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Autonomous collision avoidance on-orbit experiment in the e.Cube mission

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Abstract

Developing and testing an on-board autonomous collision avoidance (COLA) system is one of the mission goals of e.Cube - The environmental CubeSat. This 12U CubeSat mission is proposed by an Italian team from industry and academia, formed by D-Orbit, Politecnico di Milano, Temis, Università di Padova and Intelligentia. It has been selected as part of the Alcor program Italian Space Agency, which aims to position Italy as an international leader in the nanosatellites field. e.Cube will carry out three scientific experiments related to the sustainability of space operations: autonomous on-board COLA; in-orbit characterization of non-trackable debris, to support space debris modelling; and atmospheric and thermomechanical measurements during re-entry, to inform the improvement of re-entry models.

In this paper, the autonomous on-board COLA experiment of e.Cube is presented. Its architectural aspects are discussed, the dedicated on-board computer is presented, and the main algorithmic components are introduced. Particular focus is paid to the generation and processing of Conjunction Data Messages (CDMs), the training of Machine Learning (ML) models for the prediction of collision risk and autonomous decision making, and the lightweight dynamical models used for the on-board design of effective Collision Avoidance Manoeuvres (CAMs). Finally, the autonomous COLA application is analysed from the wider perspective of its integration in a federated STM and SST system.

Keywords: Collision avoidance, Cubesat missions, autonomous operations, Space Traffic Management, Space Situational Awareness, analytical methods

Nomenclature

a	Semi-major axis, km
e	Eccentricity
E	Eccentric anomaly, deg or rad
n	Mean motion of the spacecraft, 1/s
r	Orbital radius, km
t	Time, s
v	Orbital velocity (magnitude), km/s
$\boldsymbol{\alpha}$	Vector of Keplerian elements
Δt	Impulsive CAM lead time, s
μ	Gravitational parameter of the primary, km^3/s^2
ω	Argument of pericentre, deg or rad
Ω	Right ascension of the ascending node, deg or rad

Acronyms/Abbreviations

CA	Close approach
CAM	Collision avoidance manoeuvre
CCM	CAM Control Module
CDM	Conjunction Data Message
COLA	Collision Avoidance
LEO	Low Earth Orbit
ML	Machine Learning
OBC	On-Board Computer
PoC	Probability of Collision
ref	Reference value
SSA	Space Situational Awareness
SST	Space Surveillance and Tracking
STM	Space Traffic Management
TCA	Time of closest approach
TRL	Technology Readiness Level

1. Introduction

Satellite missions, like any other human activity, have an environmental impact that spans from the design and manufacturing phases to the ultimate disposal of the satellite. With the increasing use of space-based assets, there is a growing concern to understand and limit the impact of these missions on the environment, to ensure a sustainable future use of space. Actors such as the European Space Agency (ESA) and leading companies of the space sector are promoting the application of Life-Cycle Assessment methodologies to space missions [1], to get a more comprehensive view of the impact from space activities both on ground and in orbit. Focusing on the impact to the orbital regions around Earth, the most notable problematic is that of space debris.

The accumulation of space debris and the increasing satellite traffic in the low Earth orbit region has spurred multiple initiatives to advance Space Traffic Management (STM) systems and in-orbit autonomy, to ensure the safe and sustainable utilization of space. This includes private initiatives, like the automated collision avoidance system in Starlink satellites, and others promoted by space agencies and governments, such as ESA's CREAM, NASA's proposal for an STM architecture, or the EUSTM and Spaceways projects funded by the European Commission. Within these efforts, one key goal is increasing the automation of collision avoidance (COLA) activities, both on-ground and in-orbit.

Developing and testing an on-board autonomous COLA system is one of the mission goals of e.Cube - The environmental CubeSat. This 12U CubeSat mission, currently in Phase A, is being developed by an Italian team from industry and academia, formed by D-Orbit, Politecnico di Milano, Temis, Università di Padova and Intelligentia. It is funded by the Italian Space Agency as part of its Alcor program, which aims to position Italy as an international leader in the nanosatellites field. e.Cube will carry out three scientific experiments related to the sustainability of space operations: autonomous on-board COLA; in-orbit characterization of non-trackable debris, to support space debris modelling; and atmospheric and thermomechanical measurements during re-entry, to inform the improvement of re-entry models.

2. The e.Cube mission

The goal of the e.Cube mission is to contribute to the advancement of technologies and methodologies for space debris mitigation and remediation [2][3]. This goal is derived in three different objectives, that address different space debris-related aspects spanning the entire lifetime of a mission:

1. CAM: Development, validation and testing of on-board COLA;
2. DEBRIS: In-orbit characterization of non-trackable space debris object, to update and improve space debris environment models;
3. RE-ENTRY: Characterisation of the upper atmosphere for more accurate re-entry prediction and of the thermomechanical loads experienced by the spacecraft during re-entry.

