ASSESSMENT OF INTER-OPERATOR RULE-BASED COLLISION AVOIDANCE OPERATIONS

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1 ABSTRACT

The rapidly growing number of satellites in lower Earth orbit especially due to constellations will lead to an increased number of conjunctions between operational spacecraft. The ability of both objects to perform active avoidance manoeuvres may increase the risk of collisions in the case of insufficient communication, misinterpretation, or an uncoordinated avoidance manoeuvre by both operators. Precise and accepted rules have to be defined on how the manoeuvres have to be performed and what spacecraft has to evade. In this paper different approaches on decision-making processes for cases of inter-operator conjunctions are presented and discussed. Advantages and disadvantages of rule-based approaches are presented and potential feasible concepts are discussed. The activities performed as part of the Rules4CREAM-activity are presented, in which rule-based approaches should be assessed in a simulation environment.

2 INTRODUCTION

Preventing collisions in Earth's orbit is one key challenge to avoid the generation of new space debris and to allow safe and economic space operations in the future. Lower launch costs and new applications have led to a record growth in the number of satellites in the last year, especially driven by large constellations. More than four thousand operational satellites are currently in orbit [1] controlled by more than three hundred different operators. Even if only a fracture of the more than two hundred and fifty planned constellations with tens of thousands additional satellites is realised in the coming years spacecraft operators will face major challenges in ensuring safe operations.

By now the majority of collision avoidance (COLA) manoeuvres have to be performed due to conjunctions with space debris [2], but the ever-increasing number of operational satellites will lead to a growing number of potential collisions between manoeuvrable objects. The possible collision between the European Space Agency Aeolus Earth observation satellite and SpaceX Starlink44 on September 2, 2019 [3] has shown the challenges and risks linked in particular with such inter-operator conjunctions. Later incidents show similar risks and problems due to limited communication and coordination [4]. While in case of a conjunction with space debris no coordination is necessary or even possible, the possibility of uncoordinated manoeuvres by both operators poses the risk of an even increased collision probability post-manoeuvre. While there is the possibility to improve the assessment of the conjunction for both operators by sharing data, in case of no communication the situation can be assessed differently or even contradictory. Individual or even competing economic interests or political and cultural barriers can complicate or hinder the exchange between the operators and therefore increases the risk associated with an uncoordinated manoeuvre. Today, no universal standards or procedures have been implemented to define these inter-operator collision avoidance operations. Current communication and coordination are based on time-consuming phone-calls and exchanging emails. To ensure future safe and economic operations, efforts are made to develop and implement frameworks allowing automated collision avoidance operations. Those frameworks, like ESAs Collision Risk Estimation and Automated Mitigation (CREAM) [5] should provide the technologies and protocols allowing the communication and coordination between operators and other involved entities like external space situational awareness (SSA)-data providers [6].

3 DETERMINE RIGHT OF WAY FOR SATELLITES

Regardless of the exact implementation of such a framework the process of inter-operator coordination in case of a possible collision of two operational and manoeuvrable satellites has to be defined. The missing regulations and standards are recognised by the Space Safety Coalition in their 2019 "Best Practices for the Sustainability of Space Operations". It is stated that future efforts may be warranted to: *"Address maneuver*

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prioritization in the event that two spacecraft with maneuver capability conjunct. In the meantime, spacecraft operator communications and data sharing will remain the best strategy for avoiding collisions.” [7]. As part of the Guidelines for the Long-term Sustainability of Outer Space Activities the UN COPUOS stated as part of Guideline B.4 that: “*States and international intergovernmental organizations should [...] share knowledge and experience [...] with the objective of developing methods and consistent criteria for assessing probability of collisions and making avoidance manoeuvre decisions and agreeing on classes of methods applicable to different types of conjunctions. States and international intergovernmental organizations that have developed practical methods and approaches for conjunction assessments and collision avoidance manoeuvre decision making processes should also share their expertise [...]* [8].

