A Method of Compliance for Achieving Target Collision Risk in UTM Operations

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This work proposes a method of compliance to ensure that the collision risks among small unmanned aircraft systems meet the target level of safety. This method presents what is needed for a strategic conflict detection service to achieve the target level of safety when conflict between operational intents are not permitted in nominal situations. A volume-based collision risk model is first developed to calculate the UA-to-UA collision risk given any two operational intent volumes. With this collision risk model, a test strategy is then proposed to assess if a strategic conflict detection service can reduce the collision risk and meet the target level of safety. The method also specifies operational data that are required to be collected to verify if requirements on conformance are being met. Additionally, two new requirements are identified and proposed by this method beyond the current standard for strategic conflict detection. In the sensitivity analysis, three main factors contributing to the collision risk are investigated. The analysis shows that buffers should be considered in a strategic conflict detection service when deconflicting operational intents. The results also reveal that the selection of test cases plays an important role in evaluating the strategic conflict detection service, and they should be representative and sufficiently complex in evaluation tests.

I. Introduction

As one of the most disruptive technologies in recent years, the applications of Unmanned Aircraft Systems (UASs) present enormous incentives for business across many sectors, such as agriculture, delivery, healthcare, energy, security, and safety. While the commercial interest in UAS operations continues to mount up, a small scale of Visual-Line-Of-Sight (VLOS) and Beyond-Visual-Line-Of-Sight (BVLOS) operations have started in many countries. In the United States, UAS operations are allowed to fly over people with a Part 107 [1] certificate waiver or an exemption, whereas BVLOS UAS for package delivery can be operated under Part 135, unless authorized under a certificate of waiver or an exemption [2]. However, how to promote routine and scalable UAS BVLOS operations while ensuring operational safety remains a challenge for regulators and the aviation community.

In 2015, NASA, industry, and the FAA began to develop a federated and automated UAS traffic management (UTM) system [3–6] to provide core services for operators to share intent and coordinate operations. The UTM system consists of UTM Service Suppliers (USSs), Discovery Synchronization Service (DSS), Suplemental Date Service Providers (SDSP), and an interface to the National Airspace System (NAS). In the past several years, the federated UTM system has been tested and evolved through many field tests, including NASA's TCL series [7–10], FAA's UTM Pilot Program (UPP) [11], Integration Pilot Program (IPP) [12], UTM Field Test (UFT) [13], and BEYOND Program [14]. Along with the development of the UTM system, an initial USS specification and requirements were published by NASA [15].

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Based on that, the standard F3548-21 [16] was developed and published by ASTM International to mitigate the UAS operational risks by requiring core services like Strategic Conflict Detection (SCD) and Aggregated Operational Intent Conformance Monitoring (ACM).

How to ensure that the UA-to-UA collision risk meets the Target Level of Safety (TLS) is still the rudimentary question needed to be addressed before routine and scalable operations can become a reality. Although operational data were collected through aforementioned field tests and initial standards and requirements have been developed, no method of compliance (MOC) has been provided to show that the TLS will be achieved as long as those requirements and standards are satisfied. Without such MOC, it is unclear that if there exists any gap in current requirements to achieve the TLS and how much testing operational data will be sufficient to enable routine and scalable operation. Recent studies [17, 18] showed that services like SCD can reduce the UA-to-UA collision risk significantly; however, the analysis results couldn't guarantee that the TLS can be achieved for any use cases with the SCD. The results are not generalized and are dependent on scenarios, vehicle dynamics, and the way of modeling intent volumes. For instance, only trajectory-based intent was included, and it has to be modeled in a certain way, which is not required in current ASTM requirements nor proposed by authors as new requirements.

