Review on the Development of Satellite Formation and Collision Avoidance Technology

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Abstract. Formation satellites have a very broad application prospect in many aspects due to the characteristics of unlimited baselines, multi-satellites cooperative working, flexible control and strong survivability, such as distributed radar, electronic reconnaissance, three-dimensional imaging, regional navigation and positioning. In the aspect of avoiding space debris collision, the maneuvering avoidance for a single satellite is often adopted, but there are few studies on the coordinated avoidance of formation satellites. This paper introduces the concept and research status of formation satellites, and lists the common formation satellites in the world, then introduces collision warning technologies and collision geometry relation determination of formation satellites, including BOX regional warning method and collision probability warning method. In addition, the strategies of satellite evasive maneuvering are analysed, and various maneuver strategies on different purposes are introduced. Finally, analysing and comparing the research status on debris collision avoidance of formation satellites, a method to keep the working efficiency of formation satellites while maneuvering is put forward.

1. Introduction

With the development of space science, more and more spacecrafts are flying into the space, the space environment has become more and more complex. As of October 2017, the US space surveillance network has catalogued about 23,000 space targets larger than 10cm, and 18,747 public catalogued objects in orbit, of which 14,133 are space debris [1][2]. All kinds of signs show that the space field will face congestion, collision and other safety problems in the future. For the spacecraft safety in the space, collision warning is becoming more and more important. To obtain the early warning information, complete the evading within the early warning time, and ensure the safety, are the primary guarantee for the spacecraft to perform the mission in space.

At the same time, with the level of space technology continues to improve, the concept of "distributed spacecraft" comes into being—it separates some functions into several small spacecrafts. Its advantages are significant: not limited by the physical baseline, multiple satellites work together to broaden the application field, stronger flexibility, and higher survivability. For such formation satellites, collision avoidance is much more complicated. It is necessary to adjust the attitude and orbit of one or even more satellites in the formation by means of propulsion devices, at the same time, it is also necessary to keep the working status and working efficiency of the formation as much as possible. In this context, it is of great practical significance and necessity to study the control maneuver process of formation satellites under the condition of early warning.
2. Research status in the world

2.1. The conception and research status of formation satellites

2.1.1. The conception of formation satellites. The concept of spacecraft formation was proposed in the 1990s with the rapid development of small satellite technology, which is an important innovation in the field of aerospace technology. The formation of each satellite forms a virtual spacecraft by information interacting and collaborative working, in order to achieve the function that a traditional single large satellite cannot achieve in the space mission. Therefore, this concept quickly became a hot spot of academic research in the field of aerospace as soon as it was proposed.

Compared with the traditional satellites, the spacecraft formation has been improved significantly in function and performance. By placing system loads on different member spacecrafts, the spacecraft formation can achieve some special configurations that are difficult for traditional satellites to achieve, such as providing long baselines and large apertures, expanding the field of space applications. Member spacecrafts can use different modes to work independently or cooperatively. For example, in the earth observation mission, several member spacecrafts observe adjacent areas respectively, and then the observation data are spliced and arranged, which improves the efficiency of space applications. Members spacecrafts can be grouped into another configuration, or access to different loads of spacecraft, the satellite system’s flexible switching could enhance the flexibility of space applications. When some members of the spacecraft failure, the rest of the spacecrafts can be reconfigured to achieve the continuation of the system function, or just launch another spacecraft access to the system, enhancing maintainability of spaceflight in orbit.

2.1.2. research status of formation satellites. Germany’s next generation earth observation plan, TanDEM-X mission (shown as Figure 1), aims to generate high-precision 3D Digital Elevation Models (DEM) with positioning accuracy of 12m and relative height accuracy of 2m. It was launched on 21 June 2010. Due to the TanDEM-X scheme's dual technical advantages of no time loss and InSAR height detection, the expected DEM quality will reach the HRTI-3 standard with a relative elevation accuracy which is better than 2m, making it become the most accurate DEM data in the world.

