Collision avoidance strategies and conjunction risk assessment analysis tool at GISTDA

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ABSTRACT

Thailand Earth Observation satellite (THEOS) known as Thaichote is operated by Geo-Informatics and Space Technology Development Agency (GISTDA) since 2008. The orbital mission of Thaichote is Sun-Synchronous orbit (SSO) where a number of space objects during the last decades increase rapidly. These are risky to end operational satellite mission early or reduce the mission life time. It becomes a serious issue for on-orbit safety. Therefore, the collision avoidance operation has become a necessary and usual task for all operational satellites. Generally, Conjunction Data Message (CDM) received from Combined Space Operation center (CSpOC) provides conjunction event information and potential risk when a risk is higher than the threshold control. The earlier analysis is essential to decide the avoidance maneuver strategy to mitigate the collision risk. In order to handle CDM and analyze the collision risk in time, GISTDA therefore develops the risk assessment tool to provide the analysis results and support collision avoidance planning.

This paper presents the current collision avoidance operation at GISTDA. We provide an overview on the development of the conjunction risk assessment tool known as “ZIRCON” and tool’s capability that can provide the conjunction reports and visualization in the 3D geometry of motions at the Time of Close Approach (TCA) by displaying target and chaser motion over time along with the uncertainties to support a collision avoidance maneuver. In additions, the recent development of ZIRCON is able to screen potential object risks by using the Two Line Element (TLE) catalogs provided by the US Strategic Command (USSTRATCOM) against our satellites. Finally, the paper concludes the statics of conjunction events, collision avoidance experiences for 11-year operation and further development planning to support all Thailand satellites.

Keywords: Collision avoidance, ZIRCON, close approach, maneuver and conjunction risk assessment.

1 INTRODUCTION

The growth of space debris in the near Earth region directly concerns the safety of space mission. With hypervelocity of space objects, they risk to damage operational satellites or reduce a mission life time. A single collision between space objects could seriously increase the debris population that possible make further collision and most of them possible remain in orbit for many decades. This scenario is known as “Kessler syndrome”[1]. As a result, the operational collision avoidance is a key component for a successful satellite mission. Geo-Informatics and Space Technology Development Agency (GISTDA) has been performed collision avoidance operation since 2008 for Earth Observation mission known as “Thaichote” in Low Earth Orbit (LEO) region. In general, the Combined Space Operations Center (CSpOC) is the main source for the orbital information of the potential collision risk of most satellite operators. A number of Conjunction Data Messages (CDMs) notified by CSpOC are reported daily when the miss distance between space object and active satellite are less than 1 km in cross and along tracks and 200 m in radial track. In case of the risk assessments are over our certain thresholds (collision probabilities > 10^{-4} and miss distance < 1 km), the avoidance maneuver execution is required and processed within one day before the closest approach based on the latest prediction. The earlier investigation of possible critical conjunctions is essential to handle critical situations efficiently and promptly.

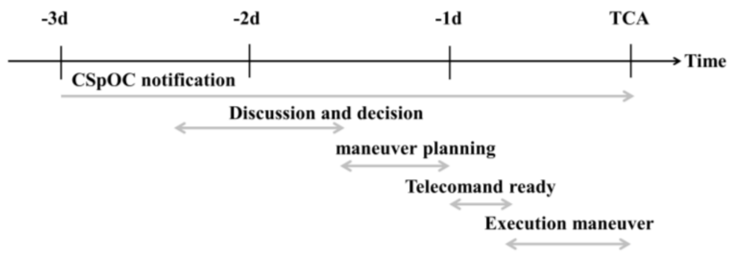
This paper describes the overview on the previous and current collision avoidance procedures at GISTDA in section 2. Section 3 describes the methodology and features of the new conjunction risk assessment tool known as “ZIRCON”. Section 4 depicts the past conjunction statistics over 11 years and space object classification of each CDMs. Then, Section 5 gives the conclusion and future development plan.