The execution of a collision avoidance manoeuvre typically requires the interruption of the mission for the time of the manoeuvre and additional timeframes prior and after to configure the satellite and change the alignment of the thrust vector. Combined with the reduced orbital lifetime of the satellite as a consequence of the used fuel this leads to costs for the operator. Accordingly, the operators try to avoid any unnecessary manoeuvre. Sharing of data in case of a conjunction between two operational objects and therefore allowing a better assessment of a possible collision will lead to a reduction in the number of performed manoeuvres. Nevertheless, in the case that the risk of a collision remains above the accepted threshold a decision has to be made who of the operators has to initiate the manoeuvre and therefore accept the costs. This coordination-process has to be accepted by both operators in order to be functional. Additionally, both operators have to come to the same assessment of the conjunction and are agreeing on the necessity of a manoeuvre. This can be best achieved by sharing data, but also requires the usage of same risk assessment parameters and thresholds. Based on these pre-requirements the decision-making has to be initiated as part of the inter-operator coordination whose outcome will determine which operator has to initiate the manoeuvre.

Different approaches and considerations on possible decision-making processes for inter-operator collision avoidance operations have been discussed by several authors [2, 9, 10, 11, 12]. Based on the results of these publications, the following aspects have to be considered when defining a decision-making process:

- Fairness: None of the involved entities should systematically be disadvantaged. The costs of the operations should be shared fair based on the implemented decision-making process.
- Transparency: The decision-making process should be transparent to all involved entities. This will ensure mutual trust and allows to cross-check the process and outcome.
- Effectiveness: The decision-making process must be able to determine one executable decision. There should be no case, where no solution could be found.
- Objectivity: The results should not be based on subjective impressions, but on objective, unambiguously defined and measurable facts. This is the basis for any automation of the process.

Different approaches on decision-making processes are existent. They are based on existing concepts from other technical or economical domains or on the experiences made in everyday life. Possible approaches could include:

- Randomised: The decision is found purely on base of a randomised process. This will lead to minimal required communication between the involved entities and requires only a minimal infrastructure.
- Negotiation and Trading: The involved entities start a bi-lateral and accepted process on which end the solution is found. This can involve auction-based systems and typically needs more communication depending on the exact implementation and the supporting infrastructure in place.
- Impact-based: The effects of the decision are taken into account as a decisive measure. This can include costs for operators, but as well effects due to the downtime of satellites for external stakeholders, like users of a communication satellite.
- Shared manoeuvre: Both operators will perform a manoeuvre to split the potential costs.
- Rule-based: Pre-defined rules are used that find a solution by comparing unambiguously defined parameters.

Each one of these approaches have different requirements regarding the necessary data and the communication between the operators. They are based on different intentions, e.g. as fair as possible or shared suffering. Other approaches like brinkmanship/Space Chicken [11] are not considered, as these will not provide effective (safe) solutions.

3.1 Rule-based Decision-making Processes for COLA

Rule-based collision avoidance decision-making uses unambiguously defined criteria to find a solution and only need minimal communication between the operators as the relevant assessment parameters and processes are pre-defined. As the determination of a valid solution only depends on the comparison on pre-defined data this can be automatically shared as soon as an event is triggered and the solution can be determined. Needed interfaces and communication are minimal, which allow a potentially simple and rapid integration in the existing processes and is well suited for full automation.

An exemplary simplified sequence diagram of the necessary communication steps between two operators in case of a conjunction is shown in Fig. 1. Note that due to the pre-definition and acceptance of rules no complex negotiation is necessary. The communication is limited to the data-sharing and additional confirmations. Additional entities can be added in this sequence, e.g. if one operator has outsourced his conjunction assessment to an external service provider. Additionally, the process can be integrated within a Space Traffic Management (STM)-framework. Depending on the functionality and responsibility of other actors involved in such a framework, e.g. a central authority supervising the rule-based decision-making process and coordinating collision avoidance operations in general, the process can be adapted and extended.

