A MODULAR AND SCALABLE COLLISION AVOIDANCE SYSTEM FOR ENHANCED SATELLITE AUTONOMY

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ABSTRACT

The increasing deployment of mega-constellations and the growing risk of collisions with space debris or inactive satellites necessitate a shift from traditional ground-based orbit maintenance and collision avoidance (CA) strategies to more autonomous onboard solutions. This paper presents preliminary results from two ongoing ESA-funded activities led by GMV, regarding onboard CA technologies, namely: Advanced Control Techniques for Increased On-board Autonomy (ACTIVA) and the On-board Autonomous Collision Avoidance Detection Testbed (OCAD). These projects aim to enhance autonomous CA capabilities through advanced risk assessment, manoeuvre design, and onboard sensing.

In particular, a novel Modular and scalable Onboard Collision Avoidance System (mOCAS) is proposed, integrating key contributions from ACTIVA and OCAD, as well as GMV's previous CA-related activities. The mOCAS architecture is designed to support both collaborative and non-collaborative conjunction scenarios. This encompasses a set of onboard conjunction detection, risk assessment and manoeuvre design methods that enables autonomous conjunction assessment, real-time collision risk mitigation, and coordinated manoeuvres between satellites via inter-satellite links.

This paper demonstrates the potential of this modular architecture to enhance satellite autonomy and contribute to sustainable space operations within a large-set of mission use-cases and operational scenarios.

1 INTRODUCTION

As mega-constellations with thousands of satellites emerge, alongside a rising risk of collisions with other space objects or debris, traditional ground-based methods for orbit maintenance and collision avoidance may soon become unsustainable. To address these evolving demands, new approaches and technologies are essential. The Collision Risk Estimation and Automated Mitigation (CREAM) is a set of activities within the Space Safety programme of the European Space Agency (ESA), focusing on advancing technologies for automated ground operations, on-board autonomy and coordination to support spacecraft navigation in increasingly crowded orbital environments.

In this context, GMV's contributions to ESA programmes started with the development of CRASS, ESA's first operational collision avoidance tool (see [3]) in the early 2000s, and have continued up to now with leading roles in the various ESA CREAM and TDE activities, including:

- CREAM#1, where a standalone CA system has been developed, focused on the ground-based automated collision risk assessment (CA) and collision avoidance manoeuvre (CAM) design algorithms and methodologies [33].
- CREAM#2, where some of the usual collision assessment algorithms and methodologies have been developed to increase the autonomy of the mission and perform the autonomous late commanding of the collision avoidance manoeuvre (CAM) through the implementation

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of the on-board CAM system in a Zynq 7030 board.

- CREAM#3 activity, where a collision avoidance coordination system between active satellites (i.e., a “rule-of-the-road”) has been designed and is currently under development.
- ELECTROCAM (TDE programme): addressing the uncertainty related to the long thrusting arcs of low-thrust platforms, with applications to collision avoidance, and the derivation of improved operational concepts to address this scenario. Findings contributed to updating ESA’s DRAMA ARES tool for low-thrust collision avoidance [34].
- CREAM-IOD: an early phase of a mission that marks a significant milestone, bringing together the advancements from previous CREAM-related initiatives developed by ESA over recent years. The aim of the CREAM-IOD mission is to fly a small satellite as example and demonstration for a next generation platform that provides technologies supporting safe operations in the space debris environment [35].

In practice, increasing automation of the Collision Avoidance System (CAS) within its overall System (ground and flight segments) can be addressed in two main complementary areas:

1. by means of proper space traffic management, i.e., centralised and automated coordinated system between satellite operators and SSA Providers, including conjunction assessment screenings, CAM design and CAM decision making (as framed in the previous CREAM#1 or CREAM#3 activities), or,
2. on the other hand, moving this automation to on-board systems, increasing the autonomy of the spacecraft itself. (as it has been proposed by CREAM#2)

This paper presents preliminary results in ESA ongoing activities led by GMV’s in on-board Collision Avoidance (CA) technology and operations, namely ACTIVA and OCAD activities, which are framed in this second approach, looking towards a higher on-board autonomy, to optimise the collision avoidance assessment, reducing the number of executed manoeuvres and the operational effort on the ground control centres. Nevertheless, an efficient (mostly) onboard-based System, such as the Modular Onboard Collision Avoidance System (mOCAS) proposed in this paper, still relies on ground support to keep a high-degree of space situational awareness.

Briefly, ACTIVA focuses on implementing advanced CA methods for risk assessment and Collision Avoidance Manoeuvring (CAM) design, while also showing how these CA systems can be interfaced with representative

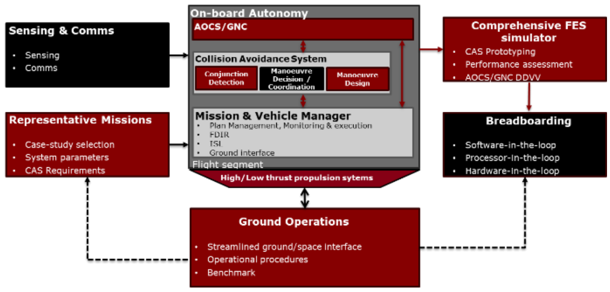

Figure 1-1: Main technical elements of an onboard CA subsystem

Attitude and Orbit Control Systems (AOCS) to close the collision avoidance loop. In turn, OCAD focuses on developing a standalone satellite payload capable of performing the beforementioned task, as well as active onboard sensing of debris and inter-satellite link communication to support the share of orbital information and coordinate manoeuvres in case of active-vs-active encounters. In both ACTIVA and OCAD, GMV’s extensive heritage and experience from previous ESA CA-related activities (namely the CREAM programme) was considered as a starting baseline.