2 COLLISION AVOIDANCE PROCESS

The operational collision avoidance activities at GISTDA have started since 2008. For previous operational process, the overall underlying concept is to detect conjunction events, which are notified by CSpOC. CDMs provide full orbital state information of chaser and covariance matrices. The information allows for a more realistic assessment of the collision risk. In mid of 2018, the collision avoidance operation is modified and ZIRCON is implemented in the operation. This section describes the previous and current operational process and maneuver strategy to mitigate the collision risk.

2.1 Operational collision avoidance process

Fig. 1 presents the timeline and overall of the previous collision avoidance process at GISTDA. Firstly, CSpOC notifies the conjunction events in advance 3 days to an operator by E-mail. CDMs are automatically stored in the database. Secondly, an operator analyses the information of CDMs to define the potential collision risk level. If the potential collision risk is examined as the over threshold control before 36 hours, a collision avoidance maneuver is planned by using the collision avoidance module (Fig. 2), which is one of six modules of in-house Flight dynamics software known as "EMERALD" [2-9], before 24 hours. Thirdly, the maneuver planning is converted to telecommand before 19 hours of the Time of Close Approach (TCA). Finally, the maneuver plan is uplinked to a satellite before 15 hours to execute a collision avoidance maneuver. In case of a chaser is not space debris. Flight dynamics team provides information to another satellite operation to analyse and define a final maneuver strategy. Based on our experiences, a number of false warnings are high and the process consumes man hours to perform collision avoidance maneuver that is described in section4.



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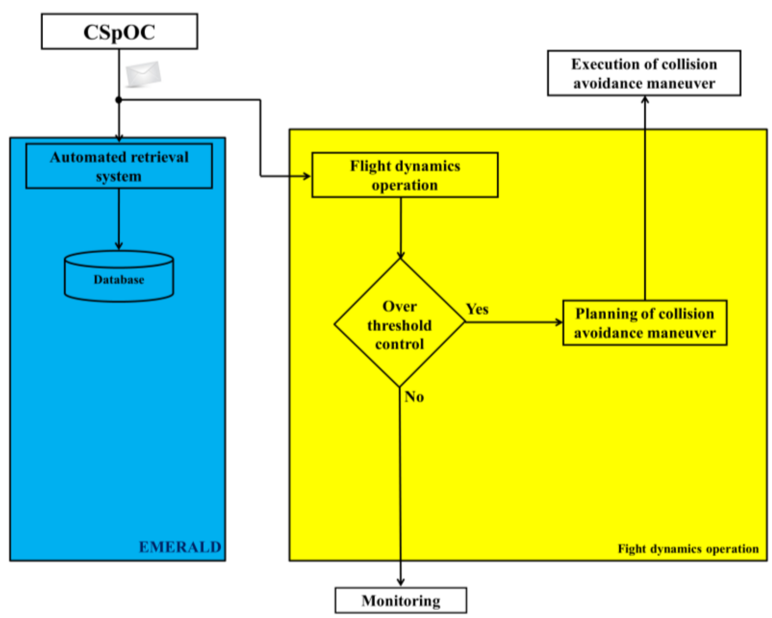

