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Collision Risk Mitigation by using Conformance Monitoring for Situational Awareness with Pre-departure Strategic Deconfliction in the Presence of Contingent Small Unmanned Aircraft in UTM

Priyank Pradeep
Analytical Mechanics Associates Inc, Moffett Field, California 94035, United States

Seungman Lee
NASA Ames Research Center, Moffett Field, California 94035, United States

Joseph P. Silva
ASRC Federal Data Solutions, Moffett Field, California 94035, United States

José Ignacio de Alvear Cárdenas
San José State University, Moffett Field, California 94035, United States

Vincent H. Kuo
Metis Technology Solutions, Moffett Field, California 94035, United States

Gautam Sai Yarramreddy
Universities Space Research Association, Moffett Field, California 94035, United States

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National Aeronautics and Space Administration (NASA)
Ames Research Center, Moffett Field, California 94035

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Collision Risk Mitigation by using Conformance Monitoring for Situational Awareness with Pre-departure Strategic Deconfliction in the Presence of Contingent Small Unmanned Aircraft in UTM

Summary

This report presents simulation-based studies that quantitatively assess the collision risk mitigation between small unmanned aircraft (sUA-to-sUA) in the small unmanned aircraft systems (sUAS) traffic management (UTM) ecosystem. Two UTM services, i.e., 4D volume-based pre-departure strategic deconfliction (SD) and conformance monitoring for situational awareness (CMSA), are utilized to evaluate sUA-to-sUA collision risk mitigation. To achieve the target level of safety in terms of collision risk, this study also attempts to comprehend the necessity of additional UTM services in addition to CMSA with pre-departure SD. This study specifically focuses on conflicts between small unmanned aircraft (sUA-to-sUA) that originate from different depots and belong to different operators. First, in this study, NASA's Flexible Engine for Fast-time Evaluation of Flight Environments (Fe^3) simulator is integrated with CMSA and 4D volume-based pre-departure SD modules for simulation-based studies. Next, the Fe^3 simulator is utilized to execute the designed simulation scenarios, incorporating varying percentages of randomly generated contingent sUA flights and differing levels of UTM services. Lastly, a data analysis is conducted, considering sUA traffic flow for different scenarios and sUA-to-sUA conflicts between flights originating from different depots. According to simulation-based research, CMSA and 4D volume-based pre-departure SD services work together to mitigate the risk of sUA-to-sUA conflicts in sUA traffic that includes both conforming and contingent sUA. This approach is more effective in avoiding sUA-to-sUA conflicts than using 4D volume-based pre-departure SD service alone. Nevertheless, results indicate that the integration of CMSA with a 4D volume-based pre-departure SD fails to eliminate all sUA-to-sUA conflicts, even when uncertainties are absent and sUA strictly follow their active operational intent, whether nominal or off-nominal. For example, the CMSA with 4D volume-based pre-departure SD is ineffective in resolving a conflict between a nominal sUA flight and a contingent sUA flight if the nominal sUA flight is already airborne when the contingent sUA flight is detected and declared contingent. The results also indicate that the location of the emergency landing port for contingent sUA flights plays a critical role in mitigating the collision risk.

1 Introduction

Small unmanned aircraft systems (sUAS) traffic management (UTM) has been envisioned to have multiple layers of a conflict management model for small unmanned aircraft (sUA-to-sUA) conflicts to ensure the safe, efficient, and scalable operations of sUA. These layers of the conflict management model are strategic deconfliction, tactical separation assurance, and collision avoidance (Ref. 1). At each layer, sUA-to-sUA conflicts are resolved through a series of maneuvers compatible with the operational environment. The objective of the first layer of the conflict management model, i.e., pre-departure strategic deconfliction, is to i) minimize the likelihood of airborne conflicts between sUA operations and ii) maximize the airspace usage, for example, by adjusting the departure times of sUA (Ref. 1, 2). The strategic deconfliction may involve re-planning routes in some scenarios. If the strategic deconfliction was not executed or failed due to uncertainties, the tactical separation assurance layer allows for prompt execution of one or more maneuvers (speed change, altitude change, and path stretch) to avoid an airborne conflict (Ref. 3–5). Finally, the last layer of protection is the onboard Airborne Collision Avoidance System (ACAS), i.e., ACAS-Xu for sUA (Ref. 6).

1.1 Background

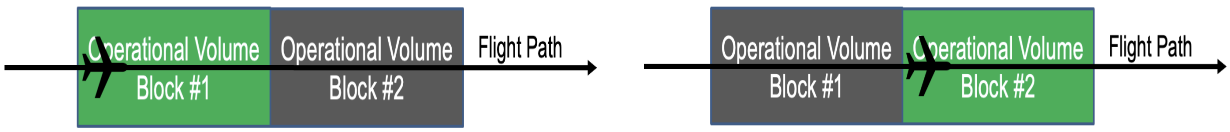
In this section, definitions and concepts that are key to understanding the current studies and results are described.

1.2 4D Volume-based sUA-to-sUA Conflict

As per the standard specification F3548-21 of the American Society for Testing and Materials (ASTM) International, sUA-to-sUA conflict in the UTM ecosystem is defined as follows: *A situation where two operational intents intersect both in space and time. For operational intents to intersect both in space and time, at least one 4D volume from each operational intent must intersect. For two 4D volumes to intersect, the spatial dimensions of the 4D volumes must share at least one point and the start/end time range for the two 4D volumes must overlap* (Ref. 7).