This work proposes the first method of compliance (MOC) to ensure that the UA-to-UA collision risk meets the TLS. The MOC is developed based on the current ASTM requirements [16] and works for situations when conflict between operational intents is not permitted. A volume-based collision risk model is developed to calculate the UA-to-UA collision risk between two operational intent volumes. A test strategy is then presented to assess if a SCD service can mitigate the UA-to-UA collision risk and meet the TLS. In addtion, new requirements are identified to fill the gap in current ASTM standards. Sensitivity analysis is conducted to understand the main factors contributing the collision risk calculation.

In this paper, Section II presents background on three fronts: method of compliance, collision risk model, and ASTM UTM specification. Section III describes the method of compliance proposed for satisfying the TLS. The MOC includes volume-based collision risk model, requirement gap identification, test strategy and operational data collection. Section IV presents sensitivity analysis for the main factors that contribute to the UA-to-UA collision risk. Section V provides the authors' insights about this method, and Section VI concludes this work.

II. Background

To better understand the method of compliance proposed in this work, it is beneficial to review the existing literature, as well as to provide background information on the collision risk model, and ASTM specification on UTM operations.

A. Method of Compliance

According to the Advisory Circulars issued by the FAA [19, 20], a method of compliance (MOC), or a means of compliance, is one method, but not the only method, to show compliance with a regulatory requirement. The complexity of an MOC depends on the complexity of the requirement. An MOC can be straightforward if a requirement could be directly addressed. For example, one requirement in AC107-2A [20] for small UAS operating over people is that a small UAS "*does not contain any exposed rotating parts that would lacerate human skin*". The FAA-provided MOC [20] is to manufacture the small UAS so that the propellers are internal to the UAS, such as in a ducted fan configuration, then the rotating parts would not be exposed, and the requirement would be satisfied.

However, suppose a regulatory requirement cannot be directly addressed. In that case, an MOC can help distill the original requirement into sub-requirements and show that satisfying the sub-requirements is equivalent to satisfying the original requirement. For example, another requirement in AC107-2A is that a small UAS "*does not exceed the applicable injury severity limit upon impact with a human being*". The FAA-provided MOC [20] is developed through an applicant's calculation of the small unmanned aircraft's maximum kinetic energy. A formula (as shown in Eq. 1) was developed under the MOC to calculate the small unmanned aircraft's maximum kinetic energy.

$$KE_{\text{impact}} = 0.0155 \cdot w \cdot v^2 \tag{1}$$

Given the weight w of the small UAS, the original requirement would be satisfied if the speed v is less than a calculated limit.

$$v = \sqrt{\frac{KE_{\text{impact}}}{0.0155 \cdot w}} \tag{2}$$

B. Collision Risk Model

As one of the most influential collision risk models, the Reich collision risk model was developed to evaluate the separation minima for flights crossing the North Atlantic Ocean [21–23]. It is approved by the International Civil Aviation Organization (ICAO) [24] to evaluate collision risks associated with a given separation minimum. The Reich model is applicable when the following conditions are satisfied:

1) Routes are parallel or close to parallel
2) Uncertainties in the vertical, longitudinal, and lateral deviation of an aircraft are independent
3) All uncertainties are time-independent
4) All aircraft are flying constant-velocity trajectories
5) Sufficient traffic data is available to derive a probabilistic distribution
6) No mitigation action is assumed when two aircraft are about to collide

Conditions 1, 2, 3, and 4 show that the Reich model is more accurate for long-range air traffic situations such as oceanic traffic. It is not applicable for risk estimation in other situations, such as terminal area conflicts [25]. It is certainly not applicable for small UAS operations that typically last about 20-30 minutes with random route orientations driven by missions and airspace constraints [26, 27]. Condition 5 shows that the Reich model is a data-driven risk model, which makes it difficult to use for small UAS operations, for which little data is currently available. The dilemma is that the collision risk needs to be understood before scalable and routine BVLOS operations can be authorized. However, there will not be sufficient and representative operational data before that happens.