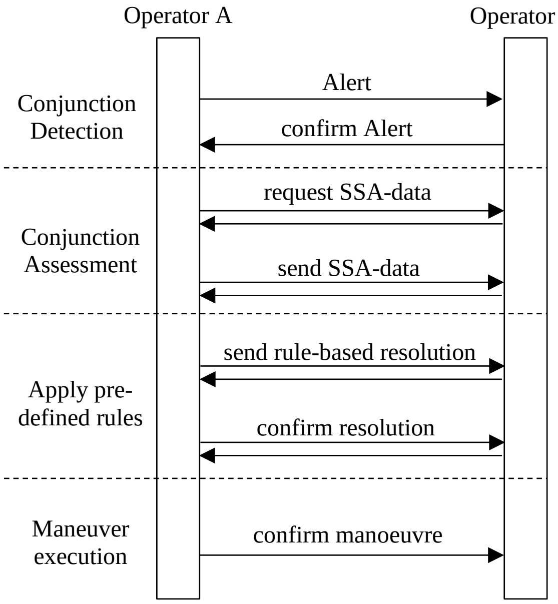

Figure 1: Simplified sequence diagram for rule-based decision-making

An execution of the process requires the presence of identical data for both operators to ensure the same basis for the application of the rules. As a fallback solution the operator who is unable to share data can be penalised by assigning him to perform the manoeuvre. This relies on the cooperation of the operator (e.g. if data-sharing is ruled out for classified objects) or requires the presence of an authority supervising the process and with the power to enforce liability.

Bi- or multi-lateral agreements between operators on rules can be implemented, which allows the application of individual rules depending on the involved operators. This allows flexibility and opens the possibility of individual complex collision avoidance agreements. The 2021 NASA/SpaceX agreement on flight safety coordination [13] includes a pre-defined rule and states that SpaceX has to: "*Perform evasive action by on-orbit Starlink satellites to mitigate close approaches and avoid collisions with all NASA assets.*". With a few numbers of such bi-lateral agreements between the largest operators the main share of possible conjunction events can be handled. They can replace generalised rules for all operators as long as no universally applied and accepted rules are implemented. As the later will require the implementation of a unified and accepted legal framework, which is not foreseeable today, bi-lateral agreements between as many operators as possible can be a potent solution to allow safe and automated collision avoidance. The technical implementation of such bi-lateral or multilateral agreements has to be evaluated, but could be implemented with the help of smart-contracts.

One potential disadvantage of rule-based operations as stated by Nag [11] is the risk of a systematic exploitation of the rules to externalise the cost of the collision avoidance manoeuvre. Additional exploitation might happen, if one operator intentionally changes the data he shares to provoke a specific outcome of the decision-making process. Disadvantageous in comparison to other more complex decision-making approaches is the simplification of the rather complex conjunctions and the not-consideration of any other circumstances. Potential optimisation or intervention is not intended due to the intentional streamlined process.

3.2 Rule-based CA-operations in other traffic domains

Rule-based operations are applied and proven approaches in other traffic domains.

In air traffic a combination of different collision avoidance approaches is implemented. On a long-term strategic basis, Air Traffic Management (ATM) controls the trajectory of individual aircraft. On short-term, to prevent an imminent collision, aircraft-integrated systems automatically negotiate a collision avoidance solution. For aircraft that are not controlled by Air Traffic Management or in case the ATM system has an outage, rule-based approaches are in place. These includes the Visual Flight Rules (VFR) [14] and Extended Flight Rules (EFR) [15]. Main decisive parameters are:

- Health status: An aircraft in distress has the right-of-way over all other air traffic.
- Operations and flight phase: Towing or in-flight-refuelling aircraft have the right of the way. Additionally, the phases of flight (climb, cruise, descent) are compared.
- Trajectory: When converging at the same altitude,

the aircraft to the other's right has the right-of-way (VFR).

- Manoeuvrability and category (balloons, glider, airships, motorized aircraft) of the aircraft involved in the encounter.
- Distance to the encounter (or the speed) of each aircraft. ("first-come-first-served")

In the domain of car-traffic the most common and known traffic rules are applied. The rules follow the discussed categories and are based on trajectories (right-before-left), operations (emergency) and on the vehicle-category (bike-exclusive lanes). Similar rules can also be found in marine-traffic [16] or in railway-traffic, where the prioritisation of individual trains is mostly based on their category (express vs. commuter vs. freight) [17].