1.2.1 Pre-departure Strategic Deconfliction Using Trajectory-Based Operational Volume Blocks

In the UTM ecosystem, an sUA operator planning to fly beyond visual line of sight (BVLOS) is required to share the trajectory-based operational intent (OI) with other sUA operators/airspace users via the UAS Supplier Service (USS) network (Ref. 1, 2). As shown in Figure 1, the trajectory-based operational intent includes a sequence of 4D (spatiotemporal) operational volume blocks (OVBs) that make up the intended flight profile (Ref. 2, 8, 9). In this research, each OVB is assumed to be fixed in space and has specified entry and exit times for the sUA of an operator per the FAA's UTM concept of operations (Ref. 1, 2, 8). In the operation planning phase, prior to departure, the sUA operator or operator's USS checks the OVBs against other sUA operations for any 4D conflicts. If any spatiotemporal overlapping of OVBs is detected, then negotiation and replanning of the operational intent of the sUA are performed (Ref. 2, 10). For example, at a crossing waypoint, whenever there is a 4D spatiotemporal overlapping of two operational intents of different sUA operators in the prediction context, then deconfliction of overlapping OVBs can be performed via temporal separation at the waypoint using the ground delay strategy for the sUA flights involved in the conflict (Ref. 2, 11).



(a) Notional view of active operational volume block # 1

(b) Notional view of active operational volume block # 2

Figure 1.—Activation (Green) and Deactivation (Grey) of Operational Volume Block (OVB) as an sUA Enters and Exits (Ref. 12)

1.2.2 Nonconforming vs. Contingent sUA Flights

When an sUA flight deviates from its coordinated and activated OI, then the OI of the nonconforming sUA is transitioned to the Nonconforming state. If the sUA remains in the nonconformance beyond a system-defined time-out period, the sUA flight is labeled as a contingent flight (Ref. 7).

1.2.3 Conformance Monitoring for Situational Awareness (CMSA)

The ASTM International's standard specification F3548-21 (Ref. 7) defines Conformance Monitoring for Situational Awareness (CMSA) as a mechanism to deliver situational awareness to stakeholders, including USSs, sUA personnel, and the operator's automation system, when an sUA deviates from its coordinated and activated OI or enters a Contingent state. Situational awareness information is disseminated by the managing USS to relevant USSs for OIs in Nonconforming or Contingent states. The managing USS executing CMSA is tasked with updating the OI by incorporating off-nominal 4D volumes to accurately represent the expected area of nonconformance or contingency. This process enhances situational awareness for relevant USSs regarding OIs in Nonconforming or Contingent states (Ref. 7, 13, 14). USSs with OIs that conflict with or are in close proximity to the resulting non-coordinated OIs are notified, enabling relevant USSs to utilize this information for strategic deconfliction. This process guarantees that all stakeholders are informed, allowing the 4D volume-based pre-departure strategic deconfliction to more effectively reduce risks associated with nonconforming or contingent sUA flights.

1.2.4 Small Near Mid-Air Collision (sNMAC)

From a safety metric standpoint, sUA-to-sUA mid-air collision (sMAC), or the loss of horizontal separation of 3 meters, may be an uncommon occurrence due to the small size of package delivery sUA (Ref. 15). Thus, for a safety metric, any loss of 15.24 m (50 feet) of horizontal separation between sUA-to-sUA is considered a small near mid-air collision (sNMAC), which is an alternative measure for sUA-to-sUA conflict (Ref. 15). This method is based on a modified version of the near-mid air collision (NMAC) loss of separation (LOS) definition, which calls for 500 feet of horizontal separation and 100 feet of vertical separation in commercial aviation (Ref. 15, 16).

1.2.5 Fe^3: Fast-Time Simulation Tool

NASA's fast-time simulation tool called "Flexible engine for Fast-time evaluation of Flight environments (Fe^3)," provides the capability of statistically analyzing a high-density, high-fidelity, and low-altitude traffic systems without conducting flight tests. Using the fast-time simulation capability of Fe^3, stakeholders can study the impacts of critical factors, define requirements, policies, and protocols needed to support a safe and efficient traffic system, assess operational risks, and optimize flight schedules (Ref. 17). It consists of two main functions, i.e., trajectory generation and collision avoidance. To keep the fidelity at a high level, 6-DOF vehicle trajectory models are implemented in the Fe^3 simulator (Ref. 17). In this research, the quadrotor model of sUA in the Fe^3 simulator is used for simulation studies (Ref. 18).

1.3 Motivation

The current study aims to compare the number of sUA-to-sUA conflicts that arise when contingent sUA are present in various UTM BVLOS scenarios, specifically using CMSA with pre-departure SD compared to using pre-departure SD alone. To achieve the target level of safety in terms of collision risk, this study also attempts to comprehend the necessity of additional UTM services in addition to CMSA with pre-departure SD. The following two metrics are used to evaluate the efficacy of CMSA with pre-departure SD across various UTM BVLOS scenarios: i) the risk ratio of sNMACs and ii) the average ground delay of sUA flights.

The remainder of the report is organized as follows. In Section 2, the framework for simulation-based studies using the Fe^3 simulator is presented. In Section 3, simulation results from this research are discussed. Finally, the main findings are summarized in Section 4.

