Charulatha et al. 2018. *Int. J. Vehicle Structures & Systems*, 10(1), 60-65
ISSN: 0975-3060 (Print), 0975-3540 (Online)
doi:10.4273/ijvss.10.1.13.

International Journal of
Vehicle Structures & Systems
Available online at www.maftree.org/eja

Satellite Cluster Close Approaches Determination for Collision Avoidance

S. Charulatha[a] and Raju Garudachar[b]

Jain University, Bengaluru, Karnataka, India
[a]Corresponding Author, Email: charulatha_1505@yahoo.com
[b]Email: raju_garuda@yahoo.co.in

ABSTRACT:

As the number of space objects in orbit about the Earth increases, it is extremely important to determine the close approaches between them. In this paper the close approaches is determined for the satellite cluster using a simulation tool STK for the following (i) satellites of interest within a cluster (ii) a satellites of interest in a cluster and the space objects as listed in the space catalog and the close approach reports are analyzed. The results have indicated that the details of intruder satellites and the duration of close approaches and their minimum separation distances or the relative distances.

KEYWORDS:

Relative satellite dynamics; Close approaches; Probability of collision; Conjunction analysis; Separation distance

CITATION:

S. Charulatha and R. Garudachar. 2018. Satellite cluster close approaches determination for collision avoidance, *Int. J. Vehicle Structures & Systems*, 10(1), 60-65. doi:10.4273/ijvss.10.1.13.

1. Introduction

In order to improve the temporal and spatial coverage, it is important to increase the revisit time of the satellites in remote sensing applications. This calls for the multiple satellites configured in different orbits in the form of constellation of satellite in close proximity in space. Such a configuration is vulnerable to collision due to close proximity of satellites in the cluster. This situation could worsen due to varying gravitational influences caused by aperiodicity of the Earth, atmospheric drag and solar radiation pressure. The on-orbit perturbations could also be caused due to satellite aging and any kind of changes in the control system in the satellites. Several studies have addressed this problem [1]. It is also important to reduce the electromagnetic interference between the adjacent satellites. Collisions due to such situations have been reported from the Anti-Satellite Test (ASAT) conducted by China and the collision of Iridium33 and Cosmos 2251 [2].

A constellation of satellite is possible by formation flying is organised as a set of more than one satellite in the form of cluster whose dynamic states are coupled through a common control law [3]. In particular, at least one member of the set must track a desired state relative to another member and the tracking control law must make use of the state at least one of other members. In a formation, the individual satellites require precise relative control depending upon the applications. Otherwise they might collide with each other if they are not controlled. The close approach events for a satellite of interest can be determined. Detection of consecutive close approach events both for primary objects and for secondary objects and the planned orbital maneuvers should be executed to avoid collision between the satellites. This study addresses the close approach determination for collision avoidance between (i) the satellite of the interest within a cluster and (ii) a satellite of interest in a cluster and the space objects.

The use of multiple satellites in a close formation can have many advantages over one single satellite. As compared to a conventional single large satellite, satellite formation can increase the reliability and redundancy of the entire mission, reduce the cost of launching and maintenance, increase the surveillance area to the great extent, and add more flexibility into the mission design. The entire mission will be aborted in the event of satellite failure with a single satellite. But a failed satellite in a formation can be mitigated by re-organising the remaining member satellites in the formation. In addition, formation flying technology enables us to easily add more satellites into the mission or upgrade any satellite.

The formation introduces new problems, difficulty in maintaining the formation geometry and difficulty in preventing inadvertent collisions between the satellite due to the inaccurate knowledge of individual satellite state or possible failures of one of the satellite. It is difficult to maintain the satellites in a stable formation to within specified precision against various orbital perturbations. Formation manoeuvre is to guide and execute control command to reconfigure the existing satellite formation to another stable formation. In many satellite formation missions, maintenance of accurate relative orientation between the satellites is difficult. Collisions can arise either from any space object passing through the formation, or from the lack of control of satellites within a cluster/formation when two satellites closely approach towards each other. In either case, probability of a future collision to be determined based on current state knowledge of the satellite of interest and the uncertain dynamic environment, and further to design a control strategy to reduce the collision probability to an acceptable level while minimizing the Δv (the change in velocity required for the orbit change) required for the manoeuvre.