Optimizing spacecraft operations involves minimizing scientific observation downtimes to improve timeliness, reducing energy demand and fuel consumption to extend mission lifetimes, and adhering to mission-specific constraints. Additionally, reducing collision risk is crucial as space debris and in-orbit spacecraft continue to grow in number. These challenges for collision avoidance require a new paradigm for CAM operations that needs to be based on automation and autonomy. Following previous CREAM activities’ results, and considering also ACTIVA and OCAD’s preliminary results, this paper proposes a modular and unified architecture, the mOCAS architecture, that encompasses all the different contributions from those activities.

Figure 1-1 outlines the onboard CA problem breakdown leveraging on enhanced on-board autonomy, and highlights the main technical elements involved. These include:

- Mission use-cases and Ground operations: to define a set of representative use-cases, including applicable operational procedures and performance benchmarks.
- Sensing and Communications: establishing the baseline technologies to be specifically used in the context of onboard conjunction detection and manoeuvre coordination, including their corresponding power and computational requirements.
- Collision avoidance subsystem: including risk assessment and manoeuvre design. Several methods are available in the literature, from analytical to numerical-based, which are applicable to different scenarios (e.g., short vs

long-term encounter models for risk assessment or high vs low-thrust spacecrafts for manoeuvre design), with different levels of accuracy and computational requirements.

- Comprehensive Functional Engineering Simulator (FES): allowing to model the specific interfaces between the mOCAS and an Attitude and Orbital Control System (AOCS), and additionally, assess the actual performance of the closed-loop system considering different spacecraft physical/mission constraints.
- Breadboarding/manufacturing: providing a set of incremental verification and validation steps towards a final mOCAS product.

Increased onboard autonomy for CA applications has been recently addressed in the literature (see [1,2] and the reference therein). In [1], the proposed system combines onboard flight software with a networked Space Traffic Management (STM) hub to enable real-time collision risk assessment and mitigation. Unlike traditional CA systems that rely heavily on ground-based tracking and operator intervention, this infrastructure seeks to enhance spacecraft autonomy by integrating onboard navigation, manoeuvre planning, and decision-making. In [2], a simplified onboard architecture, composed of a decision-making algorithm, based on machine-learning techniques, and the manoeuvre design, relying on highly efficient analytical methods is proposed. In this paper, a similar set of analytical and semi-analytical methods for high and low-thrust spacecrafts are also selected to be used within the mOCAS System. However, while a similar baseline concept for ground interactions/updates is adopted in this paper, assuming an automated coordination between the ground and the flight segment, this paper further extends the state-of-the art results reported in the literature, by proposing a modular onboard System architecture that includes autonomous sensing, orbital information sharing, and manoeuvre coordination capabilities, along with a detailed finite-state machine to manage risk assessment and manoeuvre design methods, according to each considered use-case scenario.

Therefore, the main contributions of this paper are as follows: *i)* an overview of representative CA use-cases and enabling technologies; *ii)* applicable concepts of operations for increased onboard autonomy and *iii)* a comprehensive modular System architecture which supports both ground and onboard conjunction detection, compliant with different concepts of operations.

The rest of the paper is structured as follows: Section 2 introduces the selected representative mission use cases along with their selection criteria. Section 3 discusses the proposed concepts of operations and onboard processes supported by mOCAS and outlines the mOCAS system architecture, detailing its main modules and corresponding methods. Section 5 provides an overview of key enabling technologies and methods for enhancing onboard CA autonomy to be managed by the mOCAS subsystem. Finally, Section 6 presents the main conclusions and future work.

2 MISSION USE-CASES

The use-cases have been selected as a result of a trade-off analysis which used as criteria the following aspects: *i)* impact of technology – how the mission can benefit from the increased autonomy; *ii)* data availability – how much information is available with respect to the mission; *iii)* representativeness in the relevant ecosystem – if the mission can be used as a representative for the envelope studied; and *iv)* diversity of covered envelope – to see if the mission can also cover a variety of scenarios.

It is also important to highlight that from a System's architecture perspective, the mOCAS architecture shall be able to address each of three possible scenarios:

- Conjunction with a debris.
- Conjunction with a controlled but uncollaborative (not mOCAS equipped) secondary.
- Conjunction with a collaborative secondary (sharing orbital data and covariance).

The proposed usecases are summarised in Table 2-1

Table 2-1 Use-cases

Usecase-1.1	SWARM A, short term encounter with low-thrust, with the following constraints: - Minimum time - Lowest fuel - Least likelihood of collision, while constrained
Usecase-1.2	SENTINEL-2A short term encounter with high-thrust with the following constraints: - Minimum time - Lowest fuel
Usecase-2.1	LEO – SENTIEL-2A and SSO Constellation - ICEYE
Usecase-2.2	GEO – METEOSAT – 10 (9.5 deg E) and GEO METEOSAT – 11 (0 deg) adjacent longitude slot
Usecase-2.3	GEO – METEOSAT – 10 and GTO Debris – Part of Ariane 5 SYLDA

3 CONCEPTS OF OPERATIONS AND ONBOARD PROCESSES

3.1 Concepts of operations

The early assessment regarding concepts of operations (CONOPS) and related onboard processes performed in past CREAM activities revealed several crucial factors regarding ground-based processes constraints, including *i)* Ground procedures *ii)* Possibly constrained uplink windows; *iii)* Safety time margins; *iv)* Data processing latency; and *v)* Human decision factors, thus introducing a huge operational overhead into the overall System. Therefore, when selecting the CONOPS for increased onboard autonomy, one shall consider that whenever a ground interaction is added into the CONOPS after having performed a related CA onboard function, the added time and operational cost issues are nearly the same as with a fully ground-based process.