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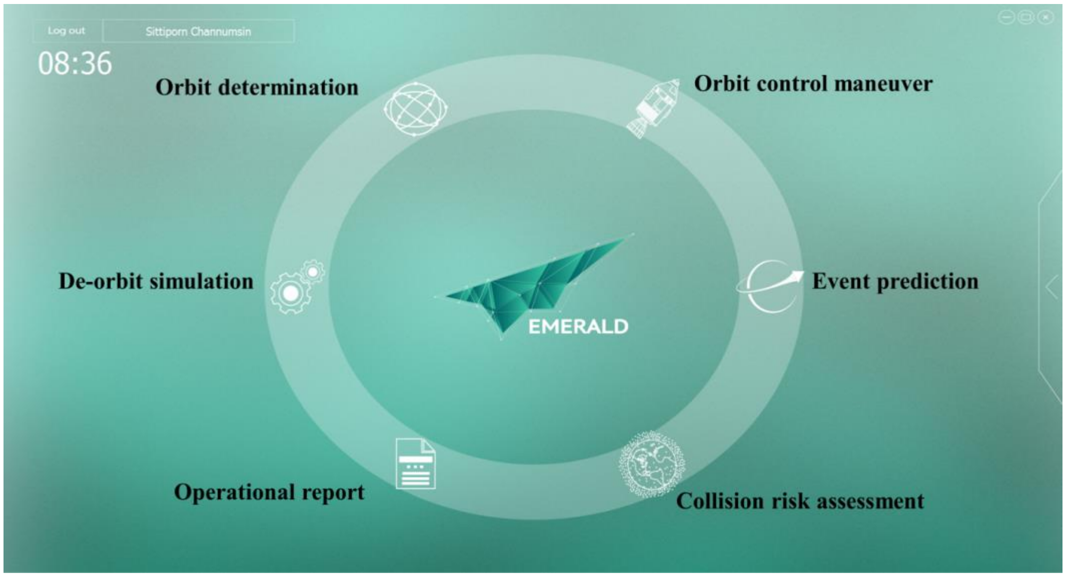
Fig. 1 Operational collision avoidance process at GISTDA a) time line process b) previous collision avoidance process.



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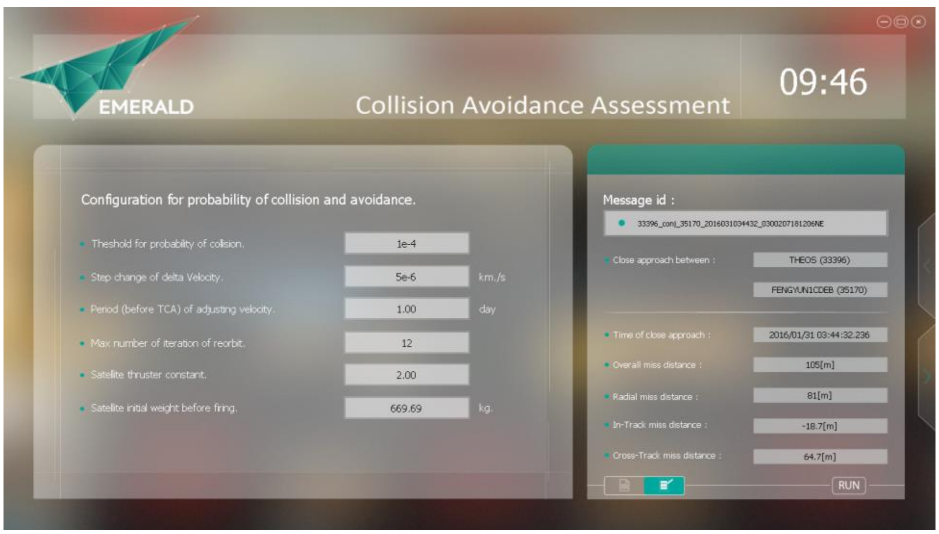

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Fig. 2 a) In-house flight dynamics software (EMERALD) b) Collision avoidance assessment.

In the new collision avoidance procedure in Fig. 3, the tool is semi-automated system to screen potential risks of space objects one time/day. The procedure consists of 3 major steps. Firstly, the potential collision risk are screening in advance 7 days by using TLE catalogues provided by the US Strategic Command (USSTRATCOM) and precise orbit data of the operational satellites provided by satellite mission control center. Secondly, if a miss distance is less than threshold control, the collision probability is calculated for the conjunction events. Then, the close approach events are listed in a report file to an operator. Finally, if the collision probability exceeds 10^{-4}, the further analysis of the close approach event is investigated in term of the trajectories of both the satellite and space object at the time of the closest approach to prepare the planning of collision avoidance maneuver.

