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AN INITIAL ANALYSIS OF AUTOMATING CONJUNCTION ASSESSMENT AND COLLISION AVOIDANCE PLANNING IN SPACE TRAFFIC MANAGEMENT

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We introduce a framework that automates the process of assessing potential satellite conjunctions in space, and generating collision avoidance maneuvers to support mitigation efforts within a novel space traffic management (STM) architecture. A software implementation of the framework was developed in a MATLAB-STK integrated environment, however, the concept and framework is agnostic to the language or environment. The software pulls from existing catalogs of spaceborne objects and ingests user-defined parameters to produce conjunction data, which could potentially aid collision avoidance planning in the STM architecture. The utility of the software in maneuver planning and exploring a performance-based tradespace of actions is demonstrated using three example cases: one-to-one conjunction, one-versus-four conjunctions, and a near head-on collision. The framework also provides a test-bed for the use of application programming interfaces (APIs) to demonstrate machine-to-machine communication between entities in our proposed STM architecture. Results from this software implementation are expected to aid distributed decision-making among various stakeholders, and inform efficient, autonomous, structured but flexible concept of operations within STM.

INTRODUCTION

There are more than 19,000 tracked objects that are currently in Earth orbit today.[*] These objects include active satellites, intact inactive satellites, and space debris of various sizes and masses. The level of congestion due to these resident space objects (RSOs) leads to many close encounters, or *conjunctions*. While most can be ignored, the higher risk ones do require intervention. This problem is forecasted to grow in the near future as improved sensors are expected to expand the current RSO catalog by an order of magnitude, and new megaconstellations with hundreds, or even thousands, of satellites are being developed.[1,2]

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[*]Based on an email conversation with Dr. T.S. Kelso (Analytical Graphics, Inc.) as an update to a previous number obtained from the Space-Track website (see `https://celestrak.com/satcat/boxscore.php`).

There is a clear need for a space traffic management (STM) system to promote safe operations in an increasingly crowded orbit regime. Nag et al.[3] and Murakami et al.[4] have proposed an STM architecture as a potential solution, which is based upon previous work done by NASA to develop a concept of operations for Unmanned Aerial System Traffic Management (UTM).[5] The UTM architecture's de-centralized, community-driven, and highly scalable approach has many attractive features for application to the issue of space traffic management. The STM architecture, shown in Figure 1, relies on automated, machine-to-machine communication between various entities to accomplish tasks that are crucial to safe operations in space. The tasks include *conjunction assessment* (detecting potential conjunctions and assessing the associated collision risks) and *collision avoidance* (generating candidate collision avoidance (COLA) maneuvers for encounters posing unacceptably high risks). Given the anticipated large quantities of conjunctions in orbit, performing these in a manual or semi-automated fashion represents a sizable workload for human operators. To enable scalability, it must be fully automated within any STM architecture.

The conjunction assessment supplier (CAS) is an entity in the STM architecture that provides conjunction assessment and collision avoidance planning services. Automating these services enables the CAS to handle multiple, simultaneous conjunction screening requests of possibly fast-changing targets. As part of the on-going research efforts to develop a prototype to demonstrate and evaluate use-cases, an initial software implementation of a *CAS framework* using commercial, off-the-shelf tools and algorithms published in literature, has been developed at NASA Ames Research Center (ARC) and will be presented in this paper.

An extensive portion of the literature on space traffic management is devoted to space situational awareness (SSA) topics such as autonomous sensor tasking, RSO estimation and cataloging, and data management and are well documented.[6–8] Such studies are important since meaningful conjunction assessment is dependent on accurate RSO data. Examples of conjunction assessment and collision avoidance services that have gone through many iterations through operational experience are also documented in the literature. The NASA Robotic Conjunction Assessment Risk Analysis (CARA) provides detailed high-interest encounter briefings to satellite operators to help them develop actionable COLA plans.[9] Analytical Graphics, Inc. (AGI) has proposed an automated web-based service architecture that delivers relevant conjunction data and actionable COLA maneuver plans to satellite operators.[10] The European Space Agency (ESA) provides collision avoidance services to third party operators by delivering optimized COLA maneuvers to mitigate high-risk conjunctions detected through their automated conjunction assessment process.[11,12] Owing to the importance of conjunction risks for large numbers of satellites, pre-Phase A constellation design software[13] budgets orbital stationkeeping, and considers the risks of propellant-less spacecraft. Industry players such as Skybox/Terra Bella have developed in-house tools[14] to support debris avoidance and COLA efforts for their fleets of spacecraft.

The novelty in this presented work is less in the tools and algorithms themselves, and more in their seamless integration within our STM architecture and application to generate a tradespace of solution metrics as a function of control variables. We aim to provide a *structured* API for allowing a marketplace of STM service suppliers (S3's), CAS, SSA providers and other players in the space industry (see Figure 1) to *flexibly* join and interact. In keeping with AGI's 'We' Approach to STM,[15] our STM architecture is expected to serve missions beyond only NASA (e.g. CARA), ESA (e.g. Debris Risk Assessment and Mitigation Analysis[11]) or industry (e.g. Skybox). The presented CAS framework here performs automated CA and COLA planning in response to a conjunction screening request, and is a step towards a highly-scalable and automated CAS framework.

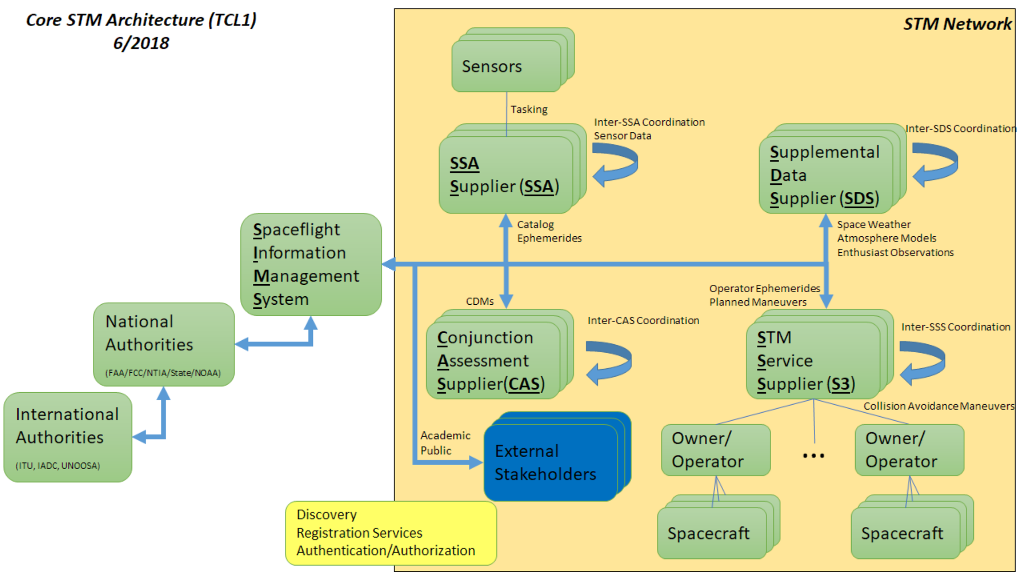

Figure 1. A notional outline of the proposed STM architecture.[3]

