Prototype Infrastructure for Autonomous On-board Conjunction Assessment and Collision Avoidance

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ABSTRACT

We are working to build a prototype infrastructure for scalable autonomous conjunction assessment and avoidance. This includes a ground hub to synchronize state information and planed maneuvers from operators and identify potential conjunctions, and on-board flight software for autonomous assessment and avoidance of collisions. This work will be flown as part of a NASA STMD flight experiment in 2023.

1. INTRODUCTION

Conjunction assessment (CA) is one of the most important components of operational satellite safety and that importance is continually growing due to the proliferation of missions and constellations in LEO. The difficulty and complexity are increased when coupled with the implementation of autonomous maneuvering for swarms or constellations, and further increased when such systems begin interacting with other autonomously maneuvering systems. With many large-scale autonomous constellations such as SpaceX Starlink, Amazon Kuiper, and other commercial providers as well as the proposed persistent LEO constellations from the SDA and MDA scheduled for deployment in the coming decade, finding a scalable solution to this problem is key to Space Sustainability.

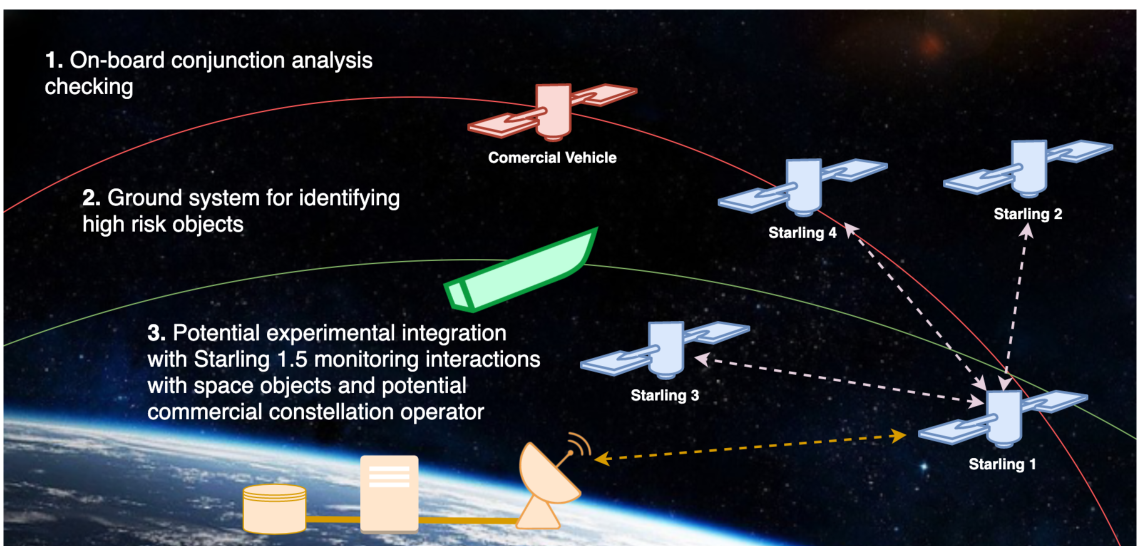


Fig. 1: Autonomous Multi-vehicle Conjunction Assessment Concept

Existing systems monitor space assets for potential collisions and alert the operators so that they can maneuver their satellites to avoid potential collisions. These systems require inefficient communication between operators and the current turnaround time is so large that unnecessary avoidance maneuvers are performed out of an abundance of caution. In many cases, as time passes and knowledge of the vehicle state improves, the conjunction risk is resolved on its own. Additionally, the current infrastructure does not have a clear path for supporting autonomous space systems that have the capacity for performing their own maneuvers. Emergent Space Technologies and the University of Texas at Austin are working to develop a prototype system to marry on-board spacecraft autonomy and navigation with a networked Space Traffic Management (STM) hub that autonomously manages a real-time space object catalog. This effort focuses on combining ground and space-based (edge) platforms to deliver the capability to quantify and assess on-orbit collision risk between space objects and use this space situational awareness to support decision-making processes that maximize desired outcomes. Several entities, such as SpaceX's Starlink satellites, have implemented autonomous collision avoidance maneuvers, but to date, these are executed in the absence of other autonomous spacecraft and oftentimes with flawed and outdated information and thus the collision risk is not realistic. To address this shortfall, we are working to develop the tools necessary to synchronize planned autonomous maneuvers and better models for estimating conjunction risk. Our team is building a prototype hub where spacecraft operators can submit the most recent state data and future planned maneuvers. This hub will screen the planned maneuvers to identify potential conjunction risks.

2. BACKGROUND

The past decade has seen a significant expansion in the growth rate of space borne objects. This is largely due to the explosion in the "New Space" industry and its efforts to find new avenues to commercialize space. These new systems are frequently being deployed in persistent low Earth orbit (p-LEO) configurations so that they can provide continuous services such as internet access or Earth observation. This density is leading towards inevitable challenges for STM and that difficulty is magnified by the goal of many of these systems to manage orbit maintenance autonomously. [1] Current proposals are to simply separate these large-scale constellations to avoid conflicts, but this is obviously a short-term solution as more and more constellations, especially those from other nations with different regulatory authorities, seek to occupy the finite space available in LEO.