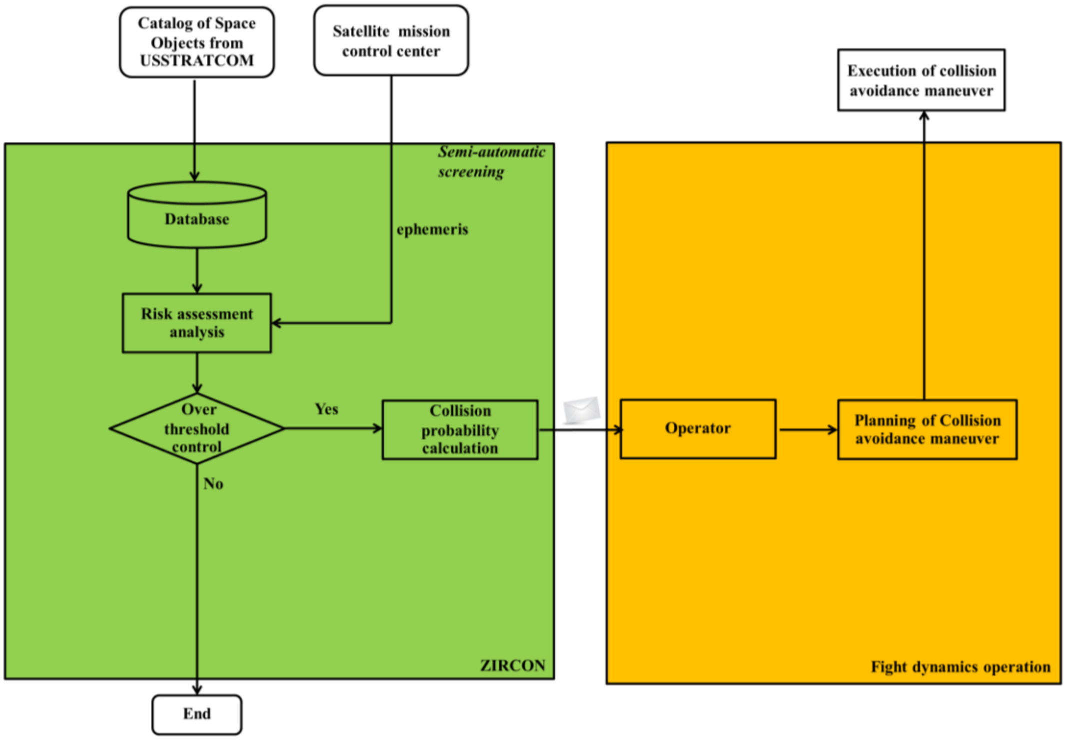
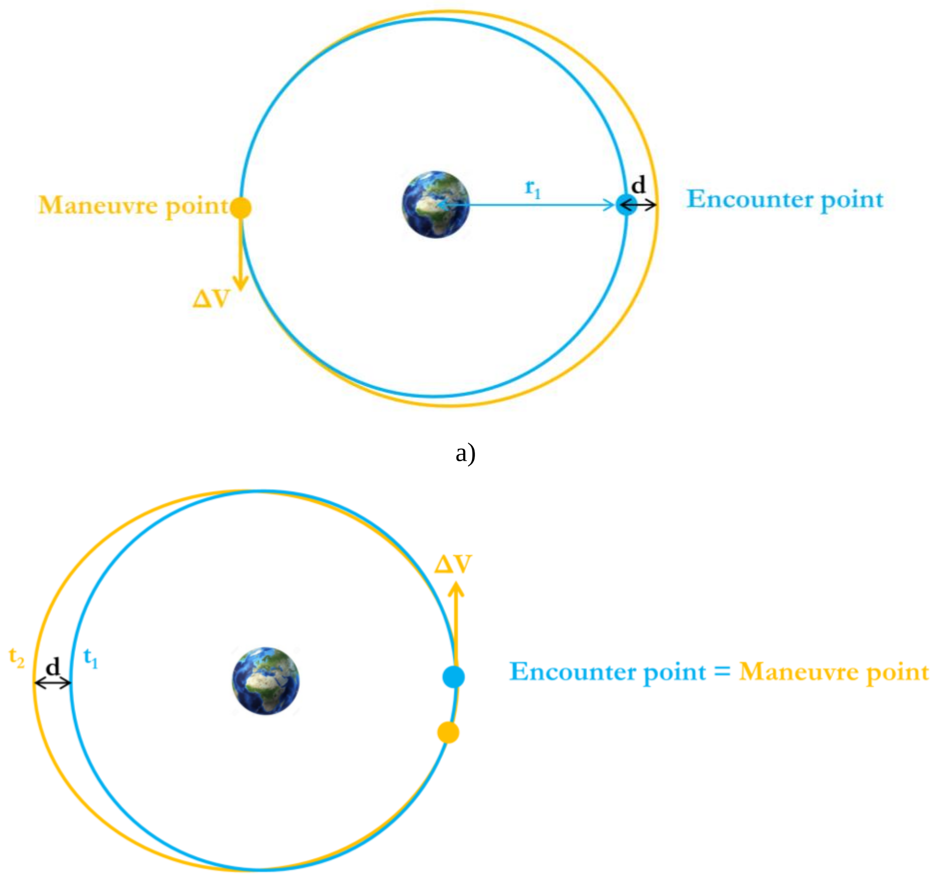


