Comparative Research on Early Warning Determination Methods of Spacecraft Collision

Sun Hongqiang\textsuperscript{1,*}, Zhang Zhanyue\textsuperscript{2} and Hu Ewen\textsuperscript{1}

\textsuperscript{1}Space Engineering University, Graduate School, Huairou, 101416, China
\textsuperscript{2}Space Engineering University, Huairou, 101416, China

\*Email: sjtushq@163.com

Abstract. With the development of space science, more and more spacecraft have entered into the space, and the operating environment of spacecraft in space has become more complex. Various signs show that the future space field will face congestion, collision and other safety problems, so the collision warning in space is becoming more and more important. It is the primary guarantee for the spacecraft to carry out its mission in space in the future to obtain the early warning information and complete the avoidance within the early time to ensure the environmental safety. In this paper, based on the perspective of collision warning and determination methods, two kinds of warning and determination methods are introduced, including BOX region method and probability method. In addition, by comparing the warning efficiency of these two methods, the results show that, under the same constraint, the probability method is more accurate and saves more space resources than the BOX region method. Considering that the spacecraft is limited in fuel and other resources when working in orbit, it is more scientific to adopt to avoid unnecessary maneuver and waste of resources.

1. Introduction.
Since most space missions are concentrated in low-earth and Geostationary Orbit regions, the vast majority of space debris is currently scattered in Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO). Figure 1 shows the distribution of space targets. LEO debris, its speed is close to the first cosmic speed, about 7 ~ 8 km/s, and spacecraft collision speed can be as high as 10 km/s, even could be up to 16 km/s[1]. The greater the mass of space debris, and the grater the damage is.

Due to the space debris which is more than 10 cm are the biggest threat to the safety of the astronauts, space missions, evasive maneuvers[2], so take the initiative to avoid spacecraft and space debris collision method, is currently the most practical value, the method of space debris collision warning is a prerequisite for successful active evasive maneuvers.
2. Evaluation method of collision warning

In space environment observation, there are certain errors in observation, determination and prediction of spacecraft and space debris in orbit, as shown in figure 2. These errors make it become more uncertain for the collision events. It is necessary to evaluate the risk of collision with corresponding criteria[3]. The main criterions are minimum distance and collision probability.  

2.1. Research status of formation satellites.

The BOX region method uses the minimum distance as the criterion for collision warning. The space area defined by the US Space Shuttle Collision Warning System is a rectangular box with the space shuttle as the center, track direction of ±25km, orbital plane normal direction and vertical track direction of ±5km. When the target enters the area, the system will give warning and provide more detailed orbital forecast data[4]. As shown in figure 3, when space debris enters this BOX area, the system will regard it as a dangerous target and conduct collision warning to provide evasive basis for subsequent spacecraft maneuvers.
Collision probability method using the near distance, time of approaching and the information such as track error covariance, with the basis of the calculated probability to determine the collision probability between spacecraft and debris, when the collision probability is greater than the given threshold, early warning system will send out warning signals, the spacecraft perform evasive maneuvers. NASA divided the probability Threshold of evasive maneuvers into Yellow Threshold with a value of $10^{-5}$ and Red Threshold with a value of $10^{-4}$. When the collision probability is greater than the red threshold, evasive maneuver is carried out. When the collision probability is higher than the yellow threshold, evasive maneuvers will be carried out without harming the target of the mission.

When the distance between the two targets is less than the sum of their equivalent radius, then it can be judged as the occurrence of collision. The calculation of collision probability by analytic method can be simplified into the following steps[5]:

1. Obtain the information (including time of approaching, the position and the speed of the spacecraft and debris, the minimum distance between them) and the error covariance matrix;
2. Establish the encounter plane and the encounter coordinate system, and project the motion state vectors of spacecraft and space debris onto the encounter coordinate system;
3. According to the errors and radius of the two targets, the joint error ellipsoid and union are formed and projected to the meeting coordinate system;
4. Calculate the collision probability based on the above data.

3. Collision warning simulation

The above two collision warning methods are simulated and verified as follows. Take the spacecraft in low earth orbit as an example. The scene is set in a space with an orbital altitude of $H=1000\text{km}$. The position of spacecraft orbits is shown in table 1. Simulation environment: STK11+Matlab2015b.

|       | Semi-major Axis | Eccentricity | Inclination (deg) | RAAN (deg) | Arg of Perigee (deg) | True Anomaly (deg) |
|-------|-----------------|--------------|-------------------|------------|---------------------|--------------------|
| Main Target | 7478.14         | 0            | 50                | 100        | 0                   | 40                 |

3.1. Early warning simulation based on BOX region

The BOX region was defined as a rectangular BOX centered on the spacecraft, with the track direction being ±25km, the orbital plane normal ±5km, and the vertical direction being ±5km. Randomly generate several debris in the space near the cuboid, including the location information of randomly generated debris.

As shown in figure 4, the central blue ball is the main spacecraft, black dashed cuboid around the spacecraft is divided by the BOX area. Circles are 100 randomly generated debris around the spacecraft space, among them, the green circles are outside the BOX cuboid region, the red circles are in the BOX the cuboid region.

Figure 4. Randomly generate space debris around the BOX area
According to the minimum distance principle of the BOX region method for collision warning of spacecraft, debris entering the BOX region is deemed as debris with collision risk, that is, all space debris marked with red circles in the figure 4. Collision warning is issued for these debris to remind spacecraft of collision avoidance. Among the 100 randomly generated space debris, 22 are distributed in the BOX region. Therefore, the proportion of warning for this random scene is 22÷100=22%.