To address the data needs for data-driven models, researchers tried to generate sUAS operational data through simulations [26–28]. Many assumptions have to be made to generate the simulated data. These assumptions cover almost every aspect of small UAS operations: flight dynamics and control, mission types, flight routes, navigation and sensors, terrain, and weather conditions. While these analyses provide insight into the collision risk of small UAS operations, it is hard to justify that the simulated data are generalized and representative, given the specific assumptions made in the simulations.

C. ASTM Standard Specification on UTM

As an initial effort to facilitate UTM-related regulations, the ASTM Committee published a standard specification for UAS Traffic Management (UTM) UAS Service Supplier (USS) Interoperability [16]. This specification is focused on strategic aspects of UAS operations. It addresses the performance and interoperability requirements, including associated application programming interfaces (APIs), for a set of UTM roles performed by the UAS Service Suppliers (USSs) supporting UAS operations. The roles defined in this specification are: Strategic Coordination (SC), comprising the Strategic Conflict Detection (SCD) and Aggregate Operational Intent Conformance Monitoring (ACM) services; Conformance Monitoring for Situational Awareness (CMSA); Constraint Management (CSTM), comprising the Constraint Management service; and Constraint Processing (CSTP), comprising the Constraint Processing service. Table 1 presents an overview of requirements and associated roles defined in the ASTM standards.

Requirements	Role				Number of Requirements
	SC	CMSA	CSTM	CSTP	
Common Requirements	✓	✓	✓	✓	11
Operational Intent Creation and Modification	✓	✓			9
Strategic Conflict Detection Service	✓				24
ACM	✓				3
CMSA		✓			25
Constraint Management Service			✓		22
Constraint Processing Service		✓		✓	10
Logging	✓	✓	✓	✓	11
Discovery and Synchronization Service					10

Table 1 Requirements defined in ASTM F3548-21 [16]

As a result of collective efforts by the community, the ASTM standards on USS is an important reference and has been widely considered as a foundation for further test, implementation, analysis, and regulation development.

III. Method of Compliance

This section presents a method of compliance that bridges the SCD service and associated requirements in current ASTM specification and the target level of safety for UA-to-UA collision risk. Gaps in the ASTM specification are identified and addressed with new proposed requirements, and a volume-based collision risk model is developed. After that, a test strategy or evaluation process to examine if an SCD service can achieve the target level of safety for UA-to-UA collision risk is proposed. Finally, the operational data that should be collected for requirement compliance verification is specified and discussed.

A. Relevant ASTM Requirements

Three types of ASTM requirements are directly related to UA-to-UA collision risk: Operational Intent Creation, Modification and Deletion, and Strategic Conflict Detection. Operational Intent Creation, Modification and Deletion basically requires a UA to conform with its operational intent with 95% conformance:

> *"Operational intents shall (OPIN0010) be constructed such that the UA's actual position is inside an operational intent in the Activated state at least 95 percent of total flight time."*

In the ASTM specification, two types of operational intents were discussed: area-based operational intent and trajectory-based operational intent. It was also suggested that trajectory-based operational intent could be developed based on the total system error (TSE) of the UAS. However, there are no requirements on how to develop operational intent other than the requirement of 95% conformance. It reflects the reality that at the current stage it is hard to define TSEs for all small UASs under different types of missions.

Strategic Conflict Detection includes two types of requirements: one permits conflict (4D overlapping) between operational intents with equal priority; another does not permit conflict (with and without equal priority). The former allows high-tempo operations; however, developing an MOC when conflict is allowed will be challenging, as it will involve advanced services like the Detect-And-Avoid service. As an initial effort, the MOC in this work focuses on the latter, where no conflict is allowed between two operational intents, corresponding to two scenarios listed in ASTM [16]: "*no conflict with equal priority*" and "*no conflict with higher priority*". Here is one of the eight requirements defined for these two scenarios:

> *"A managing USS shall (SCD0035) verify that before transitioning an operational intent to the Accepted state, it does not conflict with an equal priority operational intent when the regulation does not allow conflicts within the same priority level."*