Fig. 3 Current operational collision avoidance process at GISTDA.

2.2 MANEUVER IMPLEMENTATION

The classic optimization problem of the efficient avoidance maneuver is to estimate delta-V in three orbital directions with the minimum distance between objects and cost function. The computation of the delta-V requirement associated with the mean number of avoidance maneuvers has to be related to a defined minimum miss distance threshold. The planning selection of maneuver execution is in agreement with the selected accepted collision probability level and minimum miss distance threshold. The delta-V is computed for each point in the B-plane. The satellite has to be moved a distance that depends on the point in the B-plane at which the debris object involved in the near-miss event is located.

Avoidance strategies in Fig. 4 can be classified as two strategies: radial and along-track separations. The radial separation in Fig. 4(a) purposes to change radial direction between the two objects and the maneuver is to be executed at the orbital position diametrically opposed to TCA in order to ensure the maximal radial separation at TCA. Along-track separation in Fig. 4(b) is to maneuver the execution at the encounter point before the predicted event. This separation results in a new arrival time of a satellite at the encounter point because of the difference in the orbital period between the initial orbit and transit orbit. In term of delta-V consumption, along-track separation requires a smaller amount of delta-V than the radial separation but the execution time of radial separation is independent from the time between the maneuver and the TCA. It implies that the execution time of along-track separation is very critical. The decision of maneuver type depends on the time delay between the conjunction prediction and TCA. In addition, an operational orbit of satellites generally must be maintained throughout the satellite operational lifetime. In case of collision avoidance required to execute and the station-keeping of a satellite (e.g. ground track and local solar time) draft from threshold control, this maneuver should be considered both collision avoidance and orbit requirements to effectively use the propellant consumption.



a)

b)

Fig. 4 Collision avoidance strategies planning a) radical separation b) along-track separation.

3 METHODOLOGY

3.1 Orbital dynamics model

The total perturbative acceleration ($\vec{a}_{total}$) acting on objects are modelled by applying a gravitation potential of the Earth ($\vec{a}_{\oplus}$), third body gravity acceleration due to the Sun ($\vec{a}_{\odot}$)and Moon ($\vec{a}_{☾}$), solar radiation pressure ($\vec{a}_{SRP}$) and atmosphere ($\vec{a}_{Drag}$). The total perturbative force is:

$$\vec{a}_{total} = \vec{a}_{\oplus} + \vec{a}_{\odot} + \vec{a}_{☾} + \vec{a}_{SRP} + \vec{a}_{Drag} \quad (1)$$

The numerical integration to solve the ordinary differential equations is the Runge-Kutta method. This method provides high-accuracy solution to ordinary differential equations with reasonable computational efforts.

