Collision probability assessment for Active Debris Removal missions

IAC-14,A6,P,15x23793 - SPACE DEBRIS SYMPOSIUM

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Motivation and Goals

Active Debris Removal is believed to be necessary in order to preserve mankind's access to the vital resource of Space. Considerable investments are being made world-wide in the development of the necessary technologies and in-orbit validations are likely to materialise in the near future.

Rendezvous and interaction with an uncooperative object has never been done before and, as such, is going to be highly challenging. Many vastly different concepts for ADR technologies are being proposed and plenty of research is being done in order to try and reduce the tremendous cost of removing as many objects as believed necessary to halt the increase of the number of debris.

However little to no attention is being given to the risks associated with performing ADR. Recent studies at the University of Southampton have shown that failures of ADR missions may have a detrimental effect on the debris environment. But the most severe outcome of an ADR mission failing would be a catastrophic collision that would not only offset the benefit of such an initiative but also undermine the support for it.

This research aims to address this issue and assess various proposed ADR architectures' chance of causing a collision in orbit. It is expected that certain approaches will be more prone to this than others, potentially to an extent that would make this architecture selection criterion as important as e.g. the total mission cost. This primarily applies to the mission trajectories but these can often be associated with specific technology sets.

Conjunction Detection and Assessment

A software tool has been developed that enables arbitrary trajectories to be screened for conjunctions against the entire public Two-Line Element (TLE) catalogue. This allows orbital mechanics to be reasonably well represented while allowing individual conjunctions to be analysed and keeping the simulation durations low.

The conjunctions are found by using an adaptation of the "smart sieve" pre-filter set that allows pairs of objects that cannot physically have a conjunction, defined as an approach to within a certain distance, to be quickly discarded from the analysis in a given time step. The relative distances between the primary and the remaining secondary objects at the respective times of closest approach are found by finding the epoch when the relative range rate is zero, i.e. when the relative range takes one of its extreme values.

True and maximum collision probabilities are then computed for all the conjunctions by assuming that the orbit information of all the objects is known with the accuracy planned for the European Space Surveillance System. This approach enables the true collision probability, which would be present in real life, to be bound by finding its extrema.

A database of the physical radii of objects launched before 2003 has been kindly provided by T.S. Kelso from Analytical Graphics Inc.

Data from ESA's MASTER 2009 population has also been analysed and an average radius of various types of objects has been found. These object types were then linked to the classification of objects as present in Three-Line Elements. One of these radii was used in case a conjunction with an object of a given type took place and its radius was not present in the database.

MASTER2009 objects' radii by type

Object Type	R/B	P/L	MRO	DEB	Other
MASTER Object ID	1	2	3	4	1, 2, 3, and 4
Average radius (m)	1.7691	1.7691	0.5385	0.1558	0.3470
Standard deviation (m)	0.8145	0.7824	0.7219	0.5545	0.7803

Conjunction detection

Public TLE catalogue

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Freeware SGP4

↓

Ephemerides tables of the secondaries

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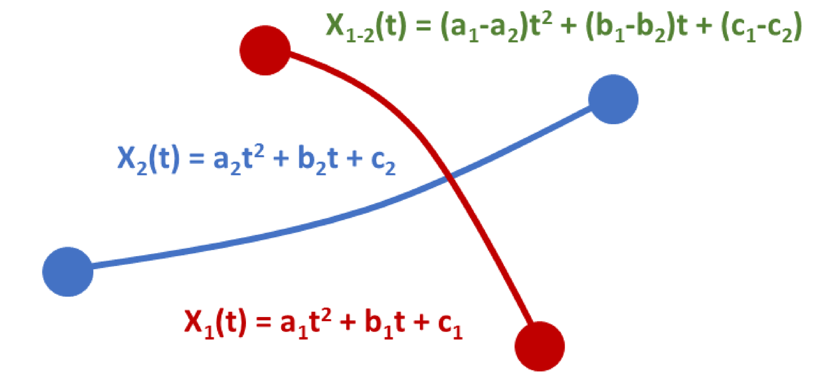
Modified "smart sieve" and piecewise cubic interpolation