B. Volume-based Collision Risk Model (VCRM)

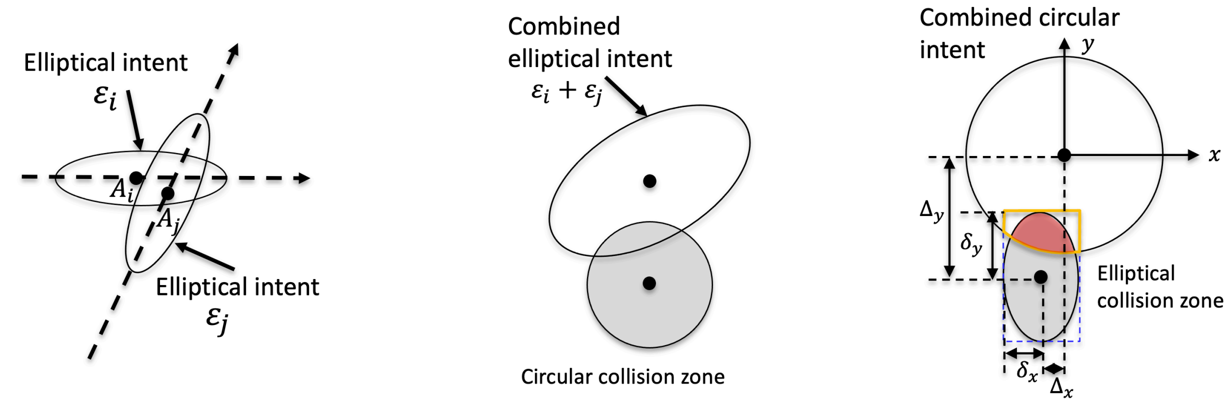
Given operational intents that follow the aforementioned requirements (e.g. OPIN0010), a risk model is needed to calculate the UA-to-UA collision risk. Because the requirement of 95% conformance alone is insufficient for risk calculation, an assumption or a new requirement has to be added for the distribution:

> *"Operational intents shall (OPIN001x) be constructed such that the probability of the UA's actual position inside an operational intent in the Activated state follows an OiDistributionType distribution."*

Without loss of generality, the $OiDistibutionType$ is assumed to be "$Normal$" or "$Gaussian$". Once these two requirements (95% conformance and normal distribution) are established, the collision risk can then be calculated given any two operational intents.

1. Collision Risk for Elliptical Intents

Elliptical shapes are typically used to represent normal distribution for both two and three dimensions, where the size in each dimension is independent and defined by the standard deviation in the same dimension. Collision risks for elliptical shapes have been well studied in the past [29–31]. To calculate collision risk between two elliptical intents (shown in Fig. 1(a)), they are first combined into one intent as shown in Fig. 1(b), where the collision zone is presented



(a) Error ellipses with normal distribution

(b) Combined error ellipse and circular conflict zone [29]

(c) Combined error circle and elliptical conflict zone after transformation. Approximation of the instantaneous probability using a rectangular [29, 30]

Fig. 1 Calculation of the probability of intent conflict

as a circle in gray. The overlapped region is where collisions may happen when the elliptical shapes include possible aircraft positions with a 100% confidence level *. In order to calculate the collision probability, the combined elliptical intent needs to be transformed to a unit circle. With the same transformation, the circular collision zone becomes an elliptical collision zone as shown in Fig. 1(c), where both the combined circular intent and the elliptical collision zone were rotated to make the major and minor axes align with the x and y axes, respectively. The conflict probability is then essentially the integral of the probability density function over the overlapped area between the circle and ellipse.