2. Absolute satellite dynamics

Study of motion of a satellite in two body problem is subjected to Newtonian's gravitational field of force. The force due to gravity is proportional to the inverse of the square of the distance between the satellite and Earth,

$$F_g = -GMm/r^2 \quad (1)$$

Where G is the gravitational constant, M is the mass of the Earth and m is the mass of the satellite and r is the distance between the satellite and the Earth. The position and velocity of the satellite in space is governed by the fundamental orbital differential equation as given below,

$$\ddot{r} = -\mu\, \boldsymbol{r}/r^3 \quad (2)$$

Where μ = GM, is the gravitational parameter. The solution of the Eqn. (2) will give the position of the satellite as shown in Fig. 1. The orbital elements semi-major axis (a), eccentricity (e), inclination (i), right ascension ascending node (Ω), argument of perigee (ω), true anomaly (θ) describe the motion of the satellite in the space with respect to an Earth centred inertial reference frame as shown in Fig. 2. The two-body approach cannot handle the perturbations acting on a satellite. The multi body problem can handle the perturbations due to various forces such as geo-potential variation, third body gravity effects due to sun and moon, atmospheric drag and solar radiation pressure. Instead of state elements (position and velocity), orbital elements are chosen to represent the perturbations geometrically. The change in orbital elements over a period of time will include all the perturbations.

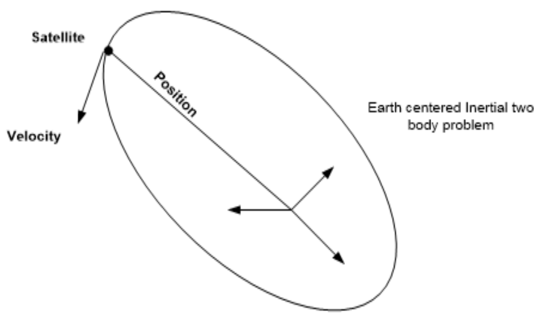

Fig. 1: Earth centred inertial two body problem

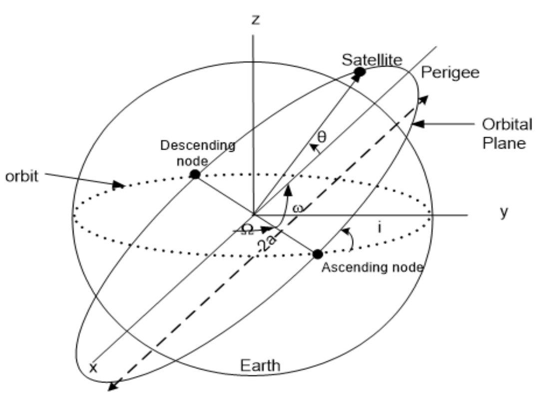

Fig. 2: Orbital elements

3. Relative satellite dynamics

While the absolute satellite dynamics deals motion of the satellite about the Earth, the relative satellite dynamics gives an idea of how two or more satellites moves with relative to each other and their relative position, velocity between the satellites in space. The relative motion equations developed in a Cartesian local-vertical, local-horizontal (LVLH) frame attached to the primary satellite as shown in Fig. 3. This LVLH coordinate frame rotates with the primary satellite's radius vector and is a convenient reference frame to describe the relative motion. This reference frame is also referred to as the Hill frame or the Clohessy-Wiltshire (CW) frame. In this coordinate frame, x lies in the primary satellite's radial direction, z lies in the direction of the primary satellite's orbital angular momentum, and y completes the right-hand system [4]. The relative motion between the satellites is described by the Hill-Clohessy-Wiltshire (HCW) Equations. in LVLH frame. In this model, it is assumed that the orbit of the primary satellite is circular. In addition, the orbital radius of the primary satellite is assumed to be much larger than the relative separation distance between the satellites.