Following these conclusions, to ensure benefits from increased onboard autonomy, onboard functions shall follow ground operations in a sequential order. This leaves four main increased autonomy System architecture concepts to consider, one of which is the fully ground-based baseline architecture, to serve as benchmark for the expected increased autonomy benefits. Figure 2-1 summarizes the main System architecture concepts options to be considered:

Concept 1 – Traditional (ground-based): Traditional ground-based process, provided as baseline reference.

Concept 2 – Onboard CAM decision refinement: This concept relies on most of the process to be executed on-ground. However, it includes the possibility to refine the manoeuvre decision onboard, using the most up-to-date results using the onboard state estimation (performed using ground uploaded state-transition matrices for propagation). If a CAM is deemed necessary then, a previously uploaded CAM is executed without any update from the onboard system.

Concept 3 – Onboard CAM refinement and selection: This concept still relies on most of the process to be executed on-ground. However, instead of having to select and execute a specific manoeuvre uploaded several hours prior to TCA, the CAM Design process corresponds to the linear combination of a set of uploaded manoeuvres. To highlight this ground dependence, the corresponding CAM Design in Figure 2-1 is identified with an O*.

Concept 4 – On-Board Risk Computation and CAM Design: This concept includes both risk computation and CAM Design exclusively computed onboard. A tailored catalogue (minicat) is regularly uploaded from ground. The mOCAS System shall include a high-fidelity onboard propagator, that allows for longer operational autonomy time (i.e., without ground interactions). With respect to concept 2 and 3, the CAM Design is fully performed onboard, without considering any pre-uploaded manoeuvres from ground. The main improvement is therefore less ground-spacecraft interaction requirements and more required onboard computational power and memory capacity to keep track of a larger onboard catalogue and a more demanding computing processing.

Concept	Processes						
	ID	Conjunction detection	Primary's orbit propagation	Risk Computation / CAM Decision	Risk Computation / CAM Decision Refinement	CAM Design	Orbit scanning
Traditional (ground-based)	1	G	G	G	G	G	G
On-Board CAM decision refinement	2	G	G	G	O	G	G
On-Board CAM decision refinement and selection	3	G	G	G	O	O*	O
On-Board Risk Computation and CAM Design (Onboard propagator)	4	G/O	O	O	N/A	O	O

O*: The CAMs are pre-computed on-ground and the on-board processing just select a linear combination of preloaded manoeuvres.

Figure 2-1: Concepts of operations for increased onboard autonomy.

3.2 Onboard processes

In this subsection, the main CA functions to support the selected concepts of operations are detailed in the sequel, along with their specific onboard implementation perspective.

Conjunction detection: For a consolidated System's architecture perspective presented in this paper, the overall mOCAS System shall be able to encompass both ground uploaded conjunctions (to be further assessed onboard using Risk Computation methods) and onboard processed conjunctions, upon onboard detection by its embedded sensors. This poses additional degrees of freedom that are addressed in the following sections.

Risk Computation / CAM Decision: from an onboard perspective, CAM Decision shall be performed as a result of the Risk Computation and trigger the CAM Design if a certain set of conditions are met (e.g., probability of collision, miss distance, time to TCA, etc). For ground-based processes, the standard approach is to compute and upload the manoeuvre a few orbits ahead with the corresponding execution epoch, and afterwards override the CAM Decision, by uploading an updated command in case it is no longer required. However, this would add to the operation the ground overheads highlighted previously. Therefore, a hybrid architecture, accounting for the possibility of computing the manoeuvre onboard and afterwards validate/override from ground is not considered as an optional scenario. On the other hand, it is important to highlight that a given onboard process can simply execute a ground command previously uploaded, as long as it does not involve additional subsequent ground-spacecraft interactions (as considered in Concepts 2 and 3).

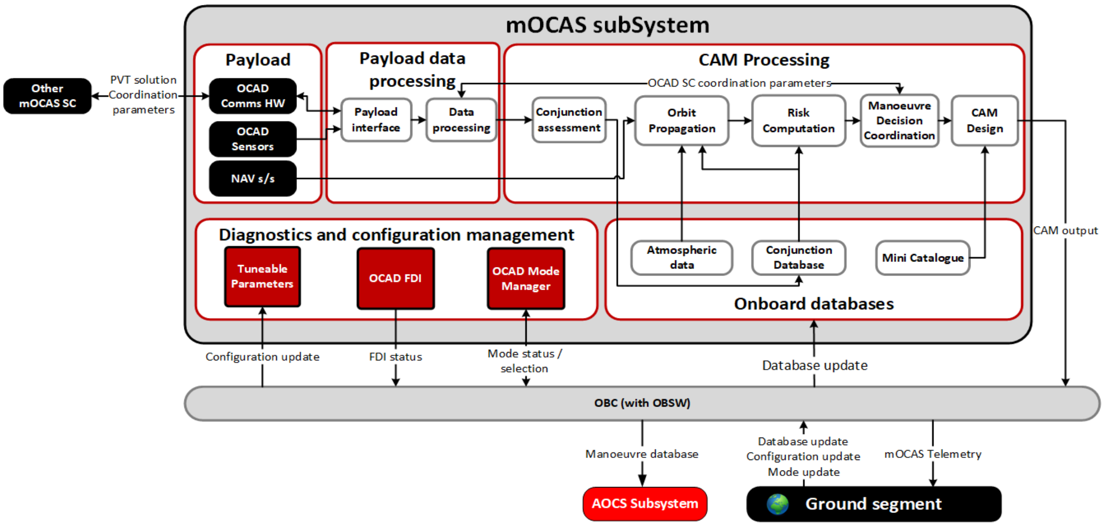

Figure 3-2: mOCAS subsytem - architecture overview.

