# ON-BOARD COLLISION AVOIDANCE APPLICATIONS BASED ON MACHINE LEARNING AND ANALYTICAL METHODS

**Juan Luis Gonzalo(1), Camilla Colombo(1)**

*(1) Politecnico di Milano, Via la Masa 34, 20156 Milan, Italy,*
*Email: juanluis.gonzalo@polimi.it, camilla.colombo@polimi.it*

## ABSTRACT

The growing numbers of both active satellites and space debris are putting significant strain on Space Situational Awareness (SSA) and collision avoidance activities. One way to address this may be to introduce higher levels of automatization. In this work, we discuss one possible implementation of autonomous on-board collision avoidance capabilities for satellites. The system is divided into two blocks: the decision-making algorithm, based on machine-learning techniques, and the manoeuvre design, relying on highly-efficient analytical methods. Furthermore, a ground-based source of SSA data is required for the system to operate. The key requirements and development status of each of these elements is discussed. Finally, a proposed CubeSat demonstration mission is briefly presented.

## 1 INTRODUCTION

The sustained increase in launch traffic and the ever-growing population of space debris are putting significant strain on Space Situational Awareness (SSA) and Collision Avoidance (CA) activities. A very significant contributor are new large constellations, such as SpaceX's Starlink, with more than 1,000 satellites already in orbit and plans for at least other 10,000. Also, improvements in SSA are allowing to track smaller objects [1], increasing the number of detected close approaches.

Current CA procedures involve high levels of coordination and interaction between different entities, as well as human intervention. On the one hand, space surveillance and tracking, collision risk assessment, and spacecraft operations are in many cases performed by different entities. Traditionally, the U.S. Strategic Command has provided a publicly available catalogue of space objects around Earth based on observations from the Combined Space Operations Center space surveillance network, and informed operators of potential close approaches. These duties are set to be transferred to the US Department of Commerce, and other private and public entities worldwide are setting up their own systems [2]. Coordination between operators for close approaches between active satellites is also paramount, as evidenced by the potential conjunction between ESA's Aeolus and SpaceX's Starlink 44 satellites on 2 September 2020. On the other hand, even if an automated initial screening is performed, the final decision for the potentially dangerous close approaches lies on human operators. A detailed overview of the methodology and tools used by ESA's Space Debris Office, which provides operational CA services for ESA missions and third parties, is offered by Braun et al. [3]. They rely on a large range of tools for space environment characterisation, risk evaluation, and Collision Avoidance Manoeuvre (CAM) design, highlighting the complexity of these operations.

A 'business as usual' strategy will not be sustainable as space becomes more congested, which has triggered different initiatives to increase automation. Significant examples are projects supported by ESA, such as AUTOCA [4] within the Advanced Research in Telecommunications Systems 4.0 programme, and the Collision Risk Estimation and Automated Mitigation (CREAM) [5] initiative within ESA's Space Safety Programme, promoting the development of technologies for automated CA and their demonstration in flying platforms. A key difference between AUTOCA and CREAM is that the former focus on artificial intelligence-supported tools for assisting ground operations, whereas CREAM promotes achieving higher levels of autonomy through artificial intelligence. Particularly, one of CREAM goals is to explore on-board CA capabilities, including autonomous decision-making without the ground segment. This approach would allow for last-minute decisions and more decentralized operations with less workload on human operators. However, several key technological advances are required to enable these applications.

Researchers from the COMPASS project at Politecnico di Milano, funded by the European Research Council, have recently introduced the Manoeuvre Intelligence for Space Safety (MISS) software tool [6] for the analysis and design of CAMs. MISS relies on analytical and semi-analytical methods, which leads to highly efficient and relatively simple algorithms. While these characteristics make MISS suitable for on-board use, past works have not dealt with the decision-making component needed for autonomous operations. In this paper, the synergies of MISS with Machine-Learning (ML) techniques for the design and implementation of autonomous on-board CA algorithms are explored. A

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clear separation into two modules allows us to leverage the advantages of each approach: the decision-making module relies on ML, while CAM design is performed through the highly efficient semi-analytical models. The training of the decision-making algorithm, and particularly obtaining historical CAM datasets that are large enough for this task, are identified as key challenges. A possible way to address this is the generation of synthetic datasets. The future implementation of on-board CA capabilities would also require the establishment of federated SSA services feeding the spacecraft with information about nearby objects: although the design of such system falls out of the scope of this work, the basic inputs that would be required from it are identified. Finally, in order to consolidate and validate all these elements and their interactions, as well as to increase their Technological Readiness Level (TRL) for future implementation in regular operations, in-orbit demonstration missions will be needed. The main elements of an in-orbit autonomous CAM demonstration experiment being proposed by the group will be presented and discussed.

