Local Information based Organization of Distributed Spacecraft Swarm Using Artificial Potential Field

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Abstract. This paper investigates the problem of distributed organization of spacecraft swarm where each spacecraft is an independent agent that can interact with neighbouring members within a certain distance. According to the global objective of the organization, each agent makes decisions on its behaviour based on its own status and adjacent members within a certain distance. By a carefully designed strategy and under certain conditions, the swarm can accomplish the global objective. In the configuration reconstruction mission, only the expected global configuration is specified. The target position of each spacecraft is uncertain and not fixed. At the beginning of the reconstruction, every spacecraft can only determine the initial target point according to certain rules. It is possible to have conflicts of destination point selections since all spacecraft can only get local information. Each spacecraft constantly adjust their target point according to the local information in the process of accomplishing this task, until the group converges into the specified global configurations. In this paper, three different target allocation strategies are designed, so that each spacecraft can do continuous selection and optimization, and finally determine a non-conflict target matching to complete the formation reconstruction task. The artificial potential field method is utilized to control each spacecraft and complete the path planning, while ensuring that the spacecraft swarm to achieve collision avoidance and other requirements. In addition, the time and fuel consumption are compared. The numerical simulations show that these three strategies make obvious optimization effects.

1. Introduction

At present, some countries have proposed and gradually implemented various swarm spacecraft plans for astronomical observation, deep space exploration, earth exploration and space technology verification. Including The NASA Cyclone Global Navigation Satellite System (CYGNSS) Mission[1], “Tiantuo-3” micro-nano satellite cluster plan, Autonomous Nanotechnology Satellite[2] DARPA F6 program[3], Edison Demonstration of SmallSat Networks[4] and others.

The distributed spacecraft swarm has the advantages of high functional density and technical performance, low investment and operation cost, strong flexibility, short development cycle and low risk. Multiple small spacecraft work together to complete complex space exploring missions has become a hotspot in the international space field. The application and development of spacecraft clusters will certainly become the strategic focus of future international space development.[5]
Intelligent Satellite swarm is essentially a problem of distributed organization where each spacecraft is an independent agent that can interact with neighbouring members. Due to the particularity of the information interaction among the spacecraft in the large-scale spacecraft formation, the architecture proposed for the small-scale formation composed of several spacecraft has some limitations when applied to the large-scale formation. Large-scale spacecraft formation control are limited by its architecture and inter-satellite communication performance, so it is difficult to obtain all state information of the system, which brings some difficulties to the collaborative control of the formation system and the strategy of spacecraft swarm formation based on local information needs to be considered.

Traditional control methods of spacecraft formation on relative orbit always base on circular orbit and ignores the influence of external perturbation, using Linear C-W Equation [6] to describe the relative motion model of spacecraft, and using consistency theory[7] and adaptive control[8] to complete formation reconstruction. In this paper, the thinking mode of swarm intelligence[9] is used as a reference. Each distributed agent in the swarm with simple strategy works together to achieve the target configuration based on local information.

2. Methodology
In this paper, only the expected global configuration is specified in the configuration reconstruction mission. The target position of each spacecraft is uncertain and not fixed. And three different target allocation strategies are designed so that each spacecraft can do continuous selection and optimization, and finally determine a non-conflict target matching to complete the formation reconstruction task.

This paper uses the artificial potential field method based on the information of the target configuration and the interaction between adjacent spacecraft within a certain range to control each spacecraft and complete the path planning, while ensuring that the spacecraft swarm to achieve collision avoidance and other requirements. At the beginning of the reconstruction, every spacecraft can only determine the initial target point according to certain rules. It is possible to exist conflicts of destination point selections since all spacecraft can only get local information. Each spacecraft constantly adjust their target point according to the local information in the process of accomplishing this task, until the group converges into the specified global configurations.