Collision Avoidance in the STM Architecture

We now discuss an operational example of how a potential collision is addressed in our STM architecture. The implementation of process automation is discussed in Nag et. al.[3] While the sequence of events in this example forms a representative basis on which the CAS framework was developed, the framework itself can be generalized across different types of entities. The main STM entities from Figure 1 that participate in this example are:

- **Owner/Operator (O/O)** - owns and flies the spacecraft of interest.
- **STM Service Supplier (S3)** - serves as the primary interface between O/Os and the greater STM community; procures STM services for the O/Os.
- **Space Situational Awareness Supplier (SSA)** - maintains a catalog of RSOs, (e.g. USSTRATCOM, LeoLabs, Planet).
- **Conjunction Assessment Supplier (CAS)** - responsible for screening RSO orbits to detect conjunctions; verifies that COLA maneuvers do not result in additional high-risk conjunctions.

In this example, **S3-A** and **S3-B** are two S3s supporting Sat-A and Sat-B, respectively. The two objects are predicted to become involved in a high-risk conjunction event. With the help of a **CAS** and an **SSA** provider, the two S3s cooperate in order to mitigate the conjunction. The chronological interactions between these players in the collision avoidance example are summarized below, as being automated within our STM architecture. The functionality of the specific **CAS** entity mentioned below will also be called **CAS**. We point out that there can be multiple **CAS** entities participating in STM in order to avoid any implication that the usage of "**CAS**" only refers to one **CAS** entity.

First, the **O/O** of Sat-A contracts with an S3 to receive its services. We shall call this S3, **S3-A**, and it now represents and supports Sat-A in the greater STM community. As a service to Sat-A's **O/O**, **S3-A** requests a conjunction screening from **CAS** for Sat-A. **CAS** uses an **SSA** provider's RSO catalog and performs the requested conjunction screening. **CAS** then returns a set of conjunction data messages (CDMs) to **S3-A**. **S3-A** uses the CDMs to assess the collision risk associated with each conjunction. In this case, **S3-A** detects a conjunction between Sat-A and Sat-B posing an unacceptably high collision risk. **S3-A** then alerts **S3-B**, who provides STM services for Sat-B's O/O. **S3-A** and **S3-B** now begin negotiating which spacecraft will maneuver, and trade-off avoidance strategies. Nag et. al.[3] lists the considerations for making maneuver decisions and algorithms for autonomous decision-making are expected to be future work.

It is assumed in this example that Sat-A maneuvers and Sat-B does not. The maneuvering S3 (**S3-A**) sends the proposed maneuver to **CAS** who subsequently screens the maneuver for any follow-up conjunctions. Here, we assume that the maneuver is shown to mitigate the conjunction and does not result in new high-risk encounters (if not, the results of the autonomous decision-making in the previous step may have been different). **CAS** clears the maneuver and **S3-A** sends the maneuver to Sat-A's **O/O** for final approval and implementation (we also assume that the **O/O** approves and executes the maneuver). Either of the **S3**s mentioned can now request additional tracking from an **SSA** provider to confirm that both Sat-A and Sat-B are at their expected post-maneuver locations. Here, we assume that they are, which concludes the collision avoidance procedure. Afterwards, nominal operations resume for Sat-A.

METHODOLOGY

CAS Framework Overview

The core functions of any CAS within the STM framework include detecting conjunctions, returning CDMs to S3s, and screening candidate COLA maneuvers for follow-up conjunctions. Since the CAS also has existing knowledge of the associated encounter geometries, it is in an excellent position to compute candidate COLA maneuvers for potential use by the S3s and O/Os that it serves. These candidate maneuvers may not necessarily be the final choice, but they provide the S3s (and O/Os) with a starting set of maneuvers to analyze, refine, and use decision-making algorithms upon. Choosing the proper maneuver and executing it is ultimately the responsibility of the O/Os; and because the S3 supporting the O/O knows the O/O's mission constraints, the S3 also supports the maneuver decision-making process.

There are four stages in the CAS framework as shown in Figure 2, which highlight its role

