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Considering the collision probability of Active Debris Removal missions

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ABSTRACT

Active Debris Removal (ADR) methods are being developed due to a growing concern about the congestion on-orbit and sustainability of spaceflight. This study examined the probability of an on-orbit collision between an ADR target, whilst being de-orbited, and all the objects in the public catalogue published by the US Strategic Command. Such a collision could have significant effects because the target is likely to be located in a densely populated orbital regime and thus follow-on collisions could take place. Six impulsive and three low-thrust example ADR mission trajectories were screened for conjunctions. Extremely close conjunctions were found to result in as much as 99% of the total accumulated collision probability. The need to avoid those conjunctions is highlighted, which raises concerns about ADR methods that do not support collision avoidance. Shortening the removal missions, at an expense of more ΔV and so cost, will also lower their collision probability by reducing the number of conjunctions that they will experience.

1. Introduction

Active Debris Removal (ADR) is believed to be necessary in order to stop the collision cascade predicted by Kessler and Cour-Palais [17] and preserve access to the vital resource of space [15]. Considerable investments are being made world-wide in the development of necessary technologies, and in-orbit validations are likely to materialise in the near future [39,8,29,31]. Even business models for ADR companies are being studied [36].

Rendezvous and interaction with an uncooperative and unprepared object has never been performed before and, as such, will be challenging. Many different concepts for ADR have been proposed and significant research is being done world-wide in order to reduce the tremendous cost of removing many objects [9,28].

Recent studies have shown that failure of ADR missions may have a detrimental effect on the debris environment [21]. The most severe and damaging outcome of an ADR mission failing would be a catastrophic on-orbit collision. This would not only negate the benefit of such an initiative but also undermine its support. Comparison of the collision risk associated with different ADR technologies was carried out by Nock et al. [27]. Work has also been done on reducing the probability of causing orbital collisions through ADR, e.g. fragmenting long electrodynamic tethers [18]. However, these analyses used long-term collision probability estimation techniques, which do not reflect the trends in collision probabilities that will be seen during operational collision screenings. This paper estimates probabilities of causing orbital collisions that are associated with various proposed ADR approaches using algorithms similar to those used operationally [13]. Only ADR mission trajectories, not technologies, are analysed. However, the type of trajectory often implies sets of specific technologies, e.g. low-thrust de-orbiting could be achieved using electric propulsion, drag augmentation or electrodynamic tethers.

First, the method of detecting conjunctions and assessing them in terms of collision probability is described. Then, three example ADR trajectory types, which correspond to different ADR approaches, and three exemplar ADR targets are presented. The trajectories are screened for conjunctions against the public two-line element set (TLE) catalogue and their collision probabilities are compared to one another. A comparison is also made to the collision probabilities that the ADR targets accumulate over a period of time in their current orbits, and conclusions are drawn hence.

2. Methodology

This section describes the methods that have been used to quantify collision probabilities of example active debris removal mission trajectories. This methodology is only briefly reviewed here, the used algorithms are described in more detail by Lidtke and Lewis [22].

2.1. Conjunction detection

A conjunction is defined as an event where the centres of mass of

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two objects are within a specified distance from one another. Specifically, the time of the closest approach (TCA) was chosen as the conjunction epoch. The collision probability between the two objects may be greater at a different time, if their attitude is accounted for, but this was ignored in this study.

Different distance thresholds in e.g. in-track or cross-track directions can also be used for conjunction detection to account for the fact that the position uncertainties are generally not the same in every direction [2,11] and so conjunctions with the same separation between centres of mass might have different collision probabilities. However, it was decided to account for this by setting the conjunction threshold distance high and equal in every direction, and accepting that certain conjunction geometries may result in very low collision probabilities with such a miss distance. Furthermore, conjunctions between more than two objects were treated as multiple conjunctions between pairs of objects.

The computational time required to identify conjunctions involving all the objects in the public TLE catalogue is significant – 14 917 objects had been observed in the 30 days preceding 7 Nov 2013 and their orbits were published via Space-Track [34]. This raises the need to implement a number of pre-filters, which discard pairs of objects that cannot have a conjunction based on fast to evaluate principles, before the more computationally-intensive range-based detection. To this end, a set of traditional algorithms, based on the “smart sieve” developed by Rodriguez et al. [32], was used here.

2.2. Collision probability estimation

This study is concerned with the collision probability, P_C, of ADR missions. A method to establish the uncertainty on the state (position and velocity) of the object is given first. Computation of the collision probability, given the uncertain positions of the objects during the close approach, is described next. Finally, an assumption regarding the physical size of the objects, which is important for P_C calculations, is discussed.