3. Artificial Potential Approach
In reconfiguration of distributed spacecraft swarm, each spacecraft can plan a feasible and safe path to reach the target point by using artificial potential field regulations after determining its target point. As an extended form of the Lyapunov function, the potential function can be used in the subsequent analyses. It is this function that may be defined analytically and used to drive the state vector of a dynamical system to the desired goal. Frank McQuade extended the artificial potential field method to on-orbit equipment.[10] That thesis, based on the Lyapunov's method[11] and extended to potential function theory, investigates an autonomous method of assembly large structures on Earth Orbit. YAO Hong extended the artificial potential field method to the cooperative control of spacecraft formations to solve the overall movement, global dispersion and configuration transformation.[12]

The collaborative control algorithm based on artificial potential field method has less computational complexity and is suitable for multi-agent real-time cooperative control. This paper extends the artificial potential field method to the cooperative control of spacecraft formations. In this scheme, multiple spacecraft in a swarm achieve formation control through attractive and repulsive forces among themselves. Based on the potential energy determined by the location and the Hill equation, the dynamic equations of the on-orbit spacecraft are established. With the orbital constraint, the artificial potential field method gets rid of the local minimum problem.

| Parameter                        | Limitation |
|----------------------------------|------------|
| the distance to the target point  | 0 m        |
| Speed when the spacecraft reaches the target | 0 m/s      |
Because the potential energy function is determined in the zero point of the coordinate system, the potential energy of the object is a function related to the position coordinates and its speed. So for every spacecraft, its potential energy \( P \) is as followed formula based on the conditions shown as Table 1.

\[
P = \frac{1}{2} k_1 \rho^T \cdot \rho + \frac{1}{2} k_2 \rho^T \cdot \rho
\]  

(1) 

where \( \rho \) is the distance from initial position \( \vec{r} \) to the target position \( \vec{r}_{\text{goal}} \) \( \cdot \) and \( \dot{\rho} \) and \( \dot{\rho}_{\text{goal}} \) are the speed of that spacecraft. \( \vec{r} \) and \( \vec{r}_{\text{goal}} \) are the accelerations. \( k_1 \) and \( k_2 \) are constant coefficients. The speed of the spacecraft is required to be 0m/s both at the starting point and at the target point. So that

\[
\vec{\dot{r}} = \vec{\dot{r}} - \vec{\dot{r}}_{\text{goal}}
\]

(2) 

\[
\vec{\dot{r}}_{\text{goal}} = 0, \quad \vec{\dot{r}}_{\text{goal}} = f (\vec{r}_{\text{goal}}, \vec{\dot{r}}_{\text{goal}})
\]

where \( u \) is the control of spacecraft and \( f \) is the orbital acceleration of gravity, related to the current position and velocity. And the derivative of equation (1) is:

\[
\dot{P} = k_1 \vec{\dot{r}}^T \cdot \vec{\rho} + k_2 \vec{\dot{\rho}}^T \cdot \vec{\rho}
\]

(3) 

Equation (3) is always negative so that each spacecraft reaches the target point with zero speed. And the derivative of \( P \) is given by

\[
\dot{P} = \left( k_1 \vec{\ddot{r}} + k_2 \vec{\ddot{\rho}} \right) \cdot \vec{\rho}
\]

(4) 

From equation (2) and equation (4), the control \( u \) can be derived as:

\[
k_2 u = - \dot{\rho} - k_1 \rho + k_2 f (\vec{r}_{\text{goal}}, \vec{\dot{r}}_{\text{goal}}) - k_2 f (\vec{r}, \vec{\dot{r}})
\]

(5) 

\[
u = - k_2 \dot{\rho} - k_2 \rho + f (\vec{r}_{\text{goal}}, \vec{\dot{r}}_{\text{goal}}) - f (\vec{r}, \vec{\dot{r}})
\]

From equation (2) and equation (5), the acceleration of every spacecraft should be

\[
\vec{\ddot{r}} = f (\vec{r}, \vec{\dot{r}}) + u = - k_2 \vec{\ddot{\rho}} - k_2 \vec{\rho} + f (\vec{r}_{\text{goal}}, \vec{\dot{r}}_{\text{goal}})
\]