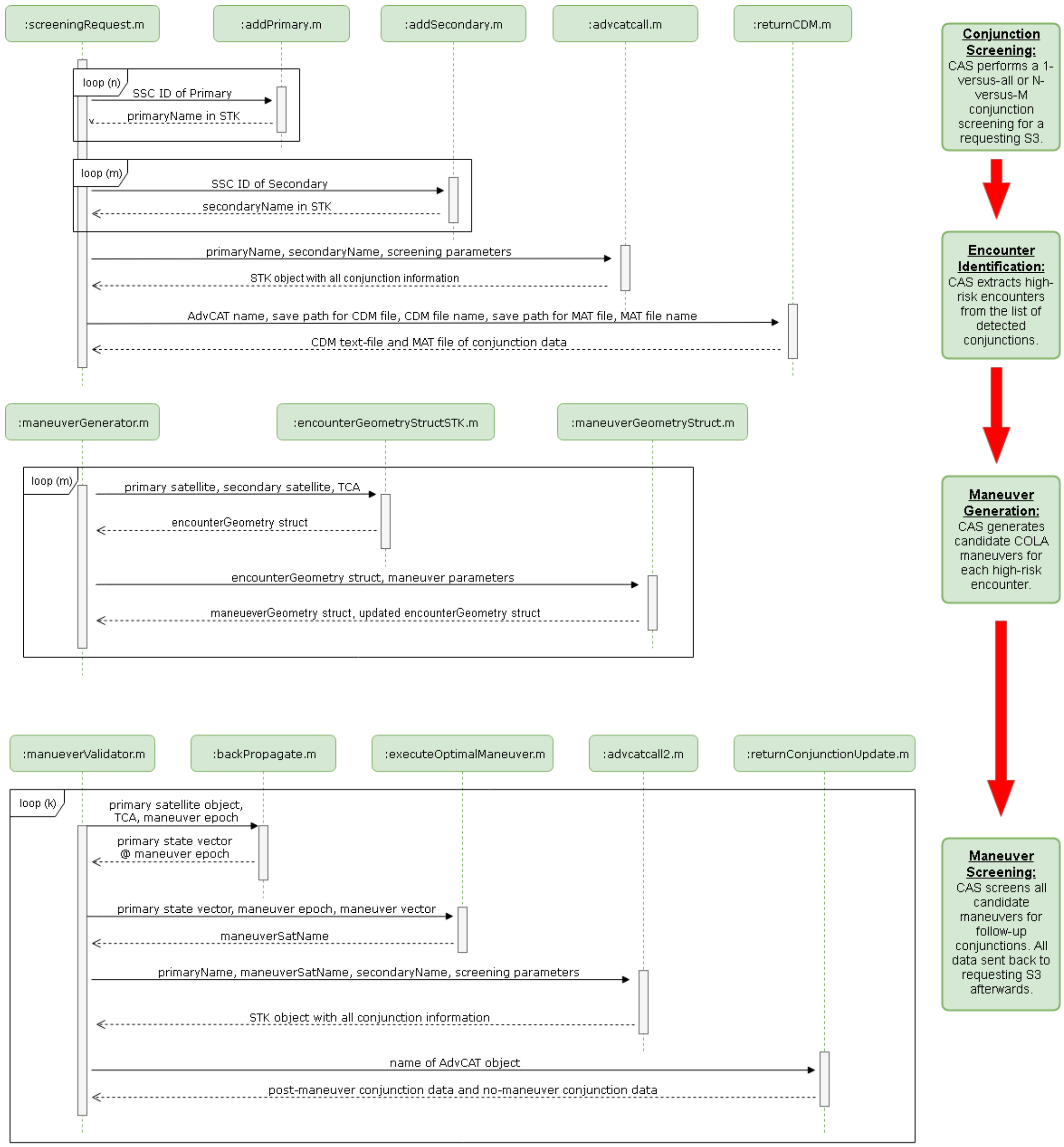

Figure 2. A sequence diagram of the methods used in the MATLAB-STK implementation of the CAS framework is shown. The four stages of the framework are also placed next to the methods that address each stage.

in the larger STM architecture. They are *Conjunction Screening*, *Encounter Identification*, *Maneuver Generation*, and *Maneuver Screening*. Transitioning from one stage to the next happens automatically in this framework. We demonstrate automated CAS functionality using commercial tools and published algorithms. However, the details of implementation (such as the specific software or algorithms used) are left up to the service providers to choose in order to best accommodate their customers' needs.

In stage 1, the CAS screens for conjunctions in response to a conjunction screening request from an S3. The request contains information about the primary satellite(s) of interest such as NORAD ID, the common name, and the state vector of the satellite at some known time. The S3 also includes "do-not-violate" thresholds in the request to be used as screening parameters. For instance, the requesting S3 may specify a 5-km minimum separation distance threshold, meaning that an encounter between the primary object and any active secondary object that is projected to violate this threshold constitutes a conjunction.* The CAS then propagates the orbits of the primary object and of the entire RSO catalog forward in time until the end of the requested screening period. If the requesting S3's thresholds are violated by an RSO, the CAS records the event as a conjunction.

After the screening is complete, the list of conjunctions is refined in stage 2 of the process. This is when additional criteria are used to determine whether a conjunction is risky enough to warrant intervention, so that maneuver planning resources are properly devoted. The true probability of collision (PoC) is a commonly-used metric in operations to assess such risks.[11,12,16–19] The true PoC is computed by integrating a three-dimensional probability density function that quantifies the uncertainty of the relative position between the primary and secondary objects.[19–22] If the uncertainty is not known, an alternative measure of risk is the maximum PoC (Max PoC), which is the worst-case PoC possible for a given conjunction geometry.[19,21,23] A PoC threshold is used to identify high-risk conjunctions from the initial list from stage 1. The conjunctions whose PoCs violate this threshold motivate the development of a COLA action, and will be referred to as *primary conjunctions*.[3]

The importance of SSA entities providing orbit state data of sufficient and actionable quality is paramount in STM because the true PoC changes significantly due to positional uncertainty. Figure 5 in Alfano (2006)[21] shows the computed PoC for a notional encounter as a function of positional deviation. The authors highlight a "dilution region"[19,23] for all deviations greater than the along-track position uncertainty value that results in the Max PoC. For smaller positional uncertainties, smaller PoCs can be related to lower collision risks. However, positional uncertainty in the dilution region, even if larger, can yield deceptively small PoC values. Therefore, computed Max PoCs are not unique to error ellipse lengths, and if the error values are within the dilution region, better data is needed to compute a more realistic PoC.

In stage 3 of the CAS framework, potential COLA maneuvers are generated to mitigate the primary conjunctions identified in stage 2. Such maneuvers are designed to increase the separation distance between two objects at the time of closest approach (TCA). Existing

*Thresholds are assumed to be agreed-upon values between the S3 and the O/O that it serves. Any number suggested here is used only for the sake of example.

maneuver planning tools like *CORAM*,[12] *closeap*,[24] and Alfano's MATLAB tool[21] can be used in this stage to identify the optimal COLA maneuvers.

Finally in stage 4, the maneuvers from stage 3 are simulated and a follow-up conjunction screening is performed. This is to ensure that each maneuver achieves its intended separation distance at TCA, reduces the associated collision risk, and does not result in any additional, high-risk conjunctions. Additional conjunctions that result from a maneuver are divided into two categories: *secondary conjunctions* and *tertiary conjunctions*.[3] A secondary conjunction is a post-maneuver conjunction between the primary satellite and the same secondary object that motivated the maneuver. A tertiary conjunction is a post-maneuver conjunction between the primary satellite and a completely different object. Once the set of maneuvers has been screened for secondary and tertiary conjunctions, the CAS returns CDMs and all candidate maneuvers to the requesting S3 for decision-making consideration and further analysis. This is the concluding step of the framework.

The goal of this framework is to provide any CAS wishing to participate in STM with a concept of operations to follow in order to provide conjunction assessment (and possibly collision avoidance) services in the STM architecture. The framework focuses on autonomous interoperability and it remains agnostic to the specific software and algorithmic implementation choices of the CAS.

Application Programming Interface (API)

In the proposed STM architecture, the S3s, CAS, and other entities communicate through application programming interfaces (APIs) to enable system-wide autonomous operations, including the procurement of various services. To retrieve the conjunction and maneuver data from a CAS, the S3s may use web service protocol request methods like the GET method. GET is one of the communication methods available between clients and servers defined in the Hypertext Transfer Protocol (HTTP) application protocol.* Here, the client is the S3 and the server is the CAS. In our simulations, we pass information between entities using HTTP methods.

Software Implementation

MATLAB-STK Integrated Environment. An end-to-end adaptation of the proposed CAS framework was implemented at our STM laboratory at NASA Ames Research Center using a MATLAB-STK integrated environment. A sequence diagram of the implementation is shown in Figure 2. AGI's STK software is the flight dynamics tool used to perform orbit propagation, maneuver execution, and conjunction screening. Meanwhile, Mathworks' MATLAB software was used to automate all of the tasks performed in STK and implement algorithms for the suggested COLA maneuvers.

Conjunction detection is implemented by STK using AdvCAT, an add-on conjunction analysis tool. A one-versus-all screening is carried out, which means that the orbit of

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*HTTP stands for "Hypertext Transfer Protocol", which is a defined set of communication methods between clients and servers. `www.w3schools.com/tags/ref_httpmethods.asp` the primary is compared to the orbits of all remaining RSOs over a week of simulation. Any event in which a secondary object violates the minimum distance threshold(s) of the primary is recorded by AdvCAT as a conjunction. In this work, we use the Max PoC instead of the true PoC to identify primary conjunctions. The conjunctions stored inside AdvCAT are accessed to create a list of primary conjunctions whose Max PoC exceeds 1×10^{-06}.

