CREAM - ESA's Proposal for Collision Risk Estimation and Automated Mitigation

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ABSTRACT

Today, active collision avoidance has become a routine task in space operations, relying on validated, accurate and timely space surveillance data. For a typical satellite in LEO hundreds of conjunction alerts can be expected every week. Processing and filtering these still leaves about two actionable alerts per spacecraft and week requiring detailed follow-up by an analyst. At ESA more than one collision avoidance maneuver can be expected per satellite and year. It is clear that such an approach requiring 24/7 expert availability to analyze more than 20 parameters and constraints generates high operational costs. The future with an accelerating launch rate and deployments of smaller satellites and constellations, as well as improved space surveillance networks delivering catalogues of up to 200k objects will render efforts by any operator following this approach an unmanageable task.

ESA's proposal for a Space Safety Programme to start in 2020 includes also a cornerstone "Collision Risk Estimation and Automated Mitigation (CREAM)". CREAM entails the development of technologies for automating collision avoidance and its demonstration with a suitable newly developed or existing flying platform.

We discuss the status of the CREAM proposal focusing on three central objectives: (a) reducing manpower efforts in particular for large constellations, (b) reducing the number of false alerts, and (c) reducing the time between maneuver decision and close approach. We will present ideas for machine learning techniques to replicate expert decisions. We discuss their application to automatic handling and analysis of the reliability of collision risk estimates, as well as implications from emerging trends in spacecraft operations, such as low-thrust maneuvering or attitude changes to control the effective drag towards a “continuous” collision avoidance process in replacement of the classical impulsive maneuvering. An efficient way to coordinate and command maneuvers is needed for the success of the CREAM concept. We will introduce first conceptual ideas how, e.g., adapting an IoT scenario could be implemented to enable late decisions on collision avoidance actions, also considering onboard trajectory estimation based on GNSS and ground-based orbit refinements. We conclude with an outlook to possible demonstration scenarios for the key technology developments, either with newly developed platform, or by using existing missions.

1. INTRODUCTION

Today, operating spacecraft faces radical and fundamental changes. Not only the amount of tracked space debris makes active collision avoidance a routine task in space operations [1,2], furthermore the accelerating commercial exploitation of space brings pressing challenges. As access to space becomes more affordable the number of players in space increases rapidly. Further, the accelerated commercialization of space utilization needs to ensure the return of the enormous investments. Guidelines, standards, and legal frameworks are undergoing adaptation driven by recent findings on space debris mitigation effectiveness and predictions of the space object population [3,4]. In parallel to the economical, societal, and policy changes we will soon see a rapid increase of validated, accurate and timely space surveillance data. Overall, there can be no doubt that the way we operate spacecraft has to adapt and evolve quickly too!

In this work we present an ESA proposal to contribute to the evolution of spacecraft operations, by addressing the development and demonstration of technologies for automating collision avoidance. The ESA proposal is made as part of the proposal for a Space Safety Programme at ESA. Preparatory activities, such as a competition for machine learning supporting the decision process in collision avoidance have already started.

2. ESA's PROPOSAL FOR A SPACE SAFETY PROGRAMME

Space poses many threats to human safety and infrastructure, both in space and on ground, ranging from space weather and Near Earth Objects (NEOs) to threats from uncontrolled objects and fragments thereof.

Ground infrastructure, for example, is vulnerable to the space environment. Space weather can disturb or damage at large scale electrical power grids. Modern societies depend on space infrastructure as part of a the critical infrastructure enabling services such as satellite navigation, weather prediction, climate change monitoring, or global communication.

ESA has the goal to "ensure European autonomy in accessing and using space in a safe and secure environment" (Joint statement on shared vision and goals for the future of Europe in Space by the EU and ESA, 2016). The proposed Space Safety Programme at ESA aims to contribute to the protection of our planet, humanity and assets in space and on Earth from threats originating in Space and to contribute to Europe providing safety from such threats as a service to its society. The proposal builds on the heritage of ESA's Space Situational Awareness Programme [5] that has been running since 2009. The scope of Space Safety is considerably extended compared to Space Situational Awareness (SSA) (Fig. 1).