The rest of the paper is organized as follows. First, the proposed conceptual architecture for autonomous on-board CA capabilities is presented, identifying its three main building blocks: algorithms for on-board CAM modelling, ML-based autonomous decision-making, and the interaction with ground-based SSA services. The CAM algorithms are presented in Section 3, summarizing their main features. Then, Section 4 discusses the main aspects in the definition of the ML algorithms for autonomous decision making. A brief review of recent advances in the field is provided, and the main challenges are identified. Section 5 introduces an autonomous on-board CAM experiment being proposed to consolidate and validate all these elements. Finally, conclusions are drawn.

## 2 GENERAL ARCHITECTURE

The proposed architecture for on-board CA is divided into two clearly defined building blocks, as represented in Figure 1: CAM modelling and design, and decision-making. The first block is based on the analytical and semi-analytical CA algorithms developed at Politecnico di Milano as part of the MISS software tool [6,7]. They allow for the efficient modelling of CAMs, both in the impulsive and low thrust cases; a more detailed description is provided in Section 3. However, although these models are suitable for on-board use thanks to their simple expressions and reduced computational cost, they only serve to the purpose of designing an optimal manoeuvre once the decision to act has been taken. For this second block, decision-making, we turn to ML approaches. The challenge here is to estimate, based on the time history of collision risks obtained from Conjunction Data Messages (CDMs), which will be the risk at the time of the close approach and whether it falls out of the acceptable ranges. A more detailed description is given in Section 4.

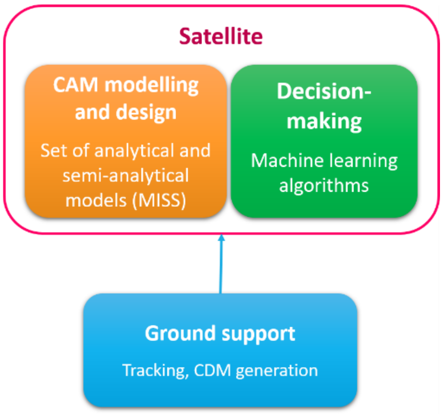


*Figure 1. Schematic representation of the on-board CA architecture*

For the decision-making and CAM design components to work, they need a source of information about the predicted close approach. In general, satellites lack the capacity to autonomously explore their environment, so they will in any case have certain dependence on information transmitted from ground. In the proposed architecture, this external input will be provided in the form of CDMs. Although this limits the autonomy of the system, relying on external sources for SSA-related data, there are several advantages from having autonomous on-board CA decision and planning capabilities. One first advantage is that the input can be just the CDM, which may be retrieved not necessarily from the satellite operator. This allows for the use of federated SSA services to upload raw collisional information to satellites. Of course, establishing such a system would require defining clear policies for international cooperation and procedures to avoid the upload of tampered data. Moreover, depending on the capabilities of the satellite, it may also be possible to perform partial updates of the collision risk based on its own navigation sensors. This could be particularly interesting for last-minute operations. And finally, for future generations of satellites it can be considered the inclusion of short-range beacon devices to detect close approaches that failed to be identified based on tracking data, or to reduce the uncertainties in the CDMs received from ground.

## 3 CAM MODELLING

The analytical and semi-analytical models integrated in the MISS software tool [6] allow for the analysis and design of CAMs in the impulsive [7] and low-thrust [8] cases. Particularly, impulsive CAM models are fully analytical, whereas the low-thrust CAM case currently requires the numerical integration of the time law to achieve an accurate enough characterization of the phasing change from the manoeuvre. Furthermore, the models allow for the computation of the state transition matrix, which can be leveraged for evaluating the evolution of covariance matrices (i.e., uncertainties) in time. Again, depending on the force models the solutions are fully analytical (unperturbed case) or semi-analytical (with drag and solar radiation pressure).

From a general perspective, the CAM algorithms are composed of three building blocks, both for the impulsive and low-thrust cases. The first one models the orbit modification, based on Keplerian elements. It uses a fully analytical model for impulsive manoeuvres and a semi-analytical one for low-thrust manoeuvres, based on averaging. The main challenge for the semi-analytical one is the description of the small change in phasing, which has a large impact on miss distance and collision risk. To ensure a sufficient level of accuracy, the time law is integrated numerically. The second block maps the orbit modifications into changes in position and velocity at the close approach using a relative motion model. Finally, the last block translates this into actionable information by analysing the effect of the manoeuvre in the b-plane and updating the collision probability. It is important to highlight that these three blocks are defined independently, so that any of them can be modified or replaced without affecting the others (as long as the interfaces are respected).