In practice, the risk thresholds should be dictated by the operators according to their preferences and operational experiences. For example, both ESA and CNES use a Max PoC threshold of 1×10^{-04} before they engage in collision avoidance planning.[11,16] For demonstration purposes here, 1×10^{-06} was chosen as the threshold for Max PoC, because having a lower threshold leads to more primary conjunctions per one primary satellite. While most of these will end up becoming false alarms, it allows us to analyze complex cases in which maneuver planning must occur for multiple primary conjunctions (i.e., a "1-versus-multiple" case). If the uncertainties (or covariance) associated with input quality (like position data) are well-understood and quantified, then a true PoC allows for a more realistic risk assessment as opposed to the over-inflated risk presented by a Max PoC. We use the Max PoC in our simulations because at this developmental stage and limited RSO knowledge, we propagate orbits using the SGP4 propagator in STK, which uses two line element (TLE)-derived state vectors as initial conditions. Since the initial TLEs are not accompanied by covariance data, we lack full knowledge of the uncertainties associated with the state vectors, making it difficult to compute a meaningful true PoC. We assumed a fixed covariance ellipsoid around each object, and use the Max PoC to assess collision risk because it is a more conservative metric in the absence of position uncertainty knowledge.[21,25]

To mitigate each primary conjunction, we generated a set of potential COLA maneuvers using the analytical formulation of Bombardelli and Hernando-Ayuso.[26,27] However, we note that the modularity of our CAS framework allows it to be replaced by any other algorithm, should it be more appropriate. Given a fixed impulse budget (in units of m/sec), this algorithm finds the optimal impulsive $\Delta \mathbf{V}$ vector orientation, given a magnitude, that maximizes the miss distance between two objects at TCA. The optimal $\Delta \mathbf{V}$ is a function of the impulse budget, the maneuver location in the orbit (true anomaly), and the geometry of the conjunction. We used 30 different potential maneuver times within the span of 20 orbits before the predicted TCA to generate a wide range of candidate impulsive COLA maneuvers. The Bombardelli and Hernando-Ayuso formulation was chosen for its ease of implementation and it was executed in MATLAB within our software implementation.

Each computed maneuver is then automatically propagated using STK's Astrogator, an add-on module that can simulate maneuvers. The post-maneuver orbit is screened using STK's AdvCAT to analyze the perturbed Max PoC between the two original objects, and to detect secondary and/or tertiary conjunctions that result from the COLA maneuver(s). The automated software generates trends for Max PoC across primary, secondary, and tertiary conjunctions based on maneuver time. This information is returned along with the list of the candidate maneuvers and the CDMs associated with the primary conjunctions. The S3s and O/Os involved in the said conjunction are then expected to decide upon which maneuver and by whom, based on the above results. We are currently working on prototype algorithms by which the agents would decide which satellite performs the COLA maneuver, assuming both have maneuver capability.

The API-based communication between an S3 and a CAS was simulated by setting up a mock CAS server. The server responds to conjunction screening requests that are simulated in Postman, an API development environment.* The MATLAB-STK code performs the tasks above from start to finish whenever the CAS server receives a screening request via Postman. The CAS response contains the CDMs, maneuver data, and resulting trades and trends discussed above.

Other Available Software. Currently, the MATLAB-STK environment is the only operational software implementation of the automated CAS framework that we have tested within ARC's STM laboratory. However, other existing software packages have been identified (commercial and in-house) that can perform all or part of the CAS's tasks. These tools can be automated in varying degrees and then integrated into the framework. Below is a non-exhaustive list of these candidate CAS tools.

- **LightForce** - LightForce is a NASA ARC in-house code that can perform conjunction detection, collision-risk assessment, and COLA planning and execution. The LightForce project studied the feasibility of using ground-based lasers to perform just-in-time COLA action. Further details about the LightForce project, simulations, and associated results can be found in Yang Yang et al.[18]
- **closeap** - *closeap* is a tool designed for conjunction detection, collision probability prediction, and COLA maneuver optimization. The tool is available as an add-on module within the commercial *focusSuite* flight dynamics tool produced by GMV. Like STK, *closeap* can be automated using an external application like MATLAB through a command-line interface. Further details about closeap is given in Escobar et al.[24]
- **CAOS-D** - CAOS-D[28] is a conjunction analysis solution that was initially developed to provide efficient hardware and software architectures. These architectures enabled the research and development of high-fidelity conjunction analysis algorithms. A"best set" of algorithms were implemented, deployed and subsequently used at the Air Force Research Lab. CAOS-D can perform autonomous all-on-all conjunction screenings on both a daily basis and an on-demand basis. On-demand conjunction screenings are performed when requests are received from users and software applications via web services. Conjunction reports are then returned after the screenings.

RESULTS AND DISCUSSION

We will discuss the MATLAB-STK implementation of the CAS framework in the form of three representative use cases. A one-to-one conjunction is first presented to illustrate the workflow of the framework. Then, a more complex, one-versus-four primary conjunctions case is shown to illustrate how the results provided by the CAS framework can be used to

*https://www.getpostman.com/

inform the overall collision avoidance decision-making process for a one-versus-multiple conjunction case. Lastly, a near head-on collision case is discussed.

The results from the CAS depend on different parameters set by the O/O or S3, such as propellant budget, collision geometry, and risk tolerance levels. They are expected to inform the decision-making process, whether human or machine, that is responsible for choosing the proper course of action based on user-defined priorities of the different parameters. Our CAS formulation and STM automation is aimed at allowing users with diverse parameters and potentially conflicting objectives to arrive at a consensus regarding a course of action in an informed and seamless manner. Throughout the remainder of the paper, we shall refer to objects involved in conjunctions either by their common names (e.g., Iridium-7), or by their 5-digit NORAD catalog ID numbers (e.g., 24793).

One-Versus-One Conjunction: *Iridium-7* versus *COSMOS 1275* debris object

Conjunction Screening and Encounter Identification. We start the CAS software simulation by sending a conjunction screening request for the *Iridium-7* satellite (NORAD ID: 24793) between 18 Oct 2018 19:00:00.000 UTCG and 25 Oct 2018 19:00:00.000 UTCG. With the absence of realistic covariance data to help us size the threat ellipsoids, we used fixed 25 km$\times$15 km$\times$10 km (along track, cross-track, radial) threat ellipsoids for all objects. Additionally, we used a range threshold of 10 km between the threat ellipsoids, meaning that if the separation distance between the threat ellipsoid of Iridium-7 and another object were projected to be less than (or equal) to 10 km, a conjunction would be recorded. TLE data from the AGI database was used to initialize and propagate all orbits in STK. AdvCAT found 1392 conjunctions in total for the one week screening duration. The Max PoC was then computed for each conjunction and a do-not-exceed threshold of 1×10^{-06} was enforced to identify the high-risk conjunctions.* A primary conjunction between Iridium-7 and a COSMOS 1275 debris object (NORAD ID: 13467) was identified for this example demonstration. The conjunction data is shown in Table 1.