2 Framework of Simulation-Based Studies

2.1 Fast-time Simulation

A fast-time simulation environment is used to understand the Collision risk mitigation for sUA-to-sUA conflicts using CMSA with pre-departure SD in the presence of contingent sUA flights in the UTM ecosystem. The framework for simulation-based studies is as follows (Figure 2 and Figure 3):

- CMSA and pre-departure SD modules are integrated with Fe^3 (fast-time simulator) to create the simulation environment.
- First-come, first-served scheduling is used for on-ground sUA flights, while the mixed-integer nonlinear programming (MINLP) solver determines the sequencing order at the crossing waypoint (Ref. 19).
- Following pre-departure SD, the deconflicted flight plans of sUA are sent to the fast-time simulator for execution. In the fast-time simulator, a specific proportion of sUA flights are altered at random to fly a deviating flight path in a contingent mode towards an emergency landing port, as shown in Figure 4.
- If a flight stays outside its active OI (active OVB) for five seconds or longer, it is declared as a contingent flight by the sUA operator.
- Whenever the CMSA module detects and declares a contingent sUA flight during the simulation run, the pre-departure SD module recalculates the scheduled times of departure (STDs)

of all on-ground sUA, accounting for both airborne nominal and contingent sUA flights belonging to the other operator. Pre-departure sUA flights, however, continue to follow the same intended flight path.

- The pre-departure SD module at a depot also takes into account the minimum departure time interval between STDs for on-ground sUA flights during initial calculation and recalculations. Nevertheless, it ignores conflicts between nominal and contingent sUA flights operated by the same operator, assuming that given the degree of position awareness and surveillance, these conflicts would be resolved by tactical separation assurance by the operator.
- The CMSA module's detection and declaration of a contingent sUA flight, communication of the contingent sUA flight's info to the pre-departure SD, and the recomputation of STDs by the pre-departure SD module do not account for the communication and computation latencies.

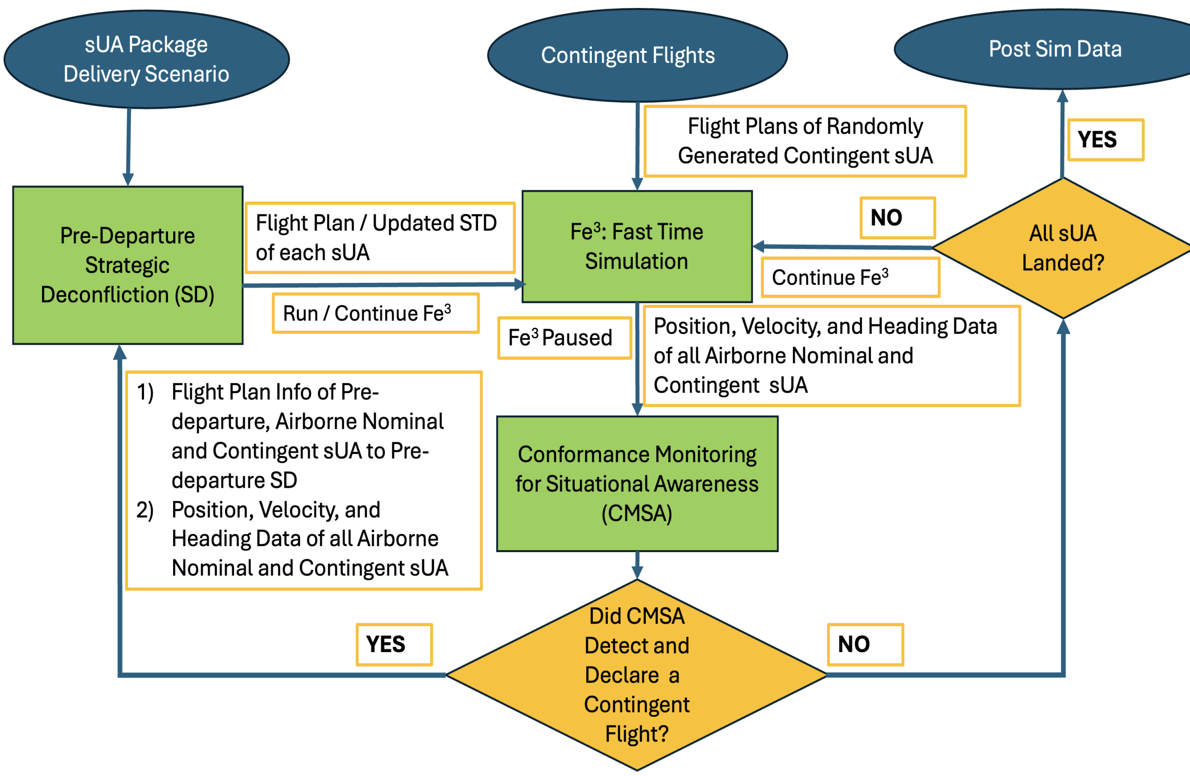


Figure 2.—Framework of Simulation-Based Studies

2.1.1 Pre-departure SD Module

In this research, the pre-departure strategic deconfliction is applied to sUA flying on the network structure of routes as shown in Figure 4. Four types of temporal separation constraints are imposed between sUA flights. First, for each sUA flight, a temporal separation constraint is imposed between

