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Self-organizing control strategy for asteroid intelligent detection swarm based on attraction and repulsion

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ABSTRACT

The self-organizing control strategy for asteroid intelligent detection swarm, which is considered as a space application instance of intelligent swarm, is developed. The leader-follower model for the asteroid intelligent detection swarm is established, and the further analysis is conducted for massive asteroid and small asteroid. For a massive asteroid, the leader spacecraft flies under the gravity field of the asteroid. For a small asteroid, the asteroid gravity is negligible, and a trajectory planning method is proposed based on elliptic cavity virtual potential field. The self-organizing control strategy for the follower spacecraft is developed based on a mechanism of velocity planning and velocity tracking. The simulation results show that the self-organizing control strategy is valid for both massive asteroid and small asteroid, and the exploration swarm forms a stable configuration.

1. Introduction

Asteroid has always been considered as the residual material generated at solar system formation. Asteroid detection is an important way to understand the origin and evolution of the solar system. With the constant improvement of space activity ability, asteroid detection rises gradually. As early as in 1989, the United States launched the Galileo to start detection of deep space objects. Galileo performed flyby detection of No. 891 Gaspra asteroid with a distance of 1600 km at the process of flying to Jupiter in 1991, and performed flyby detection of No. 243 Ida asteroid with a distance of 2400 km in 1993 [1]. 'Chang'e 2′ of China also completed rendezvous to Toutatis [2]. Hayabusa of Japan performed orbiting and landing detection on the asteroid 1998SF36 and 25143 [3]. "Dawn" prober of the United States performed detection by orbiting Vesta and Ceres from 2011 to 2012 and 2015 respectively [4,5].

There are numerous asteroids located in the asteroid belt. Detecting one or a few asteroids with a single spacecraft can hardly utilize the detection ability fully. NASA put forward ANTs-PAM plan [6–9] and tried to detect multiple asteroids by utilizing a space intelligent swarm. PAM tasks are to be completed by utilizing the space intelligent swarm formed by self-controllable pico-satellites which contains about 1000 different types of pico-satellites with a weight about 1 kg. According to different functions, pico-satellites can be divided to three types, namely *workers*, *leaders* and *messengers*. *Workers*, which account for 80% of the whole pico-satellites swarm, carry specific detecting instruments, such as magnetometer, X ray, γ ray, visible light, infrared ray and neutral mass spectrometer etc. to perform detection task. *Leaders* determine which *Worker* satellites to be used, coordinate on commanding each *Worker* satellites, and process mission data. *Messengers* realize information exchange among *workers*, *leaders* and ground stations. ANTS-PAM adopts the concept of space intelligent swarm to provide a possible and effective solution for the execution of complicated space missions in the future. The asteroid population investigation & exploration swarm (APIES) mission is designed to explore the asteroid main belt, based on the utilization of a large spacecraft and 19 micro spacecraft working cooperatively to achieve the mission objectives [10].

Space intelligent swarm, which is composed of multiple spacecraft, realizes the cooperating via self-organizing control, realizes information sharing via wireless network and realizes the flocking flight via automatic control. It has the advantages of robustness, flexibility and adaptability of scalability [11–13]. The failure of a few spacecraft in a space intelligent swarm will not affect the collaborative interaction among other spacecraft, nor affect realizing the overall objectives of space intelligent swarm. When the spacecraft of space intelligent swarm perform an space task, the controlling of each spacecraft can gradually adapt to the environment through evolutionary process thus

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to adapt to different environment and complete different complex tasks more flexibly. Space intelligent swarm is open. It allows a new spacecraft to be added and allow a spacecraft to exit the swarm. Since the behavior decision of individual only depends on the surrounding environment and neighbor individual, overall coordination and control is not required. Consequently, there is no bottleneck factor existing in the intelligent swarm restricting the quantity and scale. It can be used on control of large-scale swarm. Asteroids are mainly distributed in the asteroid belt. If the space intelligent swarm is placed in the asteroid belt, it can realize asteroid detection.