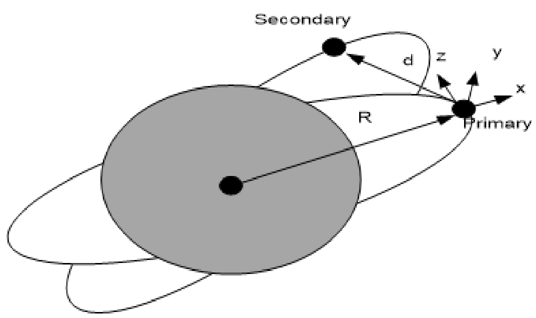

Fig. 3: LVLH frame

The motion of the secondary satellite is studied from a reference frame (LVLH) fixed at the centre of the primary satellite. With respect to the primary satellite on the circular reference orbit, the relative motion (see Fig. 4) is described by,

$$\ddot{x} - 2n\dot{y} - 3n^2\mathrm{x} = 0; \quad \ddot{y} + 2n\dot{x} = 0;$$
$$\ddot{z} + n^2 z = 0 \quad (3)$$

Where $[x\ y\ z\ \dot{x}\ \dot{y}\ \dot{z}]$ is the relative position and relative velocity in Hill's frame, $n = \sqrt{\mu/a^3}$ is the mean orbit rate with μ being the gravitational parameter and a is the semi-major axis. An advantage of the HCW equations is that it provides the geometric insight into the solutions. The geometric parameterization of the HCW equations is called relative-orbit elements (ROEs) similar to the concept of orbital elements for Keplerian motion [4].

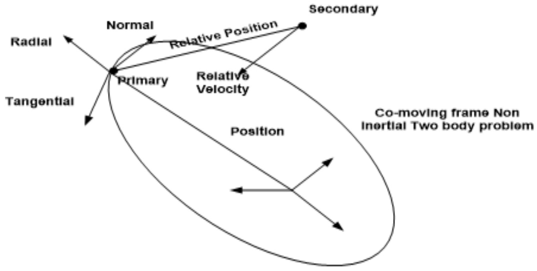

Fig. 4: Co-moving frame non inertial two body problem

4. Collision monitoring and avoidance

Collision avoidance is a general concern in a closely flying cluster of satellite with separation distances ranging from meters to hundreds of meters. Dealing with more crowded space environment requires identifying potentially dangerous orbital conjunctions and executing a suitable course of action. The problem of on-orbit collisions has become highly significant after the incident of the collision between an Iridium33 satellite and Cosmos 2251 [5]. In Fig. 5, it is shown that the current Iridium constellation with the orbits for the operational satellites shown in green colour, the spares shown in blue, and the inactive satellites shown in red. The Iridium 33 debris is shown in light blue and the Cosmos 2251 debris is shown in orange [5]. Collisions monitoring in space is based on the developed models of the relative dynamics. The dynamics models should be accurate in order to obtain precise probability of collision. The collision monitoring tracks the primary satellite and the intruders and monitors the relative distances and monitors likelihood of intersections [6]. Controlling the relative motion of the satellites is the primary concern in collision avoidance. The orbital perturbation is the major cause for the close approach of the satellites and there is a probability of collision in satellite cluster. Hence the velocity correction (Δv adjustment) is recommended to avoid collisions [7]. The probability of collision of the two satellites in the future is calculated according to the relative position and velocity at the current epoch (time). Even in the presence of inaccuracy of relative states and possible failures of one of the satellites, the configuration of the close formation flying has to ensure collision-free operations based the determination of probability of collisions [8].