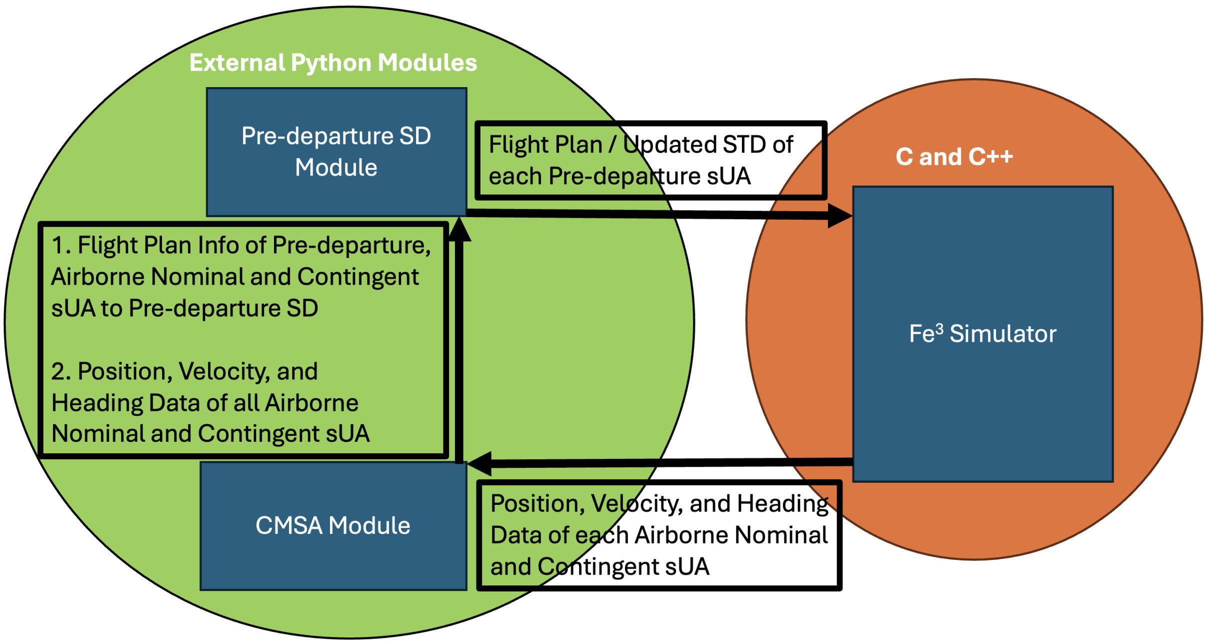


Figure 3.—Depiction of the Information Flow between CMSA Module, Pre-departure SD Module, and Fe^3 Simulator

the earliest time of departure (ETD) and scheduled time of departure (STD) as follows (Ref. 12, 19):

$$\text{STD(i)} \geq \text{ETD(i)} \tag{1}$$

where the earliest time of departure, i.e., ETD(i) of the i^{th} sUA is defined as the sum of on-demand service request time for a package delivery (ODT(i)), and the flight preparation time (Δt_{prep}) (Ref. 12):

$$\text{ETD(i)} = \text{ODT(i)} + \Delta t_{\text{prep}} \tag{2}$$

where Δt_{prep} is the time required for preparing the sUA flight, which includes time for on-demand order processing, packaging of order, loading of delivery package to the assigned sUA, and pre-flight checks.

Next, a minimum temporal separation constraint ($\Delta t_{\text{Departure}}$) is imposed between STDs of a leading sUA and trailing sUA as follows (Ref. 12, 19):

$$\text{STD(i+1)} \geq \text{STD(i)} + \Delta t_{\text{Departure}} \tag{3}$$

Next, when a rescheduling of on-ground sUA is performed by the pre-departure SD upon detection of a contingent sUA flight during the simulation (Figure 2 and Figure 3), a minimum temporal separation constraint (Δt_{CST}) is imposed between STDs of each pre-departure sUA and the current simulation time (CST) so that the STDs are computed in the future:

$$\text{STD(i)} \geq \text{CST} + \Delta t_{\text{CST}} \tag{4}$$

The value of Δt_{CST} is assumed to be 10 seconds.

Finally, a minimum temporal separation ($\Delta t_{\text{Crossing Waypoint}}$) constraint imposed between scheduled times of arrival (STA)s of two sUA belonging to different operators at the crossing waypoint is as follows (Ref. 12, 19):

$$(\text{STA(j)} - \text{STA(i)})\omega(i,j) + (\text{STA(i)} - \text{STA(j)})(1 - \omega(i,j)) \geq \Delta t_{\text{Crossing Waypoint}} \tag{5}$$

where STA(i) and STA(j) are the scheduled times of arrival to the crossing waypoint of the i^{th} sUA and j^{th} sUA, respectively, and $\omega(i,j)$ is the binary decision variable to decide which sUA will sequence the crossing waypoint first, i.e., i^{th} sUA or j^{th} sUA (Ref. 20):

$$\omega(i,j) = \begin{cases} 1, & \text{if } i^{th} \text{ sUA sequences before } j^{th} \text{ sUA}, \\ 0, & \text{if } j^{th} \text{ sUA sequences before } i^{th} \text{ sUA}, \end{cases} \tag{6}$$

Figure 4.—Network Structure of Routes for Generating Simulated UTM Scenarios in San Francisco Metropolitan Area (Courtesy OpenStreetMap(Ref. 21))

2.1.2 CMSA Module

The CMSA module periodically checks for any contingent sUA flight(s) in the simulation environment. The CMSA module identifies an sUA flight as a contingent sUA flight if it remains outside its coordinated and activated OI (active OVB) for 5 seconds or more. If the CMSA module detects a contingent sUA flight in the simulation, the pre-departure SD module recalculates the STDs for all sUA flights that are still on the ground, taking into account both airborne nominal and contingent sUA flights. In this research, contingent sUA flights are randomly generated such that they deviate from the planned flight path and fly at a constant heading towards an emergency landing port either Southwest or Southeast as shown in Figure 4.