The first two objectives are related to the safe operation of satellites in orbital regimes affected by the accumulation of space debris. On the one hand, by increasing the level of autonomy in COLA operations against tracked debris, it is possible to reduce reliance and workload on ground operators, also improving last-minute reaction capabilities. Furthermore, the advances in autonomous on-board COLA are also applicable to spacecraft-versus-spacecraft close approaches, but those will also require a negotiation or arbitration between both spacecraft that is not considered in e.Cube. On the other hand, when dealing with non-trackable debris, system designers must dimension passive protection for the spacecraft based on the nominal lifetime and the expected number of impacts based on the orbital region. Improving the statistical debris models for objects not trackable from ground, using updated in-orbit measurements, allows to improve these designs. e.Cube is equipped with a dedicated payload for the detection of small debris, and will carry out a collection campaign following a specifically designed orbit and attitude control [3][4].

The last objective is instead related to the satellite end of life. As part of debris mitigation regulations, entities such as the FCC, ESA and the IADC mandate or recommend that satellites in LEO re-enter within a maximum time window after their mission ends. This re-entry carries the risk of fragments to the satellite reaching ground, posing a risk to life and properties. The prediction of the potential impact points for fragments is affected by significant uncertainties, arising from the atmospheric model (especially the solar activity) and to the break-up process. To improve our knowledge of the latter, e.Cube will be fitted with a distributed network of sensors that will measure the evolution of thermal and mechanical loads during atmospheric re-entry.

The three experiments in e.Cube will take place in sequential phases of the mission. The autonomous COLA experiment is performed first, executing 6 to 12 scenarios. After that, the in-orbit characterization of space debris is performed during a prolonged period of time (around a year). Finally, the last experiment is carried out during the Cubesat re-entry.

3. Autonomous collision avoidance experiment

The autonomous on-board COLA architecture in e.Cube assumes that the spacecraft receives a sequence of Conjunction Data Messages (CDM), to make it as compatible as possible with current operations. This data is processed by the dedicated on-board computer in two stages. First, a machine learning (ML) component decides if a Collision Avoidance Manoeuvre (CAM) is required. Secondly, a quasi-optimal manoeuvre is computed on-board using analytical models. For the in-orbit experiment, a sequence of synthetic CDMs will be uploaded from ground, and the outcome of the decision process and CAM monitored. This section present the current development of these building blocks, including the generation of synthetic CDM datasets for both ML training and experiment execution, the selection and training of the ML component, and the analytical models for on-board CAM computation. Furthermore, the structure for the complete COLA framework is presented, and the requirements in terms of data input, combination with other data sources and possible federation of CDM uploading to the satellite discussed.

3.1 COLA system architecture

The payload for the autonomous cola experiment is the CAM Control Module (CCM), a dedicated On-Board Computer implementing the algorithms for manoeuvre decision-making and design, Figure 1. This CCM will interact only with the main OBC of the satellite, receiving the CDMs and navigational data, and returning the eventual CAM command. The reason for this architecture is twofold. First, to make it as independent as possible from the platform, clearly identifying the data interfaces with the OBC. This allows to conceptualize the CCM as an independent payload, that can be adapted to different buses. Secondly, the OBC will retain control over the commanded manoeuvres, not implemented them if they are deemed unsafe.

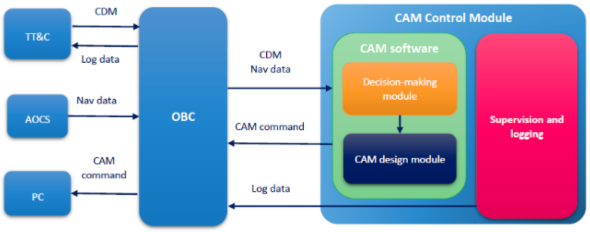

Figure 1. CAM Control Module payload

3.2 CAM experiment pipeline

During the autonomous COLA experiment, several in-flight tests will be executed for simulated close approaches with a virtual debris. The workflow for each experiment is as follows:

1. A sequence of CDMs or CDM-like messages is generated on ground, to characterize the simulated close approach for different warning times.
2. The CDMs are uploaded to the satellite, each with a delay with respect to their nominal warning time.
3. The OBC passes each CDM to the CCM.
4. The CCM processes the sequence of CDMs, updating its risk prediction as new CDMs arrive.
5. If collision risk is estimated by the CCM to be above thresholds, a CAM is computed and passed to the OBC.
6. The OBC verifies that the commanded CAM respects safety criteria, and then executes it.
7. Log data from the CCM and navigation information is transmitted to ground.

Each test will last between 2 and 3 weeks, weeks, including its definition and generation of CDMs, the autonomous operation of the CCM, and the analysis of the results. Each test will be completed before performing the following one.

The virtual close approaches and their corresponding sequences of CDMs will cover the following scenarios:

- Sequence of CDMs beginning up to 7 days before the predicted CA, with no need to perform the CAM. The objective is to check if the algorithm properly evaluates that the manoeuvre is not required.
- Sequence of CDMs beginning up to 7 days before the predicted close approach, with CAM required within the last day according to current operator 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. This test would support the interest of decentralized or federated SSA systems providing short-time warnings for CAs with debris difficult to track, in timeframes incompatible with human-based operations.

3.3 Synthetic CDM generation

CDMs are required both to define the test scenarios and to train the ML algorithms for the decision-making component.