CAM Design: from an onboard perspective, CAM Design shall be triggered by the Risk Computation / CAM Decision function, to optimize the limited onboard computational resources. This sequence of functions to be performed is tightly coupled with the fact that from an onboard perspective, this removes the constraints regarding uplink windows or other ground-based overheads. For Concept 3, CAM Design is constrained as a limited set of possible manoeuvres uploaded from ground, which are to be selected according to onboard orbit determination and propagation.

Orbit scanning: in addition to any specific manoeuvre constraints related to the mission being executed, the CAM Design shall include an orbit scanning process to ensure that the new orbit is collision free from the surrounding objects. This imposes the need to include an onboard mini catalogue of nearby secondary objects, that requires regular updates from the ground segment to account for possible secondary's manoeuvres, orbit decays or new (nearby) debris/satellites detected from ground. The onboard (local) "mini-catalogue" consists of a pool of secondary's orbits.

4 PROPOSED ONBOARD CA SYSTEM ARCHITECTURE

4.1 mOCAS Modules

The proposed mOCAS consists of five main functional modules: *i)* payload hardware support, *ii)* data processing, *iii)* onboard databases, *iv)* CAM processing, and *v)* diagnostics & configuration management. These main modules are illustrated in Figure 3-2. Additionally, Figure 4-1 presents the corresponding functional perspective of the mOCAS System, which is outlined in the sequel.

Sensing & comms module: Includes the main sensors and HW components for sensing and communications purposes. This includes:

- ISL hardware for close-proximity communication with other mOCAS payloads.
- A GNSS receiver providing the required measurements for on-board orbit determination (OD) in LEO.
- A sensor suite for debris / secondaries on-board detection.

Payload data processing: Includes the main mOCAS sensors and HW interfaces, namely:

- Interface to active onboard sensors for secondaries detection;
- Interface to nearby mOCAS compatible satellites, using ISL;
- Payload data processing, corresponding to a dedicated payload raw data processing that outputs the corresponding estimated orbital parameters to be further processed upon conjunction assessment. This module also includes communication processing to exchange navigation data with nearby spacecrafts.
- Payload data processing for on-board OD process.

Onboard databases: Includes all required (periodically updated) information to perform onboard CA processing namely:

- State transition matrices and atmospheric data for orbital propagation purposes.
- Conjunction database parameters of both onboard detected/shared and ground-uploaded objects, namely estimated secondary's state and covariance at TCA.
- Mini Catalogue of nearby objects to perform post-conjunction assessment (conjunction detection) upon CAM computation.

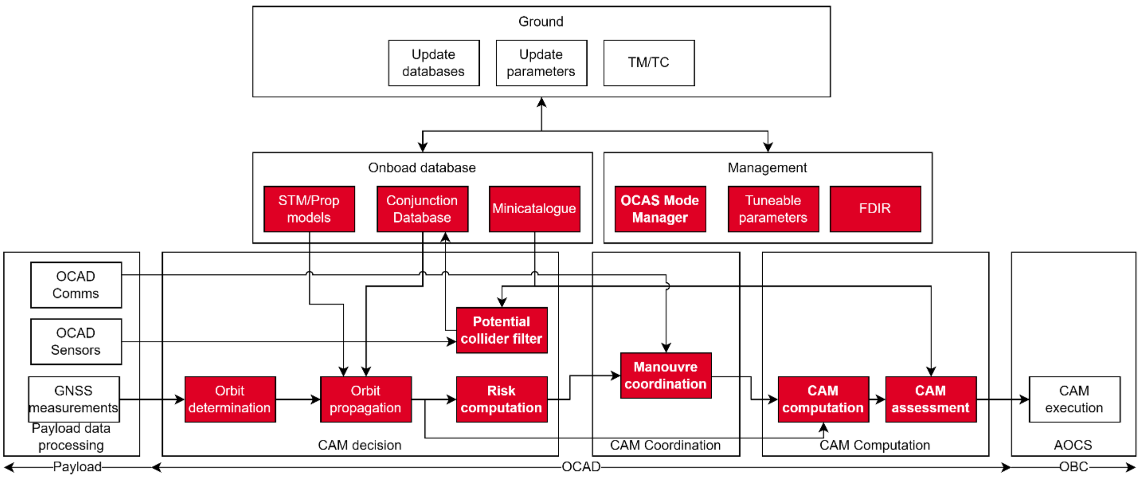

Figure 4-1: mOCAS subsytem - functions overview.

CAM processing: Includes the main CA functions to be performed onboard, namely:

- Conjunction detection with onboard detected/shared secondaries.
- Orbit propagation to determine primary's state and covariance at TCA.
- Risk computation to compute the probability of collision.
- Manoeuvre decision coordination – only applicable for the case of active vs active conjunctions.
- Collision avoidance manoeuvre computation, including post-conjunction assessment, for a reduced number of secondaries included in the mini catalogue.