![Figure 1. TanDEM-X satellite](image)

The Gravity Recovery And Climate Experiment (GRACE) mission, a twin-satellite formation flight project between the German aerospace center and NASA, was proposed in 1997 and put into orbit in 2002. The system consists of two satellites in a serial formation with a distance of 170-270km, shown as Figure 2. The relative distance between the two satellites is measured by a K-band microwave measuring device with a precision of micron and a relative speed of less than 1 m/s. The project brings the high-precision global gravity field observation experiment into a new stage and provides a powerful tool for monitoring global environmental changes.
The "white cloud" satellite system is an ocean surveillance satellite system developed by the US in the 1970s, which is used to track and locate radar and communication signals of ships and moving targets at sea. Analyzing of the early "white cloud" satellites information and satellites observations, the "white clouds" satellite constellation is a group of three satellites, the distance between the three satellites are 30-110km, using time difference of arrival techniques to realize positioning. There is no data storage on the satellites. The detection area is limited to the corresponding area of the ground station's visibility [3]. Figure 3 shows the scenario that the "white cloud" passes over the moon.

2.2. Research status of collision early warning technology

2.2.1. Typical collision warning technology. Due to the errors of spacecraft and space debris in the process of orbit observation, determination and prediction, the occurrence of collision is uncertain. Currently, in collision risk assessment, the main criteria are minimum approach distance (the corresponding determination method is Box region method) and probability (the corresponding determination method is the collision probability method). Box region method is to define a space area around the spacecraft (the main target). The space area is centered on the spacecraft, and if other space objects enter into this area, an early warning will occur. The space area defined by the US space shuttle collision warning system is a cuboid with the space shuttle as the center, track direction of ±25km, track surface normal direction and vertical track direction of ±5km. When the debris enters this region, the system will give an early warning and provide more detailed orbit prediction data. Figure 4 shows the space region defined in the Box region method. Box region method has a very obvious drawbacks, it will give a dangerous warning as long as a debris enters into the box region, which could cause waste of space resources.
Collision probability is a more accurate, effective and objective collision criterion widely used in the world. In addition to taking the two values of Miss Distance (MD) and Time of Closet Approach (TCA) as input data, the calculation of collision probability also involves the motion state of two objects and the information of orbit error covariance at the close of time. This method determines the collision probability according to the error covariance information at TCA. When probability is larger than the given threshold value, the warning system will send out an early warning signal. For the international space station and the space shuttle, NASA divides the probability threshold of evasive maneuvers into Yellow Threshold $P_Y (10^{-5})$ and Red Threshold $P_R (10^{-4})$. When probability was larger than $P_R$, evasive maneuver was performed. When the probability is larger than the $P_Y$, the maneuver can be carried out without causing harm to the target of the task. The collision probability method can make the spacecraft to avoid unnecessary maneuvering. Therefore, the space debris collision warning method based on collision probability has become the main method in this field around the world.

In addition, Foster and Estes proposed a numerical method for solving the double integral of polar coordinates according to a certain step size. Patera proposed a method to calculate the collision probability using an equivalent numerical integration model, which can be applied to objects with arbitrary irregular shapes. Chan chooses the representative error and actual approximate parameters to realize the reduction of dimension of double integral, thus obtaining one-dimensional PDF (presented as Rician distribution), and deriving the approximate analytic expression in infinite series. In addition, National University of Defense Science and Technology, Liu Jing's team from Space Center of Chinese Academy of Sciences,Space Engineering University and other universities and research institutes researched the calculation method of collision probability from different perspectives.

### 2.2.2. Collision relative geometry determination and collision location determination

In the space environment, it is possible to have multiple satellites in formation warning at the same time. According to the calculation results of the relative distance, collision position, collision direction and relative collision velocity between the formation spacecraft and dangerous debris, the geometric relationship between large debris and spacecraft can be determined. Take the 3-satellites positioning system as an example, there are two main types of possible collision:

1. Single satellite collision warning.

As Figure 5 shows below, only one satellite in the 3-satellites formation is under collision warning. At this time, the maneuver of this satellite can be considered while keeping the working efficiency of 3-satellites positioning as much as possible.
Figure 5. Single satellite collision warning

(2) Multiple satellite collision warning.