D. Sampath Kumar proposes in [5] a method to generate synthetic CDMs based on publicly available datasets, with view of its application to e.Cube. The proposed method extracts statistically meaningful data from the available CDMs, deriving covariance families for different elements.

3.4 Autonomous decision-making component

Autonomous decision-making for COLA operations is still an open topic of research. For what regards the evaluation of the models, it is important to focus on the confusion matrix, and in particular in the false negatives. A false negative in this application represents a scenario where a CAM would be required, but the ML model classifies the CA as not risky. This can lead to a collision that should otherwise be avoided. On the other hand, it is desirable to reduce the false positives, corresponding to cases where the event is incorrectly classified as risky, and an unnecessary CAM is implemented with the corresponding impact in operations and fuel.

Within Politecnico de Milano, several recent works have tried to tackle these challenges. The problem was studied by N. Boscolo Fiore in his M.Sc. thesis [6], including the perspective of the communication windows with the ground stations and how it affects the prediction process. This was motivated by the results showing limitations in improving the go/no-go results compared to the naïve approach of taking only the last CDM.

To improve the predictions, reducing the false negatives while avoiding a significant increase in false positives, A. Blasco [7] worked on the preprocessing of the data, identifying the key parameters (both simple and derived) from the CDMs that best served for the training of the ML algorithms.

3.5 CAM design model

The proposed analytical CAM framework relies on the assumption that the displacement due to the CAM is small, allowing to characterize the post-manoeuvre orbit through the modification $\delta\boldsymbol{\alpha}$ of its Keplerian state $\boldsymbol{\alpha} = [a, e, i, \Omega, \omega, M]^T$, and to map changes in Keplerian state to displacements $\delta\boldsymbol{r}$ at TCA using linearized relative motion models [11]. This $\delta\boldsymbol{r}$ at TCA (or more generally, $\delta\boldsymbol{s} = [\delta\boldsymbol{r}^T\ \delta\boldsymbol{v}^T]^T$) is then projected on the nominal encounter plane, or b-plane, to characterize the updated CA in terms of miss distance and PoC.

The procedure is configured in a modular way [9]. In the most general case, the mapping from $\delta\boldsymbol{\alpha}$ to changes in position and velocity at TCA can be expressed as [11]:

$$\begin{bmatrix}\delta\boldsymbol{r}\\ \delta\boldsymbol{v}\end{bmatrix}(TCA) = \begin{bmatrix}\boldsymbol{A}_r\\ \boldsymbol{A}_v\end{bmatrix}\delta\boldsymbol{\alpha}(TCA) \qquad (1)$$

where $\boldsymbol{A}_r$ and $\boldsymbol{A}_v$ are 3×6 matrices that depend only on the nominal orbit [10]. On the other hand, the displacement in the b-plane is directly computed from the projection of $\delta\boldsymbol{r}$ onto this plane, and the PoC is evaluated using Chan's algorithm [12] both for computational efficiency and for ease of analytical manipulation.

For the impulsive CAM, a matrix relation between the manoeuvre delta-V and the instantaneous change in Keplerian elements is obtained by integrating Gauss planetary equations over the instantaneous duration of the manoeuvre [10]. However, as noted in [13] for the case of asteroid deflection, an additional correction in the mean anomaly is needed to account for the change in mean motion during the manoeuvre lead time $\Delta t = TCA - t_{CAM}$. Both contributions can be combined in a single matrix expression:

$$\delta\boldsymbol{\alpha}\,(TCA) = \boldsymbol{G}^I(\boldsymbol{\alpha}, t_{CAM}, \Delta t)\delta\boldsymbol{v}\,(t_{CAM}) \qquad (2)$$

Combining a linear relative motion model and Eq. (2), a linear mapping between $\delta\boldsymbol{v}\,(t_{CAM})$ and $\delta\boldsymbol{r}(TCA)$ is reached. This can be leveraged to reduce the miss distance maximization problem to an eigenproblem, as noted by Conway for a different application of asteroid deflection [14]. In a later work, Bombardelli and Hernando-Ayuso [8] proved that this approach can also be extended to the PoC minimization problem, introducing the information of the combined covariance into the linear mapping. In both cases, the optimization problem is a quadratic one, and the optimal thrust direction is given by the eigenvector associated to the largest eigenvalue.

4. Broader system requirements

To effectively enable autonomous COLA in LEO, future implementations would also require the establishment of federated SSA services feeding the spacecraft with information about nearby objects.

5. Conclusions

The autonomous COLA experiment in the e.Cube mission has the scope of advancing the capabilities for increased autonomy in satellite operations. The payload for this experiment is a dedicated on-board computer called the CAM Control Module (CCM), which carries out both the go/no-go decision and CAM design, based on a sequence of CDMs. The go/no-go decision relies on ML models, while the impulsive CAM design is performed with analytical models. To test the feasibility of this approach and increased its TRL, several on-orbit tests for CAs with virtual debris will be implemented.

This autonomous COLA approach can be further advanced considering a federated approach for the transmission of SST information (for example, in the form of CDMs).

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