Diagnostics and Configuration Management: To oversee mOCAS health status and manage operational settings (tuneable parameters) and modes to ensure an adequate performance of the overall OCAD System. Therefore, it includes:

- Tuneable parameter function, to update the adjustment of key system settings
- FDIR to ensure system reliability and functionality.
- Mode manager to control the system's operational modes (detailed in the sequel), ensuring smooth transitions between different states based on mission phases or system conditions.

4.2 Mode architecture

The mOCAS architecture shall support one main function and four main OCAS modes, that run in parallel with the AOCS modes. These function and modes are described in the sequel:

Database update function: corresponds to a function that permanently runs in parallel with the remaining mOCAS modes/functions. This routine retrieves and updates the onboard databases, including State Transition Matrices (STM), atmospheric data, mini catalogue and Conjunction Detection (CD) events on every ground communications window.

Monitoring mode: is the default state of mOCAS, during which it reads the onboard conjunction database and assesses the corresponding Time of Closest Approach (TCA). This mode assesses potential colliders included in the onboard mini catalogue with a pre-specified rate, until:

- a new conjunction event is uploaded into the onboard database; OR
- a conjunction between the spacecraft and a nearby object is detected by the onboard sensors through the potential collider filter; AND
- the corresponding time remaining to TCA (*t2TCA*) falls below a multiple N, (where $N \geq 2$) of a predefined time safety margin.

The safety margin is determined based on the spacecraft's physical constraints and orbital parameters.

Decision mode: During this mode, several sequential functions are performed, namely:

- Read onboard databases: to retrieve the most up-to-date secondary's state and covariance data at TCA.
- Orbit propagation: read current S/C navigation state (provided by the GNSS receiver) and perform orbit propagation to compute the S/C state and covariance at TCA;
- Risk computation: to compute the corresponding PoC, according to the corresponding encounter type;
- Manoeuvre decision: to update and store the manoeuvre decision.

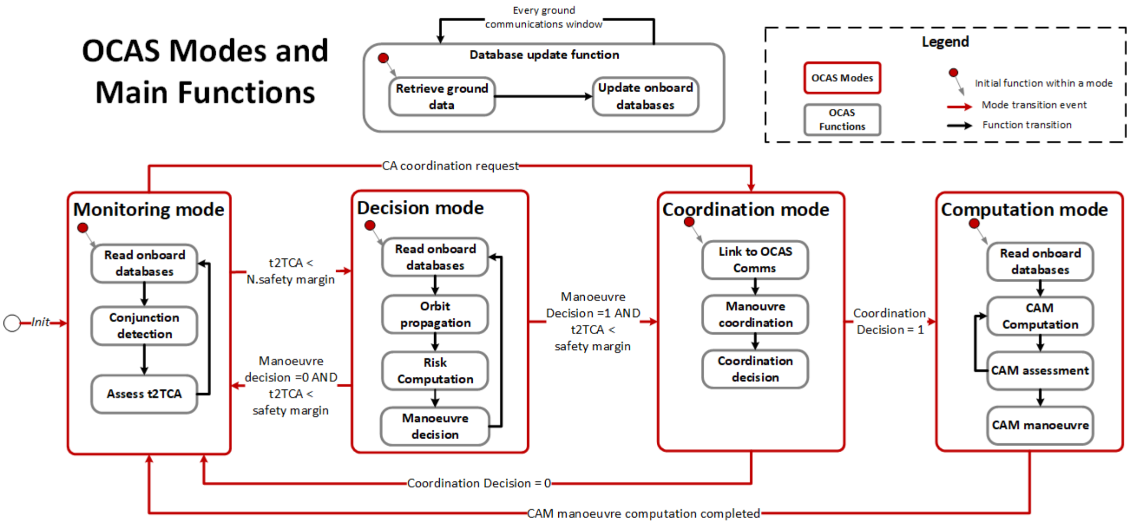

Figure 4-2: mOCAS main modes and functions.

The Decision mode is repeated in a cyclic manner, with a period that corresponds to a tuneable fraction of the spacecraft orbit (depending on the overall mission scenario).

Coordination mode: In case a CA manoeuvre is deemed necessary after the Decision mode (or in case there is a request by a nearby mOCAS compatible spacecraft), the mOCAS enters into coordination mode to coordinate the manoeuvre. If the conjunction occurs with a compatible mOCAS System (e.g., conjunction within the same constellation), after manoeuvre coordination, a final decision regarding the CA manoeuvre is taken, and thus the mOCAS system switches to either Monitoring mode (in case there is no need to perform the manoeuvre) or Computation mode (otherwise, described in the sequel). For the cases where no coordination is required (e.g., conjunction with a debris, or with an active satellite not equipped with a mOCAS system), the coordination mode is skipped by the mOCAS mode manager.

Computation mode: In case a CA manoeuvre is deemed necessary upon t2TCA < Safety margin, the mOCAS subsystem autonomously switches to Computation mode. This mode encompasses:

- Read onboard databases: to retrieve the most up-to-date secondary's state and covariance data at TCA.
- CAM computation: to compute the required thrust magnitude, direction, firing time and manoeuvre epoch to be performed.
- CAM assessment: to assess that the computed CAM maintains the collision probability below the threshold with both the main secondary object but also with the nearby objects included in the mini catalogue.

After manoeuvre computation is performed, the corresponding parameters are sent to the AOCS to trigger the CA manoeuvre at the designated time epoch (see Section 4.3 for further details). Meanwhile, the mOCAS subsystem autonomously switches to monitoring mode and all currently stored parameters—such as manoeuvre decision, *t2TCA*, and manoeuvre settings—are reset.