(6) 

However, for on-orbit spacecraft, its speed should not be determined only by the above variables, but also by the gravity. The well-known Hill Equation[13] can help a lot:

\[
\ddot{r} = \begin{bmatrix}
3w^2 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & -w^2
\end{bmatrix} \vec{r}_{\text{goal}}
\]

(7) 

Where \( \vec{r} = [x, y, z] \) =, and one of the conditions for completion of the reconfiguration is that the speed of the spacecraft at the target point is 0m/s, which is \( \vec{r}_{\text{goal}} = 0 \). So the orbital acceleration of gravity \( f \) in equation (2) can be replaced by

\[
f (\vec{r}_{\text{goal}}, \vec{\dot{r}}_{\text{goal}}) = \frac{3w^2 0 0}{0 0 0} \vec{r}_{\text{goal}}
\]

(8) 

In Artificial Potential Fields, obstacle avoidance is important, which have different degrees of repulsive force for each spacecraft. At the same time, when the distance between spacecraft is less than a certain threshold, it will also exert some repulsive force on other spacecraft to avoid other spacecraft.

\[
F_{\text{rep}} (q) = k_{\text{rep}} \left( \frac{1}{\|\vec{r} - \vec{r}_{\text{obs}}\|} - \frac{1}{\rho_{\text{th}}} \right) \frac{\vec{r} - \vec{r}_{\text{obs}}}{\|\vec{r} - \vec{r}_{\text{obs}}\|^3}
\]

(9) 

For low-altitude orbits (2000km), the gravity of each spacecraft at the target point in equation (7) is set as follows:

\[
\ddot{r} = f (\vec{r}, \vec{\dot{r}}) + u = - k_3 \vec{\ddot{\rho}} - k_4 \vec{\rho} + \begin{bmatrix}
3w^2 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & -w^2
\end{bmatrix} \vec{r}_{\text{goal}}
\]

(10) 

To sum up, in the artificial potential field, the target point produces “attraction” to the spacecraft and the obstacle produces “repulsive force”, that is, acceleration controls the spacecraft’s action to
make every spacecraft reach its determined target. And all the simulation results in this paper were obtained by setting $k_3 = 1 s^{-1}$, $k_4 = 0.1 s^{-2}$, $k_{rep} = 1 \cdot \frac{m^4}{s^5}$.

4. Target Assignment

In the configuration reconstruction mission of distributed spacecraft swarm, the target point of each spacecraft is uncertain and not fixed. Each spacecraft is an independent agent that can interact with surrounding members, and then according to the whole spacecraft group expectations, the status itself and adjacent spacecraft within a certain distance to make decisions and determine its own control behaviour, thus all the spacecraft can form the target configuration.

Task allocation problem is an important research content in multi-agent system, that is, how to allocate appropriate tasks to appropriate agents to achieve the overall optimal performance. This paper refers to some models of swarm intelligence to accomplish target point allocation, which is the collective behaviour of decentralized, self-organized systems, natural or artificial. The agents follow very simple rules, and although there is no centralized control structure dictating how individual agents should behave, local, and to a certain degree random, interactions between such agents lead to the emergence of “intelligent” global behaviour, unknown to the individual agents.

This paper assumes that the information of the spacecraft includes its position in the relative motion coordinate system and the selected target point can be shared to its neighbours within a certain distance.

4.1. 1st target matching strategy

At the beginning of the reconfiguration, every spacecraft knows its own position and the location of all the target points in the relative coordinate system so that it can calculate a sequence of target points from the nearest to the farthest according the distance to each target position and choose the nearest one as the initial target.

In the process of the reconfiguration, it is possible to exist conflicts of destination point selections since all spacecraft can only get local information. Each spacecraft constantly adjust their target point according to the local information in the process of accomplishing this task, until the group converges into the specified global configurations.