Since it is impossible to get the exact solution analytically, Hwang et. al [30] approximated the exact solution by integrating over the rectangle enclosing the ellipse (shown as the dashed blue rectangle in Fig. 1(c)) and computing the probability over the overlapped area between the unit circle and the newly-formed rectangle as shown in Eq. 3, where $p(x) = \frac{e^{-x^2/2}}{\sqrt{2\pi}}$ is the probability density function for the standard normal distribution.

$$P(x, y) = \int_{\Delta_x-\delta_x}^{\Delta_x+\delta_x} \int_{\Delta_y-\delta_y}^{\Delta_y+\delta_y} p(x)p(y)\, dx\, dy = \int_{\Delta_x-\delta_x}^{\Delta_x+\delta_x} p(x)\, dx \int_{\Delta_y-\delta_y}^{\Delta_y+\delta_y} p(y)\, dy \tag{3}$$

$\Delta_{x,y}$ are the coordinates of the center of the elliptical collision zone relative to the center of the combined circular intent. $\delta_{x,y}$ are the half width in major and minor axes for the elliptical collision zone. More details about this method on 2D integral can be found in Hwang's work [30].†

Neither Hwang's nor Paillei's method works well for turns; when an operational intent involves turns, a hybrid method [31] that leverages "bending" ellipses and numerical methods for turning segments can be utilized. It was shown [31] that the results were much more accurate around turns than other methods, and its computational time was feasible for real-time applications.

When the vertical dimension is considered, the combined circular intent in Fig. 1(c) becomes a unit sphere, and the elliptical collision zone turns into an elliptical prism. Paielli [32] computed the cross-sectional area of the collision zone (elliptical prism) when cut by a plane orthogonal to the direction of the relative velocity and used it to approximate the vertical range $[-\delta_z, \delta_z]$, as shown in Eqn. 4.

$$P(x, y, z) = P(x, y) \int_{\Delta_z-\delta_z}^{\Delta_z+\delta_z} p(z)\, dz \tag{4}$$

Since operational intents are given in four dimensions, they are associated with starting times and end times. To incorporate the temporal dimension, the overlapped time period is simply multiplied as in Eqn. 5. The unit "hour" is

*The graph here is notional as the elliptical shapes with a 100% confidence level might be infinite

†The final proposed method in [30] used an even granular approximation by cutting corners of the rectangular box outside the ellipse.

used for the temporal dimension. For example, if the collision probability $P(x, y, z)$ between two intents is 1% and their overlapped time is 20 minutes, then the final collision risk $P(x, y, z, t)$ becomes 0.33% collision-hours (equivalent to 0.2 collision-minutes after multiplying 1% by 20 minutes).

$$P(x, y, z, t) = P(x, y, z) \int_{t_{min}}^{t_{max}} dt \tag{5}$$

2. Collision Risk for Rectangular Intents

Most operational intents used by sUAS operators in the past field tests are rectangular cuboids. Although, mathematically, a rectangular cuboid is not accurate to represent a boundary for most distributions, the reasons why it is popular could be: 1) the understanding of flight technical errors for sUAS is still lacking; 2) besides trajectory-based intents, area-based intents can be arbitrary.

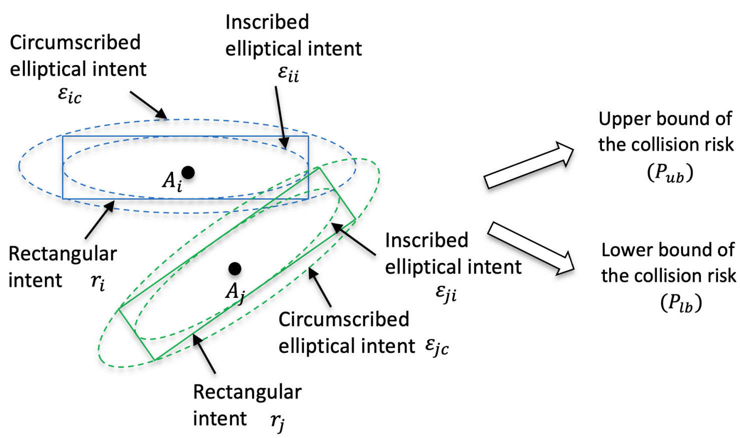


Fig. 2 Inscribed and circumscribed elliptical intents to approximate the collision risk between rectangular intents

