Update on ESA's Space Safety Programme and its Cornerstone on Collision Avoidance

Tim Flohrer, Klaus Merz, Jan Siminski
ESA Space Debris Office, Email: tim.flohrer@esa.int
Holger Krag
ESA Space Safety Programme Office

Abstract

ESA's (European Space Agency) Member States have put forward a Space Safety Programme at the Space19+ Council meeting at Ministerial level in 2019. The Programme groups all activities on risk management into the three segments: Space weather, Planetary Defence, and Space Debris and Clean Space.

In the segment addressing Space Debris and Clean Space ESA aims at developing the technologies that make Europe capable of monitoring and safely managing its space-related traffic, equipped with (automated) systems free from causing damage. A cornerstone component for this objective is included in the programme: "Collision Risk Estimation and Automated Mitigation (CREAM)".

CREAM encompasses the

- development of techniques for automated manoeuvre decisions,
- concept studies and protoflight developments for the use of Signal-in-Space commanding,
- development of techniques and protocols supporting manoeuvre coordination between operators and services providing space debris monitoring,
- and aims at testing these techniques with a selected technology demo mission.

We report on the current status of the Space Safety Programme, and focus on the area of collision avoidance. In particular we report on the preparatory activities for CREAM performed during 2019 and present the ongoing and next activities.

1. ESA's Space Safety Programme

1.1 Overview

Recognising the importance of space as an integral part of society and economical wealth, the safety of space-based infrastructure is at the focus of ESA's new Space Safety Programme. The programme addresses both, man-made and natural hazards as they pose a risk to European infrastructure, with the objectives to contribute to the protection of our planet, humanity, and assets in space and on Earth from threats originating in Space. As introduced in the outline of the proposal [1], the programme structure comprises three topics:

- Space Weather,
- Planetary Defence, and
- Space Debris and Clean Space.

The programme proposal for Space Safety received an overall subscription of ~435M€ at the Space19+ council at ministerial level in Seville, Spain, in November 2019. The successful proposal introduces Space Safety as a new basic pillar of ESA's activities. The budget puts ESA in a position to proceed with implementing a combined core element for technology developments and demonstration for the three topics from 2020. In addition it allows to progress now with all four proposed cornerstones under the programme, which are:

- an operational space weather mission at Lagrange point L5 to enable future provision of space weather nowcasts and forecasts with enhanced accuracy and timeliness,
- a post-impact characterization for demonstration and further validation of the asteroid kinetic impact deflection technique (Hera),

- a debris removal mission to address the debris risks and at the same time support the establishment of a market of in-orbit servicing (ADRIOS – Active Debris Removal and In-orbit Servicing), procured as a service from the Swiss start-up ClearSpace, and
- an automated collision avoidance system (CREAM - Collision Risk Estimation and Automated Mitigation).

CREAM considers that collision avoidance manoeuvrers are a costly but necessary routine today [3]. A high false alarm rate due to uncertainties in the data, limitations due to decision deadlines set by the system architecture and operations concept, and risk due to difficult coordination among operators are commonly understood as drivers for urgently needed improvements, especially in view of the rapidly increasing traffic in LEO.

1.2 Focus areas in the Space Safety core element for Space Debris and Cleanspace

The core element of the Space Safety Programme builds upon the results of the SSA Programme [1]. The activities in all of the three topics address both, threat awareness, as well as responsiveness to the threats. For the Space Debris and Cleanspace area these are in particular:

- ensuring the availability of data through developments of ground-based and space-based sensor technologies [3],
- running a community approach for further development and maintenance of data processing technologies through a so-called “SST core software” [3],
- test operations for the Expert Centre technology [3,4,5],
- improving risk models, e.g. for re-entries [6,7],
- means for space debris mitigation, e.g. technology studies for photon pressure based momentum transfer [8,9] and maturation of technology for better compliance with mitigation guidelines, as well as technical developments for future compliance monitoring [10, 11, 12], and
- life cycle assessment modelling of space activities to identify hotspots and propose technological solutions.