Given that most of the target configurations are concentrated, when a spacecraft exchanges information with another spacecraft in the communication distance and finds that the target point of the two spacecraft is the same one, the spacecraft farther to this target point is still heading to the target point, and the other spacecraft choose sub-optimal target. Artificial potential field method can help spacecraft avoid collision with other spacecraft and reach the final target point.

| Table 2. Fuel Consumption of 8-spacecraft |
|------------------------------------------|
| X Label (m/s) | Y Label (m/s) | Z Label (m/s) |
| 1 | 7.3392 | 6.5572 | 5.0379 |
| 2 | 9.3449 | 10.7258 | 7.2993 |
| 3 | 2.6644 | 11.3350 | 7.3319 |
| 4 | 1.8511 | 11.8738 | 6.7698 |
| 5 | 7.2117 | 7.2576 | 5.0244 |
| 6 | 3.9472 | 5.9216 | 6.7279 |
| 7 | 0.8330 | 4.4455 | 5.0126 |
| 8 | 4.1498 | 5.7681 | 5.0154 |

This strategy was applied to the task of forming a cube from eight spacecraft in a plane on the orbit of 2000km and the simulation results is shown in Figure 1. It takes 184.78s for eight spacecraft to complete the reconfiguration, and the sum of fuel consumption (velocity increment) of all spacecraft is 178.011m/s. The fuel consumption of each spacecraft is shown in 0.

4.2. 2nd target matching strategy
Data analysis found that many spacecraft have reached a certain target point, but then give this target to the later spacecraft for reducing additional fuel consumption.

In view of the above situation, if the distance between a spacecraft to its target point less than a certain threshold at this moment, the target point is assigned to the spacecraft and is fixed. When other spacecraft that also choose this target communicates with this spacecraft and finds that the target point fixed, and then the others need to select the suboptimal target.

The other rules remain the same, every spacecraft calculate a sequence of target points from the nearest to the farthest according the distance to each target position and choose the nearest one as the initial target at the beginning. When a spacecraft exchanges information with another in the communication distance and finds that the target points are the same one, the spacecraft closer to this target point choose sub-optimal target, the other one is still heading to the target point.

This mode of assignment can be used in the above eight spacecraft mission and the simulation result is shown in Figure 2. The time required for the formation reconstruction of eight spacecraft is 108.42 s, which is nearly half of the time using the first strategy. The sum of fuel consumption of the spacecraft is 120.8247 m/s, which is reduced by nearly one third compared with the first strategy, and the fuel consumption of each is shown in Table 3.

| X Label (m/s) | Y Label (m/s) | Z Label (m/s) |
|---------------|---------------|---------------|
| 1             | 7.3392        | 6.5572        |
| 2             | 9.3449        | 10.7258       |
| 3             | 2.6644        | 11.3350       |
| 4             | 1.8511        | 11.8738       |
| 5             | 7.2117        | 7.2576        |
| 6             | 3.9472        | 5.9216        |
| 7             | 0.8330        | 4.4455        |
| 8             | 4.1498        | 5.7681        |

Figure 2. The trajectories of swarm

4.3. 3rd target matching strategy

In the previous strategy, the priority order of the spacecraft to select the target point is determined by the distance between the initial position of the spacecraft and all the target points. With the spacecraft moving, the distance changes a lot. This paper proposed some improvements. Spacecraft choose sub-optimal target based on the distance between the current position and the target point other than the distance between initial position and the target point. And the target point that has been ceded to other spacecraft in the competition should be removed from the order of priority.