2.1.3 sUA Trajectories

To study UTM BVLOS flight operations in the presence of contingent sUA flights, a quadrotor aerial vehicle model (flight kinematics, flight dynamics, power required, and energy consumption) is incorporated in the Fe^3 simulator to compute sUA trajectories (Ref. 17, 22). In this research, the Fe^3 simulator is used to generate sUA trajectories. The tactical separation assurance functionality of the simulator is intentionally turned off to isolate and understand the efficacy for CMSA with 4D volume-based pre-departure strategic deconfliction of sUA in the presence of contingent sUA flights in the UTM ecosystem.

2.1.4 UTM Scenarios

Figure 4 illustrates a network structure of routes that exhibit varying levels of air traffic density for sUA operations (Ref. 23). This figure highlights the critical intersections and potential bottlenecks that can impact the safety and efficiency of sUA operations. For various case studies, the traffic density of sUA on each route is varied using combination of OVB sizing, and on-demand service requests as shown in Table 1. The on-demand service request to deliver packages using sUA at each operations depot is simulated using a Poisson distribution (Ref. 12, 19).

Pre-departure SD of sUA flights is initially carried out in a deterministic environment, that is, without contingent sUA flights, to resolve sUA-to-sUA conflicts for various UTM scenarios. The nominal sUA flights are then randomly converted to contingent sUA flights (as indicated in Table 1) in the fast-time simulation environment to examine how different UTM services affect safety and efficiency metrics like the risk ratio of sNMAC and the average ground delay. Contingent sUA flights land on either the emergency Southwest location or the emergency Southeast location, as indicated in Table 1 and Figure 4.

Considering the 2.4 nm by 4.0 nm airspace area shown in Figure 4, and the on-demand package delivery rate per depot of $[\frac{1}{15}, \frac{1}{30}]\ \frac{1}{\text{Seconds}}$ translates to a maximum air-traffic density of [14.57, 7.28] $\frac{\text{sUA Operations}}{\text{hr}.km^2}$, in the absence of different types of temporal separation constraints.

Table 1.—Values of Parameters Used in Simulation-Based Studies

Definition	Value
OVB Sizing (Transit Time):	[15, 30] Seconds
Package Delivery On-Demand Rate:	$[\frac{1}{15}, \frac{1}{30}]\ \frac{1}{\text{Seconds}}$
Percentage of Contingent sUA Flights:	[0, 10, 30] %
Contingent sUA Flights Emergency Landing Locations:	Southwest (37.772, -122.470) Southeast (37.758, -122.410)

2.2 Safety and Efficiency Metrics

The following safety and efficiency metrics are computed for various scenarios post-simulation for sUA-to-sUA conflicts of sUA in the cruise phase belonging to different operators:

2.2.1 sNMACs Risk Ratio

In a UTM scenario, the number of sNMACs for sUA-to-sUA conflicts between sUA flights originating from different depots is computed based on the definition for NMAC per (Ref. 24), i.e., when the lateral separation between flight track of sUA $\leq$ 50 ft and vertical separation between flight track of sUA $\leq$ 15 ft at any instance of simulation time. Therefore, for a given UTM scenario, the number of sNMAC instances is computed as follows:

$$\#\text{ of sNMACs} = \sum_{i=1}^{N_A}\sum_{j=1}^{N_B} d_{ij} \tag{7}$$

where N is the total number of sUA flights in a given UTM scenario, N_A and N_B are the total number of sUA flights departing from depot A and depot B, and d_{ij} is the binary variable for a pairwise conflict between sUA(i) and sUA(j) departing from different depots, defined as follows:

$$d_{ij} = \begin{cases} 1, & \text{pairwise sUA, i.e., (i,j) are in sNMAC,} \\ 0, & \text{otherwise,} \end{cases} \tag{8}$$

The sNMAC risk ratio is computed as follows (Ref. 25):

$$\text{sNMACs Risk Ratio} = \frac{(\#\text{ of sNMACs})_\text{n}}{(\#\text{ of sNMACs})_\text{m}} \tag{9}$$

The number of UTM services available in the scenario is represented by n and m in the numerator and denominator of Equation 9, while the number of sNMACs indicates the number of sUA-to-sUA conflicts that were noted in the corresponding UTM scenario. Since the goal is to measure the safety benefits of using different services, n must be greater than m. For example, n could represent the availability of CMSA and pre-departure SD services, and then m would represent either the availability of pre-departure SD alone or none of the UTM services. However, in this research, m represents the availability of none of the UTM services. If the sNMACs risk ratio is less than one, then the UTM service(s) reduces the number of sNMACs. For example, a risk ratio of 0.1 indicates a 90% reduction in risk; therefore, small values are desirable (Ref. 25).