Fig. 2: Historical Growth of Space Borne Objects

Current conjunction assessment is highly dependent on DOD's Combined Space Operations Center (CSpOC), formerly the Joint Space Operations Center (JSpOC). CSpOC uses the Space Surveillance Network to maintain a catalog of RSOs down to about 10 cm [1]. CSpOC now provides collision avoidance analysis to any registered space user in the form of automated conjunction messages [2]. CSpOC planned an overhaul of their operational conjunction assessment system (SPADOC) to modernize it into the JSpOC Mission System (JMS) [3]. However, this program was apparently unsuccessful, and the SPADOC system is still in use [4]. CSpOC supports operational missions globally in both defense and civil applications. For NASA missions, non-Human Spaceflight operations rely on Conjunction Analysis and Risk Assessment (CARA), an Agency-level program. CARA supports about 70 active missions in Earth-orbiting regimes. CARA uses a three-step process in which managed assets are screened against a catalog by CARA analysts at Vandenberg Air Force Base; an automated tool (Conjunction Assessment System [CAS]) processes the trajectories and CARA team manually analyzes conjunctions; and CARA works with mission teams to plan and execute risk mitigation strategies [5]. However, these historical systems will likely not be able to keep up with growing STM demands.

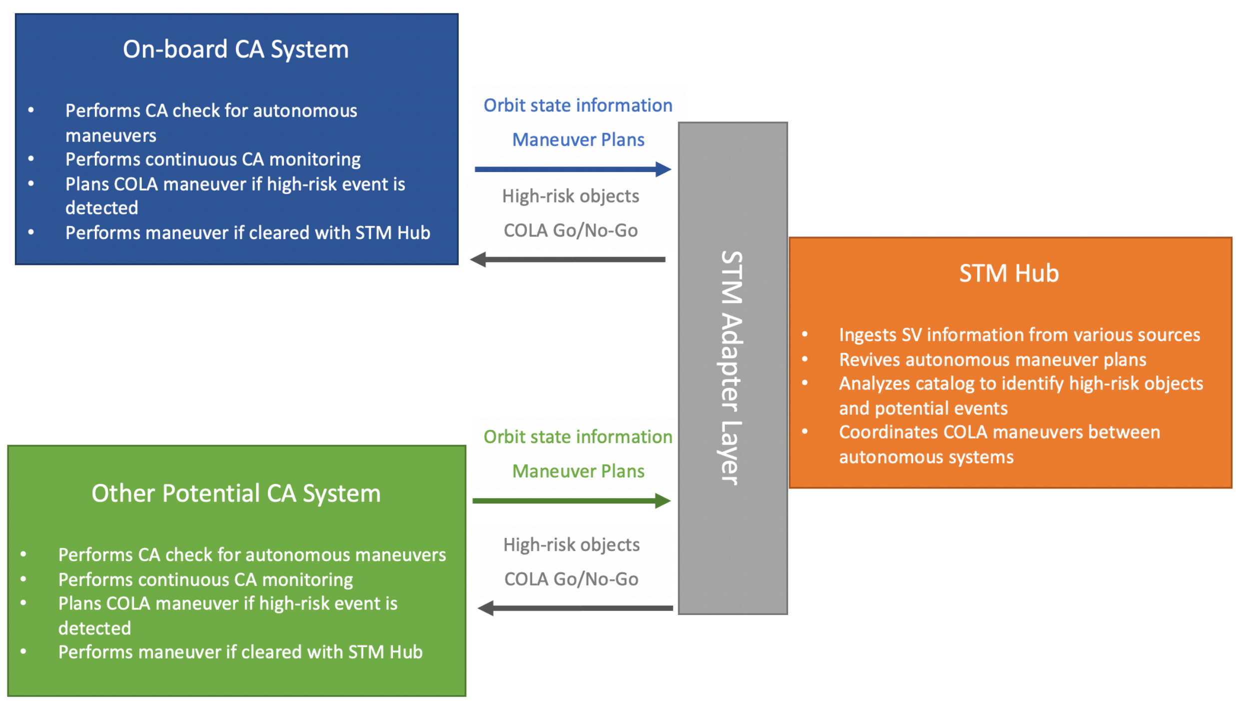
Commercial companies have begun to offer conjunction-related services. COMSPOC® provides products and services to support threat assessment for operators. COMSPOC's products are primarily directed at threat assessment due to maneuvers from other spacecraft, and providing services for simulation and training, vulnerability assessment, and maneuver reconstruction [6]. SpaceNav provides SSA analysis as a service to operators to perform collision risk management and plan avoidance maneuvers [7]. Research by LeoLabs, Inc and Planet Labs, Inc demonstrated the use of LeoLabs' ground radar to provide additional orbit determination capabilities on demand, possibly supplementing high-covariance warnings from CSpOC or another source [9]. LeoLabs offers ground-based radar tracking as a subscription service [9].

Research publications in conjunction assessment have a wide spread of topics, but relatively few focus on operational requirements and mission operations. Nag et al. develop a prototype Space Traffic Management (STM) system using a common API to facilitate communication between operators, regulators, and service suppliers. Example operations include synchronizing multiple RSO catalogs and determining which spacecraft maneuvers to prevent an impending conjunction [10]. JPL researchers performed automated spacecraft conjunction assessment for spacecraft at the Moon and Mars [11]; however, this work is relatively old and has a much less challenging environment. Jung, Seong, and Anh developed a tool to automatically generate detailed conjunction analysis reports, triggered by messages from external sources like CSpOC [12]. Similarly, Laporte describes a French program that processes CSpOC data and performs additional analysis before communicating to operators [2]. These systems have begun to explore the potential for scalable STM frameworks but have not been evaluated in the context of an operation environment and do not incorporate autonomous FSW capabilities into their infrastructure.

3. PROPOSED SYSTEM CONCEPT

The proposed system for autonomous conjunction assessment is made up of two major components. There is the flight software that determines the space vehicle's state, maintains a small catalog of potential objects that represent potential collisions, and autonomously manages the vehicle's orbit. This orbit management includes monitoring the potential collisions with updated state information from the on-board navigation, and planning avoidance maneuvers if necessary. The second component is the STM hub. The STM hub is responsible for maintaining a full catalog of objects, updating the catalog entries based on new data, accepting proposed maneuvers from spacecraft, propagating them forward to detect possible conjunctions, computing the probability of those potential conjunctions, and reporting that information out to the spacecraft. The design and functionality of these systems are described in the following sections.