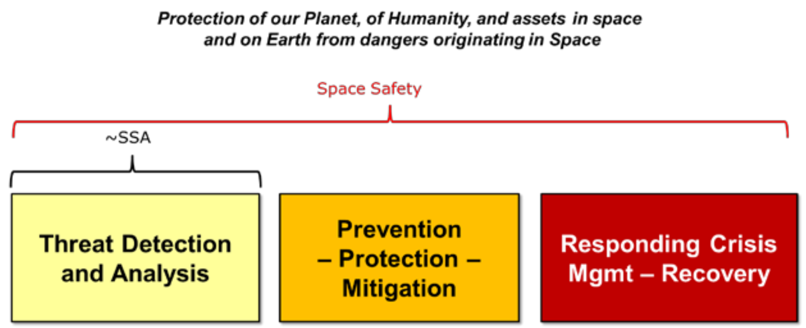

Fig. 1. Space Safety extending the context of SSA in ESA.

ESA's Director General included the development of an ESA Space Safety initiative in his vision and plan laid out in the Resolution "Towards Space 4.0 for a United Space in Europe". The resolution has been endorsed at the Council meeting at Ministerial level in December 2016. As specified in the resolution a proposal for a Space Safety Programme will be presented for agreement at the Council meeting at Ministerial level (Space19+) in November 2019.

Space Safety addresses three topics:

1. Space Weather, with a cornerstone of an operational space weather mission at Lagrange point L5 to enable future provision of space weather nowcasts and forecasts with enhanced accuracy and timeliness;
2. Planetary Defense, with a cornerstone of post-impact characterization for demonstration and further validation of the asteroid kinetic impact deflection technique to complement early detection and warning activities with the development of deflection capabilities; and
3. Space Debris and Clean Space (debris prevention for the future and remediation of past activities), with the cornerstones of (a) a debris removal mission to address debris and at the same time support the market of in-orbit servicing and (b) an adequate pre-emptive approach with respect to future activities and to enable the safe operation through an Automated Collision Avoidance System ("CREAM- Collision Risk Estimation and Automated Mitigation").

Space Safety is a global effort and requires collaboration and partnerships. Building upon existing partnerships the established responsibilities, roles, and frameworks are an important aspect in the Space Safety proposal. It is assured through direct interaction, that EU and ESA activities are complementary.

3. CREAM PROPOSAL

As cornerstone of the proposed Space Safety Programme, CREAM will develop the needed techniques towards automated decision, planning, and execution of collision avoidance actions, and will demonstrate these developments. CREAM has as main goal "to conduct safe and efficient collision avoidance maneuvers without human intervention". The motivation of CREAM is based on expected major changes to the operation of spacecraft. Beside outlining the motivation behind CREAM, we present in this section the CREAM elements together with first conceptual ideas foreseen for development beginning 2020, a related machine learning competition as preparatory activity, and steps towards a demonstration mission.

3.1. Motivation

ESA's own collision avoidance service can be used as an example for the growing complexity of such efforts. ESA covers its own fleet of about 20 spacecraft with a collision avoidance service, see Fig. 2 for an historical break-down. Under a data sharing agreement with the US ESA receives in total several hundreds of conjunction alerts per spacecraft and week. Further analysis during the routine process reveals that among these alerts about two events are actionable alerts.

An analyst is needed to process these actionable alerts, considering several constraints and applying different methods and tools (see [1,2] for a description of the processes and Fig. 3 for some involved tools). A close coordination with the experts from the flight control teams, flight dynamics, and ground stations is mandatory before implementing an avoidance scenario. Obviously, arrangements for shift works are required to ensure a 24/7 availability of all experts. Not all actionable alerts lead to executing collision avoidance maneuvers. The actual ratio is about 5-10 actionable alerts per conducted avoidance maneuver. In consequence, at ESA at least one collision avoidance maneuver per spacecraft and year is performed. These "false alerts" requiring actions but do not lead to performing a maneuver should not be mixed up with the reaction risk threshold for maneuvers. In most cases not performing a maneuver does not lead to a collision, as usually a reaction threshold of 1:10000 is applied.

The described "classical" process contributes with considerable costs to the overall mission operations effort. In 2018 ESA estimates that every year about 14 MEUR equivalent man effort are spent worldwide on maneuvering spacecraft in LEO in response to false alerts [6].