Self-organizing control is the key technology of space intelligence swarm. Dario Izzo and Lorenzo Pettazzi [14] designed equilibrium morphology technology of space intelligent swarm based on the swarm control method put forward by Gazi et. al [15,16]. to realize the predefined swarm configuration. The spacecraft individual control is constituted by three behaviors, gathering, docking and avoidance. The combination of the three behaviors is to determine the target speed of spacecraft. And the spacecraft feedback control algorithm for speed tracking is put forward. Sreeja Nag and Leopold Summerer [17] further studied the spacecraft swarm self-organization control based on linear function, quadratic function, Gaussian function and other artificial potential field functions, and carried out simulation verification of the three strategies and mixed strategy, namely the dispersion and swarming of spacecraft swarm, avoiding threats by changing the swarm center and avoiding risks not changing the swarm center. Literature [18,19] adopted a self-organizing control strategy similar to that in the aforementioned literature, and further studied the method to achieve space swarm control by utilizing electromagnetic force. Carlo Pinciroli et. al. put forward a pico-satellite swarm control method for the control force constituted by global force, local force and damping term. The simulating calculation realized autonomous control for more than 500 pico-satellites [20].

Specific to asteroid detection task utilizing space intelligence detection swarm, the authors put forward a self-organizing control strategy based on leading-following and studied the control model for asteroid of central gravity and weak gravitation. Firstly, the theoretical model of the asteroid space intelligent detection swarm was provided. Section 2 put forward the leading-following model of asteroid space intelligent detection swarm and Section 3 presented the self-organizing control strategy. Secondly, the behavior of asteroid detection swarm under central gravity and weak gravity was studied respectively in Section 4 and Section 5. Finally, Section 6 concludes the paper.

2. Leading-following model of asteroid space intelligent detection swarm

It is assumed that asteroid space intelligent detection swarm is composed of n probes which move in a three-dimensional space. Ignore the space dimensions of the probe, and consider it as a point in the space. It is assumed that r is the space position vector of all the probes. It can be expressed as $(\mathbf{r}_1^{\mathrm{T}}, \mathbf{r}_2^{\mathrm{T}}, \ldots, \mathbf{r}_i^{\mathrm{T}}, \ldots, \mathbf{r}_n^{\mathrm{T}})^{\mathrm{T}}$ and $\mathbf{r}_i = (x_i, y_i, z_i)^{\mathrm{T}}$, namely $\mathbf{r}$ is the vector formed by x_i, y_i and z_i in three dimensions, where $i = 1, 2, \ldots, n$. Then the temporal first-order derivative $\dot{\mathbf{r}}$, $\dot{\mathbf{r}} = (\dot{\mathbf{r}}_1^{\mathrm{T}}, \dot{\mathbf{r}}_2^{\mathrm{T}}, \ldots, \dot{\mathbf{r}}_i^{\mathrm{T}}, \ldots, \dot{\mathbf{r}}_n^{\mathrm{T}})^{\mathrm{T}}$ and second derivative $\ddot{\mathbf{r}}, \ddot{\mathbf{r}} = (\ddot{\mathbf{r}}_1^{\mathrm{T}}, \ddot{\mathbf{r}}_2^{\mathrm{T}}, \ldots, \ddot{\mathbf{r}}_i^{\mathrm{T}}, \ldots, \ddot{\mathbf{r}}_n^{\mathrm{T}})^{\mathrm{T}}$ of $\mathbf{r}$ are the velocity vector and acceleration vector of all the probes respectively.

When adopting leading-following model, it is assumed that there is only one leader spacecraft in the whole asteroid space intelligent detection swarm, and the other $n-1$spacecraft follow the leader by adopting self-organizing strategy. Without loss of generality, the leader is marked as 1 and the spatial position coordinate is $\mathbf{r}_1 = (x_1, y_1, z_1)^{\mathrm{T}}$. The other probes are followers. The spatial position coordinates are $\mathbf{r}_2, \ldots, \mathbf{r}_n$ respectively.