1.3 Recent activities related to CREAM

We previously introduced plans for a global open competition for machine learning that should study the decision process in collision avoidance [1]. In Autumn 2019 ESA’s Advanced Concept Team (ACT) organized this competition in partnership with ESA’s Space Debris Office. The so-called “Spacecraft Collision Avoidance Challenge” [2] considered the overall motivation for CREAM as starting point. As machine learning can contribute to solving the current gaps, and in order to focus in CREAM on suitable approaches, ESA compiled for the competition a dataset of 187000 conjunction alerts out of the millions received at ESOC. Participants were asked to model the risk evolution and to predict the final collision risk between orbiting objects. The competition formally closed on 16 December 2019 (see Fig. 1) and findings have been published [2].

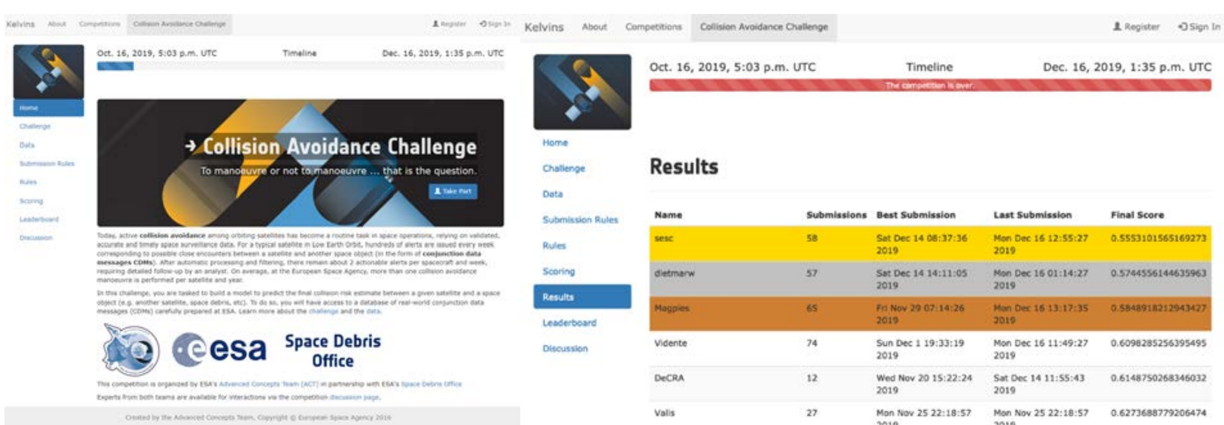

Fig. 1. Screenshot at the beginning and end of the Spacecraft Collision Avoidance Challenge, https://kelvins.esa.int/collision-avoidance-challenge/

As Ref. [2] concludes, this first attempt using (mostly) automated, off-the-shelves machine learning pipelines for predicting collision avoidance actions is not superior to naive forecasting models. Still, machine learning models might be able to improve the decision making process, i.e. better predictions have been proven to be possible compared with the last known risk as baseline.

The topic has been addressed as well by the Frontier Development Lab (FDL) in Summer 2020. FDL Europe is a public-private partnership with ESA supported by commercial partners and academia such as Google Cloud, Nvidia, IBM, and the University of Oxford. A challenge has been presented with the title "Conflicts and collisions: Can we use machine learning to support human operators conducting large-scale constellation management?".

The team consisting of students and researchers from institutions in UK and Germany proposed to solve the task by predicting the uncertainty evolution instead of relying on the collision probability estimate alone. They achieved this by training a long short-term memory network (LSTM) using about 15,000 historic events and then predicting the future evolution of a conjunction event by processing the corresponding sequence of previous conjunction warnings. As an alternative approach they synthetically generated future conjunction warnings based on probabilistic programming by inferring distributions on orbits and observations. The usefulness of findings could be validated through known events. It was interesting to see that besides improving space weather predictions the efficient and automated sharing of ephemeris and planned manoeuvres was identified as a key topic for further work. It was also found that a calibrated probabilistic model and the predictor (both was announced to be made available as a Python package "Kessler") will enable the creation of synthetic training sets.