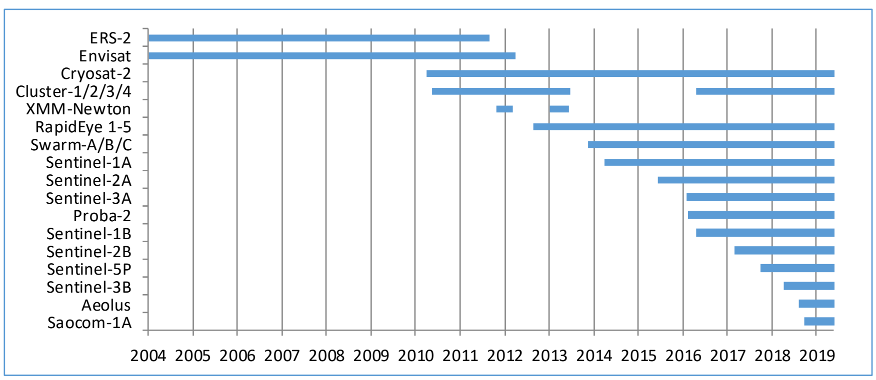

Fig. 2. Growth of satellite missions covered under ESA's collision avoidance service.

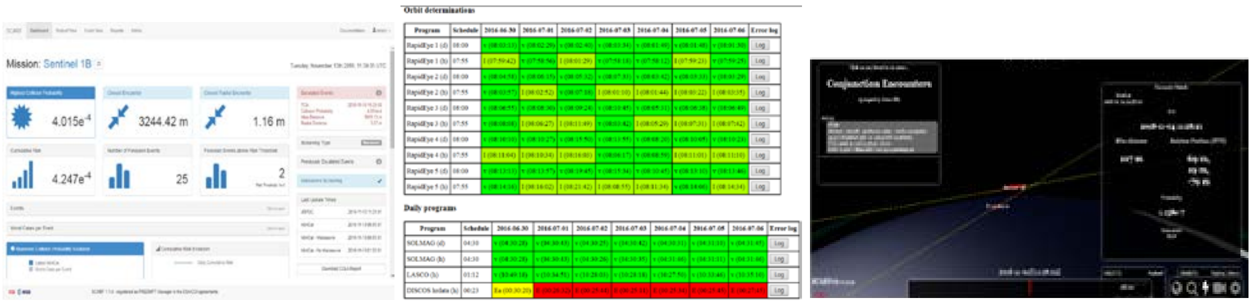

Fig. 3. Snapshot of key elements in the current collision avoidance process for ESA missions [1].

An accelerating launch rate and deployments of smaller satellites and constellation traffic has already started to set in (see Fig. 4). This trend towards commercialization of the traffic will continue, or even accelerate with the deployment of large constellations to very different altitude bands.

It is further known already that space surveillance networks will soon be delivering catalogues of up to 200k objects. Sticking to the described approach for collision avoidance will render any efforts by operators to follow this "classical" approach an unmanageable task. It is needed to investigate alternative maneuver decision criteria beyond the estimated collision risk. Such alternatives may need to consider the emerging low-thrust maneuvering of modern spacecraft or even to use attitude changes to control the effective drag. Both can make it possible to implement a "continuous" collision avoidance process in replacement of the classical impulsive maneuvering.

The large catalogues can be processed if investments into the computing infrastructure and data processing are made. The associated uncertainties of the orbital information and time-consuming decision processes require to either accept a higher collision risk, or to re-think the approach. Ref [1] outlined already in 2016 possibilities for such further development options, among them:

- trending of the probable risk evolution of individual events,
- coordination among operators to deal with repetitive conjunctions of the same object pairing,
- formalization of the latency times between orbit determination and conjunction updates, and
- cross-agency/industry consensus on how to set collision avoidance maneuver thresholds.