Based on the aforementioned assumption, the leading-following model of asteroid space intelligent detection swarm is divided to two parts. The first part is that the whole space intelligent swarm adopts self-organizing control strategy to realize a space intelligent swarm composed of followers and leader. The followers follow the leader to perform swarm flight. The self-organizing control strategy is as shown in Section III. The second part is the trajectory planning of leader. It is required to realize the surrounding flight of the leader around the asteroid. If the mass of asteroid is huge, its gravity is bigger relative to the sun's gravity. Under such circumstance, the leader can fly along the orbit around the asteroid under the effect of central gravity. When the asteroid's mass is very small, its gravity relative to the sun's gravity can be ignored. Under such circumstance, the leader fly along sun's gravity orbit under the effect of central gravity of sun. The duration of forming a circle trajectory, which may be possible in the case of satisfying some conditions that are used for Hill equation [21], is too long to be applicable for a real space detection mission. To this end, under the assumption of weak gravity asteroids, trajectory planning strategy was designed based on elliptical cavity virtual potential field. It can control flight of the leader around the asteroid.

3. Self-organizing control strategy of space intelligent detection swarm

The self-organizing control strategy of space intelligent swarm adopts the intelligent swarm self-organization control strategy based on artificial potential function. Assumed that the spatial position of the follower i is $\mathbf{r}_i = (x_i, y_i, z_i)^{\mathrm{T}}$, $i = 2, \ldots, n$. The expected speed is expressed as.

$$\dot{\mathbf{r}}_i = \sum_{j=1, j\neq i}^{n} (\mathbf{u}_{ij}^{IA}(\mathbf{r}) + \mathbf{u}_{ij}^{IR}(\mathbf{r})) \tag{1}$$

when a follower is performing speed planning, the interaction of all other spacecraft of the whole space intelligent swarm shall be considered, namely including the interactions of other followers and the leader. The artificial potential function adopted in literature [16] can be expressed as:

$$\mathbf{u}_{ij}^{IA}(\mathbf{r}) = -a(\mathbf{r}_i - \mathbf{r}_j) \tag{2}$$

$$\mathbf{u}_{ij}^{IR}(\mathbf{r}) = b(\mathbf{r}_i - \mathbf{r}_j)\exp\left(\frac{\|\mathbf{r}_i - \mathbf{r}_j\|^2}{c}\right) \tag{3}$$

$\mathbf{u}_{ij}^{IA}(\mathbf{r})$ is the function of attraction between two individuals and drives them close to each other. $\mathbf{u}_{ij}^{IR}(\mathbf{r})$ is the repulsion function between the two individuals and drives them away from each other. It can be seen from literature [16] that the balance distance δ between two individuals is $\delta = \sqrt{c\,\ln(b/a)}$ and the swarm will converge to an open ball with radius of no greater than $b/a\sqrt{c/2}\exp(-1/2)$.

In order to realize tracking of the planned speed put forward in formula (1), the following control is adopted.

$$\mathbf{f}_i = k_i(\dot{\mathbf{r}}_i - \mathbf{v}_i) + \ddot{\mathbf{r}}_i - \mathbf{a}_i \quad i = 2, \ldots, n \tag{4}$$

Where, k_i is a proportionality factor. Generally, it can be set as a constant; $\dot{r}_i$is the expected speed of the follower i and its expression formula is (1); $\boldsymbol{v}_i$ is the actual speed of the follower i; $\boldsymbol{a}_i$ is the accelerated speed of the follower i under non-control state; $\ddot{\mathbf{r}}$ is the derivative of expected speed. $\dot{r}_i$ It can be expressed as.

$$\ddot{r}_i = \frac{d\dot{r}_i}{dt} = \frac{\partial \dot{r}_i}{\partial r_i}\dot{r}_i + \sum_{j=1, j\neq i}^{n} \frac{\partial \dot{r}_i}{\partial r_j}\dot{r}_j \tag{5}$$