Additionally, there is a required adapter layer component that bridges the two systems. The purpose of this adapter layer is to provide a connection between the FSW and the STM hub for mission specific applications. The flight software operates on Emergent's Gear framework which allows it to be implemented on any middleware based FSW and the ground hub has an API based on REST for its specification that can be rapidly deployed and integrated with other systems. For example, to perform STM in LEO the STM hub can be deployed as part of Earth-bound infrastructure so that various operations centers can access it over the internet, this is the deployment model for an upcoming experiment with NASA and SpaceX. [13] The architecture also supports forward-looking deployments such as proposed NASA Lunar or extra-planetary constellations, where the hub could be deployed in a FSW framework such as Emergent's Cirrus space cloud compute and networking service for STM without ground operators in the loop. This deployment model could also support resilient STM operations in the presence of a ground operations loss for constellations such as the P-LEO constellations that the SDA is fielding.



4. CONJUNCTION ASSESSMENT FLIGHT SOFTWARE

To enable autonomous maneuvers that are coordinated with other spacecraft and resident space objects (RSOs) a flight software (FSW) deployment was developed based on Emergent's existing FSW products. The onboard FSW system is made up of four main components:

1. Autopilot: Provides autonomous control and conjunction assessment computations
2. Navigator: Calculates and propagates spacecraft position and reports it to other components
3. External Catalog Application (ECA): Maintains a list of objects that could potentially collide with the spacecraft
4. Commander: Manages the interactions between Autopilot and the ECA and coordinates reactions to high probability of collision (PC) events

A summary of the FSW architecture is shown in Fig. 3 and more details on these components and their application for autonomous STM are provided in the following paragraphs.

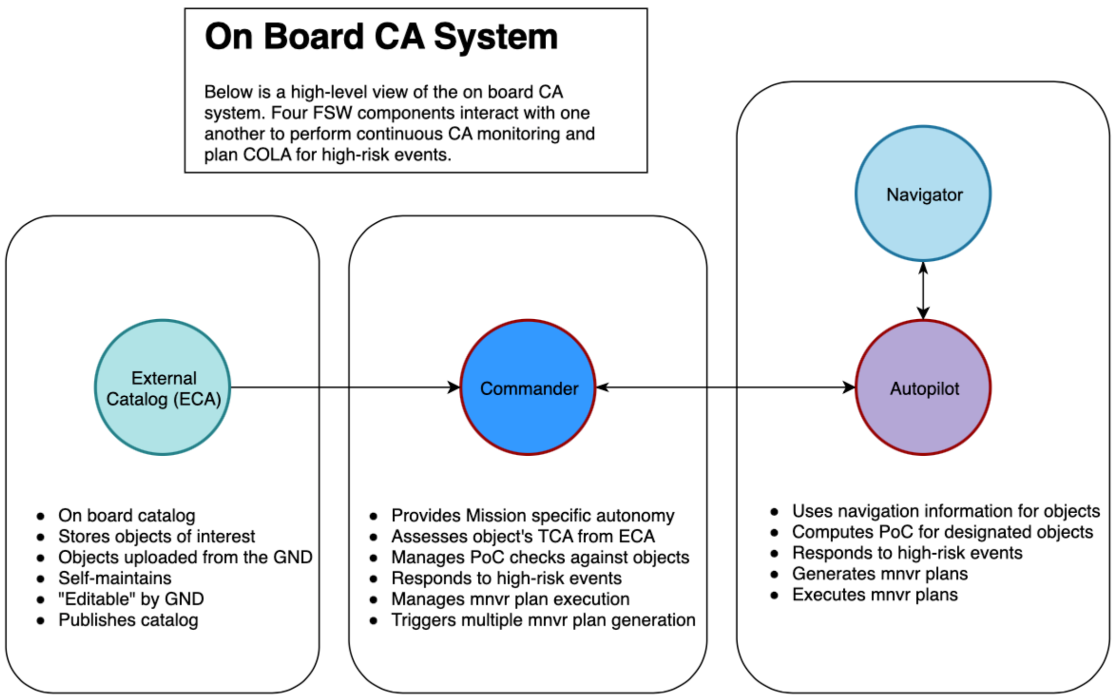


Fig. 3: Conjunction Assessment FSW Components

Autopilot provides semi-autonomous maneuver guidance and control for a spacecraft or a group of spacecraft flying in formation. Autopilot is made up of three main services:

1. Cluster Flight Manager (CFM): Maintains an inventory of spacecraft within and relevant to the formation and manages external interfaces with Autopilot and external systems. This inventory is implemented with a limited number of entries because of the computational and memory requirements of planning operations.

2. Orbit Maintenance Service (OMS): Monitors orbital status of vehicles, predicts violation of orbital constraints, validates potential orbits, and monitors collision probability for vehicles in CFM's inventory. The hybrid CA calculation is performed using a novel algorithm based on a weighted average of the Mahalanobis distance and instantaneous probability of collision computations, the results of which can be seen in Fig. 4. These two values present an upper and lower bound for the system conjunction risk. A weighted average is tuned to match the results of Mote Carlo Analysis but can also be tuned to be more conservative in cases where safety is critical. [15]