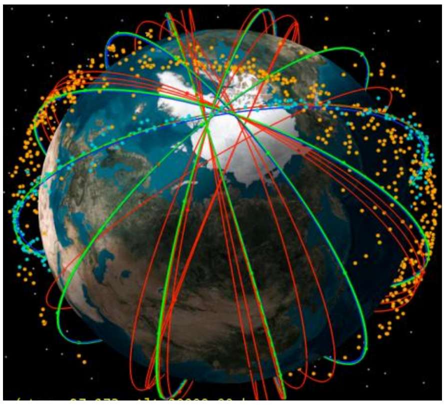

Fig. 5: Iridium constellation and collision debris

The basic problem is to determine when two objects will have a likelihood of conjunction where the risk of collision is unacceptably large. The identification of potentially dangerous conjunctions requires finding pairs of satellites that are likely to be very close to each other and the time at which the close approach occurs. Once high-risk conjunctions are identified, the probability of collision can be determined if the uncertainties in each orbit and the relative motion of the satellites are determined [9]. The relative distance between each pair of orbiting objects is sampled and a simplified model of the relative motion is used to identify potential conjunctions efficiently during a time step.

5. Determination of close approaches

Conjunction analyses determine the risk to a particular satellite of interest (the primary object) posed by the set of all other orbiting objects, the secondary objects [10]. One common measure of the risk of collision is the distance between two objects at the point of closest approach as determined from the ephemeris. The separation distance is selected to be much larger than the actual physical dimensions of the bodies involved to account for uncertainty in the ephemerides. The method for determining close approach events for objects containing ellipsoidal threat volumes (uncertainties in the ephemerides) about the satellites is considered. Ellipsoidal shapes provide a method for distinguishing different levels of position uncertainty in three orthogonal directions as shown in Fig. 6. A close approach event is considered to occur whenever the closest distance between an ellipsoid about a primary satellite and ellipsoid about another orbiting object is less than selected threshold distance. The determination of close approaches is based on the assumption of both objects to be in orbit about the Earth where the ephemerides of both objects are known and no propulsive forces are being applied.

The method of determining close approaches to the primary object typically involves a set of filters to eliminate objects which are candidates for close approaches from consideration in order to reduce computational burden. The source of data (the secondary space objects used for determining close approaches) which defines the orbital elements of the tracked objects in orbit about the Earth is the space catalogue maintained by the United States Space Command. The relative distance between the ellipsoids is given by,

$$\vec{d} = \vec{R} + \mathrm{M}\vec{P} - \vec{r} \tag{4}$$

Where M is the rotation matrix that transforms the secondary ellipsoid frame of coordinates to the reference primary ellipsoid LVLH frame of coordinates [10] as shown in Fig. 6. The trajectories of the satellites are then sampled at certain time steps to obtain the relative distance between the satellites. The relative distance is compared with selected threshold distance. If the relative distance is lesser than the selected threshold distance during the time steps, the time of closest approach is computed.

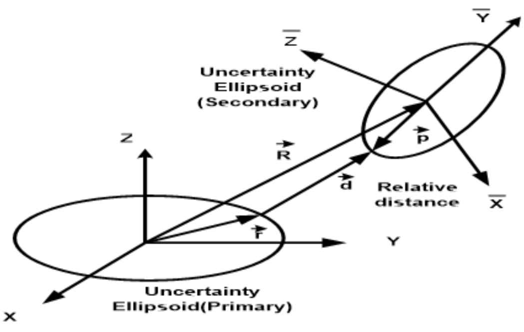

Fig. 6: Relative distance between primary & secondary ellipsoids

6. Common filtering techniques

For a problem containing only two objects, orbital conjunctions are identified by computing the distance between the two objects at all points in time during the analysis period and determining if the distance ever falls below a selected threshold distance [9]. Since applying this methodology to the problem of a single object versus the entire space catalog of nearly 20,000 objects (or worse yet to the problem of all catalog objects vs. all other catalog objects) is a computational challenge. The objective of the process is to find all conjunctions between a set of objects of interest, referred to as primary objects, and the set of all catalogued orbiting objects are referred to as secondary objects. To improve the efficiency of detecting close approaches based on the minimum separation distance, the series of three filters are designed through which candidate objects have to pass before a final determination of the close approach distance is made. The three filters are the apogee/perigee filter, the orbit path filter, and the time filter. The apogee/perigee filter eliminates pairings that lack overlap in the respective ranges of radius values regardless of planar orientation. The orbit path filter (also known as the geometric pre-filter) takes planar orientation into account to eliminate pairings where the distance (geometry) between their orbits remains above some selected threshold distance, irrespective of the actual locations of the satellites along their paths. The time filter identifies pairs that have survived other screening processes but are unlikely to be in close proximity during the analysis interval [9].