2.2.2 Average Ground Delay

The following equation calculates the average ground delay for a UTM scenario (Ref. 12):

$$\text{Minimize} \quad \frac{\sum_{i=1}^{N_A}\text{GD(i)} + \sum_{j=1}^{N_B}\text{GD(j)}}{N_A + N_B} \tag{10}$$

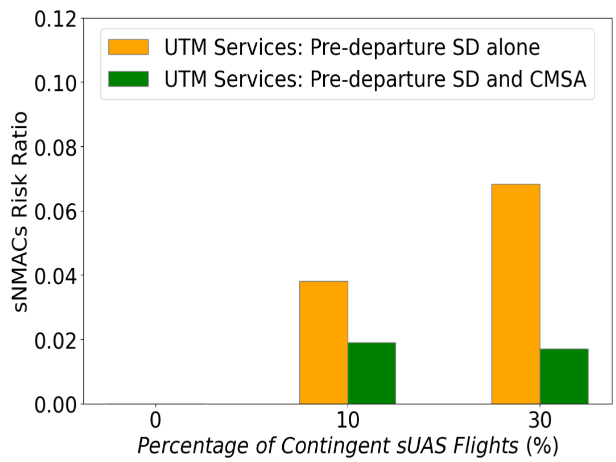
where GD(i) and GD(j) are the ground delays of the i^{th} sUA of the operator A, and j^{th} sUA of the operator B, respectively. Here, N_A and N_B are the total number of flights scheduled to depart from depot A and depot B, respectively.

The ground delay of the i^{th} sUA is defined as the difference between its STD and ETD as follows:

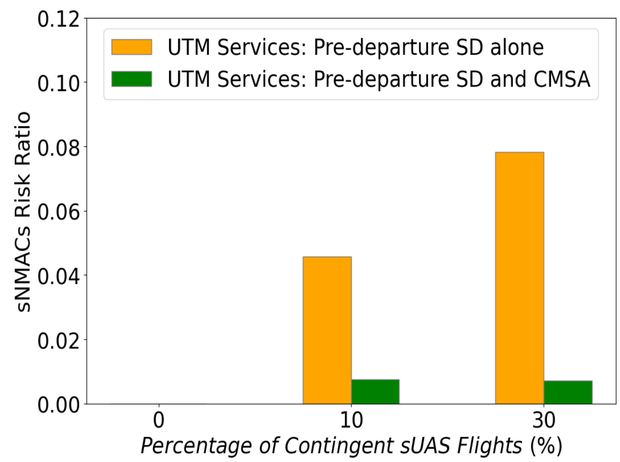
$$\text{GD(i)} = \text{STD(i)} - \text{ETD(i)} \tag{11}$$

3 Results

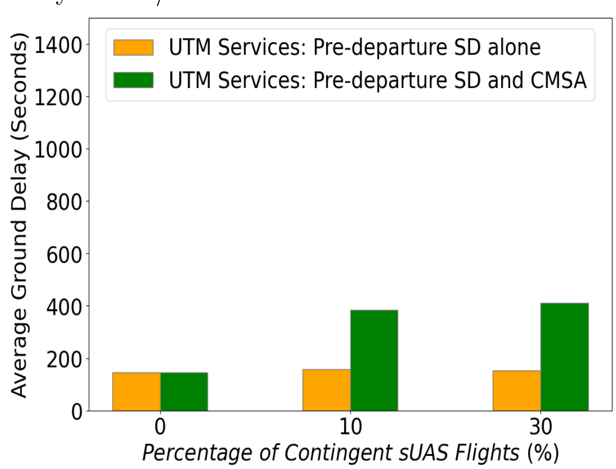
In case studies I and II, the sUA traffic for each depot is modeled using a Poisson distribution, with mean inter-departure intervals of 15 and 30 seconds, respectively, as indicated in Table 1. The minimum temporal separation between the leading and trailing sUA's STDs departing from the same depot is equal to the OVB transit time in seconds. Two OVB lengths, 300 and 600 meters, have been chosen based on the transit time (T_{OVB}) 15 and 30 seconds of an sUA in the active OVB, based on the groundspeed of 20 m/s in the absence of wind, as shown in Table 1. The following three levels of UTM services are considered for each UTM scenario: i) pre-departure SD and CMSA both absent, ii) pre-departure SD only, and iii) pre-departure SD and CMSA both present.



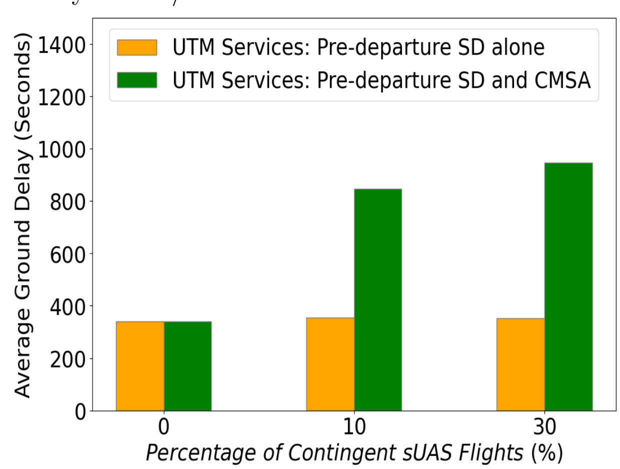
(a) OVB Transit Time 15 Seconds and Package Delivery Rate 1/15 Seconds^{-1}



(b) OVB Transit Time 30 Seconds and Package Delivery Rate 1/30 Seconds^{-1}



(c) OVB Transit Time 15 Seconds and Package Delivery Rate 1/15 Seconds^{-1}



(d) OVB Transit Time 30 Seconds and Package Delivery Rate 1/30 Seconds^{-1}

Figure 5.—Case Study I (Emergency Landing Port Near the Depot B): i) Subfigures 5a and 5b: sNMACs Risk Ratio, and ii) Subfigures 5c and 5d: Average Ground Delay

3.1 Case Study I: Emergency Landing Port Near the Depot B

This case study is based on 4-by-4 routes structure, with emergency landing port located near the depot B as shown in Figure 4. There are in total 100 sUA flights per scenario, with 50 sUA flights scheduled from each operations depot. Ten runs with various seed values for traffic generation make up each datapoint, and the outcomes are then averaged across all runs. The results suggest the following:

- As illustrated in Subfigures 5a and 5b, for a given scenario, the sNMACs risk ratio reduces in the presence of 4D volume-based pre-departure SD and CMSA when compared to 4D volume-based pre-departure SD acting alone.