To reduce the influence caused by the accidental event, do above random space debris of scene simulation in many times to get average number of warning and warning probability, as shown in figure 5, although each time the randomly generated 100 space debris, the number of dangerous debris is variable, but it showed a trend of the distribution of the number is in the 20 or so. After processing these 1000 sets of data, the median of dangerous debris is 21 and the average is 20.8830.

Figure 6. shows the relationship between the number of randomly generated debris and the proportion of dangerous debris. It can be seen that when the number of randomly generated debris is small, the proportion of dangerous debris tends to be unstable and divergent. When the number of randomly generated debris reaches a certain level (thousand degrees), the proportion of dangerous debris shows a convergence trend, and the convergence trend becomes more stable with the increase of the total number of debris. According to figure 6, the proportion of dangerous debris converges at y=0.20874, so the average warning rate in this scene is 20.874%.

Figure 5. Number of dangerous debris in multiple scenarios (BOX region method)

Figure 6. The number of debris and the dangerous ratio (BOX region method)
3.2. Early warning simulation based on collision probability

In a number of randomly generated debris are generated in the space area centered by the main spacecraft, including the location and velocity information of randomly generated debris as the initial conditions.

As shown in figure 7, the blue ball in the center is the main spacecraft, and the circle represents the generated space debris randomly around the spacecraft. After the calculation of collision probability, the space debris with collision risk is marked as red, and the debris without collision risk is marked as green. The BOX area for the spacecraft is represented by a black dotted line.

Through comparison, the following two points can be drawn:
1) Not all the debris in the BOX area exceeds the collision risk of the safe threshold;
2) The collision probability of debris outside the BOX area is not always below the safety threshold.

Among these 100 randomly generated space debris, there are 10 of them have collision risk. Therefore, the proportion of warning for this scenario is 10÷100=10%.

To reduce the influence caused by the accidental event, do above random space debris of scene simulation in many times to get average number of warning and warning probability, as shown in figure 8, although each time the randomly generated 100 space debris, the number of dangerous debris is variable, but it showed a trend of the distribution of the number is in the 10 or so. After processing these 100 sets of data, the median of dangerous debris is 11 and the average is 10.7050.

Figure 9 shows the relationship between the number of randomly generated debris and the proportion of dangerous debris. It can be seen that when the number of randomly generated debris is small, the proportion of dangerous debris tends to be unstable and divergent. When the number of randomly generated debris reaches a certain level (thousand degrees), the proportion of dangerous debris shows a convergence trend, and the convergence trend becomes more stable with the increase of the total number of debris. According to figure 9, the proportion of dangerous debris converges at y=0.10677, the average warning rate in this scene is 10.677%.
Figure 8. Number of dangerous debris in multiple scenarios (collision probability method)

Figure 9. The number of debris and the dangerous ratio (collision probability method)

3.3. Compare and analysis
For this scenario, the probability of collision warning and collision warning BOX area method are compared, as shown in figure 10, the collision probability method used to determine the number of dangerous debris is around 11, and the BOX area method used to determine the number of dangerous debris is around 21, significantly higher than the early warning method number.

Therefore, the use of BOX area collision warning will produce more than a few “false alarms”, which will cause waste to the spacecraft within fuel and other resources, not conducive to the continuous work in space.

Figure 10. Comparison of the number of danger warning
4. Conclusion
The space environment of spacecraft in orbit is complex, so it is very important to avoid dangerous space debris. In this paper, two common collision warning methods, namely BOX region collision warning method and collision probability warning method, are compared. These two methods respectively calculate collision problems from geometric and analytical perspectives. After comparing the two methods, which can be found that the warning number of BOX area method is more than collision probability method, this because the BOX area method just takes the distance between the spacecraft and debris into consideration, and neglects the collision velocity and other important judgment information. To a certain extent, it creates a "false alarm" phenomenon, mobile the spacecraft with no risk of collision, wasting fuel of spacecraft, also caused the waste of space resources. Two conclusions can be drawn:
1) Not all the debris in the BOX area exceeds the collision risk of the safe threshold;
2) The collision probability of debris outside the BOX area is not always below the safety threshold.
Therefore, the collision probability calculated by using the distance, velocity and error covariance information between space spacecraft and debris is more accurate, and the number of dangerous debris screened by threshold value is relatively small, thus reducing the number of maneuver. Considering that the spacecraft is limited in fuel and other resources when working in orbit, it is more scientific to adopt collision probability calculation method to avoid unnecessary maneuver and waste of resources.

References
[1] Li Yiyong, Shen Huairong, Li Zhi. Environmental hazards of space debris and countermeasures [J] Missile and space delivery technology, 2008 (6): 31-35
[2] Sun Hao, Dong Jie, Luo Chao. Enlightenment from research and development of space debris monitoring technology [J]. Chinese Radio, 2016(3):63-64.
[3] Bai Xianzong. Study on prediction error and collision probability of space target orbit [D]. National university of defense technology, 2013.
[4] Cheng Tao, Liu Jing, Wang Ronglan. Research on collision probability method in space debris warning [J] Journal of space science, 2006, 26(6):452-458
[5] Huo Yurong. Research on error analysis method of space debris collision warning [J].Science and technology of China, 2016(7).