7. Minimum separation distance & time of close approach analysis

Distances between ellipsoid ephemerides can be calculated in order to evaluate when and how fast a collision may occur. For many applications, such as distributed space based radar, the relative separation can vary from 250m down to 10m [11]. The determination of a minimum separation distance is based on using elliptical threat volumes (uncertainties in the ephemerides) about the primary and secondary objects. Conjunctions occur when the threat volumes have an intersection. The sum of the radii of the threat volumes is equal to the minimum separation distance [10]. Whenever the relative distance is less than selected threshold distance, close approach event has occurred and the time of close approach is noted as given in the Fig. 7 [12].

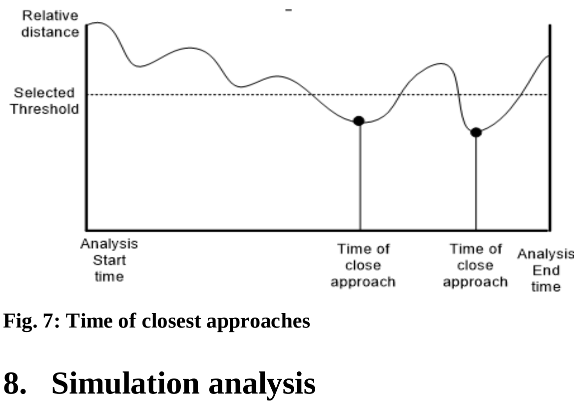

Fig. 7: Time of closest approaches

8. Simulation analysis

The simulations consist of two or more satellites that are placed in any orbit close to each other. The simulation environment set up in STK includes full force dynamic model. The position of each spacecraft in inertial space is numerically integrated using the equations of motion [13]. Once the environment is set up, several simulations are executed to study various maneuvers around the satellites of interest. These maneuvers are analyzed for closest point of approach and visual situational awareness. Simulation results are based on the close approaches between the satellites within the cluster as well as the satellite within the cluster and any space objects. Collocation and orbital view with any nearby objects are also analysed.

8.1. Determination of close approaches between the satellites within the cluster

In this case study, a cluster of 12 satellites in 20°, 25°, 30° inclinations, 4 satellites in each orbit at the orbital height of 1336km (typical altimetry mission satellites) is considered. The satellite clusters are named as satellite 1 to satellite 12 (refer Table 1). The following parameters are used in the simulation:

- Selected threshold distance = 100 km.
- Primary satellite: Satellite 1.
- Separation distance between the satellites in the cluster = 1 arc, Minimum ~2 km.

If the minimum separation (relative) distance between the primary satellite (satellite 1) and the other satellites (Satellite 2 - 12) in a cluster is lesser than the selected threshold distance, then they are called Intruder satellites. These Intruders have close approaches with the satellite 1 as listed in the Table 1. 27 close approaches were found in simulation.

Table 1: Close approaches within the satellite cluster

Intruder satellites	Duration of conjunctions in mins	Minimum separation distance in km
Satellite 5	2	Intersect
Satellite 9	1	Intersect
Satellite 2	120	2.242748
Satellite 10	1	2.242748
Satellite 6	2	2.242748
Satellite 11	1	4.485496
Satellite 3	120	4.485496
Satellite 7	2	4.485496
Satellite 12	1	6.728244
Satellite 4	120	6.728244
Satellite 8	2	6.728244
Satellite 7	5	4.481227
Satellite 6	5	2.240613
Satellite 8	5	6.72184
Satellite 5	5	0.000001
Satellite 12	3	6.702641
Satellite 11	3	4.468427
Satellite 10	3	2.234214
Satellite 9	3	0.000001
Satellite 7	5	4.481227
Satellite 6	5	2.240613
Satellite 8	5	6.72184
Satellite 5	5	0.000001
Satellite 12	3	6.702641
Satellite 11	3	4.468427
Satellite 10	3	2.234214
Satellite 9	3	0.000001