The already applied and proven rulesets from other traffic domains show potential approaches on how to define robust rulesets and what suitable parameters can be to determine the right of the way. The underlying categorisation and intention can be adopted. Nevertheless, although many similarities can be recognised with the domain of space traffic, the unique circumstances due to the space environment and orbit mechanics lead to fundamental differences in the collision avoidance process. This includes above all the necessary lead time for a successful process which for spacecraft today is at least several hours or days in contrast to seconds or minutes for aircraft [18].

3.3 Rules for Satellite COLA

Suitable rules for space-based operations have to take these aspects into account and should therefore be based on parameters already known in advance, at least to a specific degree.

Orbit and conjunction-geometry-based rules can be based on the known trajectories of both objects or as a more generalised rule on different orbit-types like sun-synchronous orbits or high eccentric Earth orbits. This will mimic the most basic rules known from other traffic-domains, like "priority to the right", where decisions are only made on basis of the relative position or movement to each other. The implementation of such a rule seems oversimplifying the complexity of a satellite conjunction but has the advantage that a solution can always and easily be found, is unambiguously and the integration of the rule is simple as the data is available. Depending on the exact formulation of the rule, assessments have to be made, to determine how specific mission-types and therefore operators are affected due to such rules, as specific satellite-applications have to use distinct orbits and can therefore be systematically (dis-)advantaged.

Satellite parameter-based rules take the characteristics of the individual satellites into account, like the size, mass or volume. The parameters are typically known and can therefore provide a good basis for a decision-making process. Similar to the orbit and conjunction-geometry-based rules this approach also makes the decision dependent on a rather arbitrary parameter, but therefore guarantees the only purpose: to ensure the successful decision-making. The application requires the knowledge of these parameters, problems can arise if some of them are unknown or cannot be shared due to economic or political interests. Potential other parameters could be the lifetime of the satellite, the original planned lifetime or a combination of these two.

Rules can also be based on the *technical capacities and potential constraints* of the involved satellites and operators. This could include a decision based on the available propulsion-systems, the amount of fuel left on board or the health status of the satellite. As cases of emergency or distress are typically considered in all other traffic domains possible malfunctions should be taken into account, especially if they could lead to a failing manoeuvre.

Mission-based rules could use the mission-type, the mission-phase (LEOP, deployment, EoL, …) or the Space Sustainability Rating (SSR) [19] for determining the right of the way. As been done for emergency or rescue vehicles in other traffic domains, rules can be adapted that favour satellites with specific missions, which are typically used for greater good. It has to be discussed what satellites and missions will fall under such a category and if for example science missions could be declared as beneficial to the general public. As most of the future satellites will serve the same mission as communication satellites, additional rules have to be implemented to resolve conjunctions between them. In case of the mission-phase a rule can be defined that satellites in their normal operational mode could be prioritised in favour of satellites in deployment or de-orbit operations and in favour of spare satellites. The usage of the SSR of the mission as a decisive parameter will directly incentivising operators to make efforts to improve the SSR and therefore contribute to more sustainable space operations.

Additional rules can be based on synthetic indicators that can be calculated in a suitable model, which will allow to implement the concept of impact-based decision-making described in Chapter 3. This makes it possible to take into account more complex effects, which are suitable for determining the right-of-the-way if desired. These indicators can include:

- Mission downtime
- Life-time reduction of the satellite
- Impact on other stakeholders (e.g. earth observation on communication satellite: no observation pictures vs. no internet for customers)
- derived cost for operator

It should be noted that the usage of such indicators is only suitable, if standardised and deterministic models are used and all the data necessary to use the models have been made available for all involved entities.

To account for the possibility that one rule will not lead to an unambiguously outcome a cascading set of rules can be implemented. Tab. 1 shows the exemplary outcome of the decision-making process based on different rules in a sample scenario.

