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Short and long-term reconstruction of in-orbit fragmentation events

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Abstract. Over the past decade, the number of space debris has steadily increased. Consequently, the risk of collision between debris and active satellites has also increased, threatening the safety of space operations. Therefore, it is crucial to characterise fragments as soon as possible after their formation, to gather information about the fragmentation event which has generated them. In this context, the PUZZLE software has been developed at Politecnico di Milano to reconstruct past in-orbit breakups. This research aims at improving the current routine to obtain more accurate results and at optimising it for the analysis of fragmentations in the GEO and MEO regions.

Introduction

The exploitation of the space environment has massively increased over the last decade, resulting in a growing number of services relying on in-orbit satellites. In recent years, space debris have become a major concern for space agencies worldwide, as the majority of the population in space is represented by fragments which have been generated by in-orbit fragmentations such as collisions and explosions. Considering this scenario, the Inter-Agency Space Debris Coordination Committee has formulated mitigation guidelines concerning the disposal of satellites, yet the compliance to these measures is still too low for a sustainable use of space, hence the number of space debris is increasing. The consequence of this growth is a higher collision risk between satellites and fragments. Fragmentation events are difficult to predict, however the constant tracking of space objects allows to detect newly generated fragments. The analysis of the fragments upon formation is crucial to assess whether they have been generated in a new fragmentation event, allowing to characterise the breakup and reduce the risk it poses to other satellites.

Several methods have been developed to this aim, exploiting different features of the orbital motion of the fragments. Andrisan et al. [2] developed the Simulation of On-Orbit Fragmentation Tool (SOFT), to determine the epoch and the objects involved in a breakup using backward propagation and the position of the centre of mass.

Dimare et al. [3] characterise a fragmentation by defining an orbital similarity function between the orbital elements of the detected fragments. Several orbital similarity functions have been evaluated to correlate fragments with known orbits to parent(s), like it is usually done for asteroid families.

Frey et al. [4] developed a method to search for a fragmentation event in the long-term, i.e. in the order of years, exploiting a continuum approach for fragmentation modelling in LEO, based on the density of objects. The estimation of the epoch of the breakup is carried out by looking for the convergence of objects in inclination and right ascension of the ascending node (RAAN), which have been considered as robust features in LEO.

This work focuses on the PUZZLE software [1,5], which was developed at Politecnico di Milano with the purpose of detecting and analysing occurred fragmentations and the corresponding objects involved in them.

Methodology

The PUZZLE software analyses a set of unclassified Two-Line-Element (TLE) data to assess if a fragmentation has occurred in the recent past in Low Earth Orbit (LEO). The software has been developed for the reconstruction of fragmentation events both in the short-term (order of days) [5] and long-term (order of months to years) [1], however the methodologies implemented differ according to the time frame. The first step in the routine is the pre-filtering of the TLE data, which is performed in both cases. The aim of this step is to filter out outliers in TLEs, which could be due to errors in the initial orbit determination process [1]. For each set of TLEs associated to the same Satellite Catalogue Number, the filtering algorithm proposed by Lidtke et al. [6] is implemented.

A significant difference between the two versions of PUZZLE is the type of orbital elements used in the analysis. The short-term routine employs osculating orbital elements, which are propagated backwards with the Standard General Perturbations 4 (SGP4) propagator [7]. The long-term version instead uses mean Keplerian orbital elements, propagated with the PlanODyn propagator [8]. As opposed to SGP4, PlanODyn requires the Ballistic Coefficient (BC) for the propagation, therefore in the long-term PUZZLE routine the BC is estimated according to the method by Gondelach et al. [9] after the pre-filtering module, introducing a significant source of uncertainty.

The initial fragments are grouped into different families according to their orbital characteristics by means of pruning and clustering algorithms. Several methods have been implemented:

- A triple-loop filter, similar to the one proposed by Hoots et al. [10];
- An orbit inclination filter;
- An orbit RAAN filter;
- A Hierarchical Clustering Method (HCM) as in Zappala et al. [11].