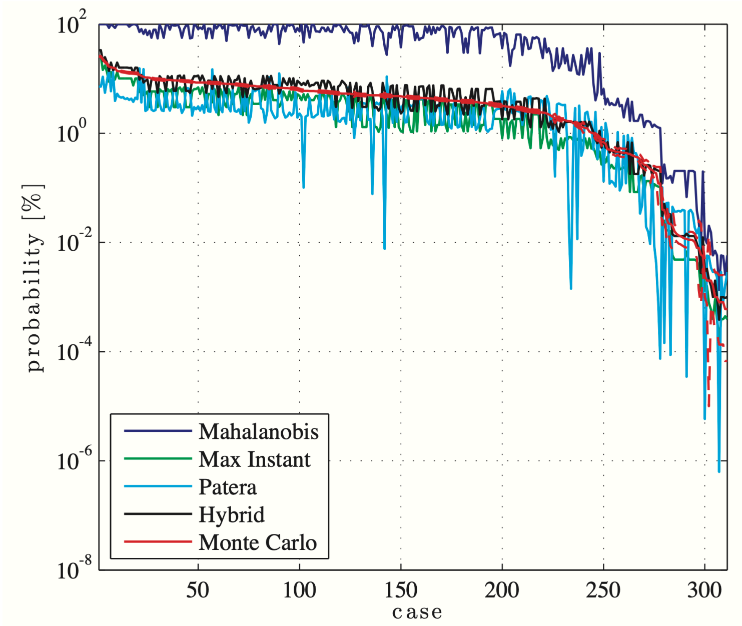


Fig. 4: Autopilot On-board Conjunction Assessment Algorithm Performance Compared with Common Methods

3. Maneuver Planning Service (MPS): Generates maneuver plans based on requests from OMS. A maneuver plan is a series of one or more maneuvers for one or more modules to reach a target orbit(s) within a specified time window. MPS allows a requestor to specify maneuver goals, constraints, and design parameters, and responds with optimized maneuver plans that are computed using a combination of simulated annealing (SA), a finite burn solver, and linear programing (LP) for optimization. The optimization requires iteration consisting of multiple steps, each of which is responsible for checking different constraints, as summarized in Fig. 5. SA is used to search the maneuver planning space for candidate solutions. A candidate solution from the SA algorithm is passed to a finite burn solver, which uses the Gim-Alfriend state transition matrix (STM) to solve a LP problem and convert the SA output into a sequence of finite burns. The resulting finite maneuver's cost is weighted by total maneuver cost and constrained by a maximum maneuver magnitude. The process repeats until the requirements are satisfied or an SA iteration limit is reached.

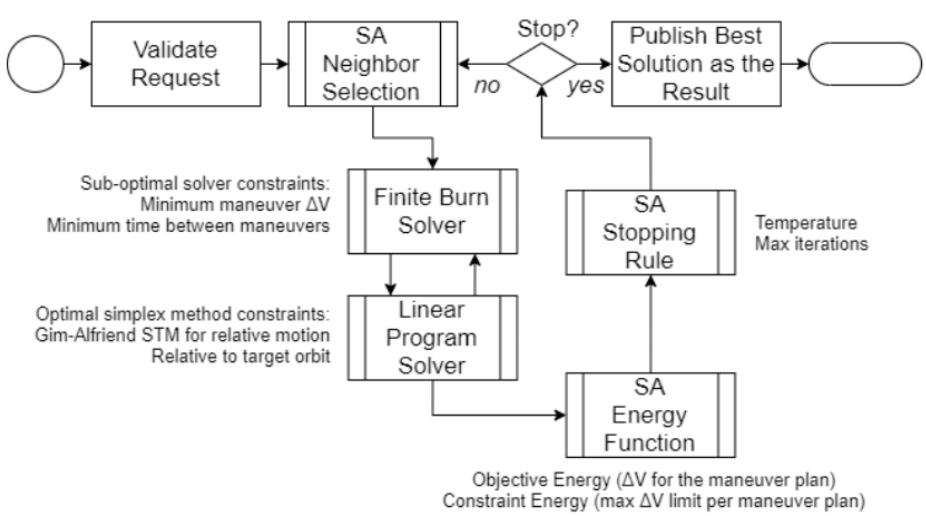


Fig. 5: Autopilot Maneuver Planning Pipeline

Navigator provides a validated efficient on-board extended Kalman Filter for spacecraft operations that is used to supply real-time state information to Autopilot. Navigator can associate state elements with each cluster module to fuse sensor measurements coming from multiple modules. Navigator also supports Consider Kalman Filtering of states. Consider filtering enables parametric uncertainty to be included in covariance calculations without explicitly estimating the uncertain 2 states, providing potentially a large computational savings. Navigator enables efficient onboard navigation that accounts for:

1. Absolute position and velocity
2. Relative position and velocity
3. GPS clock bias and drift
4. Relative range sensor bias
5. Unmodelled accelerations

This enables substantially more accurate and repeatable navigation and autonomous guidance when coupled with Autopilot as demonstrated by the Monte Carlo analysis comparing operations with Navigator and with standard GPS Position, Velocity, and Timing (PVT) in Fig. 6. Navigator can also be configured to support relative measurements between spacecraft instead of GPS enabling the fully autonomous constellations Concept of Operations (CONOPS) discussed above. [16]