As shown in the figure 6 below, a number of satellites in the 3-satellites formation are under collision warning. At this time, the maneuver of these satellites can be considered while keeping the working efficiency of three satellites positioning as much as possible.

Figure 6. Three satellites collision warning

In the orbital coordinate system, Wang Yuefeng’s team [4] (from National Defense University) reached the following conclusions based on the collision relationship:

1. Head-on collision:
   Before the collision happen, the relative distance in X and Z directions is almost 0. At this time, if the relative distance is Y >0, a head-on collision will occur.

2. Rear-end collision:
   Before collision happen, the relative distance in X and Z directions is almost 0. If the relative distance Y is less than 0, a rear-end collision will occur.

3. Other co-planar collision:
   The relative distance in the Z direction is almost zero before the collision happen:
   - If the relative distances are X>0 and Y>0, the large debris will collide with the aircraft in the front from upward side.
   - If the relative distance X<0 and Y>0, then the large debris collided with the aircraft in the front from bottom side (These two collisions would be dangerous enough to cause the craft to disintegrate and potentially explode violently).
   - If the relative distance is X>0 and Y<0, the large debris will collide with the aircraft in the rear from upward side.
If the relative distance X<0 and Y<0, the large debris will collide with the aircraft in the rear from bottom side (These two collisions are less harmful, but it is still possible to make the spacecraft disintegrated or flight mission interrupted).

In addition, Guo Rong from this team proposed a local collision location determination method: when large debris approaches the space vehicle, the relative motion of two space objects can be regarded as a linear motion, and all perturbation effects can be ignored. In any two adjacent moments, the orbital coordinate system can be "stationary" and the linear equation of the relative distance of the corresponding two moments can be obtained.

The intersection point between the linear equation and the aircraft configuration is the initial collision point. Then, the relative position of the next moment and the previous relative position are taken to form the linear equation, and the intersecting point coordinates with the aircraft configuration can also be obtained. The iterative calculation can be terminated within the required range until the error is acceptable. Through verification, the calculation results of this method can control the precision of the collision point in meters.

2.3. Research status of orbital maneuvering
Short-term avoidance strategy (height separated method):
To forecast the intersection of incident, in N orbital circles before the incident happen, providing a single direction speed increment ΔV along the track, as a result, the orbital height of the objects is separated by a certain distance. This evasive strategy is suitable for the events with short prediction time, and the events have a close geometric relationship. As shown in the Figure 7, A is the orbital transition point, B is the collision point, and C is the position of satellites after the maneuvering at the moment of collision

![Figure 7. Height separated method](image)

This was used by the European Space Agency (ESA) to resolve a high-stakes rendezvous between its ERS-1 satellite and Russia's Kosmos-614 satellite successfully. According to the forecast, this event would take place on June 25, 1997 13:24:46 UTC, ESA control the orbit to provide satellite ERS-1 of 1 m/s (reverse) orbital velocity increment before incident happen, through this maneuver, making ERS-1 satellite orbital altitude is 4 km lower than Kosmos-614 satellite’s altitude, thus greatly reduce the collision probability.

Mid-term avoidance strategy (trace separation method):
If the focus is on saving fuel, or if the forecast of a rendezvous event is sufficiently early (at least a day or more in advance), a medium-term avoidance strategy can be adopted. Before the incident, in the direction along the track, giving one or several small velocity increment ΔV motor to avoid collision, the result is to increase the distance between satellite and debris along the track direction. Since the separation distance along the track direction between the satellite and debris is proportional to the length of the glide arc between the target body's maneuver and the rendezvous time, the increment of velocity needed is approximately 0.06/n(m/s) for each 1km of separation distance along the track direction (where n is the number of loops of the glide track after maneuver). If the given rendezvous warning time is early enough, the trace separation method should be used, and it is best suited for
non-head-on rendezvous events. The Figure 8 shows the situation of the satellite returning to the original orbit after the time of collision. If the satellite returns to the original orbit before the time of collision, the satellite will also pass the collision point B, but it will miss a certain time (or distance) at the time of collision.