8.2. Determination of close approaches between a satellite in the cluster and the space objects

In this case study, the 12 satellite cluster along with catalogued space objects is considered. The catalogued space objects are identified by prefix "tle" which stands for two line element which contains the space object number along with the information of their motion. The following parameters are used in the simulation:

- Selected threshold distance = 100 km.
- Primary satellite: Satellite 1.
- Separation distance between the satellites in the cluster = 1 arc, Minimum ~2 km.

If the minimum separation (relative) distance between the primary satellite (satellite 1) and the other satellites (Satellite 2 - 12) in a cluster, including space objects in the "Space Catalog" is less than the selected threshold distance, then they are called Intruder satellites. These Intruders have close approaches with the satellite 1 as listed in the Table 2. 31 close approaches were found in simulation.

Table 2: Close approaches within satellite cluster and space objects

Intruder satellites	Duration of conjunction in mins	Minimum separation distance in km
Satellite 5	2	Intersect
Satellite 9	1	Intersect
Satellite 2	120	2.242748
Satellite 10	1	2.242748
Satellite 6	2	2.242748
Satellite 11	1	4.485496
Satellite 3	120	4.485496
Satellite 7	2	4.485496
Satellite 12	1	6.728244
Satellite 4	120	6.728244
Satellite 8	2	6.728244
tle 0466 5	1	74.09366
tle 0378 5	1	74.319466
tle 2203 7	1	91.198933
Satellite 7	5	4.481227
Satellite 6	5	2.240613
Satellite 8	5	6.72184
Satellite 5	5	0.000001
Satellite 12	3	6.702641
Satellite 11	3	4.468427
Satellite 10	3	2.234214
Satellite 9	3	0.000001
tle 08180	1	95.955601
Satellite 7	5	4.481227
Satellite 6	5	2.240613
Satellite 8	5	6.72184
Satellite 5	5	0.000001
Satellite 12	3	6.702641
Satellite 11	3	4.468427
Satellite 10	3	2.234214
Satellite 9	3	0.000001

8.3. Collocation and orbital views

If the separation distance between the ellipsoids are greater than selected threshold separation distance, no close approach event is occurred. The orbital views of the cluster and its any nearby objects are presented in Fig. 8 to Fig. 10 for the instances of no collision, highly probable collision and intersection of satellite or space objects respectively.

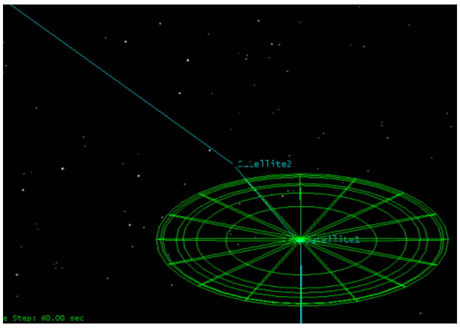

Fig. 8: Orbital view of primary satellite ellipsoid - green colour ellipsoid indicates that there is no collision

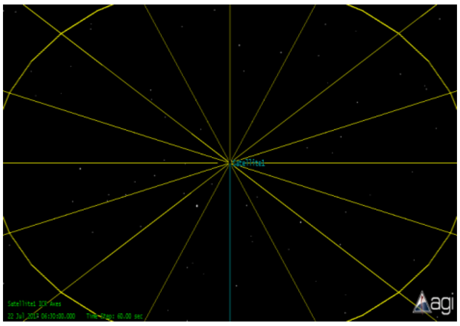

Fig. 9: Orbital view of primary satellite ellipsoid - yellow colour ellipsoid indicates that there is a probability of collision