3.2 Collision probability

In the applied method, the collision probability can be determined in term of the combined position uncertainty of the target and risk object at TCA [10, 11]. The combination of position is defined as a sum of each object radius and the shape is considered as an elliptical sphere. The object attitude at the conjunction is not taken into account and the position uncertainty is described by a 3D Gaussian distribution. The position uncertainty of two objects is assumed to be uncorrelated and the velocity uncertainty is neglected. Due to short-term encounter, two objects are considered to be moving along straight lines at constant velocities, and the position uncertainty during the encounter of both objects are also assumed to be constant. Based on these assumptions, the three-dimensional problem in B-plane to calculate the collision probability can be reduced to a two-dimensional problem. The B-plane is perpendicular to the relative velocity vector at TCA. The collision probability is computed as:

$$P_c = \frac{1}{2\pi\sqrt{\det(C_B)}}\int_{-Rc}^{Rc}\int_{-\sqrt{Rc^2-x_B^2}}^{\sqrt{Rc^2-x_B^2}} \exp[-\frac{1}{2}\Delta\hat{r}_B{}^T C_B{}^{-1}\Delta\hat{r}_B]dydx \tag{2}$$

where x_B is relative distance in x axis, R_c is the sum of the two object radius centered at the predicted fly-by location. $\Delta\hat{r}_B$ is a conjunction position within the B-plane, and then C_B is covariance matrix.

3.3 Conjunction risk assessment tool features

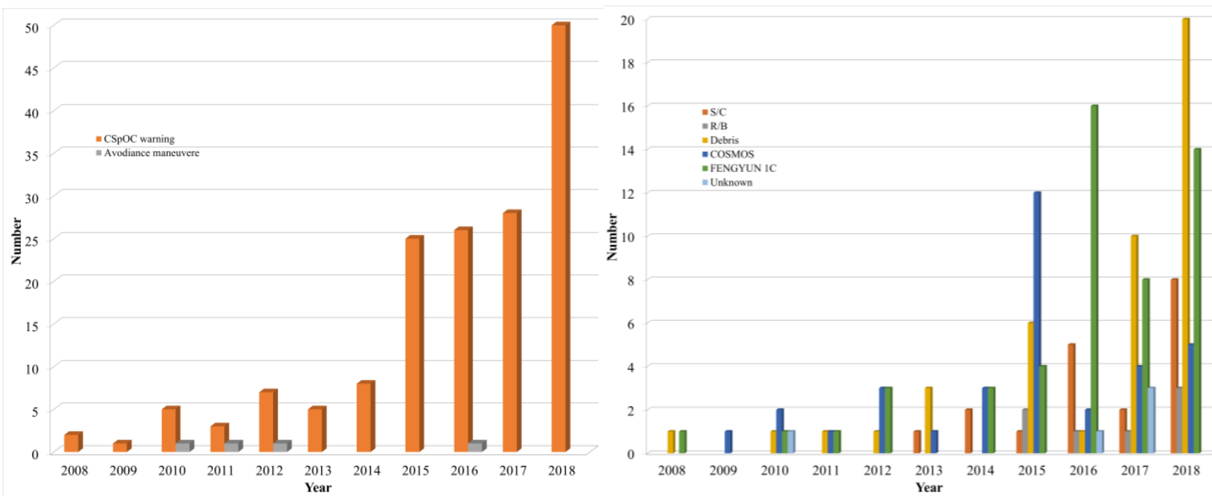
In addition screening the potential risk of ZIRCON, it can provide 3D visualization in Fig. 5 and essential analyzed information: the target and chaser trajectories, miss distance and collision probability for the better understanding of the close approach geometry and implementation of collision avoidance maneuvers. An interactive control of camera position, view angle, time, and zoom is high flexibility for the visualization of conjunction details and object positions at TCA. Some of the key features are:

- Risk assessment analysis tool.
- 3D visualization and graphical interface
- CDM managements (sorting)
- Recording of simulation events
- Automatically Email to operator.
- 3D visualization and graphical interface
- Report generation

Fig. 5 3D visualization analysis of the conjunction risk assessment tool: ZIRCON.