The triple-loop filter consists in two geometrical filters and a time one. Its purpose is the identification of the fragments for which a close approach is possible while discarding the rest. The first filter is an apogee-perigee filter, to check if the geometry of the analysed pairs of objects is compatible. The second filter evaluates the MOID of the pairs of orbits. A threshold is set to reject the objects whose MOID is too high. The last filter generates angular windows around the MOID, converts them into time windows and searches for overlapping windows for each pair of objects. The triple-loop is implemented in both versions of PUZZLE, however the time filter is not used in the long-term investigation as it loses accuracy far from the event [1].

The inclination and RAAN filters are implemented only in the long-term version of the software. The inclination filter exploits the natural feature of LEO orbits for which inclination is little affected by perturbations. The RAAN filter is based on the boundedness of the RAAN for fragments and parent objects candidates near the event epoch [1].

The HCM is implemented only in the short-term routine. The algorithm is exploited to divide the objects into groups according to their orbital parameters at the fragmentation epoch. A similarity distance function is defined starting from the one proposed by Zappala et al. [11] and modifying it to account for all orbital parameters. The metric is evaluated for each couple of objects, grouping together the closest ones in an iterative approach until all the objects are assigned to a group and families have been formed.

After the backward propagation of the objects, the epoch estimation and parent identification of the fragmentation event is carried out. In the short-term method, the triple-loop is coupled with the propagator to detect clusters of objects in terms of position in time. Then, the HCM is employed to identify the fragments and the parents involved in the event. The long-term analysis instead exploits the RAAN filter to identify clusters of objects while backpropagating. A 2D histogram in sine and cosine of the RAAN allows to count the objects in each angular region and discard the objects which were not involved in the event. The parent identification process is carried out by matching the candidates with a catalogue. The last step of the PUZZLE approach consists in simulating the fragmentation with the NASA standard breakup model [12,13], to estimate the number and the distribution of the generated fragments.

Limitations and future work

The PUZZLE software has been tested to reconstruct several known fragmentation cases, giving accurate results. However, some limitations exist. The algorithms implemented in the routine are sensitive to the size of the TLE set used as input, leading to significant computational times. The bottleneck is the triple-loop module, hence future work will be dedicated to its improvement from a computational point of view, investigating parallel computing strategies. Moreover, the algorithms will be revised to search for new possible pruning and clustering criteria and to improve the existing ones. For the long-term version, the revision will include a refinement in the computation of the BC which is a significant source of uncertainty.

A further step will be taken to harmonise and integrate the long-term and short-term versions of the software. The main idea is to include settings able to automatically switch from the long to the short-term search and vice versa according to the timeframe of the event and the input TLEs. In this way, the short-term investigation could also be used as a refinement of the long-term one [1]. In this framework, the PUZZLE approach will be improved in terms of automatisation of the selection of the settings for the automatic recognition of breakups. Appropriate values of the thresholds required by the algorithms will be investigated and validated through sensitivity analyses, such that the selected settings could be used for any fragmentation according to the orbital region.

Another limitation of the current versions of the software is that they have been designed to work only in LEO, as they exploit some natural features of this orbital region. Indeed, when trying to apply the same algorithm to fragmentation events at higher altitudes, the fragmentation identification fails. Therefore, the goal for future work is the extension of PUZZLE to other orbital regions (i.e., GEO and MEO) to allow the early analysis of detected fragments.

The last improvement of the software deals with the inaccuracy of the available data about space debris, which impacts the results achievable with PUZZLE. For this reason, future work will introduce uncertainty propagation in the algorithm by adding additional TLEs. Several uncertainty propagation methods will be considered, however the Gaussian Mixture Model and Unscented Transformation are expected to be the most suitable ones to properly represent the non-linearity of the problem. Preliminary analyses [14] have shown an improvement in the accuracy of identification of the event epoch and of the parent object(s) when including uncertainties, hence it is expected that the software will work also for cases that failed before, while reducing the sensitivity to input control parameters.

Conclusions

As the space debris population keeps growing, it is necessary to be able to track and characterise fragments originated in fragmentation events. In this work, the PUZZLE software for the detection and analysis of breakups has been presented. Two separate versions of PUZZLE can deal with fragmentation events occurred in the past in the short and long-term. Despite the good results obtained with the current routines applied to known fragmentation events, future work will be dedicated to the improvement of the implemented algorithms to guarantee more accurate results in a reduced computational time. Moreover, it will be crucial to extend the software to the GEO and MEO regions, to have a more global vision of the debris population.

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