The current capabilities of these models include:

- The optimization of impulsive CAMS, both for maximum displacement and minimum collision probability. Several application test cases can be found in [7,9].
- The optimization of low-thrust collision avoidance manoeuvres, taking as parameters the available thrust acceleration, the anticipation of the manoeuvre and the length of the thrust arc. This application is investigated in [6,8].
- The computation of state transition matrices. They are computed analytically for the impulsive case, and semi-analytically for perturbed and low-thrust cases.

## 4 AUTONOMOUS DECISION-MAKING

The models in Section 3 would allow a satellite to autonomously compute an optimal avoidance manoeuvre given a CDM and the time to act, but they are insufficient for the task of deciding whether the CAM is actually needed. Although they can provide some information on the time evolution of risk through uncertainty propagation, this does not consider other sources of information such as how additional observations allow to reduce uncertainties as we approach the time of the predicted encounter. This would be analogous to current human-driven operations, where the decision to act may be delayed until more accurate CDMs become available as the time of the predicted conjunction approaches.

For this task, ML algorithms can be applied. The problem can be treated as a regression task, trying to predict the final risk based on a sequence of CDMs. This approach has been considered by several authors [10], but a particularly significant milestone was the Collision Avoidance Challenge organized by ESA as part of the CREAM initiative [11]. The participating teams were asked to build a model to estimate the final collision risk based on a dataset of real-world CDMs provided by ESA. The submissions were evaluated based on their capability of discriminating high risk and low risk events (with a threshold of $10^{-6}$), and estimating the final risk at close approach of the former. A summary of the outcomes of the competition, covering the definition of the training and evaluating datasets, the scoring function, and the solutions proposed by the leading teams can be found in [11]. Two of these conclusions are of particular interest for this application: the difficulty to define a proper training set, and the adequacy of ML algorithms for the decision-making task.

The scarcity of real-world data to train the algorithm could be addressed by generating synthetic datasets, from orbital information like two-line elements or by introducing virtual debris. An example of dataset generation can be seen in the work by Vasile et al. [10].

The definition of a decision-making algorithm for the proposed framework is still an ongoing activity. One key aspect is the availability of the analytical and semi-analytical approximations for the evolution of uncertainties, Section 3, that assist in the generation of synthetic datasets.

## 5 ON-BOARD EXPERIMENT

To test this framework, an autonomous CA experiment will be included as part of a CubeSat demonstration mission that the COMPASS group is proposing in collaboration with several Italian partners, called e.Cube [12]. e.Cube aims at contributing to the advancement of technologies and methodologies dedicated to space debris mitigation and remediation. To meet this goal, three different experiments are devised: 1) implementation and validation of on-board autonomous CA capabilities; 2) untraceable space debris in-situ detection, acquiring data to support current and future models for small debris; 3) re-entry characterization, providing direct measurements on the atmospheric conditions and the spacecraft mechanical behaviour during re-entry. In the following, the key aspects of the on-board CA experiment are outlined.

The CA experiment will consist of several in-flight

CAM tests for simulated close approaches with a virtual debris. For each test, a sequence of CDM-like messages describing the predicted close approach for different warning times is generated on ground and uploaded to the spacecraft, and from it passed to a dedicated on-board computer called CAM Control Module (CCM). The CCM will then decide if and how to instruct the spacecraft to perform the manoeuvre. The goals of the experiment, both during development phase and in-orbit testing phase, are to:

1) Validate the whole architecture, including information transmission as CDMs.
2) Validate the decision-making algorithm, and its feasibility to be executed by the on-board computer.
3) Validate the analytical models for impulsive CAM design, and the feasibility to execute them in the on-board computer.
4) Test the performance for last-minute scenarios.
5) Contribute to increasing the TRL of autonomous on-board operations.

### 5.1 CAM Control Module

The main payload of the CAM experiment is the CCM, a dedicated on-board computer implementing the algorithms for on-board CAM decision-making and design. To make the CCM as independent as possible from the rest of the platform, it will only interact directly with the CubeSat's main on-board computer, receiving from it the synthetic CDMs sent from ground and navigation information from the CubeSat's sensors, and generating a manoeuvre command when it determines a CAM is required. The CAM command will be handled by the on-board computer like a command sent from ground to perform a manoeuvre. This not only addresses manoeuvre safety concerns by keeping final authority with the main computer, but also helps define a more generic architecture. The CCM will also log the key parameters related to the CAM decision-making and design process, and they will be transmitted to ground for analysis.