Figure 8. Trace separation method

French space agency (Centre National d’Etudes Spatiales, CNES) has used this method to resolve a high-risk rendezvous between its SPOT-2 satellite and debris from the explosion of ARIANE-1 v-16. According to the forecast, this event would occur on July 24, 1997 02:27 UTC. Before the rendezvous happen, debris are flying in front of the SPOT-2 satellite, and the relative velocity is about 4.67 km/s, the CNES provides a speed increment ΔV on the along track direction, made the distance increasing to more than 2 km in the direction along the trails, greatly reduced the collision probability.

In addition, Zhang Yasheng [5] took the maximum invisible time as an indicator to analyze the constellation coverage performance when one or more satellites were missing. Considering the fuel consumption and time the maneuver need, a satellite phase adjustment method is proposed, which is shown as Figure 9. Then based on the worst combination of satellites, using the satellite phase adjustment method, proposed a method to minimizing the transfer time basing on rapid reconfiguration of uniform phase constellations.

Figure 9. Satellite phase adjustment method

Zhang Dongqing [6] of Harbin Institute of Technology proposed a short-term avoidance strategy based on gradient descent method in his paper. The collision probability density function is obtained at the collision point. the satellite position after maneuver can be shifted in the direction of the negative gradient of the collision probability density function.

In the literature, Feng Hao [7] from the department of Beijing Space Vehicle proposed a maneuver strategy based on closed-loop trajectory. The drift of the normal satellite ground trajectory and the adjustment process are as Figure 10: When the trajectory of the ground is \( \Delta L/2 \) located at the eastern boundary (positive to the east), adjust the half-length axis to \( a = a_0 + \Delta a \) (\(a_0\) is the nominal value of the half-length axis). The trajectory of the ground drifts westward. Then, due to the influence of atmospheric resistance, the half-length axis gradually decreases. At \( a = a_0 \), the trajectory just drifts to the western boundary \( -\Delta L/2 \). Thereafter, the semi-major axis continues to decrease, but the trajectory
drifts to the east instead. When \( a = a_0 - \Delta a \), the trajectory drifts to the eastern boundary, then the half-length axis needs to be adjusted again, otherwise the trajectory will continue to drift eastward beyond the boundary allowed. The adjustment is \( 2\Delta a \). Therefore, the ground trajectory constitutes a closed loop, that is, the trajectory maintaining control loop, as shown in the figure below.

![Figure 10. Trajectory maintaining control loop](image)

3. Comparison of research status

Based on the comprehensive research status, the following conclusions can be drawn:

(1) Satellite formation technology is put into use worldwide. In the space target evasive maneuver, the method widely used in the world is to give the spacecraft an instantaneous pulse speed, so that it deviates from the original orbit, so as to reduce the risk of collision. However, when the orbit changes, the working state of the vast majority of satellites will change, and there are few studies on how to keep the working efficiency of formation satellites to the greatest extent when maneuvering.

(2) In terms of collision warning technology, BOX area method and collision probability method are mainly used for collision warning, among which collision probability method can avoid many unnecessary maneuvering evasions of spacecraft and save maneuvering resources. Therefore, collision probability method is a commonly used collision warning method around the world. At the same time, the accuracy of the collision point can be controlled in meters by the local collision position determination method.

(3) In the aspect of spacecraft maneuvering, the methods most commonly used are height separated method and trace separation method. However, such avoidance methods fail to take the working efficiency of satellites during the avoidance period into consideration. Therefore, with the goal of keeping the working efficiency during the avoidance maneuver, multiple factors such as positioning effect, energy consumption and avoidance time can be taken into account comprehensively to build a function optimization model, so as to formulate the most appropriate orbital maneuver mode.

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