- From Subfigures 5c and 5d, it can be observed that the average ground delay of sUA flights increases in the presence of 4D volume-based pre-departure SD and CMSA compared to 4D volume-based pre-departure SD acting alone. This observation can be attributed to the fact that the pre-departure SD module recomputes STDs of all on-ground sUA flights whenever a contingent flight is detected and declared by the CMSA module to avoid new sUA-to-sUA conflicts.

- Additionally, Subfigures 5c and 5d demonstrate that as OVB sizing increases, so does the average ground delay of sUA flights.

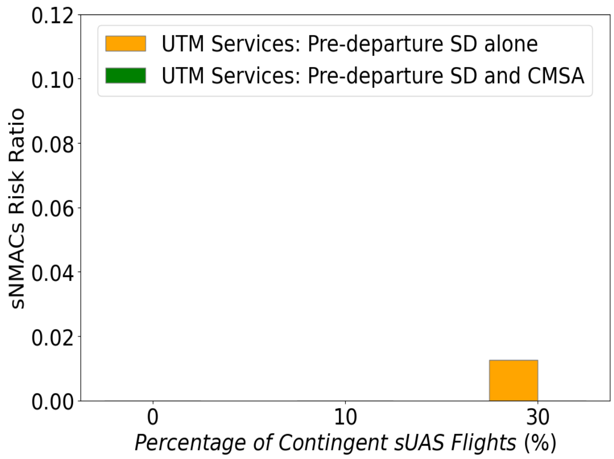
- Further analysis of flight track data for nominal and contingent sUA flights belonging to different operators revealed that when contingency was detected and declared, CMSA with pre-departure SD was unable to resolve conflicts between contingent sUA flights and nominal sUA flights that had already taken off. Therefore, multi-layered services, such as airborne SD, tactical separation assurance, and onboard detect and avoid (DAA) systems, along with pre-departure SD and CMSA, may be needed to mitigate conflicts between already-airborne sUA and contingent sUA flights.

3.2 Case Study II: Emergency Landing Port Away from the Depot B

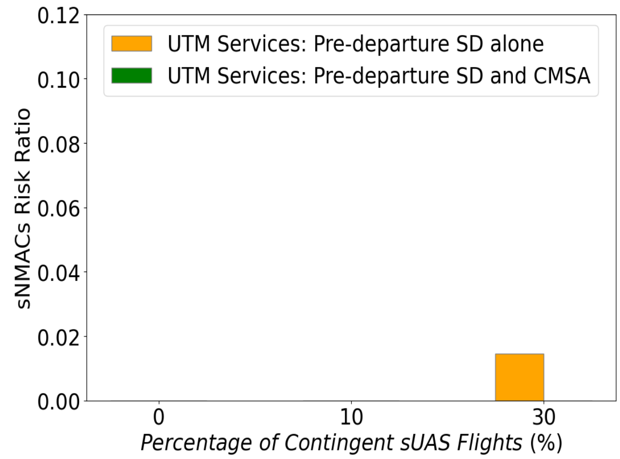
This case study is based on 4-by-4 routes structure, with emergency landing port located away from the depot B as shown in Figure 4. There are in total 100 sUA flights per scenario, with 50 sUA flights scheduled from each operations depot. Five runs with various seed values for traffic generation make up each datapoint, and the outcomes are then averaged across all runs. The results suggest the following:

- For a given scenario, the sNMACs risk ratio decreases when 4D volume-based pre-departure SD and CMSA are present as opposed to when 4D volume-based pre-departure SD is acting alone, as shown in Subfigures 6a and 6b.

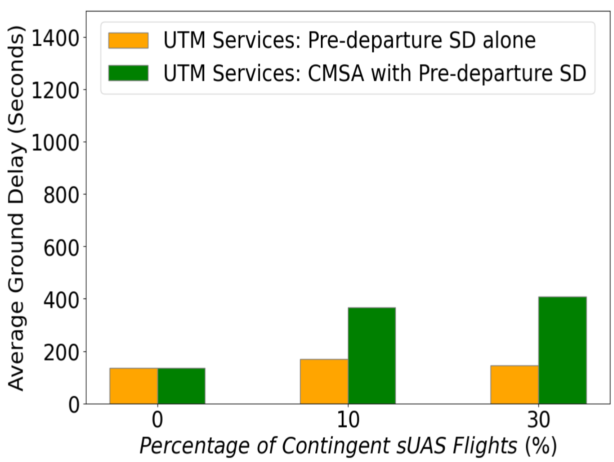
- Despite the fact that Subfigures 6a and 6b display zero values for sNMAC risk ratios when both UTM services, i.e., pre-departure SD and CMSA are present. The conflict between nominal sUA flights that have already taken off and contingent sUA flights were not resolved by CMSA with pre-departure SD. A detailed look at the small simulation data (five runs) showed that there were no conflicts between contingent and already-airborne nominal sUA flights in those simulation runs.