Table 1: Rule-based decision-making involving Operator A (public entity, worse SSR, less fuel) and Operator B (public entity, better SSR, more fuel)

	rule	**result**
generalized rules	"private satellites give public satellites right-of-the-way"	Not applicable; next rule needed
	"satellites with more fuel on board have to give right-of-the-way	B must manoeuvre
Bilateral agreement (overrules generalized rules)	"satellites with worse SSR need to perform the manoeuvre"	A must manoeuvre
	"Operator A always provides right of way for Operator B"	A must manoeuvre

4 RULES4CREAM

The previous presented concept of rule-based collision avoidance operations is simulated and assessed as part of the "Rules4CREAM"-activity (R4C) at the Technical University of Darmstadt. This project is conducted within of ESA's General Support Technology Program (GSTP) to support the cornerstone CREAM of the Space Safety Programme. The goals of this activity are:

- The development of different rulesets partially derived from other traffic domains.
- Identification and modelling of a future LEO population based on current trends and proposed constellations.
- A simulation-based application of the rulesets in this environment.
- A holistic analysis and assessment of benefits and disadvantages of individual rulesets.
- The derivation of requirements and constraints for the technologies and data standards to be developed in CREAM.

The requirements on decision-making processes, defined in Chapter 3, and especially the aspects of fairness and effectiveness should be tested in the scope of this activity for different rulesets. As a possible implementation and application of these requires the acceptance by the operators, it has to been shown that on average no operator is being disadvantaged substantially or at least not compared to any direct competitor. It should be tested if rules that require the availability of more data and therefore imply a deeper and more complex integration into the existing processes are more suitable to meet the defined requirements than relatively simple rules like "priority to the right – adapted for space".

4.1 Approach

In order to be able to make a trustworthy statement about the suitability of the rulesets a substantial number of representative conjunction events has to be assessed. As part of the Rules4CREAM activity a large-scale orbit simulation has been implemented and different future populations of the Earth's LEO have been created to allow the simulation-based generation of the conjunction events. As part of a COLA-process model the different rulesets are applied to the generated data and the implications are assessed.

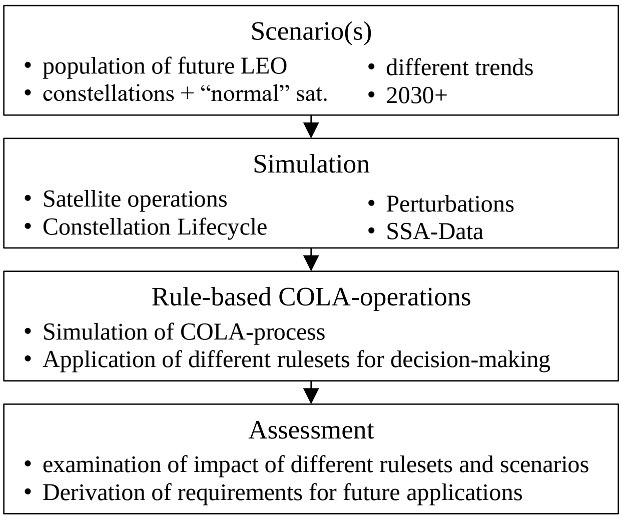

Figure 2: Submodules realised in the Rules4CREAM-activity

Due to the accumulation of planned constellations in Lower Earth Orbit the activities focus currently on all objects with a perigee below 2000km. Space debris is not considered in the simulation or database as application of the rulesets is not relevant for conjunctions with debris. Accordingly, satellites without any propulsion system are not further considered in the assessment process, as they cannot manoeuvre. Possible achievable changes of the orbit due to an intentional increased or lowered atmospheric drag by changing the attitude of the satellite are not considered as a feasible option for collision avoidance manoeuvres.

4.2 Scenario / Propagation of the Future LEO-population

In order to allow a conclusive evaluation, the generation of a realistic future satellite population is necessary. To enable the simulation and the generation of deterministic conjunction events with all the data needed for a later application of a wide variety of rulesets several parameters of the involved satellites have to be reasonably defined.