2. Activities for the cornerstone CREAM in a first phase

The overall motivation for CREAM has been already discussed previously [1]. The authors present the objectives of the CREAM cornerstone as the development of technology for automated collision avoidance to reduce man-power efforts and to reduce the time between manoeuvre decision and close approach, and thereby reduce the number of false alerts. Currently, collision avoidance efforts are driven by the need to have experts available 24/7, and the need to block extra resources at ground-stations. For the late decision on manoeuvre execution signal-in-space commanding is a viable scenario in CREAM. Different implementation options exist to upload optimized manoeuvre plans to spacecraft. In CREAM the development and testing of emergency command paths is considered as a need, as well as coordinated manoeuvre planning especially for a traffic scenario with large constellations.

The need for coordinated planning is also fuelled by the several new public and commercial surveillance systems that are becoming operational and provide conjunction warnings. Not only the increased number of objects in a catalogue are a matter of concern here, also the possibility of inconsistent information and resulting discrepancies between catalogue sources calls for manoeuvre coordination. A robust data fusion to use all available information to support the manoeuvre decision with consensus solutions is a possible way to proceed.

Means to aggregate and combine driving parameters helps in predicting the evolution of a given event. The same is true for the related uncertainties. It is known by operators of collision avoidance systems that a single assessment of selected parameters, such as the collision probability, can increase suddenly once new surveillance and tracking data arrives. The reliable prediction of the collision probability and the identification of the stability of the conjunction event remains a major challenges for any process automation. This is further complicated as each avoidance manoeuvre decision needs to take all (i.e. also secondary) events into account in order to keep the overall collision risk minimised.

Such an optimization is expected to be performed on ground due to the large size of the catalogue and number of possible event, and also to account for any operational constraints. Traditionally, collision avoidance assesses one event at time. The expected catalogue growth, the availability of multiple sources, and the existence of large constellation will soon require global trajectory optimisation taking into account multiple conjunctions. On-board late decision and autonomy, as well as coordination, will benefit from storing and exchanging the optimization results in a suitable format.

Following the described key areas for development of technologies, the preliminary conceptual ideas [1], and by making best use of the subscriptions at Space19+ of 3M€ total to fund CREAM, ESA structured the first period of CREAM (2020-2022) in three distinct areas:

- automated avoidance manoeuvre decision and design,
- development and testing of late commanding paths and operations concepts, and
- means for coordination of operators and catalogue providers.

Additionally, further activities address the software development supporting CREAM developments and the development of potential decision rules. These rules must respect the constraints of orbital dynamics, satellite design and operations. Simple, transparent, acceptable, and fair rules are needed that can be adhered to by all in the global community.

The development will not be tailored to ESA's operational fleet of satellites, but will aim at the wider community of spacecraft operators. A positive market potential of the developments is central for CREAM and related industrial contributions to the tools or precursors will be incentivised.

Due to the funding constraints the originally proposed demonstration mission [1] for CREAM in this period of the programme will instead be proposed for the next period of the programme.

2.1 Automated avoidance manoeuvre decision and design

The first building block of a future full CREAM system will be developed as a standalone software application supporting avoidance manoeuvre decision and planning already before a full CREAM system becomes available. The development will look into the parameters driving decisions, i.e. determining constraints, sensitivity, uncertainties, and correlation. Using historic data for close approaches and machine learning will be encouraged to identify correction factors and to improve covariance realism. The development will support data fusion from multiple conjunction data providers for consensus building. With these results the development will provide manoeuvre designs for classical impulsive, continuous low-thrust, and drag augmentation avoidance manoeuvre strategies. The strategies will address a global trajectory optimisation to reduce the overall collision risk in case of actions with secondary close conjunctions.

2.2 Development and testing of late commanding paths and operations concepts

For the development of viable operations concepts involving inter-satellite links for distribution of relevant data trade-offs between on-ground data processing and in-space processing are needed in a first step. The key parameters for this decision on the split level are the achievable data rates, costs, and the readiness level of protocols for integration. The goal of this building block is the complete preparation for a demonstration experiment with an established operator, ideally of a constellation. In the demonstration the handling of the various platform constraints is central for the success of CREAM. It will be needed to demonstrate as well the feedback loop as secondary conjunctions are always possible and may exceed the risk thresholds.