Table 1. Iridium-7 versus COSMOS 1275 debris conjunction data.

Primary Object ID	24793
Secondary Object ID	13467
TCA	21 Oct 2018 08:56:13.771 UTCG
Max POC	1.772×10^{-05}
Range at TCA	0.392 km

Maneuver Generation. The maneuvers demonstrated below were generated for the Iridium-7 spacecraft, assuming it has propulsive maneuvering capabilities. A similar maneuver tradespace can be automatically generated for all active spacecraft in any conjunction, and the decision on the final maneuver lies with the S3. In this example, since the other object is debris, the onus of maneuvering is on Iridium-7 alone. Our selected maneuver generation

*In computing PoCs, AdvCAT only uses the 1-sigma uncertainty values as represented by the axes of the threat ellipsoid.

algorithm seeks the $\Delta\mathbf{V}$ vector orientation, given a magnitude, that maximizes the miss distance at the TCA. An example ΔV budget of 1 m/sec was assumed.* Furthermore, we selected a customizable maneuvering time period of 20 orbits (of approximately 90 minutes each) before the predicted TCA. During this time period, 30 stations along the orbit of Iridium-7 were selected as candidate maneuver locations, from which an S3 or O/O can make a decision based on maneuver screening results below.† The corresponding encounter geometry was computed using results from within STK and familiar orbit mechanics relationships. The result is a set of 30 distinct $\Delta\mathbf{V}$ vectors that correspond to the chosen locations, only one of which will be eventually implemented by the O/O. The maneuver locations were then translated into maneuver epochs since it is more intuitive to think in terms of "when to maneuver" rather than "where to maneuver."

Maneuver Screening. The CAS software executes each candidate maneuver at its intended epoch using STK's Astrogator, to evaluate its COLA performance. The resulting miss distances due to each maneuver (1 m/sec magnitude) are shown in Figure 3, arranged as a function of execution epoch on the X-axis. The screening for primary conjunction mitigation makes it clear that earlier maneuvers create larger separation between the two RSOs. The perturbed orbit is then screened twice via STK's AdvCAT, for secondary conjunctions, and for tertiary conjunctions, both using the same thresholds set at the beginning of the simulation for consistency. A 1-versus-1 conjunction screening involving the original COSMOS 1275 debris object searches for secondary conjunctions against COSMOS 1275, and another against the entire RSO catalog searches for tertiary conjunctions.

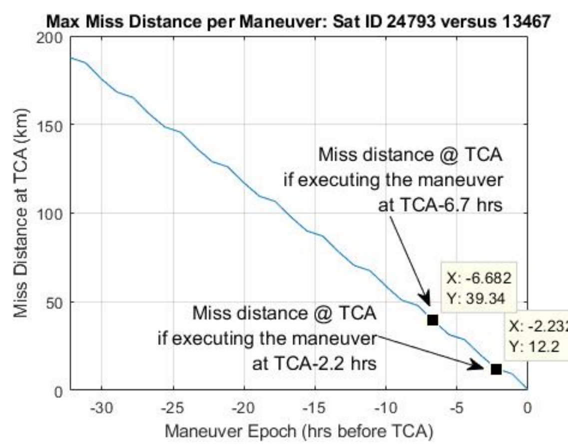


Figure 3. The expected miss distance between Iridium-7 and the COSMOS 1275 debris object at TCA as a function of a tradespace of maneuvers (arranged by epoch), intended to mitigate a predicted, primary conjunction. The miss distances computed by the maneuver planning algorithm and STK nearly match, with a maximum error of 0.4%.

The effectiveness of any candidate maneuver in reducing the collision risk of the primary conjunction can be seen in Figure 4. Squares denote the changed Max PoC of the

*In the STM architecture, the ΔV budget would be one of potentially many constraints determined by the O/O and communicated to the CAS by the S3.

†The number of orbits and number of maneuvering stations were arbitrarily chosen.

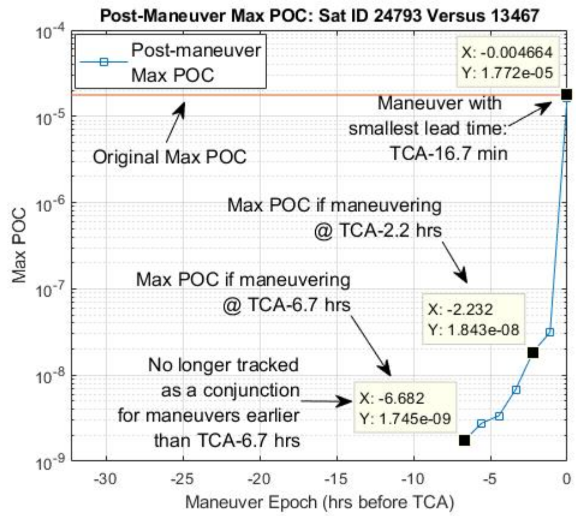


Figure 4. Reduced Max PoC between Iridium-7 and COSMOS 1275 debris object at TCA, as a function of a tradespace of COLA maneuvers arranged by epoch. Earlier maneuvers lead to smaller PoCs, as expected. The solid horizontal, red line shows the original Max PoC from Table 1 for reference.

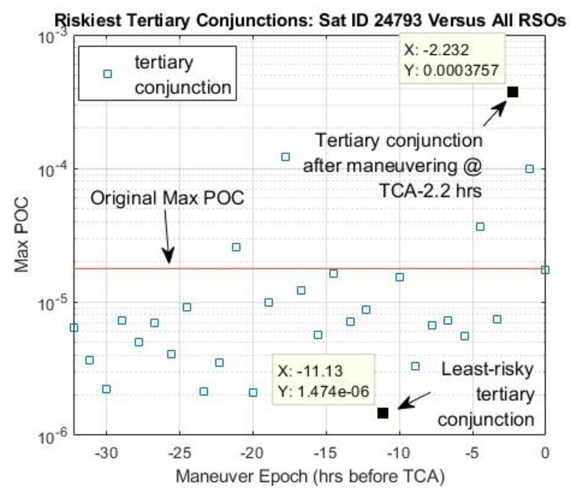


Figure 5. Risk of tertiary conjunctions (square symbols) caused due to a tradespace of COLA maneuvers, arranged by epoch, to prevent an identified primary conjunction. Some tertiary conjunctions have an even higher Max PoC than the primary conjunction (square symbols above the solid line).

event following a maneuver. The original Max PoC of the event is shown as a solid line for reference. The maneuver at TCA minus 2.2 hrs is chosen as an example to illustrate collision risk. Performing this maneuver reduces the Max PoC of the event from the original value of 1.772×10^{-05} to 1.843×10^{-08}. We also see from Figure 3 that the expected miss distance corresponding to this maneuver is approximately 12.2 km, which is almost 12 km greater than the undisturbed miss distance (Range at TCA) reported in Table 1. In Figure 4, no data points appear to the left of the maneuver at TCA minus 6.7 hrs. This is because all maneuvers with earlier execution times create such a large separation between Iridium-7 and the COSMOS 1275 debris object, that AdvCAT no longer detects close encounters between the two. Figure 3 also shows that the separation distance between the two objects continues to increase as the maneuver lead time increases. Maneuvering at 6.7 hrs creates a separation distance of about 40 km, which is greater than (1) all three dimensions of the fixed threat ellipsoids, and (2) the 10-km threat ellipsoid separation threshold.