To calculate the collision risk for rectangular intents, this work proposes to use inscribed and circumscribed elliptical shapes to approximate the collision risks. As shown in Fig. 2, inscribed and circumscribed elliptical intents are first generated for each rectangular intent. Then the collision risk between two inscribed elliptical intents and the collision risk between two circumscribed elliptical intents will be the upper and lower bounds for the collision risk between two original rectangular intents. It is worth mentioning that the collision risk between circumscribed elliptical intents can be lower than the risk between inscribed ones, but it can also be higher than the latter. Their relationship is decided by two main factors. Because the size of the collision zone is fixed while the volumes of circumscribed intents are larger than the volumes of corresponding inscribed intents, a larger volume leads to lower risk. On the other hand, inscribed intents are further apart from each other; more separation means lower risk. This work takes the average of the upper and lower bounds as the approximation of the final collision risk (as shown in Eqn. 6).

$$P_{rect}(x, y, z, t) = \frac{P_{in}(x, y, z, t) + P_{circum}(x, y, z, t)}{2.0} \tag{6}$$

3. Collision Risk Per Flight Hour

For any given test case, the number of collisions per flight hour R_{fh}, can then be expressed as the sum of $P_i(x, y, z, t)$ for any pair of operational intents over the total flight time as in Eqn. 7. Here N is the total number of operational intent pairs, and M refers to the number of sUASs. T_j is the total flight time for the jth flight. The total flight time should be in hours, because $P(x, y, z, t)$ is computed in hours as described in the previous section.

$$R_{fh} = \frac{\sum_{i=1}^{N} P_i(x, y, z, t)}{\sum_{j=1}^{M} T_j} \tag{7}$$

C. Evaluation Process

Once the collision risk model is developed for calculating collision risk between two operational intents, the proposed method of compliance, including testing and validating, can then be depicted in Fig. 3.