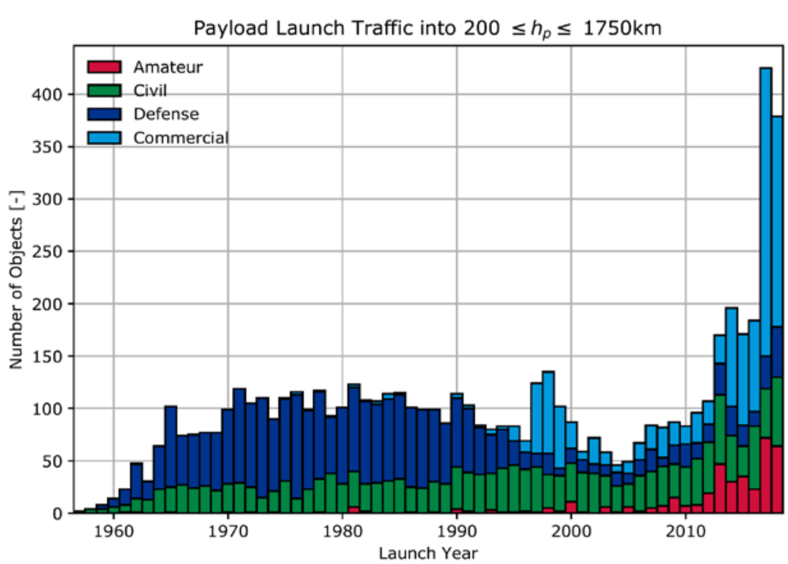

Fig. 4. Evolution of payload launch traffic [7].

3.2. First conceptual ideas for CREAM elements

In CREAM different technologies for automating collision avoidance will be addressed to

- reduce manpower efforts, especially for a traffic scenario with large constellations in orbit, through the automation of operator tasks,
- minimize the time between maneuver decision and close approach, e.g., adapting an IoT scenario, and
- reduce the number of false alerts.

Automation of spacecraft operator tasks

CREAM will approach automation by employing and maturing machine learning approaches to replicate expert decisions. A good starting point for training the machine process ESA will use its central database of the current process [1] that holds more than 1 million entries on past close approaches, including decisions taken. The possible approaches could start out from unsupervised classification of approach geometries to build classes of no risk, stable risk, potentially dangerous, unstable situation, etc.

The unsupervised identification of actionable alerts can then be extended to revisit the recommendation of maneuver design options. By considering also findings on trends in the related predictions, and machine-based estimates of data update frequencies the machine learning techniques will be applied also considering artificial intelligence techniques for automated maneuver decisions. These activities will be supported by developing techniques for automatic handling and analysis of the reliability of collision risk estimates, such as dilution of probability, analysis of acquired conjunction history to identify decision drivers, improved covariance realism based on history of conjunction data provided by space surveillance systems, and further improving nonlinear uncertainty modelling.

It is expected that it will be possible to consider platform constraints and to address secondary conjunctions as well – hence automation will contribute also to a reduction of false alerts.

Automation will also accelerate the avoidance process and minimize the time between decision and event, as maneuver sequences can be pre-optimized and stored already onboard in a generic form – ready for a late go/no-go decision.

Minimizing time between maneuver decision and close approach

Satellite operations are based on decisions in a ground segment. This in particular includes the decision to avoid collisions by maneuvering (or not) a spacecraft – but these decisions are often premature. Late updates on the orbital information of target or chaser can often render maneuver decisions unnecessary (see Fig. 5). Let’s assume that the processing of late data to arrive at a decision and avoidance action could be done on-ground or on-board. It then requires a trade-off between on-board processing power and communication data rate and latency.

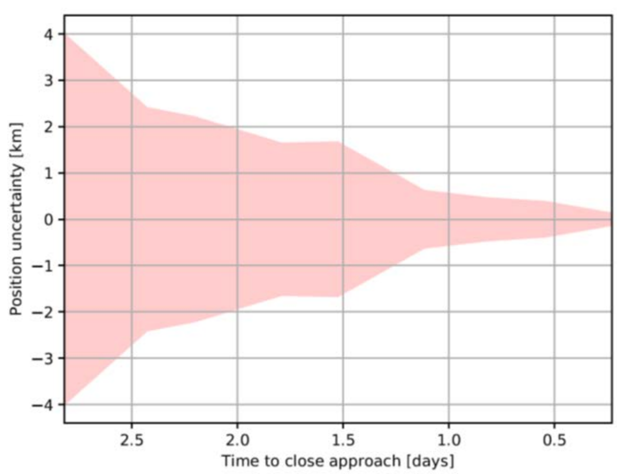

Fig. 5: Late decisions are desired to exploit better knowledge of target and chaser orbits.

The current population of tracked objects is dominated by far by non-maneuverable objects. Coordination of avoidance actions between involved conjunction partners is rare, but essentially cumbersome if it materializes. The Combined Space Operations Center (CSpOC) runs via space-track.org an accessible register of contact data for operators, which is very helpful to establish coordination. The progress of standardizing data exchange formats is also very positive to ensure efficient coordination.