Such a method can be applied in the above task and the simulation result is shown in Figure 3. And it takes 98.6638 s to complete the task, the fuel consumption of each spacecraft is shown in Table 4, and the sum of fuel consumption of the spacecraft is 112.4682 m/s, which is slightly shortened.

| X Label (m/s) | Y Label (m/s) | Z Label (m/s) |
|---------------|---------------|---------------|
| 1             | 5.5099        | 4.5176        |
| 2             | 3.8582        | 4.7856        |
| 3             | 4.3568        | 7.6835        |
| 4             | 4.8494        | 6.4218        |
| 5             | 2.4779        | 2.5042        |
| 6             | 3.5139        | 3.7904        |
| 7             | 0.9437        | 3.6791        |
| 8             | 2.5010        | 0.8347        |

Figure 3. The trajectories of swarm

5. Comparison and conclusion

The above simulation results have proved the feasibility and effectiveness of the proposed method. By extending this method to the reconfiguration of more spacecraft, it is found that spacecraft can complete the selection of target points based on local information and get a safety trajectory to
complete the mission. This section compared the time and fuel consumption in the reconfiguration of 42 spacecraft from a plane to a ball using above three strategies. And Table 5 is the result of the comparison.

On the basis achieving the target configuration, the three strategies showed significant improvement in the consumption of fuel and time.

Just because the target points are concentrated, this paper set that the spacecraft closer to this target point is still heading to the target point, and the other spacecraft choose sub-optimal target when the target points are consistent in most cases. These methods and strategies may not apply to all missions. Finding a general target allocation method is the next research focus. In addition, local information limits the optimization effect, and the algorithms of intelligent control and artificial intelligence need to be used to approach the global optimum.

**Table 5.** Fuel Consumption analysis of 42-spacecraft swarm organization

|          | 1st strategy | 2nd strategy | 3rd strategy |
|----------|--------------|--------------|--------------|
| Trajectories in LVLH frame | Time(s) | Fuel(m/s) | Time(s) | Fuel(m/s) | Time(s) | Fuel(m/s) |
|          | 1239.2514    | 3876.656     | 457.2380     | 2297.796     | 397.7956 | 1656.546     |

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**References**

[1] Ruf C, Gleason S, Jelenak Z, et al. The NASA Cyclone Global Navigation Satellite System (CYGNSS) Mission[J]. 2013.

[2] Clark P E, Curtis S, Rilee M, et al. ANTS: Exploring the Solar System with an Autonomous Nanotechnology Swarm[C]// Lunar & Planetary Science Conference. 2002.

[3] Maciucu D, Chow J, Siddiqi A, et al. A Modular, High-Fidelity Tool to Model the Utility of Fractionated Space Systems[M]// Encyclopedia of Aerospace Engineering. 2010.

[4] Yost B. EDSN - Edison Demonstration for SmallSat Networks Overview[J]. 2013.

[5] Wen Xin. Space Exploration is Entering the Era of Spacecraft Cluster[J]. People's Forum, Academic Frontier, 2017(05):21-28.

[6] Clohessey W H. Terminal Guidance System for Satellite Rendezvous[J]. Aerospace Sci, 1960, 27(9).

[7] Ren W. Formation Keeping and Attitude Alignment for Multiple Spacecraft Through Local Interactions[J]. Journal of Guidance Control & Dynamics, 2012, 30(2):633-638.

[8] Ruiter A D. Adaptive spacecraft formation flying with actuator saturation[J]. Proceedings of the Institution of Mechanical Engineers Part I Jo urnal of Systems & Control Engineering, 2010, 224(4):373-385.

[9] Bonabeau E, Dorigo M, Theraulaz G. Swarm intelligence: from natural to artificial systems[M]. Oxford University Press, Inc. 1999.

[10] Mcquade, Frank. "Autonomous control for on-orbit assembly using artificial potential functions." University of Glasgow. 1998(1997).

[11] R. Kalman, and J. Bertram. "Control system analysis and design via the second method of Lyapunov: (I) continuous-time systems (II) discrete time systems." IRE Transactions on Automatic Control. Vol. 4, No.3, 2003, pp. 112-112.

[12] Yao, Hong and Tang, Yafeng. "Coordinated control of spacecraft formation based on the artificial potential field /"// China Intelligent Automation Conference. 2009, pp. 883-889.

[13] Clohessey, W. H. "Terminal Guidance System for Satellite Rendezvous." Aerospace Sci. Vol. 27, No. 9, 2012, pp. 653-658.