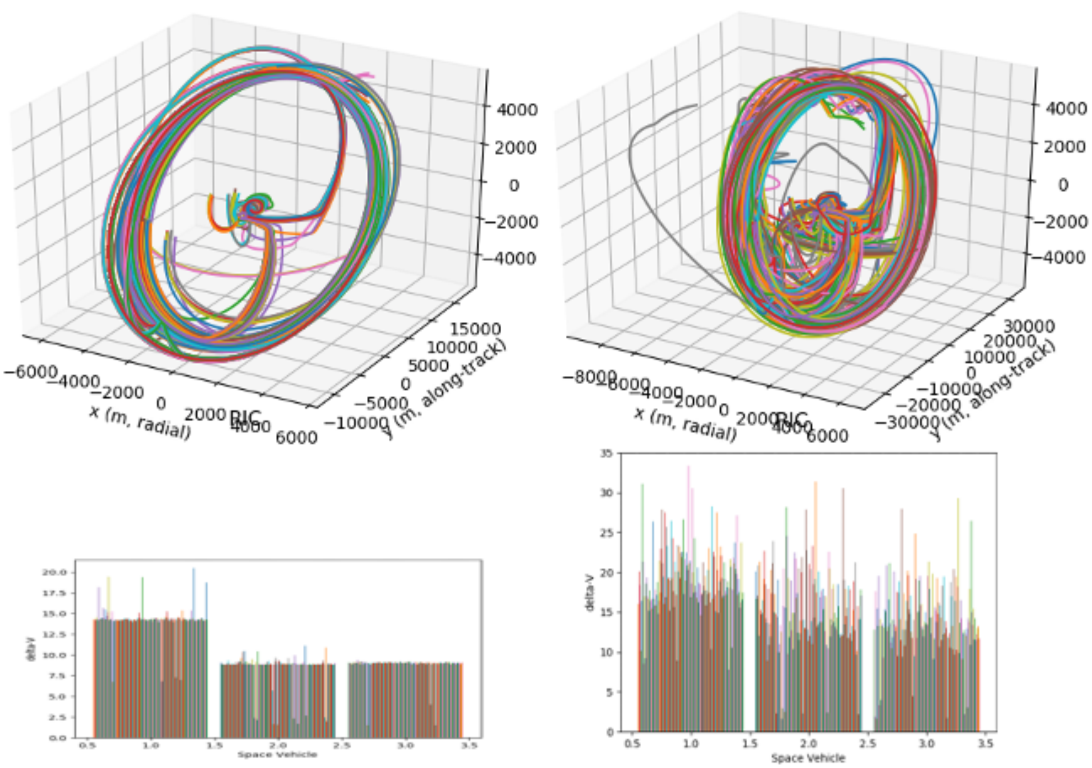


Fig. 6: Monte Carlo Performance of Autopilot using Navigator and Standard GPS PVT

Commander is a suite of services to provide autonomous orchestration and execution for agents or multi-agent systems. Initially developed as part of a NASA Phase 2 STTR for modular autonomy, Commander provides autonomous orchestration of generic FSW applications based on telemetry for mission execution. The hierarchical components run as individual apps on each Space Vehicle (SV):

1. Mission Manager: Coordinates the mission plan across a cluster, swarm, or constellation of SVs. It follows a mission plan that reduces the need for direct ground control
2. Execution Manager: executes the SV plan as directed by the Mission Manager. Based on dynamic SV operational state, the planned SV task sequence is selected, and the relevant system commands are sent

3. Timeline Manager: Manages low level task scheduling, interactions, and resource deconfliction

Additionally, Commander is frequently used in conjunction with modular "helper" applications that are used to provide complex state assessments that feed into the Commander system. When deployed in a standard configuration, as shown in Fig. 7, a single Mission Manager tends to be deployed as the main point of interaction for the ground. This Mission Manager monitors high level mission objectives and coordinates the system's Execution Managers. The Execution Managers coordinate state by ingesting telemetry, determining the system state, and commanding the relevant actions on each specific vehicle. The timeline manager on each vehicle then coordinates the low-level actions and ensures conflicting actions are not scheduled and communicates the results to the vehicle execution manager. [17]

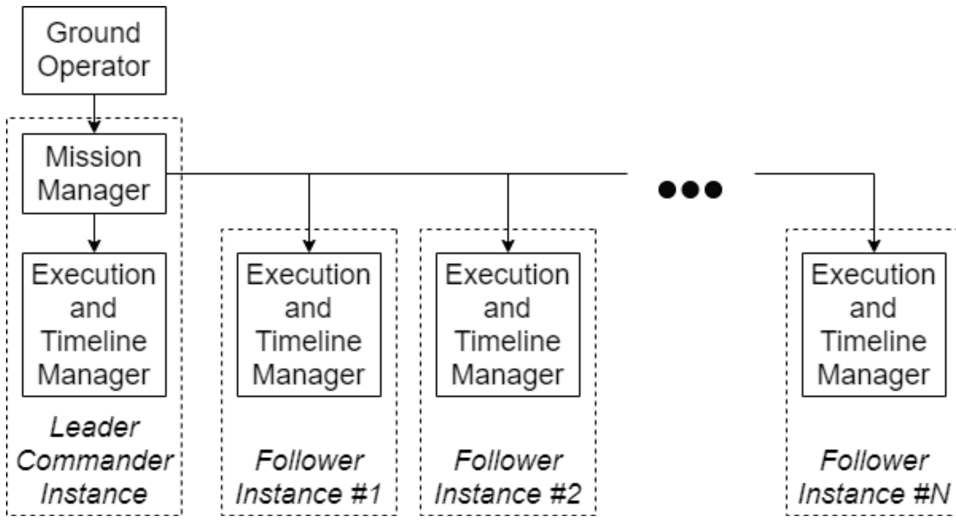


Fig. 7: High Level Commander Architecture

The final component for the CA FSW is the External Catalog Application (ECA). This is responsible for maintaining a catalog of objects of interest that have a predicted PC with the spacecraft that exceeds a specified value within a defined window of time into the future. The application ingests the catalog of objects of interest generated by the STM hub and publishes the information on the time of closest approach (TCA) and the object of interest state at TCA. When empty the ECA simply accepts the list of objects sent by the ground, checks that it is within the memory limits set for the application, and sends the respective acknowledgment or failure message. If there is an existing message, the ECA checks for matching object of interest IDs and merges the associated entries, otherwise a new entry is generated. The catalog then periodically runs to publish a catalog message detailing the catalog entries and check for staleness in entries. The application also regularly application checks the entries and removes any whose TCA has passed and has a staleness that exceeds a programable threshold.

The full FSW CA system is achieved by combining interactions of all the above applications, largely coordinated with Commander. A high-level UML summary of these coordinated behaviors from the FSW applications, the ground, and the vehicle is shown in Fig. 8.