Virtually every maneuver (except the one with the lead time of only 0.005 hrs, or 16.7 min) sufficiently lowers the collision risk and increases the miss distance, as shown in Figure 4. While this is a positive outcome, it illustrates the mitigated risks of the primary and secondary events only. The CAS software also automatically investigates the results of the 1-versus-all follow-up screening to look for tertiary conjunctions through the end of the one week screening period. Figure 5 shows the worst post-maneuver Max PoC recorded by AdvCAT after each candidate maneuver, arranged by epoch of execution (X-axis).* We see that conjunctions riskier than the original are introduced by some of the maneuvers, thus exposing unfavorable maneuvers. For example, although the maneuver at TCA minus 2.2 hrs reduces the collision risk with the COSMOS 1275 debris object, it results in a tertiary conjunction with a Max PoC of 3.757×10^{-04} (greater than the original!). According to Figure 5, the maneuver suggested at TCA minus 11.13 hrs results in the orbit with the least-threatening tertiary conjunction (Max PoC of 1.474×10^{-06}).

The above analysis indicates that the earliest maneuvers do not always mitigate all risks, and the full tradespace of possible COLA actions and associated results must be investigated. Trade results such as those shown in Figures 3, 4, and 5 are returned with the CDMs to the S3, to provide a preliminary look at candidate maneuvers and their effect on the conjunction of interest. Additional considerations such as impact on mission operations may also be evaluated by the S3. Our framework eases the decision-making process for the O/O by automating the COLA generation and evaluation process as much as possible.

One-Versus-Four Conjunctions: *COSMOS 1603*

The CAS software is capable of providing information to decide between conflicting potential maneuvers, in the event of multiple conjunctions. We selected the COSMOS 1603 (NORAD ID: 15333) active satellite as the subject of a new use case simulation. A week-long conjunction screening revealed four primary conjunctions. As shown in Table 2, each event's predicted Max PoC exceeds the 1×10^{-06} threshold.

Table 2. Primary conjunction data between COSMOS 1603 and four other satellites.

Primary Object ID	15333	15333	15333	15333
Secondary Object ID	41343	36155	41364	30266
TCA	2018-10-26T20:22:07.044	2018-10-27T22:29:50.445	2018-10-29T11:11:50.596	2018-10-30T21:34:57.080
Max POC	1.8110e-05	3.9934e-06	2.8317e-05	2.9533e-06
Range at TCA	0.393 km	0.788 km	0.319 km	0.914 km

*The **worst Max PoC** related to a maneuver belongs to the conjunction whose Max PoC is the largest out of all conjunctions that result from that maneuver.

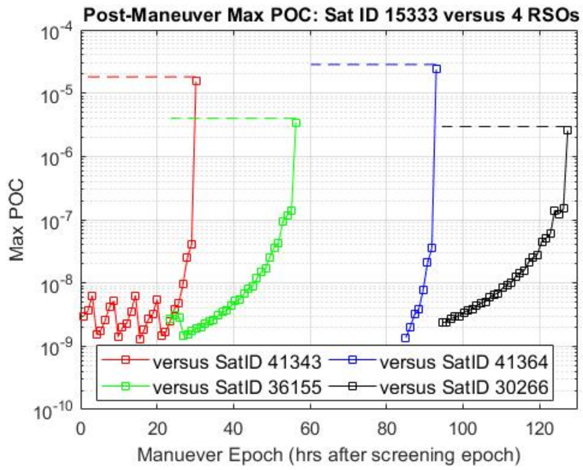
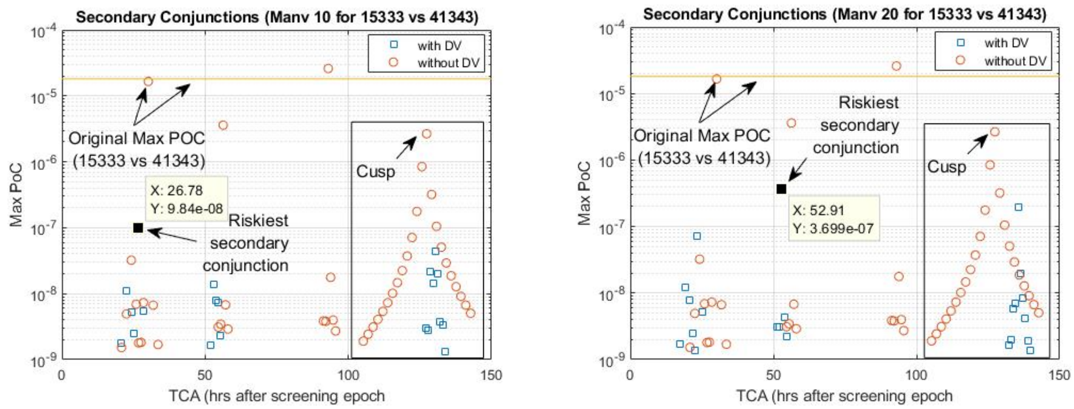


Figure 6. The post-maneuver Max PoCs of four primary conjunctions of COSMOS 1603 (NORAD ID: 15333) against four active spacecraft, as a function of a tradespace of maneuvers, arranged by the epoch of maneuver execution. Screening epoch is defined as the simulation start time. The original Max PoC of each event is shown as dashed lines for reference, and the TCA for each event corresponds to the point where the dashed and solid lines intersect.

As before, 30 impulsive maneuvers of 1 m/sec magnitude were computed for each of the four conjunction events, as candidates from which the S3 can select (or request additional trades). Figure 6 compares the Max PoC drop if each candidate maneuver were executed individually, plotted on the X-axis as a function of the epoch of maneuver execution. Like in Figure 4, the suggested maneuvers lower the collision risks significantly, especially those with earlier execution times, for any of the primary conjunctions. However, since the four events are so close to each other in time and each COLA maneuver takes time, the S3 or O/O will have to carefully choose the sequence of maneuvers that mitigate all appropriately. For example, the last candidate maneuver against 41343 (red) corresponds to the first few candidate maneuvers against 36155 (green), thus only one of them can be selected for execution. The non-monotonic nature of the red curve can be attributed to similar orbits of the two satellites. Unlike the one-on-one use case, primary conjunction mitigation is no longer independent. Figure 6 does not detail how a maneuver designed for one of the primary conjunctions in Table 2 affects the others. There may be a risk of increasing the PoC of a later primary conjunction by maneuvering to avoid an earlier one.