With the deployment of large constellations the current practice of ad-hoc coordination through human interface to operator processes will become inefficient, as close approaches between active objects will become more likely. This makes coordination and communication with other satellite operation programs necessary, to align maneuver strategies. New message protocols need to be developed. The huge progress for similar problems in non-space applications is addressed through IoT (Internet of Things), which will be an excellent starting point for automated communication among operators, and – of course – involving also service providers for space monitoring data. Also it is of paramount importance for the success of CREAM that developed protocols and message formats need to be defined along with international agreements. CREAM will develop communication protocols for maneuver coordination and will aim at joint demonstration with operators of large constellations, especially addressing the need for quick response solutions.

Several options exists for a possible use of emergency commanding paths to trigger a collision avoidance maneuver execution with very late decision time. If on-board decision is possible, all required information for a decision (i.e. orbits and covariance of all chasing satellites for all maneuver and backup options) need to be uplinked. The final decision would then have to be downlinked or communicated to all other concerned spacecraft. On the contrary a processing on ground would require to communicate the decision to the affected spacecraft and to all other concerned operators. A preloaded maneuver command sequence would foresee a time-tagged execution as it is already the case in most operation scenarios today.

Ref [8] introduces a related Emergency Command Path System Concept for Galileo and assesses the Signal-in-Space (SiS) data capability. SiS, as well as adapting an IoT scenario with the already possible use of Iridium receivers or alternatives, are the most promising options for distributing forecasts.

From [8] it seems very much possible to link the coordination efforts with on-board trajectory estimation, the global optimization to reduce the collision risk comprehensively for all upcoming events and spacecraft, and the described use of pre-optimized maneuvers stored on-board that are triggered for execution through alternative communication channels.

Reducing the number of false alerts

The false alert probability is a major issue in collision avoidance today. There is consensus that the reduction of the false alert rate can only be obtained by reducing the uncertainties, i.e. by better tracking means and by enabling later decisions.

In CREAM we will study if and how the distribution of close-approach forecasts among satellites can in fact be combined with on-board trajectory estimation based on GNSS and with ground-based orbit refinements through dedicated tracking. Such dedicated tracking of conjunction partners will in any case be required through a dedicated sensor network.

Preparatory activities

As a preparatory activity for CREAM in 2019 a global open competition for machine learning is under preparation in collaboration with ESA’s Advanced Concept Team. It addresses the aspect of judging on the criticality of a close approach and thus a key component of the proposed concept for automated collision avoidance in the Space Safety Programme proposal.

The competition is making use of the database of conjunction alerts at ESOC by providing a subset as training data for tuning the machine learning algorithms. Participants will be asked to judge on the severity of close approaches based on conjunction information which is cut off a few days before the conjunction event, thus mimicking the situation operators face when deciding whether or not to start preparation of an avoidance manoeuvre. The participants’ results will be evaluated on a separate test data set using also conjunction data closer to the event (after the cut-off time).

The competition will be accessible via ESA's Kelvins platform operated by the Advanced Concepts Team at https://kelvins.esa.int/.

3.3. Demonstration mission

The proposal for CREAM includes the implementation and demonstration with a selected (existing) technology mission. ESA aims at showcasing the full process of automated collision avoidance with a space component, i.e. to identify, optimize and execute collision avoidance maneuvers without human intervention. Such a demonstration will allow to compare late GNSS-based orbit determination with the on-board processing of uploaded conjunction forecasts, the on-board decision taking, and to compare the processing on-ground to commanding via the emergency path.

The selection of the mission is still open. ESA searches for a spacecraft with the capability to perform maneuvers with chemical or electric propulsion in and against flight direction (ideally without slewing and very few maneuver constraints in general). The mission shall have access to a flexible number of ground-station passes (up to ten per day on request would be preferred, which allows for maneuver monitoring during the testing and for ad-hoc cancelling). It would also be preferred if the orbit is exposed to a significant number of conjunctions in order to limit waiting time for the tests, (i.e. a LEO mission at an altitude of 650km < h < 1000km).

Depending on the selected commanding scenario a Galileo GNSS receiver needs to be present and/or larger processing power must be accessible on-board to process conjunction data. Similarly, a powerful transmitter/receiver must be available for uplink/downlink data in case satellite has to take decisions without the ground segment.

A public-private-partnership (PPP) with industry may also be considered for the demonstration through appropriate newly developed platforms and using new exchange protocols between operators for CREAM will defined.

An overall roadmap with key milestones leading to a successful demonstration mission in 2025 is given in Fig. 4.

Fig. 4. CREAM high-level roadmap.

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