4 Statistics and collision avoidance experiences

Fig. 6 shows the statistics on the identified conjunction events and a number of collision avoidance maneuver between 2008 and 2018. The trend of CDMs by CSpOC in Fig. 6(a) has significantly increased since 2015 and there are 4 times to execute the maneuver. In general, after receiving the CDMS, CSpOC requires an operator to upload the satellite ephemeris to confirm the CDMs that is actual risk. Most of CDMs are not over thresholds control (miss distance < 1 km) after uploading the latest satellite ephemeris. As a result, a high number of false warnings are due to insufficient accuracy of satellite ephemeris based on TLE. The classified sources of each chaser object in close approach events are presented in Fig. 6(b) over the years. The 62.88 percent of all notifications are the two fragmentation events of Fengyun-1C in 2007 and Cosmos-2251/Iridium-33 in 2009. It can imply that the Fengyun-1C and Cosmos-2251/Iridium-33 events results in an increasing number of close approach events.



a) b)

Fig. 6 a) History of CDM notifications by CSpOC (2008-2018) b) Classification of object sources.

5 Conclusion

This paper presents the current collision avoidance procedure, which the conjunction risk assessment tool called “ZIRCON” is implemented. ZIRCON allows GISTDA to screen orbit paths of satellites to identify the closest approaches with space objects based on USSTRATCOM catalogues. The screening process of ZIRCON is semi-automated and conjunction events are forecasted the potential risk of space objects in advance 7 days. ZIRCON can provide 3D visualization of close approaches to understand the close approach geometry and decide the better effective maneuver. The statistical data of the history of CDMS highlight the significant changes in orbital environment in 11 years and reflect to the high number of false alarms. For the future development planning, ZIRCON will be developed to be fully automated screening system for serving future GISTDA’s satellites and a large number of space objects. Then, a web-based tool will be developed and implemented to concise and support operators for monitoring and communicating within the mission control team.

6 ACKNOWLEDGEMENT

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7 REFERENCE

1. Kessler, D.J., *Collisional Cascading: The limits of population growth in Low Earth orbit.* Advance Space in Research, 1991. 11(12): p. 63-66.

2. Aorpimai, M., V. Malayavej, and P. Navakitkanok, *High-Fidelity Orbit Propagator for Precise Antenna Pointing in LEO Satellite Operation* in *20th Asia-Pacific Conference on Communications*. 2014: Pattaya, Thailand.
3. Aorpimai, M. and P. Navakitkanok, *Orbit Control Manoeuvre Strategy for Post-Mission De-Orbiting of a Low-Earth-Orbit Satellite.* Applied Mechanics and Materials, 2015. 781: p. 495-499.
4. Aorpimai, M., P. Navakitkanok, and S. Jantarang. *Automated Flight Dynamics System for Thaichotes Satellite Operation*. in *2nd IAA Conference on Dynamics and Control of Space System*. 2014. Rome, Italy.
5. Channumsin, S., et al., *Development of an Orbital Trajectory Analysis Tool.* Engineering Journal, 2017. 21(7): p. 123-139.
6. Udomthanatheera, P., P. Navakitkanok, and M. Aorpimai, *The development of satellite orbit analysis and determination process system: EMERALD*, in *37th Electrical Engineering Conference*. 2014: khon kaen, Thailand.
7. Channumsin, S., et al., *Design and Validation of flight dynamics system.* Engineering Journal, 2019. 23(2): p. 97-117.
8. Channumsin, S. and S. Jaturut, *Analysis of coupled attitude and orbit dynamics for uncontrolled re-entry satellite*, in *The 2019 International Electrical Engineering Congress.* 2019: Cha-am, Thailand.
9. Channumsin, S., et al. *Autonomous systems of real-time monitoring and satellite mission analysis too*. in *69th International Astronautical Congress*. 2018. Bremen, Germany.
10. Alfriend, K.T., et al., *Probability of Collision Error Analysis.* Space Debris, 1999. 1: p. 21-35.
11. Akella, M.R. and K.T. Alfriend, *Probability of collision between space objects.* Journal of Guidance, Control and Dynamics, 2000. 23.
12. Stoer, J. and R. Bulirsch, *Introduction to Numerical Analysis* 1980, New York: Springer-Verlag.