Acta Astronautica 99 (2014) 193–200

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

On selecting satellite conjunction filter parameters

Salvatore Alfano *, David Finkleman *

Analytical Graphics Inc., Center for Space Standards and Innovation, 7150 Campus Dr., Suite 260, Colorado Springs, CO 80920-6522, USA

ARTICLE INFO

Article history:
Received 5 August 2013
Received in revised form
10 December 2013
Accepted 6 February 2014
Available online 22 February 2014

Keywords:
Conjunction assessment
Close approach threshold
Collision avoidance
Statistical error types
Decision criteria

ABSTRACT

This paper extends concepts of signal detection theory to predict the performance of conjunction screening techniques and guiding the selection of keepout and screening thresholds. The most efficient way to identify satellites likely to collide is to employ filters to identify orbiting pairs that should not come close enough over a prescribed time period to be considered hazardous. Such pairings can then be eliminated from further computation to accelerate overall processing time. Approximations inherent in filtering techniques include screening using only unperturbed Newtonian two body astrodynamics and uncertainties in orbit elements. Therefore, every filtering process is vulnerable to including objects that are not threats and excluding some that are threats, Type I and Type II errors. The approach in this paper guides selection of the best operating point for the filters suited to a user's tolerance for false alarms and unwarned threats. We demonstrate the approach using three archetypal filters with an initial three-day span, select filter parameters based on performance, and then test those parameters using eight historical snapshots of the space catalog. This work provides a mechanism for selecting filter parameters but the choices depend on the circumstances.

1. Introduction

Dealing with an ever more crowded space environment requires identifying potentially dangerous orbital conjunctions and executing a suitable course of action. The problem of on-orbit collisions or near misses is receiving increased attention in light of the collision between an Iridium satellite and COSMOS 2251. The International Space Station conducted a debris avoidance maneuver on 31 October 2012 to avoid a piece of Iridium 33 debris. Even a small Ecuadorean satellite has collided with debris. This paper contributes to conjunction assessment and collision avoidance by applying principles of signal detection to identify possible orbital conjunctions with quantifiable confidence and rapid and efficient computation [1].

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 those close approaches occur. 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 can be determined. The linear separation between the mean orbits of two satellites is the most-used initial discriminant. Mean orbits are not really the satellite trajectories on the time and distance scales of conjunctions and collisions. The satellite trajectories differ from the mean orbits because there are deviations due to physical perturbations. This is a necessary expedient but not the only simplification or source or error.

2. 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

* Corresponding authors.

http://dx.doi.org/10.1016/j.actaastro.2014.02.004
0094-5765

below a selected threshold. This paper deals with selecting those thresholds. 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 versus all other catalog objects) is a computational challenge, this also accelerates executing time-critical and time-fragile operations.

Hoots et al. [2] designed a series of three filters to expedite identifying threatening close approaches. Two are geometrically based on orbit proximity over time, and one seeks temporal coincidence among orbits that are close.

Healy [3] exploited parallel processing to screen for threatening conjunctions rapidly. Rodriguez et al. [4] suggest that the complexity of the orbit path and time filters and imply “a lack of robustness.”

Recognizing this, researchers “pad” orbits with heuristically determined spatial bands as avatars for unknown effects of uncertainties and simplifications.

We will examine the rationale of several commonly-used filters and demonstrate error cases for each. Requirements for the use of computational *pads* will then be examined. The reliability of the filtering process will be evaluated using “all-on-all” examples where results will be generated with and without the use of conjunction filters. Computational time savings will not be addressed due to the tremendous variability associated with platforms, operating systems, and hardware used for data storage. Being able to determine keepout thresholds concretely must conserve computational effort and achieve a user's most suitable balance between missed conjunctions and false alarms. The methodology that follows can be applied to any filter.

All results in this paper were generated using the publicly available catalog of Two Line Element Sets (TLEs). Errors were initially assessed by finding all unique conjunction pairings for 14,546 objects in the public TLE catalog with minimum ranges of less than 5, 10, 30, and 50 km for the three day period beginning at 22 Feb 2012 19:00:00.000. Although TLEs were used exclusively in this study, the analysis method that follows will work with any trajectory source. The approach that follows can be used with any type of trajectory source data involving natural satellite motion.

3. Conjunction filters

These filters are subject to false positive identifications (Type I errors) as well as false negative identifications (Type II errors). A Type I error occurs when the filter determines the satellite pair should be assessed further but no conjunction is found. This is to be expected because the screening is based on aggregated orbital characteristics and not precise satellite positions over the time interval. The ratio of non-conjuncting pairs forwarded by the filter to the total number of non-conjuncting pairs assessed is a figure of merit. Specificity, or false positive rate, is defined as one minus this ratio. A Type II error occurs when the filter determines the satellite pair should not be assessed further but a conjunction exists. This reveals that the predicted satellite positions will come closer than the minimum distance between orbits determined by the filter. The sensitivity, or true positive rate, is the ratio of actual conjuncting pairs forwarded by the filter to the total number of conjuncting pairs. A Type II error is one minus this ratio.

Type II errors result from the simplifying assumptions that went into the development of the various filters. By adding a pad or buffer to the desired distance threshold one can reduce such errors and avoid missing possible conjunctions at the expense of more Type I errors. Reducing or eliminating Type II errors may require large pads which will, in turn, increase the computational burden. The pads should account for the precession of the nodes and apsidal rotation as well as the secular and short-periodic variations for all the orbital elements (semi-major axis included). Such padding should strike a balance between timeliness and accuracy as determined by the user.

It is important for the user to configure the pad settings such that operational requirements are met in a timely fashion with an acceptable limit of Type II errors. This requires both step size control and distance bounds based on natural motion. Pad settings should be chosen in a manner that allows the end user to know whether the tool was exercised with a focus on accuracy or speed. If precision alone is important, one must be certain that the filters will not prematurely eliminate a pair of satellite from consideration that might be found to have a conjunction; Type II errors are shunned[1]. Such assurance comes with increased processing time as the computations would take much longer due to very conservative (large) pad settings. To maximize positive detections, no Type II errors, the simplest approach is to turn the filters off and assess every pair, accepting the increase in downstream computations. The padding characteristics presented in the following test cases assume natural relative motion and should not be used if the ephemeris of either satellite contains maneuvers unless those maneuvers are included in process models.

4. The apogee/perigee filter

Apogee/perigee filters admit only satellite pairs with overlapping Earth central radii, such as in Fig. 1 [8].

Researchers have expedients for establishing apogee and perigee ranges. Some use approximate rates of those elements to project values at epoch based on the mean motion and eccentricity. Mean motion is part of a TLE but is not readily available for other forms of orbit data. Computations associated with the apogee/perigee filter need only be performed once for each object, not once for each pair of objects. To characterize the errors associated with pad sizes for this filter, we conducted a large scale conjunction screening analysis[2]. This involved finding all unique conjunction pairings for 14,546 objects in the public TLE catalog with minimum ranges of less than 5, 10, 30, and 50 km for the three day period beginning at 22 Feb 2012 19:00:00.000. 50 km is considered a reasonable upper limit for distance screening based on probability-based actions [5]. For this analysis, three days

[1] It is impossible to eliminate all false detections while still enjoying any detections at all. Zero false alarms is absolutely unachievable.

[2] STK 9.2.3 was employed for this purpose.