4.3 OCAS / AOCS Interfaces

In order to enhance the development of an mOCAS system that is independent/agnostic of other onboard systems, it is proposed that mOCAS includes its own embedded GNSS navigation subsystem. Additionally, the manoeuvre calculated by mOCAS should be recorded in a manoeuvre database, to be later read by the AOCS, functioning similarly to a ground telecommand sent from the ground. This allows for a modular approach for the mOCAS subsystem, that provides the required functionality (replacing or complementing the ground operations) while at the same time being able to operate independently of the AOCS subsystem.

5 APPLICABLE TECHNOLOGIES & METHODS

The proposed mOCAS System architecture shall include a set of applicable methods and technologies whose selection is still ongoing. This Section provides a brief overview of the preliminary applicable technologies and methods to be adopted within the mOCAS System.

5.1 Onboard Sensing

In CREAM#2 project, onboard CA operations relied on the ground segment to upload a catalogue of objects and their estimated state and covariances in order to estimate closest approaches and the PoC of the conjunction. Thus, a possible conjunction with non-catalogued objects could not be processed. In the OCAD project, on-board detection of secondaries is addressed to close this gap. Additionally, on-board sensing could be used to potentially improve upon the ground secondary's catalogued state and covariances, improving the conjunction risk assessment and potentially reducing the need for CA manoeuvre.

From the early assessment only two possible sensing technologies have been assessed as adequate to perform this function onboard:

- Active radars systems.
- Visual-based systems (i.e. camera) [38].

From the assessed technologies, for secondary object's detection, it has been proposed for the mOCAS to be equipped with a camera and a suitable image-processing algorithm. This is mainly due to the power requirement of the alternative radar system considered. Indeed, the mOCAS design strives to reduce to the minimum the system's Size Weight And Power (SWAP).

Additionally, within the OCAD activity, the feasibility of detecting an unknown secondary with a visual-based system is under investigation. From the preliminary assessment, this could be achieved in GEO, thanks to the smaller relative velocity between assets allowing longer exposure times also taking advantage of reduced disturbances from Earth being in the camera frame.

5.2 ISL Communications

If the primary and secondary spacecrafts were able to share their latest on-board state estimations, the mOCAS system of each would be able to estimate the risk of the conjunction with more recent and potentially more accurate information, also improving the conjunction risk assessment and potentially reducing the need for CAM. The two assets could also coordinate the manoeuvres. On-board two-way communication requires an ISL. Also in this case, there are two main technologies which have assessed and considered [37]:

- A Radio Frequency ISL.
- An optical ISL.

While an optical ISL would provide a much larger data-rate, the mOCAS design just requires sharing orbital data and the information needed for manoeuvre coordination. Also, from a conceptual perspective, the mOACS system is mainly a payload on the host-satellite, and strong pointing-requirement (as it would be the case for the optical ISL) shall be avoided.

As a large data-rate is not required, and for the lower directivity, a RF ISL has been selected. Also, currently the communication between the two mOCAS happens without third parties in the loop, e.g. ground segment or GEO relay satellites to allow full on-board autonomy.

5.3 Conjunction detection

In order to perform collision probability assessment of objects orbiting Earth, the first step is to determine their closest approaches while moving along their respective trajectories. In an all vs. all object catalogue screening scenario, a simplistic approach over just one day for all 28,000 catalogue objects implies an intensive computational effort. Hence, to reduce the computational burden when computing the relative distance between object pairs in typical catalogue screening scenario, the amount of object pairs to be compared is first being drastically reduced by efficiently filtering out unlikely pairs, such as, e.g., GEO objects when screening for a LEO object. Preliminary filters to narrow down the population include removing out-dated (Orbit determination epoch very old compared to analysis time span, e.g., > 30 days) and decaying objects. Conjunction detection methods include well-established techniques like filters [4, 5] and [6], as well as more recent developments and concepts such as spatial binning and artificial intelligence methods [7].

In the here proposed mOCAS, the main conjunction detection processes shall be performed on the ground segment. Namely, the ground segment shall be responsible of performing conjunction screening for a large set of objects, thus handling most of the required high computational power and interfacing with SSA/SST to obtain the most up-to-date information. Then, a small subset of nearby objects and possible conjunction events can be uploaded to the spacecraft in the form of a mini catalogue of secondary objects. That catalogue can then be used onboard for both:

<u>Onboard Conjunction detection:</u> Having the possibility to perform conjunction detection onboard allows for rapid, autonomous response to high-risk conjunctions, reducing dependency on frequent ground communication, namely:

- to address communication constraints that limit uplink opportunities for CDM (Conjunction Data Message) and catalogue updates, which can compromise overall system reliability.
- to process the secondary objects detected by the onboard sensors.

<u>Manoeuvre computation:</u> Computing a manoeuvre to avoid one potential collision may cause a spacecraft to endanger another asset or come dangerously close to another piece of debris. CAM policies can include additional constraints to prevent such scenarios, using the onboard mini catalogue.

In the here proposed OCAS System, upon a preliminary design and analysis, a sequence of filters to detect possible conjunctions on board is proposed, namely: *i)* the apogee-perigee filter [30][31][32], *ii)* the XYZ sieve [31], *iii)* the r^2 sieve [31], the minimum distance sieve [31], and i*v)* the fine R^2 sieve [31].