The on-board CAM software is composed of two modules: the decision-making module and the CAM design module. The decision-making module is based on ML algorithms trained on ground, as overviewed in Section 4, and determines whether a CAM is needed or not to keep the collision probability below a given threshold based on the sequence of CDMs and navigation information. The CAM design module, implementing the analytical and semi-analytical models in Section 3, determines the optimal CAM to meet the post-manoeuvre risk. The software implemented in the CCM will also include a supervision module, tasked with: 1) logging the principal parameters related to the operation of the other two modules, and 2) verifying that the generated CAM commands do not exceed a predefined operational envelope. Figure 2 shows a schematic representation of the CCM and the CAM software.

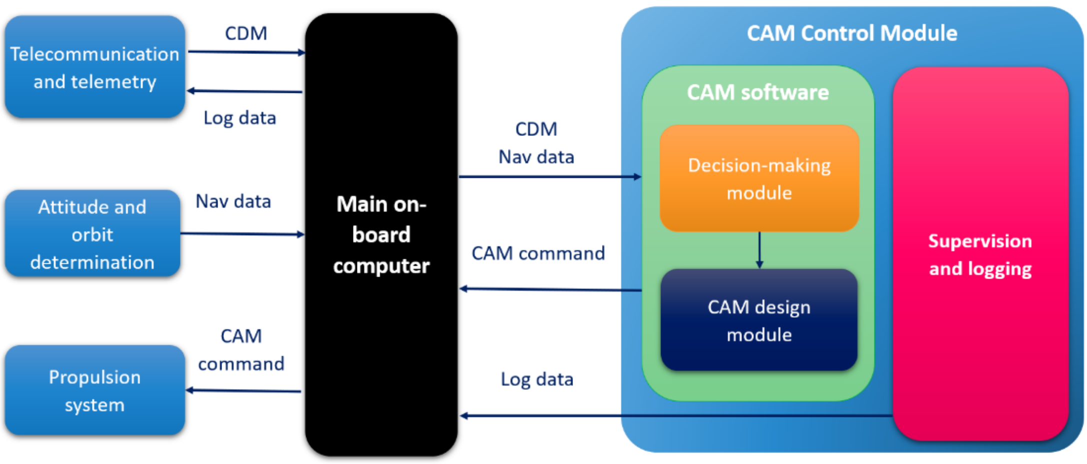


*Figure 2. Schematic representation of the CAM Control Module and software*

### 5.2 CAM Experiment

In the CAM in-flight experiment, several tests for simulated close approaches with a virtual debris will be performed. For each test, a sequence of synthetic CDMs will be transmitted from ground to the spacecraft, and the CCM will autonomously decide, compute, and command the required manoeuvre to be performed by the CubeSat. Different warning times, from 1 orbit to 7 days, and different levels of uncertainties will be considered to demonstrate the resiliency of the algorithm. The outcomes of the manoeuvre will be measured through the state after manoeuvre compared with the expected one, and the change in collision probability.

The following 3 scenarios are considered:

- Sequence of CDMs beginning from up to 7 days before the predicted close approach, with no need to perform the CAM. The objective is to check if the algorithm properly evaluates that the manoeuvre is not required. No fuel consumption.
- Sequence of CDMs beginning from up to 7 days before the predicted close approach, with CAM required within the last day according to current practices. The objective is to test both the decision-making algorithm and the CAM outcome.
- Last-minute autonomous CAM, to verify the feasibility of a spacecraft performing a CAM based on last-minute SSA data.

## 6 CONCLUSIONS

The ongoing activities by the COMPASS project towards the implementation of on-board autonomous collision avoidance capabilities have been presented. The proposed approach separates the optimal manoeuvre design from the decision-making process. The former is supported by analytical and semi-analytical methods that provide fast and reliable solutions to manoeuvre design, as well as for propagating uncertainties. The decision-making process relies on machine learning algorithms: this is an ongoing work, and the key challenges are the definition of training datasets and the selection of an algorithm that fits the particularities of our application. The analytical and semi-analytical CAM models can assist in this task, for the efficient generation of synthetic datasets. For the system to work as proposed, ground support is still needed as information source in form of CDMs. By relying on standard CDMs as external data source, the system could work with data from a federated network of SSA providers. This will increase the responsiveness of the system, no longer constrained to the communication windows with the satellite operator.

To test the feasibility of this framework, the validity and correctness of the algorithms, their suitability for on-board implementation, and the transfer of CDMs, a dedicated experiment has been proposed as part of a CubeSat mission. The mission itself is devoted to advancing different technologies related to the characterization and mitigation of space debris. The key element of the autonomous CAM experiment is the CAM Control Module, a dedicated on-board computer implementing the decision-making and manoeuvre design algorithms.

As previously indicated, these activities are currently ongoing. Next steps will be the trade-off and selection of algorithms for the decision-making component, and the advancement of the proposed demonstration mission.

## 7 ACKNOWLEDGEMENTS

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