Table 2: Parameters generated for each satellite as part of the scenario generation

	Parameter	Usage in R4C
Orbit Data	• Keplerian elements • State vector • Orbit-type	• Initial input for simulation • Orbit-based rulesets
Satellite Parameters	• Lifetime • Health status • Propulsion system • Mass, size	• COLA-model • Satellite-based rulesets • Conjunction detection
Operator Data	• Operator • Operator-type • Operator country	• COLA-model (grade of communication) • Operator-based rulesets
Mission Data	• SSR • Type • Station-keeping • Mission phase	• Operations-simulation (station-keeping, …) • Mission-based rulesets

Note that additional data needed for the simulation of the COLA-process is generated as part of the simulation (e.g. SST-Data).

The future population is generated by combining a baseline population of non-constellation satellites with a dataset of pre-defined constellations. For the generation of the future baseline population a database of today's satellites was generated and analysed. Different sources were combined for this [1, 20, 21, 22, 23, 24] nevertheless several critical parameters, especially regarding the propulsion system are missing. Other missing parameters include specific operators especially for Chinese-launched satellites and information about expected mission lifetime. Therefore, several subclasses of satellites have been generated (e.g., by mass, orbit and mission type) and a correlation analysis of the individual parameters has been conducted to find corresponding and linked ones and typical distributions within these classes. Missing datasets have been filled based on the found distributions.

The exact future development of the satellite population is not foreseeable and individual unexpected events can have a huge impact on the growth rates (e.g. catastrophic collision, restriction of launches by governments). Therefore, based on current studies, different scenarios have been defined representing these different developments, as well as the availability of future launch systems and the developing of new applications for satellites [25, 26, 27, 28, 29]. Individual growth trends have been specified for the different classes as well as shifts in the distribution of parameters due to technological changes (e.g. more electric propulsion system). The individual growth rates and distributions are applied to the existing population to generate a reasonable number and set of future satellites. The individual parameters are assigned based on the found distributions and under consideration of operational and orbit-mechanic-induced constraints, like the connection of semi-major axis and inclination for sun-synchronous orbits or the accumulation of sun-synchronous satellites above the terminator.

Over two hundred proposed constellations have been analysed and categorised. As much of the data for future constellations is unknown the same approach is used as for the non-constellation population by filling the missing parameters with reasonable assumptions. As most of the analysed constellations will never be implemented, an assessment criterion has been developed based on the current status of the project, potential funding, the company size and the size and mission of the constellation itself. This allows an estimation about the probability of implementation and is used in the different scenarios to choose how many and which constellations should be implemented.

4.3 Simulation

The generated population is simulated in a large-scale and long-term orbit simulation with all-on-all conjunction screening and detection applied. The population is assumed to be static, meaning that the number and distribution of satellites does not change over the simulation runtime. Satellites that have re-entered during the runtime will be added back to their initial orbit. Perturbations and typical operations (depending on the satellite mission and type) are simulated over the course of the runtime (typically several years to take long-term perturbations into account) and are the main focus of the simulation, as they are constantly changing the orbits of the objects and generate new and changing conjunctions.

The propagation of the individual objects is done by using Keplerian orbit mechanics to calculate the position between two timesteps and to apply the calculated orbit changes due to perturbations or operations at these specific timesteps. To limit the needed runtime to a reasonable amount, the chosen time steps are typically about 1 to 6 hours long. Although this will lead to jumps in the propagated orbits, this approach is suitable, as the focus of the simulation is not to detect specific single conjunctions, but to generate a representative number of all conjunctions with realistically distributed characteristics (e.g. involved operators, orbit types). Simulated perturbations include the gravitational effects up to J_4, 3rd body perturbations due to the sun and the moon, effects due to the atmosphere and due to solar radiation. Simplified analytical approaches [30] are used to determine the impact of each of these effects on the satellite orbit for one time step and are then applied to set new orbit parameters. The approaches have been validated against numerical propagators and show a good approximation.

Simulated satellite operations include deployment and de-orbit manoeuvres for constellation satellites as well as four different station-keeping modes for all of the manoeuvrable objects. These cover two approaches to regulate the orbit altitude, one to control the local time of ascending node and one to guarantee a repeating ground-track. Applied thresholds of these modes are dependent on the mission type and other parameters. Deployment operations are modelled based on the current used procedure by SpaceX and OneWeb. Orbit data of deployment operations have been analysed and a generic model has been developed, taken into account that multiple orbital planes are filled with one launch. The rate of change in the semi-major axis, the distribution of the individual planes and number of launched satellites can be changed. Fig. 3 shows the modelled change in semi-major axis over time for three sets of satellites heading for different planes and launched together. The corresponding drift of the right ascension of the ascending node relative to the first orbital plane is shown in Fig. 4. Spare satellites for individual constellations are considered.