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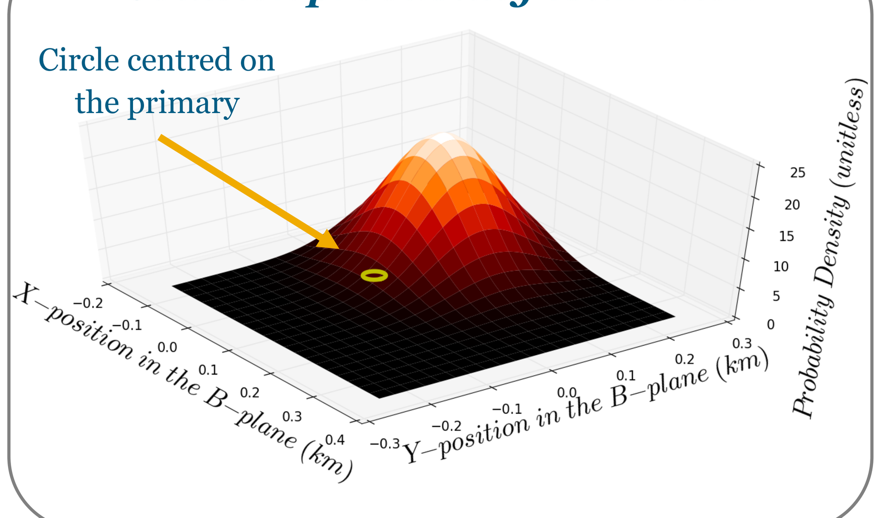
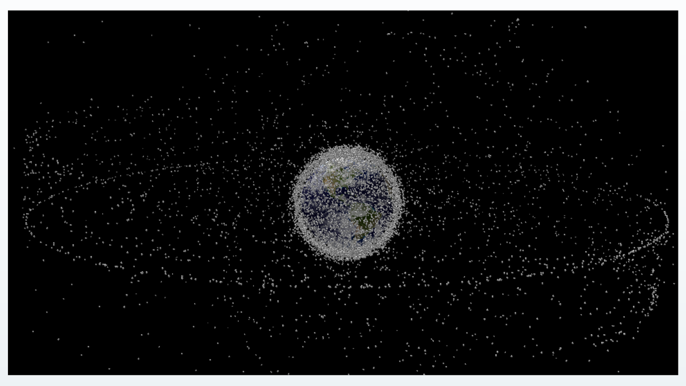
Conjunction epochs and geometries

Collision probability estimation



Active Debris Removal Mission Simulation



An example object, a Zenit-2 Rocket Body (R/B), has been chosen as target and several example ADR architectures were analysed.

The collision probability of the Zenit-2 R/B in its current orbit over the duration of one year was also computed for comparison.

Radius of 6.377 was used in all the probability calculations (Zenit-2 only) for every architecture. This is because this study did not look at preliminary design of any of the architectures and only the highest-level differences in the risk posed to the debris environment were of interest.

All ΔV calculations were performed using mass of the Zenit-2 only (9850 kg) as well. All architecture-specific mass additions were ignored also in this area for the aforementioned reasons.

Example ADR architectures

1) **Impulsive chemical transfer with long cost arcs**—representative of multi-debris removal missions with chemical de-orbit kits that performs controlled de-orbit into South Pacific Ocean Uninhabited Area. A long coast phase that imitates trying to reduce the amount of fuel used when travelling between multiple debris was included in the trajectory.
2) **Impulsive chemical transfer and de-orbiting of a single debris**—active change in orbital inclination that reduces the coast phase's duration but increases the fuel consumption is performed. It is representative of an ADR mission targeting a single object.
3) **Low-thrust transfer**—representative of electrodynamic tethers, drag augmentation devices, or the "ion beam shepherd". It is the most fuel-efficient but takes the most time to de-orbit the target and does not provide a controlled re-entry.

Architectures Comparison

Architecture	Impulsive	Impulsive no-drift	Low-thrust	Reference Zenit-2 orbit
Mission duration (days)	11.55	0.13	593.14	365.25
Specific Impulse (sec)	300	300	3400	N/A
Fuel mass (kg)	712.93	2206.91	38.18	N/A
Accumulated maximum collision probability (-)	1.49E-04	3.73E-05	9.94E-03	6.38E-03
Accumulated true collision probability (-)	1.12E-11	1.11E-16	1.56E-03	1.85E-03
Controlled de-orbit (T/F)	1	1	0	0

Conclusions

Clear differences exist between all examined architectures and the reference collision probability of the target in its current orbit. These allow the following conclusions to be drawn:

1) Certain architectures may be more prone to causing an orbital collision than letting the object reside in its environment longer. It can hence be inferred that, depending on the removal mode, it may be less dangerous to the environment to perform fewer removals per year but in a safer manner.
2) If the entity performing the removal causes an orbital collision it may be held responsible as it was in control of the debris when it took part in the collision. This could result in:
   - Financial damage compensation claims
   - Damaging Active Debris Removal company's profile
   - Reduction of the international support and accompanying loss of funding for ADR
3) Most of the collision probability is accumulated due to very close conjunctions that can be forecast. Therefore incorporating collision avoidance into the ADR architecture may vastly reduce the risk to the environment introduced during such operations.

Acknowledgements

Authors would like to thank the ESA Space Debris office for allowing them to use the MASTER 2009 population. Dedicated thanks go to Dr Holger Krag and Dr Tim Flohrer for their extremely valuable feedback and help in validating the collision probability algorithms.

Big thanks Dr David Vallado for distribution of the SGP4 propagator code, without which this research would never be possible in the timeframe available.

The authors would also like to express their gratitude to Dr T.S. Kelso for useful comments regarding the collision probability algorithms, maintaining the CelesTrak website and provision of the objects' physical radii database.

The authors would also like to acknowledge the use of AGI's Systems Toolkit in the verification process of the developed simulation framework.

Most of all, sincere thanks to Dr Claudio Bombardelli for providing an example low-thrust ADR trajectory.

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