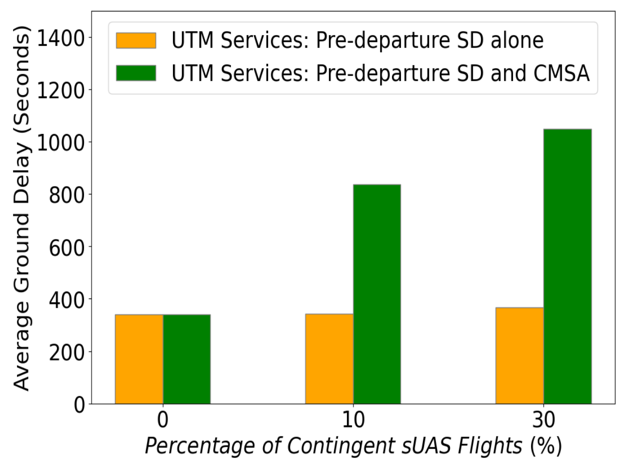
(a) OVB Transit Time 15 Seconds and Package Delivery Rate 1/15 Seconds^{-1}



(b) OVB Transit Time 30 Seconds and Package Delivery Rate 1/30 Seconds^{-1}



(c) OVB Transit Time 15 Seconds and Package Delivery Rate 1/15 Seconds^{-1}



(d) OVB Transit Time 30 Seconds and Package Delivery Rate 1/30 Seconds^{-1}

Figure 6.—Case Study II (Emergency Landing Port Away from the Depot B): i) Subfigures 6a and 6b: sNMACs Risk Ratio, and ii) Subfigures 6c and 6d: Average Ground Delay

- As shown in Subfigures 6c and 6d, the average ground delay for sUA flights increases when 4D volume-based pre-departure SD and CMSA are both used, compared to when only 4D volume-based pre-departure SD is used. This happens because the pre-departure SD module recalculates the STDs for all on-ground sUA flights whenever the CMSA module detects and declares a contingent flight to avoid new sUA-to-sUA conflicts.

- Additionally, Subfigures 6c and 6d demonstrate that as OVB sizing increases, so does the average ground delay of sUA flights.

- Comparing Subfigures 5a and 5b with 6a and 6b, respectively, reveals that the emergency landing port's placement positively affects the UTM ecosystem's safety (lower sNMAC risk ratios) when the emergency landing port is positioned away from the second operator.

3.3 Discussion

The simulation approach used in this study has been valuable for illuminating the impacts of pre-departure SD and CMSA on identifying and resolving collision risks among sUA operating alongside contingent sUA in the UTM airspace. The UTM community could conduct additional studies to understand how multi-layered services, such as airborne SD, tactical separation assurance, and onboard detect and avoid (DAA) systems, along with pre-departure SD and CMSA, impact overall collision risk and efficiency.

The results also indicate that the location of the emergency landing port for contingent sUA flights plays a critical role in mitigating the collision risk. As a result, research is required to determine the best emergency landing port location in relation to the given network structure of routes in UTM.

4 Conclusions

This report presented simulation-based studies that quantitatively assessed the collision risk mitigation between small unmanned aircraft (sUA-to-sUA) in the small unmanned aircraft systems (sUAS) traffic management (UTM) ecosystem. Two UTM services, i.e., 4D volume-based pre-departure strategic deconfliction (SD) and conformance monitoring for situational awareness (CMSA), were utilized to evaluate sUA-to-sUA collision risk mitigation. To achieve the target level of safety in terms of collision risk, this study also attempted to comprehend the necessity of additional UTM services in addition to CMSA with pre-departure SD. This study specifically focused on conflicts between small unmanned aircraft (sUA-to-sUA) that originate from different depots and belong to different operators. First, NASA's Flexible Engine for Fast-time Evaluation of Flight Environments (Fe^3) simulator was integrated with CMSA and 4D volume-based pre-departure SD modules for simulation-based studies. Next, the Fe^3 simulator was utilized to execute the designed simulation scenarios, incorporating varying percentages of randomly generated contingent sUA flights and differing levels of UTM services. Lastly, a data analysis was conducted, considering sUA traffic flow for different scenarios and sUA-to-sUA conflicts between flights originating from different depots. According to simulation-based research, CMSA and 4D volume-based pre-departure SD services worked together to mitigate the risk of sUA-to-sUA conflicts in sUA traffic that included both conforming and contingent sUA. This approach was found to be more effective in avoiding sUA-to-sUA conflicts than using 4D volume-based pre-departure SD service alone. Nevertheless, the research showed that integrating CMSA with a 4D volume-based pre-departure SD did not eliminate all sUA-to-sUA conflicts, even when uncertainties were absent and sUA strictly followed their active operational intent, whether nominal or off-nominal. For example, the results indicated that the CMSA with 4D volume-based pre-departure SD was ineffective in resolving a conflict between a nominal sUA flight and a contingent sUA flight if the nominal sUA flight was already airborne when the contingent sUA flight was detected and declared contingent.

The simulation approach used in this study has been valuable for illuminating the impacts of pre-departure SD and CMSA on identifying and resolving collision risks among sUA operating alongside contingent sUA in the UTM airspace. The UTM community could conduct additional studies to understand how multi-layered services, such as airborne SD, tactical separation assurance, and onboard detect and avoid (DAA) systems, along with pre-departure SD and CMSA, impact overall collision risk and efficiency. The findings also demonstrated that the positioning of the emergency landing port for contingent sUA flights is pivotal in reducing collision risk. As a result, further research is required to determine the optimal emergency landing port location in relation to the given network structure of routes in UTM.

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