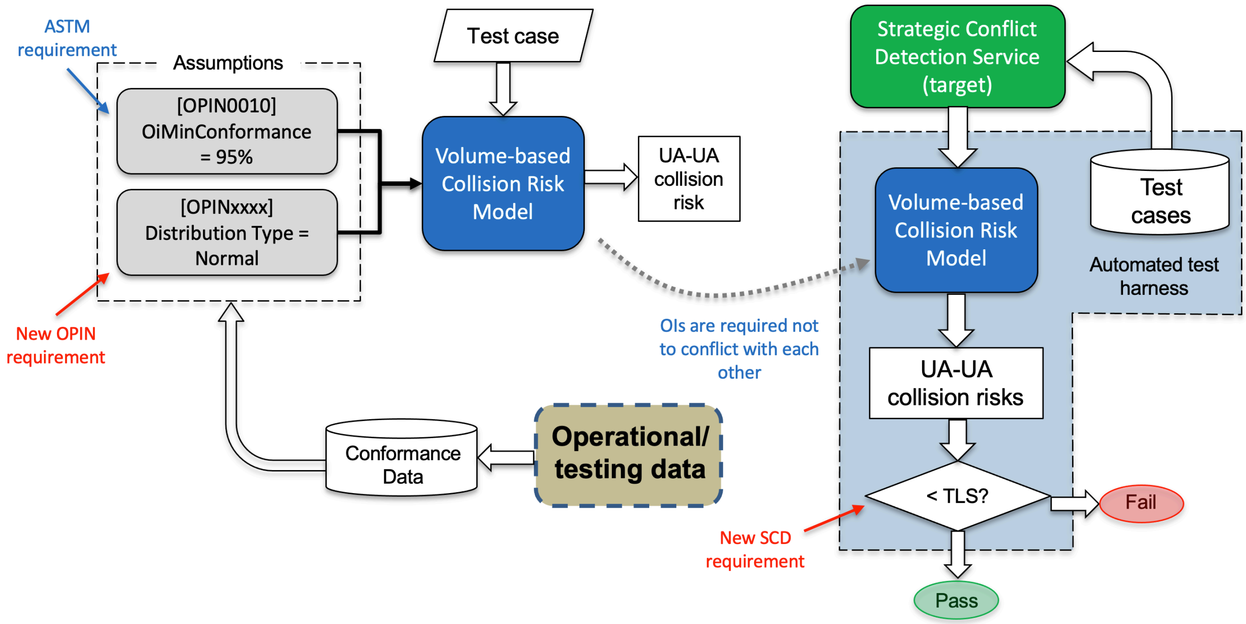


Fig. 3 Method of Compliance: Flow Diagram

The volume-based collision risk model (VCRM) can be incorporated into an automated test mechanism. A set of test cases needs to be identified to enable the test process. The test cases can be developed based on business or market prediction to represent typical missions with proper balances among different mission types. The set of test cases can be different in terms of operational area and density. They can also evolve over time when business cases are evolving. With a set of test cases and the collision risk model, a target strategic conflict detection service can then be tested. The test results will show if the overall collision risk per flight hour (R_{fh}) is less than or equal to a target level of safety (TLS) as in Eqn. 8, where K is the total number of test cases, and N_k and M_k are the number of operational intent pairs and number of flights in the k_{th} test case, respectively.

$$R_{fh} = \frac{\sum_{k=1}^{K} \sum_{i=1}^{N_k} P_{k,i}(x, y, z, t)}{\sum_{k=1}^{K} \sum_{j=1}^{M_k} T_{k,j}} \leq TLS \tag{8}$$

Since current ASTM requirements (SCD0035 and the rest requirements mentioned in Sec. III.A) only require an operational intent not to conflict with other intents when the intent overlap is not permitted, they are sufficient for operations to meet the TLS. New requirements based on TLS should be defined. For instance, the following SCD001x can be developed to replace SCD0035:

> *"A managing USS shall (SCD001x) verify that before transitioning an operational intent to the Accepted state, it* ***maintains necessary spatial or temporal distance from*** *an equal priority operational intent* ***to meet the target level of safety*** *when regulation does not allow conflicts within the same priority level."*

D. Data Collection for Requirement Compliance

The bottom-left portion of Fig. 3 presents how operational data can be used to validate the assumptions (the requirements on operational intent creation). The desired data include the time history of vehicles' position data and the time history of operational intents. These data should be collected to show if operators comply with the requirements on conformance percentage and distribution, as they are critical to the accuracy of the risk assessment.

If collected data shows that the conformance percentage is lower than 95%, the requirement on conformance is then not satisfied and the actual collision risk will be higher than the TLS. Therefore, the operations are not safe unless operators adjust their approach to generate operational intents. Whereas, if the data shows that the conformance percentage is higher than 95%, the requirement on conformance is satisfied, and the actual collision risk might be lower than the TLS. The operations are safe; therefore, they should continue.

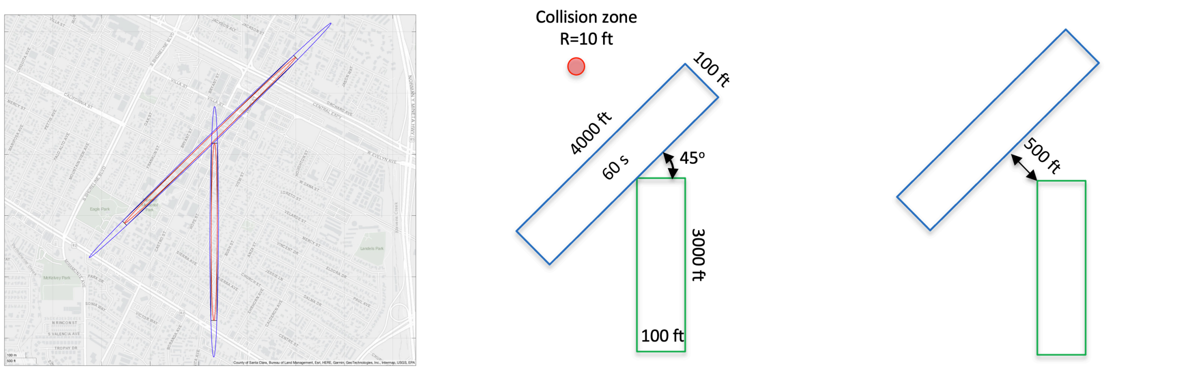
Additionally, if a vehicle's position data show that they do not follow the normal distribution, then the distribution type in the collision risk model needs to be adjusted for accurate risk assessment. Otherwise, the statement that the TLS can be satisfied with the SCD might be undermined.