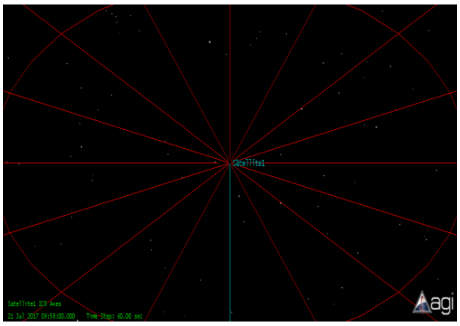

Fig. 10: Orbital view of primary satellite ellipsoid - red colour ellipsoid indicates that there is a satellites intersection

9. Conclusion

For the formation assumed, the analysis has been carried out and the results are obtained. It is found that there were 27 and 31 close approaches between the primary satellite and the cluster, between primary satellite, cluster and space objects respectively. When the close approaches were able to be determined, the collision avoidance manoeuvre can be planned.

REFERENCES:

[1] M. Krupa, W. Poth, M. Schagerl, A. Steindl, W. Steiner, H. Troger and G. Wiedermann. 2006. Modelling, dynamics and control of tethered satellite systems, *Nonlinear Dynamics*, 43(1-2), 73-96. https://doi.org/10.1007/s11071-006-0752-z

[2] B. Weeden. 2013. *Anti-Satellite Tests in Space - The case of China*, Secure World Foundation.

[3] D. Wang, B. Wu and E.K. Poh. 2017. Satellite Formation Flying: Relative Dynamics, Formation Design, Fuel Optimal Maneuvers, Formation Maintenance, *Intelligent*

Systems, Control and Automation: Science and Engg., 87. https://doi.org/10.1007/978-981-10-2383-5.

[4] R.E. Sherrill. 2013. *Dynamics and Control of Satellite Relative Motion in Elliptic Orbits using Lyapunov-Floquet Theory*, PhD Thesis, Auburn University, Alabama, USA.

[5] T.S. Kelso. 2009. Analysis of the Iridium 33-Cosmos 2251 collision, *Proc. 19th AIAA/AAS Astrodynamics Specialist Conf.*, Pittsburgh, Pennsylvania, USA.

[6] M.E. Campbell. 2005. Collision monitoring with in satellite clusters, *IEEE Trans. Control System Tech.*, 13(1), 42-55. https://doi.org/10.1109/TCST.2004.838550.

[7] J. Su and Y. Dong. 2010. Electromagnetic satellite cluster collision prediction and avoidance, *Proc. IEEE Int. Conf. Intelligent Computing and Intelligent Systems*, Xiamen, China. https://doi.org/10.1109/ICICISYS.2010.5658625.

[8] M. Hu, G. Zeng, H. Yao and Y. Liu. 2010. Optimal collision avoidance maneuver control for formation flying satellites using linear programming, *Proc. 29th Chinese Control Conf.*, Beijing, China.

[9] S. Alfano and D. Finkleman. 2013. Operating characteristic approach to effective satellite conjunction filtering, *Proc. AAS/AIAA Spaceflight Mechanics Meeting*, Kauai, Hawaii.

[10] V. Coppala and J. Woodburn. 1999. Determination of close approaches based on ellipsoidal threat volumes, *Proc. AAS/AIAA Space Flight Mechanics Meeting*, Breckenridge, Colorado, USA.

[11] M.E. Campbell. 2002. Collision avoidance in satellite clusters, *Proc. American Control Conf.*, https://doi.org/10.1109/ACC.2002.1023266.

[12] F.R. Hoots, L.L. Crawford and R.L. Roehrich. 1984. An Analytic method to determine future close approaches between satellites, *Celestial Mech.*, 33, 143-158. https://doi.org/10.1007/BF01234152.

[13] D.A. Vallado. 2001. *Fundamentals of Astrodynamics and Applications*, 2nd Edition, Space Tech. Library, Microcosm Publishers.