2.2.1. State uncertainty

Ephemerides of all the objects are known with the accuracy of some Space Surveillance and Tracking (SST) system. Conjunction screenings and assessments, and decisions to mitigate the collision risk, are performed by the operators based on these data. Thus, assuming that the ephemerides are known with the accuracy of the SST system gives an estimate of the collision risk that will be accepted by the operators.

The European Space Agency has defined an accuracy envelope that the European Space Surveillance System (ESSS) shall provide [12,19]. If the system is built according to these requirements, the position of all the objects in orbit will be known with accuracy no worse than 40, 200, and 100 m in the radial, along-track and cross-track reference frame in the low Earth orbit (LEO) regime at all times [12]. These standard deviations can readily be used to construct covariance matrices from which the collision probability can be computed.

Because ESSS will catalogue the LEO objects with the said accuracy at any time, propagation of the covariance is not necessary because, in reality, the position uncertainty may only be less. Lower position uncertainty corresponds to lower collision probabilities, unless an extremely close conjunction is recorded. This behaviour of collision probability with varying magnitude of the orbit uncertainty has been investigated in more detail by Alfano [3].

2.2.2. Collision probability estimation

Every conjunction is analysed in a B-plane frame of reference centred on the primary (the ADR mission target) to compute the collision probability of every encounter [6,4,10]. Position covariances of both objects (velocity covariance is ignored) are rotated to the B-plane according to the algorithm given e.g. by Berend [6]. The matrices are added to form a combined covariance matrix C, which assumes uncorrelated uncertainties of both states. Rectilinear relative motion and time-invariant position uncertainty are assumed in the vicinity of the TCA, thus allowing the covariance matrix to be projected onto the B-plane and reducing the number of dimensions of the problem from three to two [6,10]. McKinley [25] has shown that even for relative velocities of 0.013 km/s, the rectilinear relative motion assumption resulted in collision probability estimates to be in the same order of magnitude as when this assumption was relieved. Moreover, Frigm & Rohrbaugh [14] found that this assumption held in over 99% cases for LEO and GEO satellites that they analysed. Thus, this assumption is not expected to affect the results of this study because P_C of most conjunctions will not be affected by it.

The position covariance matrix C is then converted into a probability density function (PDF) and integrated inside a circle with radius equal to the combined radii of the two objects collision radius and centred on the primary [6,10]. This integration yields the probability that both objects' centres of mass will be within the collision radius during the closest approach, i.e. the collision probability P_C.

The integral of this PDF can be expressed as an infinite series of analytical terms, thus reducing the time required to compute the collision probability for every conjunction [10]. However, a sensitivity study revealed that, when the probability density is low, this approach is inaccurate due to floating point truncation errors. Such conjunctions were expected to occur often in this study due to relatively low state uncertainty and large conjunction screening distance. Thus, a direct integration of the PDF, using a two-dimensional Simpson numerical integration scheme with 5000 integration intervals [30], was used instead.

2.2.3. Object physical size

TLEs come with no information as to the size of the associated objects. Therefore, certain assumptions had to be made to enable the collision radius to be estimated and the P_C to be computed.

A database containing the physical radii of objects launched up to 2003 (up to catalogue number 28057), originally compiled by The Aerospace Corporation, was used to allow the collision radius to be computed for some conjunctions. For the remainder of the catalogue, statistical data from the MASTER reference population of 1 May 2009, which is a reference population used e.g. in some IADC (Inter-Agency Debris Coordination Committee) studies, were used. This population comprises 19 630 objects larger than 10 cm, and associates each object with a hard body radius and a type, i.e. classifies it as a rocket body (R/B), payload (P/L), mission-related object (MRO), or debris (DEB). An average radius was computed for all the objects of a given type present in the MASTER reference population. The standard deviation of every group was also found and the results are shown in Table 1.

Some of the MASTER object types can be directly linked to TLEs through three-line element sets that contain information about the type of certain objects in their common name fields. Because the three-line element set catalogue does not distinguish mission-related objects, the data for this type of object were not directly utilised. Moreover, three-line element sets of some objects do not classify the objects as payloads, rocket bodies or debris. For these objects, the average size of the entire MASTER 2009 (all four types of objects) population was used.

When an object was not present in the database of radii and P_C had

Table 1

Radii of the objects according to their types (rocket bodies (R/B), payloads (P/L), mission-related objects (MRO), and debris (DEB)) as present in MASTER reference population of 1 May 2009 and discerned in Space-Track's three-line element sets. Details given in text.

Object type	R/B	P/L	MRO	DEB	Other
MASTER Object ID	1	2	3	4	1,2,3 and 4
Average radius (m)	1.769	1.035	0.539	0.156	0.347
Standard deviation (m)	0.815	0.782	0.722	0.555	0.780