5.4 Risk assessment

Short-term encounters

High relative velocity close conjunctions are common in LEO, MEO and GEO regimes and relative motion in most of the cases can be assumed rectilinear. Additionally, the positional covariance and the Probability Density Function (PDF) are assumed to remain constant during the encounter. For high relative velocity (short-term) encounters of resident space objects, eight main state-of-the-art methods are typically considered for a collision probability computation. This consists of five numerical methods: Foster [8], Alfriend and Akella [9][10], Patera [11], Alfano [12], Berend [13], and three analytical methods: Chan [14], Serra et al. [15] and Pelayo-Ayuso [16].

Within ACTIVA and OCAD activities, four different risk assessment methods were implemented (Alfano, Chan, Serra and Akella & Alfriend) and assessed using Foster's method (an independent implementation adopted from the CARA tool) as the ground truth. A thorough performance assessment was conducted, including more than 1000 ESA provided CDMs from the selected use-case scenarios. From the performance assessment, only two methods, namely Alfano's method and Akella & Alfriend's method were considered compliant with the expected accuracy (relative PoC error less than 10%, 3-sigma, w.r.t ground truth method). In particular, from the obtained results (see Figure 5-1), in terms of performance accuracy, Alfano's method is shown to be the most accurate, producing no false positives or negatives for the decision thresholds considered.

The performed assessment also provided evidence that the expected computational time of Alfano's method is indeed adequate to an embedded computer such as Zynq® 7030 with an expected average computation time around 5 miliseconds which corresponds to several orders of magnitude lower than Akella & Alfriend's method. Therefore, the selected risk assessment method to be used in the mOCAS within the decision mode (for short-term encounters) is the Alfano's method [12].

Long-term encounters

In some orbital regimes, like GEO, due to satellites operation, it is common to have close conjunctions with low relative velocity. In this case it is necessary to count on nonlinear effects. The main state-of-the-art methods to compute a probability of collision for low relative velocity (long-term) encounters are: Patera [17], Alfano [18], McKinley [19]), the voxel method (Alfano [18]), Coppola [20] and Hall's method which is based on Coppola's algorithm [21][22][23].

In the context of OCAD, the analysis of long-term encounters use-cases is performed considering different orbital regimes and different conjunctions geometries. These conjunctions are assessed in [29].

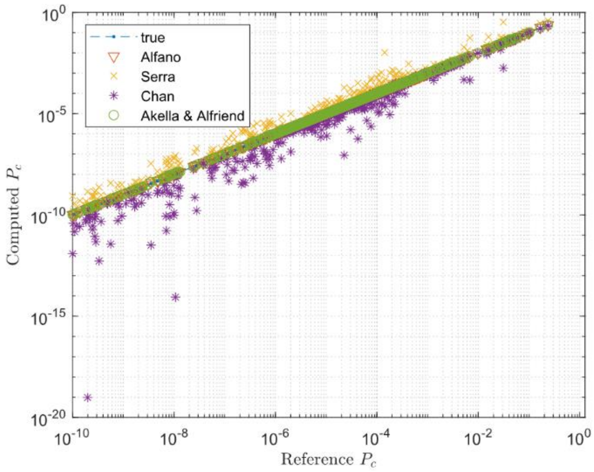

Figure 5-1: Computed probability of collision with respect to 1000 ESA CDMs.

From the preliminary analysis performed in the context of OCAD, Hall's method was selected as the reference long-term encounter method to be used within the mOCAS subsystem.

It should be noted that, more recently, advanced methods based on increased computational power (Scaled PoC [11], Predicted PoC [24], or Dilution of Probability [25]) and through the use of machine learning (prediction of state vector and secondary's covariance at TCA [26]; prediction of risk level evolution [27]; provide a correction to the propagated state vector, included in a CDM [27]) have been proposed. However, they may require additional computational power from the on-board computer or may not be suitable for specific cases due to the shape or size of the satellite model, or their focus on analysing edge-case scenarios. Additionally, most are only relevant for onboard detection. Therefore, they are not part of the proposed mOCAS, even though its architecture allows for future upgrades or replacements to the traditional methods.

5.5 Manoeuvre coordination

Manoeuvre coordination for spacecraft collision avoidance applications involves a series of challenges, including: *i)* real-time decision making, *ii)* communication delays, *iii)* scalability and *iv)* safety [39].

Different methods can be found in the literature to address the coordination problem, including purely randomized, impact based, fair-share or rule-based approaches [36],[56-60].

The method described in [28] provides a thorough analysis that considers several elements (negotiation strategies based on weights and cost function). When triggered, a set of parameters are loaded in the agents that will enter the negotiation process. According to, the work done in [28] coordination parameters include:

- Fuel Consumed

- Average Fuel Consumption
- Deviation from Design
- Cost of CAM
- Lifetime left
- Orbital Parameters
- Covariance Matrix

For each of these parameters, weight values are provided. They represent the importance that the satellite operator assigns to each parameter. The values for weights can vary between [0,1].

For the mOCAS System, using the lessons learned reported in [28] together with a rules-based approach (see [60] and the references therein) for manoeuvre coordination within the ground segment shall also be adopted, taking into account specific constraints of the onboard segment (e.g., determinism, computational burden and time constraints for coordination decision).

5.6 CAM design

CAMs can be divided into two main categories: impulsive (high thruster acceleration, short duration) and low thrust (low acceleration, continuous dynamics). In both cases, CAM design is a trajectory optimisation problem to find the guidance law that minimises the propellant required to achieve, in general, a prescribed value of collision probability. In the literature, CAM design is tackled using, mainly, three distinct methods: analytical, indirect optimisation and direct optimisation.