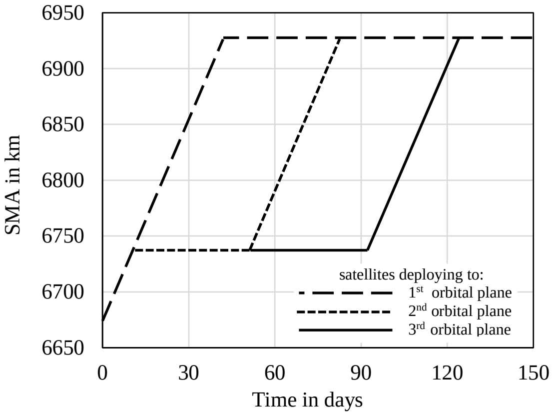

Figure 3: Semi-major axis over time since launch as implemented in the conjunction-deployment model

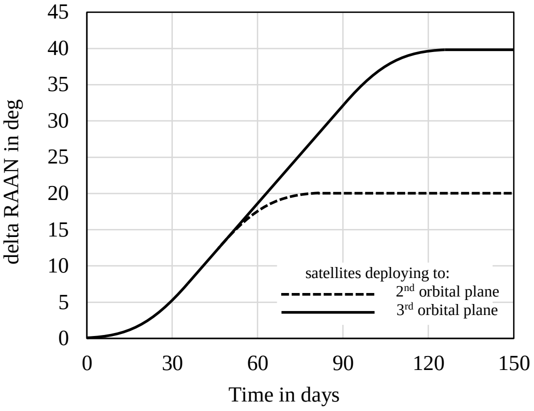

Figure 4: Difference of RAAN over time relative to the first orbital plane implemented in the conjunction-deployment model

The conjunction detection module includes a statistical and a deterministic variant for high-performance all-vs-all conjunction detection. Both variants are based on the Orbit Path Filter and the Orbit Trace Method – both geometric conjunction detection algorithms – which have been extended to allow the simulation of constellations as well, while keeping the computational burden at a low level. The implementation of two conjunction detection variants enables continuous cross-validation of the produced conjunction data.

Fig. 5 shows an exemplary result of the simulation with the population of active satellites as of the 31st of December 2020 as an input. Each dot represents an event with a miss distance (MD) at the time of closest approach below1km. The simulation covered one year and detected 53,008 conjunctions (14,442 events for MD<0.5km and 659 events for MD<0.1km). Red dots symbolise intra-operator events of which the majority are SpaceX-internal events. Blue dots represent events with two different operators involved. The effect of the Starlink-constellation is seen as the accumulation of events at the latitude of 53°.

4.4 COLA-Model

The COLA-model is currently under development and will include the simulation of today’s and possible future (inter-operator) collision avoidance operations. Different decision-making processes and especially rule-based approaches can be implemented.

As the simulation will generate deterministic conjunctions and their geometry, the simulation of the actual COLA-process requires to model realistic SSA-data available for the involved operators. A model has been implemented, which allows the calculation of typical covariances for each object based on the set time of measurement and the source of data, respectively the measurement method. The model covers TLE-accurate data sources, typical CDM-accuracies, SLR and operational, typical GNSS-derived orbit data.

The implemented COLA-process model will allow any combinations of these different sources for each conjunction and therefore allows the assessment of its impact on the process and the rule-based decision-making. Especially scenarios, in which there could be a conflicting assessment of the conjunction because of different data available to the operators, will be examined and used to test the robustness of the implemented decision-making processes. Furthermore, different grades of inter-operator communication and data-sharing are considered and examined, as well as different grades of automation.