A complexity of this system is a result of the limited number of entries within Autopilot's internal catalog. This requires Commander to manage the objects within Autopilot's catalog and the objects located in the ECA based on their TCA and the current time. While this seems like unnecessary complexity and the size of the catalog within Autopilot could simply be increased, it does provide significant savings in terms of computational resources. When new catalog entries are published from the ground Commander stores the ID and TCA for the objects. Commander also starts monitoring the ECA for publication of its catalog messages and alerts the ground if publication does not occur. Commander monitors the data being published by the ECA to determine whether or not objects need to be added or removed from Autopilot's catalog and when PC checks need to be triggered within Autopilot. When Commander identifies an object whose TCA is within a configurable range of the current time, it publishes that object to the Autopilot inventory if it has not already and triggers a PC check within Autopilot. Commander then confirms that Autopilot has performed the commanded PC check. Finally, Commander monitors the TCA of objects published from the catalog and removes them from the Autopilot catalog if a configurable time after the TCA has passed.

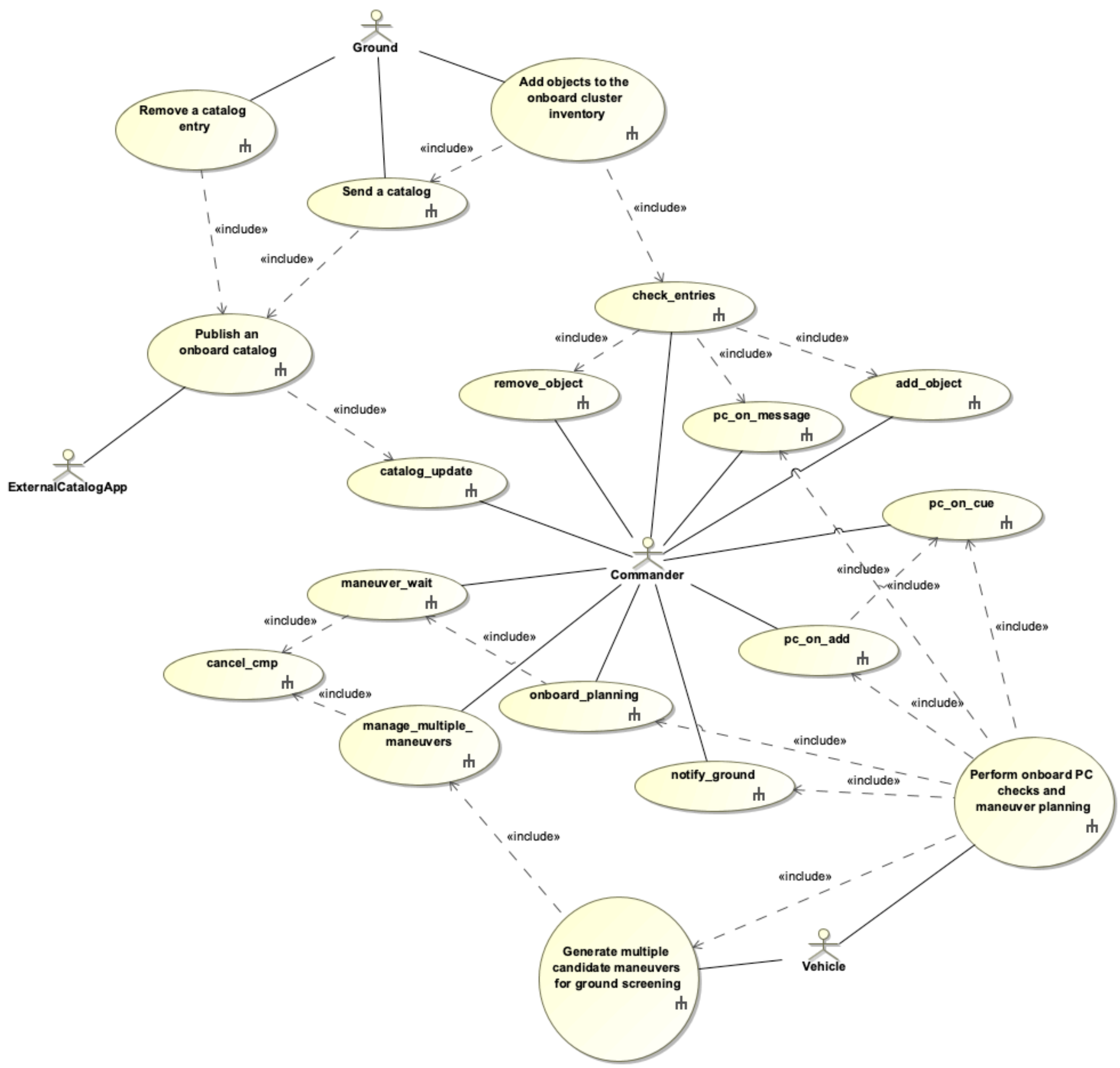


Fig. 8: Autonomous Conjunction Assessment FSW System Actions

If Autopilot detects and publishes the message for an upcoming high PC event, Commander will notify the ground and trigger onboard maneuver planning for an avoidance maneuver. Commander can trigger Autopilot to plan one or multiple maneuvers. Commander stores these candidate adjustment maneuvers, consisting of relative orbit changes from the current orbit. In the single avoidance maneuver case, the maneuver plan is published to the ground. The system can be configured either in Go mode or No-Go mode, where Commander waits for a Go response to proceed or a No-Go message to cancel planned maneuvers. The No-Go mode is also suitable for semi-autonomous operations where the ground is not always in the loop. In the multiple maneuver configuration Commander cancels maneuvers after Autopilot plans and requests different maneuvers from the list of candidate adjustment maneuvers until the maneuver plan limit has been reached. When the maneuver plan limit has been reached, Commander does not cancel the final maneuver. This multiple maneuver method is intended to provide the system with multiple maneuver options to submit to the STM hub to avoid system iterations. We are working to implement the ability to restore a canceled maneuver plan within Autopilot and once completed Commander will be able to select any of the planned maneuvers based on the feedback of the STM hub.

