of pulses applied to prevent collisions is 1 012. Strategy-2 has a fuel consumption of 44.938 819 197 896 287 m/s, and the number of pulses applied to prevent collisions is 274. Fuel consumption of Strategy-3 is 16.622 778 609 066 955 m /s. The number of pulses applied to prevent a collision is 86. Compared with strategies under the initial condition, Strategy-3 saves more fuel, and the number of pulses applied is also fewer.

However, the position setting of the target point in this paper is relatively concentrated. The three strategies will have a low probability of not reaching the target point for the more scattered target points, so this scheme may not be suitable for all spacecraft cluster missions. The next step of research is to find a better solution to avoid this situation. Besides, local information may limit the optimization effect, and intelligent control and artificial intelligence algorithms can be considered to achieve global optimization.

4 Conclusions

Three strategies based on the principle of dual-pulse rendezvous maneuvers are designed to complete the spacecraft cluster's reconstruction. Strategy-1 and Strategy-2 determine the priority of the spacecraft based on the distance from the target point. For Strategy-3, the spacecraft close to the target point has a higher priority. Strategy-1 uses a unit pulse to avoid a collision. Strategy-2 and Strategy-3 switch the target points when two spacecraft encounter more than once and use a unit pulse to avoid a collision. Numerical simulations show that the three strategies are effective. When each spacecraft in the cluster does not fix its target point, the spacecraft cluster can use a limited number of pulses to complete the formation reconstruction task within the specified time. Strategy-3 is better than Strategy-1 in all simulation cases in the sense of less fuel consumption with different completion times and given location. It is more effective than Strategy-2 in most of the completion time. With a random initial position and given time, Strategy-3 is better than Strategy-1 in about 70% of the cases and more stable. In the comparison of the three strategies, Strategy-3 for refactoring can achieve the best results.

References

[1] WEN X. Space exploration is entering the era of spacecraft cluster[J]. Frontiers, 2017(4):19-26.

[2] REN W. Formation keeping and attitude alignment for multiple spacecraft through local interactions[J]. Journal of Guidance Control and Dynamics, 2007, 30(2): 633-638.

[3] ZHANG Bo, LUO Jianjun, YUAN Jianping. A satellite formation cooperative control strategy based on information consensus[J]. Acta Aeronautica et Astronautica Sinica, 2010, 31(5):1004-1013. (in Chinese)

[4] ZHANG S J, DUAN G R. Cooperative control for distributed satellite formation keeping[J]. Journal of Astronautics, 2011, 32(10):2140-2145.

[5] DANG Zhaohui. Study on bounds model and control for spacecraft cluster[D]. Changsha: National University of Defense Technology, 2015. (in Chinese)

[6] JING X N, LIANG X L, ZHANG J Q, et al. Research on optimized control for aircraft swarms combat formation[J]. Computer Simulation, 2017, 34(4): 90-94.

[7] REN W. Formation keeping and attitude alignment for multiple spacecraft through local inter-actions[J]. Journal of Guidance Control and Dynamics, 2012, 30(2): 633-638.

[8] JIANG Fanghua, LI Junfeng, BAOYIN Heixi, et al. Two-point boundary value problem solutions to spacecraft formation flying[J]. Journal of Guidance Control and Dynamics, 2009, 6(6):1827-1837.

[9] XIANG Kaiheng, XIAO Yelun. Research on fuel consumption of pulse orbit change in space rendezvous[J]. Chinese Space Science and Technology, 1999(3):3-5. (in Chinese)

[10] CURTIS H D. Orbital mechanics for engineering students[M]. UK: Butterworth-Heinemann, 2010.

[11] TANG S Y, ZHU Y F, LI Q, et al. Survey of task

allocation in multi agent systems[J]. Systems Engineering and Electronics, 2010, 32(10):2155-2161.

[12] JAMESON A J, SCHMIDT W, TURKEL E. Numerical solution of the Euler equations by finite volume methods using Runge Kutta time stepping schemes[J]. AIAA Journal, 1981(6):1259-1277.

Acknowledgement This research was supported by the Advanced Research Project of China Manned Space Program.

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Author contributions Prof. **WANG Shuquan** proposed the research topic, designed research plans, provided instructional support, and revised the manuscript. Mr. **YU Binggu** implemented the research process, conducted the analysis, interpreted the results, and wrote the manuscript. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: ZHANG Tong)

基于局部信息的分布式航天器集群重构

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摘要:航天器集群的目标是使用尽可能小的燃料消耗完成队形重构任务。为了研究基于局部信息分布式航天器集群的重构问题,利用双脉冲交会机动原理设计了3种避免碰撞的目标选择策略。策略1在目标点发生冲突时根据与目标的距离确定目标点的选择,并使用单位脉冲来避免碰撞;策略2更改了避免碰撞的策略,当两个航天器不止一次相遇时,交换两个航天器的目标点;在策略3中,更接近目标点的航天器具有更高的优先级,当两个航天器不止一次相遇时,也会交换两个航天器的目标点。对3种策略分别对给定位置、不同完成时间、随机位置进行对比,数值仿真结果表明,这3种策略都可以在规定的要求下完成航天器集群重构。对于不同的完成时间和给定位置,策略3的燃料消耗要比策略1低并且在大部分完成时间下也要比策略2的燃耗低,在随机位置测试中大概70%的情况策略3比策略1燃耗低且整体更加稳定。

关键词:航天器集群;队形重构;相对Lambert问题;双脉冲交会;分布式机动