2.3 Means for coordination of operators and catalogue providers

Starting with the assessment of suitability of existing protocols, also in non-space areas (e.g. internet-of-things) the third building block will develop and test communication protocols between operators and catalogue providers. The design will consider the results from the already ongoing activity to develop acceptable rulesets for manoeuvre coordination. A prototype implementation will then be tested in a simulated space traffic environment.

3. Summary

ESA started with a new Space Safety Programme in 2020. The programme combines activities in space weather, planetary defence, and space debris and clean space. All proposed cornerstones and a core element will progress in the first period of the programme. Missions include a space weather mission to Lagrange point L5, the asteroid missions HERA, and a demonstration of active debris removal through a service procured from ClearSpace. In the core element the range of technology developments under the previous SSA programme of ESA will be extended. For space debris the focus is on space debris observation and data processing, risk modelling, life cycle assessments, space debris mitigation, technologies for compliance monitoring, and environment remediation. ESA will progress with developing the technologies for automated collision avoidance system through the space safety cornerstone CREAM with three focal areas addressing automated decision, late commanding, and coordination means. The procurement of the activities has started, and first results are expected from mid of year 2021.

4. References

[1] Tim Flohrer, H. Krag, K. Merz, K., and S. Lemmens, CREAM-ESA's Proposal for Collision Risk Estimation and Automated Mitigation. Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS), 2019.

[2] Thomas Uriot, Dario Izzo, Luis Simoes, Rasit Abay, Nils Einecke, Sven Rebhan, Jose Martinez-Heras, Francesca Letizia, Jan Siminski, Klaus Merz. Spacecraft Collision Avoidance Challenge: design and results of a machine learning competition. arXiv:2008.03069, 2020.

[3] T. Flohrer, H. Krag. Space Surveillance and Tracking in ESA's SSA programme. Proceedings of the 1st NEO and Debris Detection Conference, Darmstadt, Germany, 2019.

[4] B. Jilete, T. Flohrer, T. Schildknecht, C. Paccolat, M. Steindorfer. Expert Centres: a key component in ESA's topology for Space Surveillance. Proceedings of the 1st NEO and Debris Detection Conference, Darmstadt, Germany, 2019.

[5] J. Silha, T. Schildknecht, G. Kirchner, M. Steindorfer, F. Bernardi, A. Gatto, I. Prochazka, J. Blazej, B. Jilete, T. Flohrer. Conceptual Design for Expert Coordination Centres Supporting Optical and Laser Observations in a SST System. Proceedings of the 7th European Conference on Space Debris, Darnstadt, Germany, 2017.

[6] J. Beck, I. Holbrough, J. Merrifield, D. Briot, M. Spel, E. Minisci, S. Lemmens. Progress in probabilistic assessment of destructive re-entry. 1st International Conference on Flight Vehicles, Aerothermodynamics and Re-entry Missions. Monopoli, 2019.

[7] anonymous. DIVE - Guidelines for Analysing and Testing the Demise of Man Made Space Objects During Re-entry, ESA-TECSYE-TN-018311, accessible via https://estimate.sdo.esoc.esa.int/dive, ESTEC, 2020.

[8] H. Krag, S. J. Setty, A. Di Mira, I. Zayer, T. Flohrer. Ground-Based Laser for Tracking and Remediation – An Architectural View. IAC-18-A6.7.1. Proceedings of the 69th International Astronautical Congress (IAC), Bremen, Germany, 2018.

[9] S. J. Setty, T. Flohrer, H. Krag. SLR for SST: an analysis on requirements and achievable orbit improvement. Proceedings of the 1st NEO and Debris Detection Conference, Darmstadt, Germany, 2019.

[10] F. Letizia, S. Lemmens, B. Bastida Virgili, H. Krag. Application of a debris index for global evaluation of mitigation strategies, Acta Astronautica, 2019.

[11] F. Letizia, S. Lemmens, H. Krag. Environment capacity as an early mission design driver, Acta Astronautica, 2020.

[12] S. Lemmens, F. Letizia. Space Traffic Management through Environment Capacity, Handbook of Space Security: Policies, Applications and Programs, Springer, 2021, In Press.