We have currently demonstrated the capabilities of the proposed system's FSW components in software-in-the-loop simulations. Successfully demonstrating the capability to manage a catalog of potential conjunctors and respond to high PC events. We are currently working to transition to processor-in-the-loop testing. This FSW is being developed for deployment as part of an extended mission upload to the NASA Starling swarm of CubeSats.

5. CONJUNCTION ASSESSMENT SPACE TRAFFIC MANAGEMENT HUB

The STM hub is made up of two core components, the catalog and the CA algorithms. It also has supporting APIs to enable interactions. The components of the STM hub are displayed in Fig. 9. The catalog maintains and stores states of potential conjunction objects as orbital ephemeris (OEM) files. The CA algorithms are used to detect potential collisions and compute the probability of collision between objects. The conjunction detection algorithms are based on the "Smart Sieve" method from Rodríguez et al. and implemented using the University of Texas's open source caspy library [18] [15]. The conjunction screening algorithms provide two services: generating the list of objects of interest that pass within a specified radius of given primary object and the respective TCAs, and detecting possible collisions to be passed to the PC computation algorithms when evaluating proposed maneuvers. The list of objects of interest is passed to the CA FSW for evaluating possible future collisions against the on-board navigation. For proposed maneuvers, the initial Conjunction Data Message (CDM) generated by the screening algorithm is passed to the PC computation algorithm. PC computation is achieved using a modified version of the open-source NASA CA Risk Analysis (CARA) tools. [16] These tools were modified from their initial Matlab™ implementation to support running in the open-source Octave environment to enable seamless containerized deployment. The supporting APIs allow for data to be submitted to the STM hub to update the state of objects in the catalog and receive the resulting conjunction data messages. The STM hub requires an adapter layer to connect it to the FSW component and this can take many different forms based on the mission needs. If required for a specific mission, this adapter layer can also connect the STM hub to external data sources and other spacecraft operations. External data sources allow the STM to perform CA against objects that are not directly interacting with the hub. Allowing connections to other spacecraft operations enables the STM hub to support operations with manual operations centers or other potential autonomous control systems.

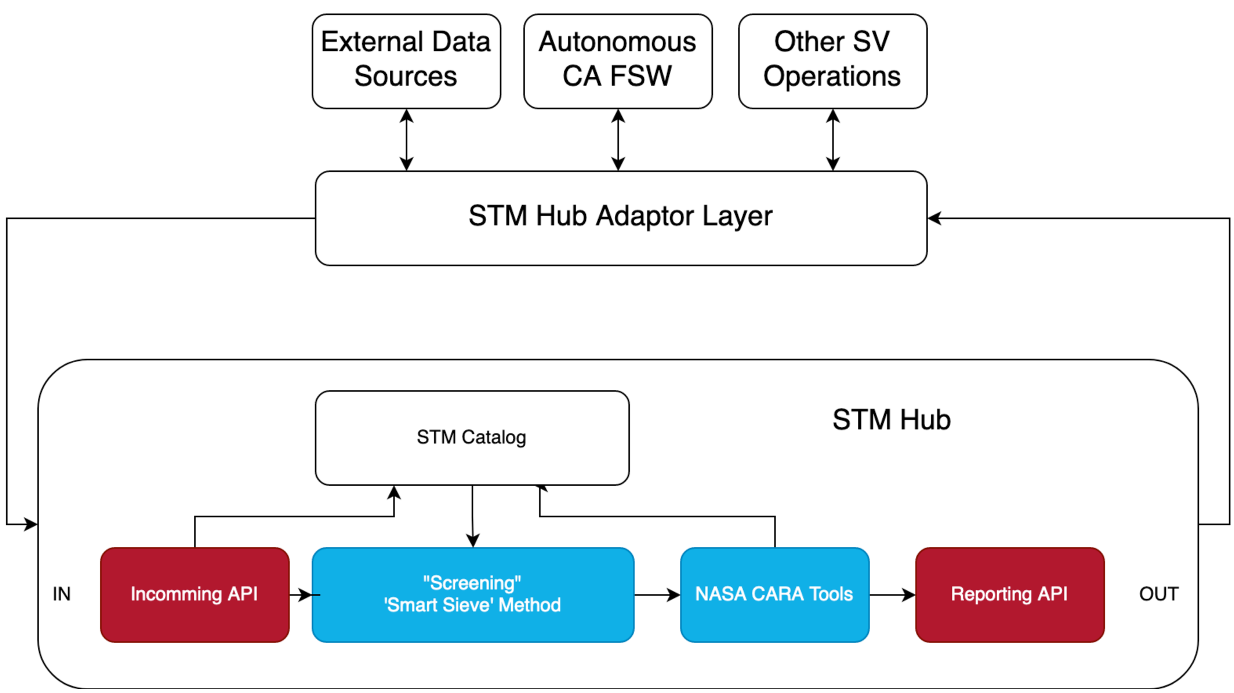


Fig. 9: Basic STM Hub Architecture

6. UPCOMING LEO STM EXPERIMENT

The autonomous STM system described above will be deployed durring an upcoming experiment as part of the NASA Starling Mission. This experiment will be deploying the autonomous CA FSW and STM hub described above. The FSW implementation is deployed as described above with the Go option for maneuver execution and will attempt to demonstrate both the single and multiple maneuver responses to high probability of collision events. Substantial implementation work has gone into the STM hub adapter layer to enable the specific experimental CONOPS. The hub is collecting external data from Space-Trak and from the UT Astrograph catalog, hosted as part of IBM's ARCADE Environment [17]. The STM hub is connected to a prototype STM system being developed by NASA Ames that allows the Starling mission operations team and other operators, such as the SpaceX Starlink team, to connect and interact with the hub. The updated high-level design for this specific implementation of the STM hub is shown in Fig. 10.