To plan for primary conjunction mitigation, the CAS software computes post-maneuver *secondary* conjunctions using STK's AdvCAT. Since secondary conjunctions only involve the original high-risk secondary objects, only a 1-versus-4 screening is performed. Figure 7(a) shows the Max PoCs of secondary conjunctions that result by implementing the 10th maneuver from the set of maneuvers analyzed for the 15333-versus-41343 conjunction (i.e., the red markers in Figure 6). Figure 7(b) shows the same, but for the 20th maneuver. Maneuvers were chosen from the 15333-versus-41343 set because it is the earliest conjunction, and any mitigating action could create secondary and/or tertiary conjunctions. The Max PoC threshold was not enforced to capture all of the possible secondary conjunctions. Figure 7 shows that there are no secondary conjunctions violating the 1×10^{-06}

threshold, if either maneuver were executed. It also demonstrates that an earlier maneuver does not always maximize the PoC reduction, and specifically in this example, the delayed maneuver 10 is more advantageous than maneuver 20, in terms of inducing the least risky secondary conjunctions. The maximum post-maneuver Max PoC in Figure 7(b) (earlier maneuver) is greater than that shown in Figure 7(a) (later maneuver), as further detailed in Table 3. Data provided by the CAS can thus aid better decision making.



(a) Maneuver epoch: TCA-10.2 hrs

(b) Maneuver epoch: TCA-21.5 hrs

Figure 7. Secondary conjunctions resulting from two candidate maneuvers (executed at 10.2 hrs in (a) and 21.5 hrs before TCA in (b)) designed to mitigate the 15333 versus 41343 primary conjunction are compared. The secondary conjunctions include all five satellites in Table 2. Max PoC data with (blue) and without (red) the said maneuvers (DV = ΔV) is compared. The original Max PoC of the 15333 vs 41343 primary conjunction is shown as a solid, yellow line for reference.

The distinct cusp traced out by the red circle markers in Figure 7, denoting the unaffected environment (i.e., without any COLA burns), involves conjunctions with only one secondary object: Sat ID 30266. Closer inspection in STK showed that the phasing of the orbits of 15333 and 30266 led the two objects to gradually approach one another until they converged to create the primary conjunction event identified in column 4 of Table 2 (which is also the tip of the curve). Then, the orbit phasing eventually led to the two objects diverging afterwards. Trends and plots produced by CAS and re-analysis opportunities within our STM visualization environment allows users to easily identify orbital behavior around conjunctions.As with the Iridium 7 versus COSMOS 1275 debris case, plots showing tertiary conjunctions resulting from each maneuver within a set were also generated during the simulation. An example is given in Figure 8, which shows the resulting tertiary conjunction with the highest Max PoC for each candidate maneuver generated for the 15333-versus-41343 primary conjunction tradespace. The figure shows that maneuvering at TCA minus 3.4 hrs to avoid the primary conjunction with 41343 introduces the least risky tertiary conjunction (Max PoC = 1.45×10^{-06}). In contrast, an earlier maneuver at TCA minus 19.2 hrs leads to an even riskier conjunction (Max PoC = 1.29×10^{-04}) than the primary one between 15333 and 41343 (Max PoC = 1.81×10^{-05}). The eventual decision for which maneuver to choose lies with the S3 and O/O of both spacecraft, the negotiations for which are facilitated by the described tradespace of results on primary conjunction mitigation, as well as secondary and tertiary conjunction production, provided by the CAS.

Table 3. The riskiest secondary conjunction between the two maneuvers involves a different object.

	Maneuver 10	Maneuver 20
Lead Time (hrs before TCA)	10.2	21.5
no. of conjunctions (w/ $\Delta\mathbf{V}$)	20	22
Worst Max PoC (w/ $\Delta\mathbf{V}$)	9.84×10^{-08}	3.70×10^{-07}
Secondary ID	41343	36155

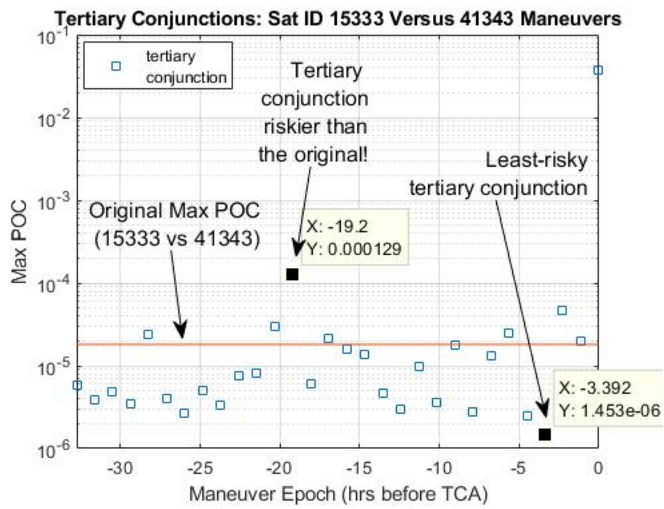
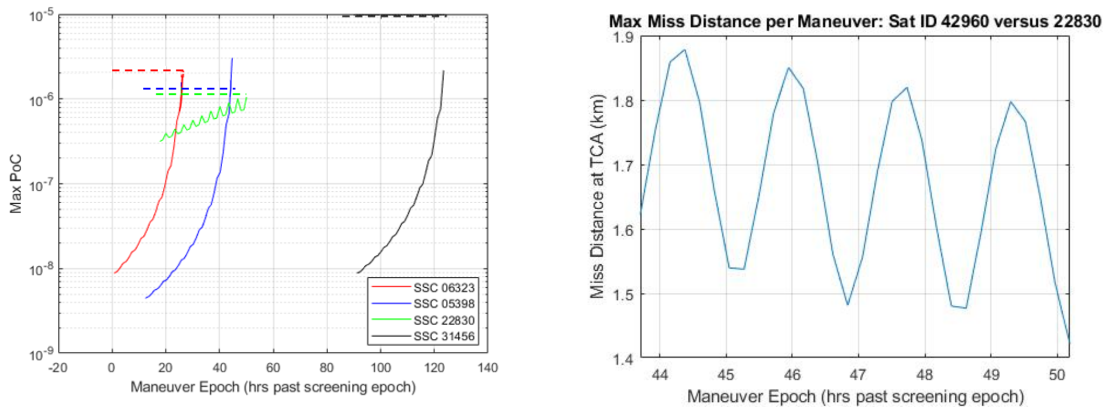


Figure 8. The tertiary conjunction with the highest Max PoC is plotted against the corresponding maneuver from the full set of candidate maneuvers to mitigate the 15333-versus-41343 primary conjunction. The candidate manuevers are arranged by the epoch of execution (X-axis).