Analytical models for impulsive CAM are based on STMs that provide a linear mapping between state deviations at manoeuvre time and state deviations at TCA. The optimal manoeuvre can then be computed solving an eigenvalue problem, as originally proposed by Conway for asteroid deflection [40]. Bombardelli et al. [41] refined the methodology, using the squared Mahalanobis distance as objective function. The latest development in this regard is an analytical formulation of the STM in Keplerian elements proposed by Gonzalo et al. [42].

Low-thrust manoeuvres, on the other hand, follow different possible approaches. The first is based on an indirect formulation that is solved analytically through a series of assumptions, the most popular being fully tangential thrust, or the energy-optimal solution [43,44]. Indirect methods search for the solutions by imposing the necessary optimality conditions, such as Pontryagin's Maximum Principle or the Hamilton-Jacobi-Bellman equation; these lead to a set of differential equations referred to as "adjoint" or "costate" equations normally formulated as a Two-Point Boundary Value Problem (TPBVP). The second approach exploits a linearisation of Gauss equations to provide an analytical formulation of the manoeuvre effects [45,46]. Finally, direct methods formulate the trajectory optimisation as a Nonlinear Programming (NLP) problem by discretising the continuous trajectory. Most methods modify the constraints to be convex such that convex optimisation techniques can be employed. This is done for both impulsive [47] and low-thrust [48] CAMs.

While analytical methods offer the best computational performance, which is desirable for onboard implementations, they are less flexible than numerical methods for the inclusion of operational constraints. A balance between both is required to meet the mOCAS objectives, resorting to a combination of analytical and semi-analytical algorithms. In the following, two approaches for CAM design are presented, both for high and low-thrust propulsion systems. The first solves the problem through an eigenvalue formulation, while the second employs analytical and semi analytical solutions of the CAM Optimal Control Problem (OCP). The pipeline is tailored to handle a primary conjunction scenario and evaluates the mini-catalogue of nearby objects, verifying whether the manoeuvre might trigger additional close approaches.

The eigen-problem-based approach is applied both for impulsive and low-thrust CAM. For the latter, the eigen-problem approach with analytical STM has been extended to low-thrust CAMs [49,50]. The low-thrust problem is converted into a series of impulsive problems exploiting the Sims-Flanagan transcription [51]. This yields the optimal thrust profile that minimises collision probability. The fuel-optimal solution is obtained by pruning the less optimal nodes. The eigenvalues represent the nodes' optimality, while the contribution of each node is directly mapped onto the b-plane. Eclipse constraints can be imposed by neglecting the nodes in the shadow region (computed analytically with either cylindrical or dual cone shadow models). By exploiting rotation matrices, several operational constraints regarding the satellite attitude are applied. Most notably, maximum rotational velocity constraints, Earth or Sun pointing constraints, inter-satellite communications constraints, and star tracker constraints.

This project also leverages analytical impulsive and indirect OCP low-thrust formulations for Fuel-Optimal (FO) CAM planning. The impulsive approach [52] aims to minimize Δv for single-impulse CAMs under Square Mahalanobis Distance (SMD), linked to a safety PoC threshold, or Miss Distance (MD) constraints. It employs a Keplerian STM to form a quadratic constraint in Δv, solved in closed form via Lagrange multipliers. Meanwhile, the indirect OCP formulation [53] focuses on designing a preliminary Energy-Optimal (EO) CAM for low-thrust propulsion, solved analytically via a TPBVP with STM-based Hamiltonian dynamics for specified tangential and radial directions. A FO refinement then builds on the EO solution by identifying candidate firing windows through a bisection method. This is followed by an NLP approach with bespoke analytical propagators for both ballistic and thrusting arcs—particularly for tangential thrust [54]—ensuring that boundary conditions on MD/SMD are met. Finally, radial manoeuvres [55] rely on differential algebra and Picard–Lindelöf iterations to model the state evolution, with a Newton-based method determining the optimal switch-off time for just-in-time CAMs under radial thrust.

After designing the CAM policy for the main conjunction, with any of the methods described above, the pipeline evaluates whether the CAM induces additional conjunctions with nearby objects over a finite time horizon. It propagates the primary object's trajectory using J_2-perturbed dynamics while synchronizing secondary objects' states to a common reference frame for precise encounter analysis. The TCA is identified by detecting local minima in the relative distance between objects, later refined through a Keplerian propagator. Covariance matrices are then propagated via STM to compute PoC. The decision logic ensures validation of the main manoeuvre if all PoCs within the mini-catalogue remain below the safety threshold. If a new conjunction arises before the main TCA, ground intervention is required, as simplified models cannot optimize simultaneous CAMs for multiple conjunctions. However, if secondary conjunctions occur after the main event, the same strategy used for the main conjunction is applied to plan a follow-up manoeuvre within the defined time horizon. This method enables autonomous and optimized CAM execution while maintaining compliance with collision risk constraints.

6 CONCLUSIONS AND FUTURE WORK

As a global conclusion, the future challenges for collision avoidance require a new paradigm for CAM operations that needs to be based on automation and autonomy. This new approach is required to reduce the risks of collision, the mission's operation costs and will contribute to increase the operational lifetime and therefore the scientific return. Recent developments within ACTIVA and OCAD activities provide a further step towards realizing that vision, namely by proposing a modular architecture that can be used in different mission scenarios, while being compliant with different spacecrafts constraints (e.g., low-thrust vs high-thrust) and onboard sensing capabilities.

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