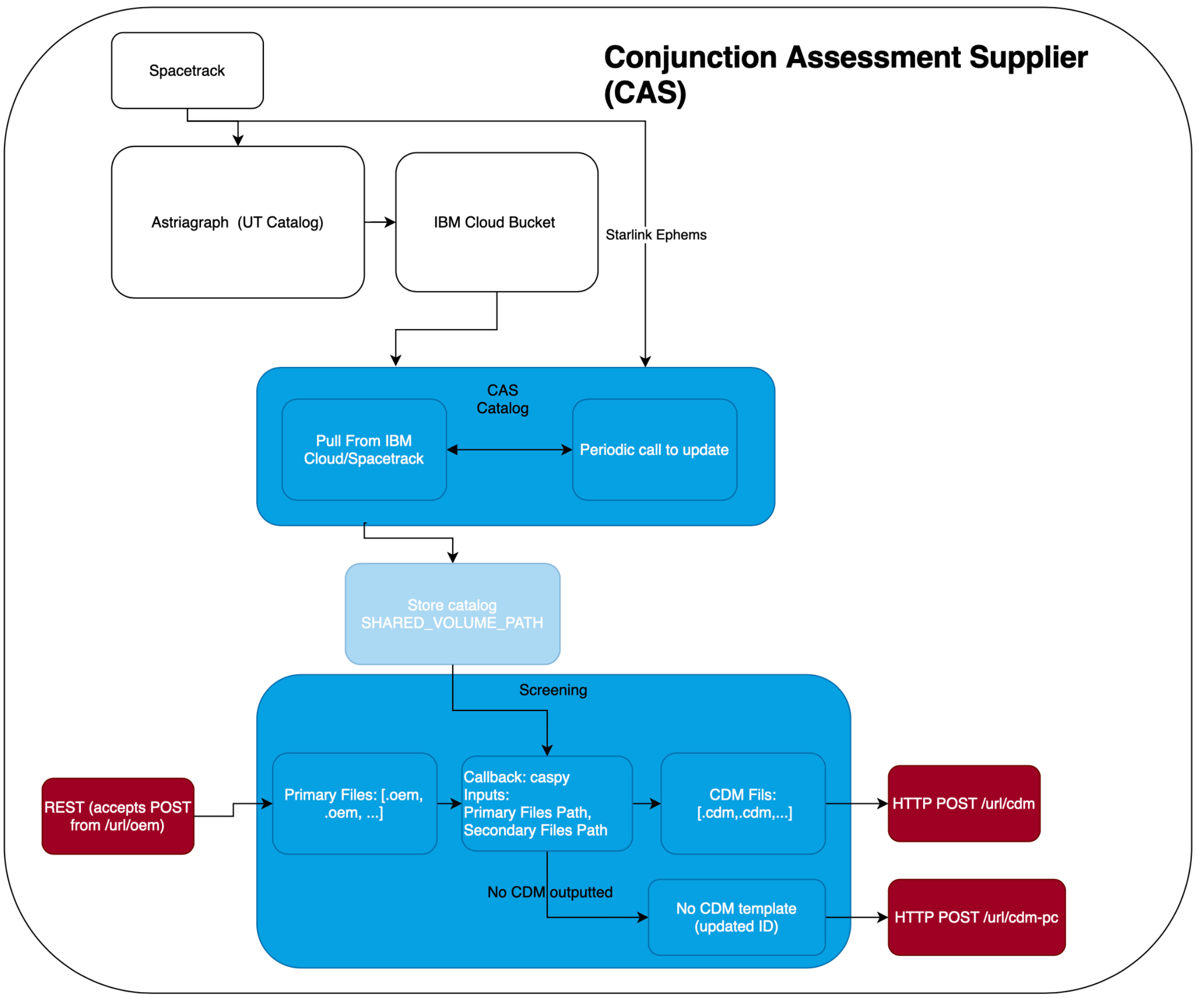


Fig. 10: STM Implementation for Upcoming STM Experiment

Once the primary Starling mission, which is leveraging Emergent's Navigator and Autopilot as part of its Reconfiguration and Orbit Maintenance Experiments Onboard (ROMEO) experiment among other complex swarm operations, is complete our team will work with NASA and SpaceX to perform STM experiments to evaluate this implementation of the proposed STM system. The NASA Starling vehicles are currently targeting 565 km for deployment, relatively close to the SpaceX Starlink constellation. This will allow the coordination of the autonomous maneuvering capabilities on the proposed FSW components and Starlink's autonomous maneuvering and CA system through the proposed STM hub. We expect these experiments to be completed in the latter half of 2023. [18] [13]

7. CONCLUSIONS AND FUTURE WORK

To manage the future growth of the population of systems in Low Earth Orbit, autonomous systems for conjunction assessment will be required to avoid operational gridlock. The proposed system for conjunction assessment has the potential to lay the groundwork for future autonomous coordinated systems. We have successfully demonstrated the proposed flight software and ground software systems in simulation and are working to integrate into an operational deployment. We are working with NASA and SpaceX to deploy the system as part of a follow-on experiment to the upcoming Starling mission. This experiment will demonstrate the proposed system in an operational context and evaluate the feasibility for larger scale deployment. Finally, we are beginning to research the practical effects of scaling the systems for integration with more potential operators of autonomous constellations. Deploying and evaluating the proposed STM system for this application will pave the way for fully autonomous operations and STM of constellations where ground interaction is impractical.

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