Near Head-On Collisions

The case of a near head-on collision was identified when we performed a conjunction screening for the Iridium 107 satellite (NORAD ID: 42960). A small user-defined 1 cm/s impulsive ΔV budget was assumed. The effect of a set of candidate maneuvers on the Max PoCs was obtained and superimposed on the same plot, for each of the four conjunctions (different colors), as shown in Figure 9(a). It is interesting to note that three of the four conjunctions happen within a 20-hour window. To determine the optimal course of action for such a short period, data similar to those shown in Figures 7 through 8 can again be used; for the sake of brevity, the equivalent results are not discussed in order to focus on the unique behavior shown by the green curve in Figure 9(a).

The Max PoC curve for the 42960 versus 22830 conjunction, shown in green in Figure 9(a), demonstrates that the maximum drop in the collision risk due to the candidate COLA maneuvers does not even exceed one order of magnitude. The jagged behavior of the green curve also suggests that some candidate maneuvers do not achieve a big enough separation distance to successfully lower the collision risk. Investigation using the CAS software revealed that the right ascension of the ascending node (RAAN) of the two satellite orbits were approximately 180 deg apart, and that their inclinations and altitudes were similar. This is a near head-on collision scenario, with important implications on the optimal maneuvers, that the CAS is efficiently capable of bringing to the users' attention.



(a) Iridium 107 versus four primary conjunctions.

(b) Post-maneuver miss distances.

Figure 9. (a) Iridium 107 (NORAD ID: 42960) involved in four primary conjunctions, one of which (green) is predicted to be a near head-on collision, resulting in a jagged pattern in the PoC curve. (b) The post-maneuver miss distance at TCA follows small, oscillatory changes for the near head-on collision case, consistent with that of the green curve in Figure 9(a). 1-cm/s maneuvers within four orbits (approximately 7 hours) before TCA are shown.

Recall that our selected maneuver generation algorithm computes the optimal orientation of the impulsive $\Delta\mathbf{V}$ that maximizes the separation distance (relative position) at the predicted TCA. Following the $\Delta\mathbf{V}$, the shift in the relative position has three components: radial, along-track, and out-of-plane. In this case of a near head-on collision, the secular along-track displacement due to the maneuver is significantly reduced and the non-secular radial component dominates.[*29] The result is that some candidate maneuvers yield smaller separation distances than others as demonstrated by the oscillation shown in Figure 9(b). Overall, the maximum separation distance achieved by each maneuver is on the order of 1 km, which is small compared to other values we have shown previously. The smaller separation distances explain why the reduction of Max PoC in the green curve of Figure 9(a) is not as great as we have seen in the other cases. Consequently, there are fewer options for maneuver times that can generate enough separation between the two objects such that the Max PoC is reduced to a tolerable value at TCA.[†] This sensitivity to maneuver epoch

[*]The out-of-plane contribution is assumed to be negligible here for the case of a near head-on collision. Unless an expensive maneuver that changes the inclination or the RAAN can be afforded, we assume that the O/O will want to rely on the radial and along-track separation to achieve the max miss distance.

[†]Bombardelli notes that the separation distance is maximized when the maneuver is executed $n + 1/2$ orbits prior to TCA.[29]

is captured by the the oscillating nature of the curves. One possible solution is to increase the $\Delta\mathbf{V}$ budget to create larger separation distances than those shown in Figure 9(b).

There is also the likelihood of the same two objects becoming involved in another primary conjunction, after the COLA maneuver, due to their nearly similar orbits. Recurring conjunctions could require an O/O to look into more expensive maneuvers to change the RAAN (or inclination), but this is not always feasible for a given mission. Cases like these represent a different kind of COLA strategy compared to the previous conjunctions, and the CAS is expected to provide sufficient data to analyze it appropriately.

FUTURE WORK

Future refinements to the current state of the CAS framework in order to improve the quality of the conjunction assessment services it provides, are currently underway. We are also exploring integration of the framework with other components of the STM architecture, including functionality for COLA negotiation and automated decision making under space situational awareness and/or conjunction data uncertainty.

Covariance Data and the PoC. Orbit propagation during the conjunction searches by the CAS software presented in this paper used TLE data, which does not include uncertainties. This forced us to assume a fixed threat volume around the objects during propagation, which led to the adoption of the Max PoC (the worst-case scenario) as the metric by which to assess collision risk. In the future, we would like to propagate orbits using state vectors with covariances associated with them. The covariances can then be propagated along with the orbit forward in time, so that the uncertainties of the position are known at the TCA. In turn, this allows the CAS to compute a true PoC in place of the Max PoC. We are working to establish the API between the CAS and the SSA entities in our architecture. The API allows the CAS framework to request the primary satellite's state vector, which includes covariance data, from an SSA server. The intent is to retire the current Max PoC-based method of risk assessment in stage 2. Instead, the covariance data will be used in the PoC computations to enable a richer risk assessment when identifying primary conjunctions.

Hard-Body Radius and the PoC. Computing the PoC also requires knowing what the sizes of the two objects involved are.[20,21] The default value of the hard-body radius in AdvCAT (equal to 1 m) was used to compute the PoCs because the actual sizes of all RSOs were unknown at the time of simulations. PoC results would be more accurate if the sizes of the objects are properly captured. In future refinements of the risk-assessment routine in the framework, we will correctly model the sizes of the spacecraft. If the size of the object is not available on a public database like SpaceTrack, we could require an S3 to provide the current best estimate of their asset's hard-body radius at the time of the screening request.

Additional Software. Software integrability is of primary importance to enable a modular and scalable CAS framework. Incorporating into the framework other existing conjunction assessment tools like *closeap* and LightForce, or maneuver tradespace generation and evaluation tools other than the one presented is the subject of future investigation.

S3 Decision-Making. The current CAS simulations provide data comparing PoCs for different maneuver strategies, with the intent of informing the decision-making process of the S3 during course-of-action planning. For example, academic literature has demonstrated the use of autonomous decision-making using partially observable Markov decision processes (POMDP).[30] We are developing the algorithms that choose which maneuver is most appropriate, per S3-O/O preferences, and will present them in a future publication.

Monitoring Conjunctions. In some cases, a primary conjunction is predicted many days after the creation date of the state vector used in the conjunction screening. Numerical errors in propagation degrade the accuracy of the predicted orbits making it possible that the detected conjunction may not even occur at all in reality. In this case, the cognizant S3 would wait for new orbit data and repeat the screening before considering that conjunction to be a threat. An automatic recurring screening request to monitor conjunctions over variable simulation periods that account for evolving state vectors is also under investigation.

CONCLUSION

We presented a preliminary version of the CAS framework, which performs conjunction assessment and collision avoidance planning in an automated fashion. This framework was developed to support safe operations in a novel STM architecture. A MATLAB-STK implementation of the framework demonstrated the automatic, sequential execution of conjunction screening and risk assessment, collision avoidance maneuver planning, and maneuver screening. Three example conjunction cases were discussed: one-to-one, one-versus-four, and a near-head on collision. The results demonstrate the complexity of maneuver planning especially in the event of secondary and tertiary conjunctions, and the utility of our developed CAS software in simulating and analyzing the tradespace of possible actions, and their associated performance. We plan to use the results to develop distributed decision-making to support the autonomous concept of operations of the STM architecture.

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