5 CONCLUSIONS AND FUTURE WORK

Rule-based approaches have the potential to be a feasible solution to determine what operator has to initiate an avoidance manoeuvre in case of a potential collision between two manoeuvrable satellites. Potential technological barriers to implementation are low and the approach is known and proven in other traffic domains. Acceptance and thus the wider adoption will be determined primarily by how fairly the rules are valued by the entities involved. Bi-lateral frameworks offer the potential for initially limited application between interested operators and could form a transition to multilateral or universal frameworks.

Further research will be focusing on the specific technologies and data needed to allow the implementation of rule-based approaches and on the precise definition of feasible rulesets. Assessment of these individual sets will be done with help of the simulation environment developed in the Rules4CREAM-activity.

The ongoing development of the simulation environment focuses on the validation of the implemented models and generated scenarios. Further optimisation of the code is planned as well as the implementation of additional features is planned. This will include an extension beyond LEO and the integration of space debris objects to allow comparative studies and to allow the consideration of follow-on risks. The COLA-model will be extended to allow the simulation of other decision-making processes like auction-based approaches and to simulate possible future STM-supported operations with multiple entities involved.

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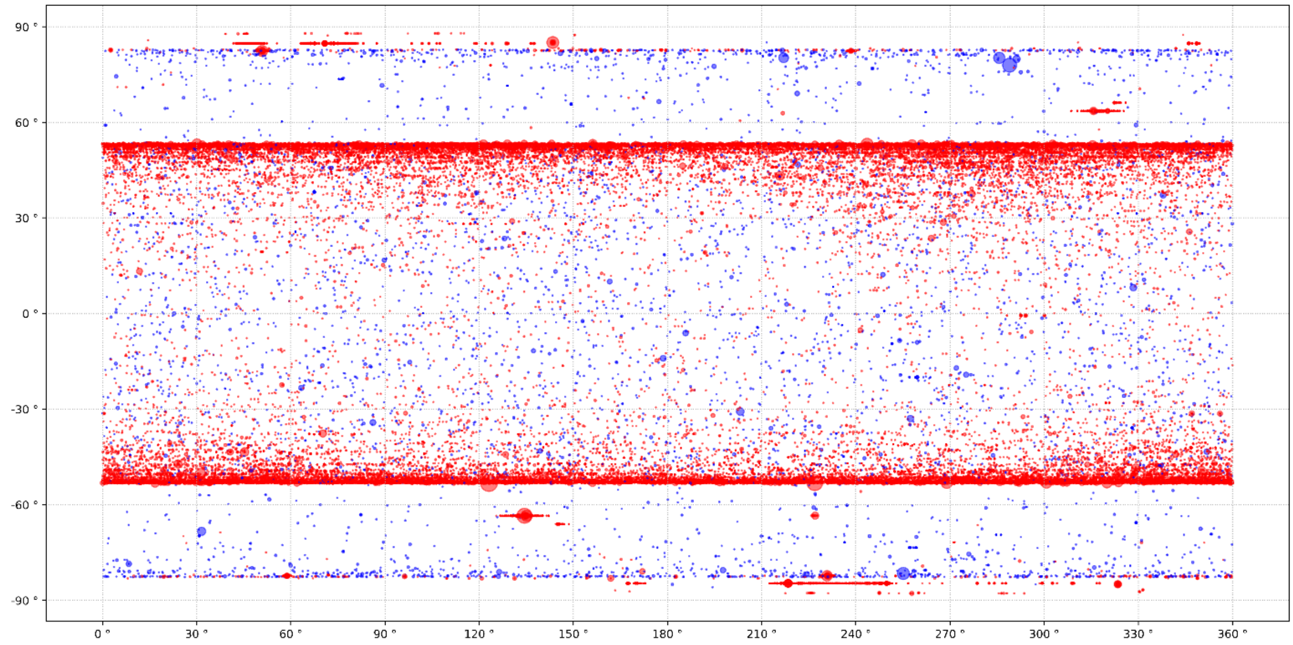

Figure 5: Detected conjunction events of the LEO population as of 31st of December 2020 for a one-year simulation. Dots represent events with less than 1km miss distance at the time of closest approach. Dot size is inverse to the distance. Red dots symbolise events with one operator and blue dots with two different operators involved.

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