IV. Sensitivity Analysis

In this section, sensitivity analyses are conducted to understand contributing factors that affect the collision risk. Three main factors are investigated: strategic conflict detection service, the layout of operational intents, and the size of operational intents. Without loss of generality, a cylinder with a radius of 10 ft and height of 10 ft is assumed to be the collision zone for a UA in this work, because changing the size of the collision zone will affect the results but not the trends.

A. Strategic Conflict Detection

The strategic conflict detection service plays a critical role in mitigating the collision risk and ensuring that the TLS is satisfied. Two types of SCD are considered here: (1) An SCD that allows deconfliction between two operational intents without any spatial buffer and (2) an SCD that enforces two intents separated with a buffer. The former meets SCD0035 in the ASTM specification, and the latter follows the proposed requirement SCD001x suggested in Sec. III.C. For simplicity, they will be called SCD_0 and SCD_{buf}, respectively, in the following sections.



(a) Actual coordinates used in the calculation (b) SCD_0, collision risk = 3.2×10^{-6}. (c) SCD_{buf},collision risk = 7.5×10^{-7}.

Fig. 4 Comparison with different SCD services

Fig. 4(b) shows a sample test case with two operational intents resulting from the SCD_0 without taking into account any extra buffer. Actual coordinates, as in Fig. 4(a), were used in risk calculation. However, for simplicity, notional graphs are presented for explanation. Both intents are assumed to have a duration of 60 seconds and completely overlap each other in time. Their geometry, relative position, and orientation are notionally shown in the figure. With the assumption that vehicle trajectory will conform to operational intents with 95% confidence (as required by OPIN0010), applying Eqn. 6 in the VCRM proposed in Sec. III.B, the calculated collision risk is 3.2×10^{-6}, with 7.3×10^{-7} between two inscribed elliptical intents and 5.6×10^{-6} between two circumscribed ones. On the other hand, Fig. 4(c) shows the sample of two operation intents resulting from the SCD_{buf} that imposes a 500-ft buffer between intents. The calculated collision risk is then 7.5×10^{-7}, which is much lower than the calculation for SCD_0. If the total flight hour is one, utilizing Eqn. 7, the collision risks per flight hour for SCD_0 and SCD_{buf} are then 5.3×10^{-8} and 1.25×10^{-8}, respectively. The reduction in collision risk in Fig. 4(c) with the SCD_{buf} is due to the extra separation needed by the non-zero collision zone and the tail part of the distribution for vehicle locations, which corresponds to the additional 5% likelihood that the UA might go outside of the 95% operational intent.

B. The Layout of Operational Intents

The layout of operational intents is critical to the UA-to-UA collision risk as well. The previous section showed two operational intents that intersect with an acute angle. Fig. 5 presents a different layout where two operational intents are parallel and next to each other. The collision risk calculated using the VCRM model is then 2.1×10^{-4}, which is much higher than 3.2×10^{-6} in Fig. 4(b). While applying SCD_{buf} with a 100-ft buffer, the UA-to-UA collision risk decreases to 5.7×10^{-8}. Compared to the risk reduction with a 500-ft buffer in the previous section when intents are not in parallel, a smaller buffer results in a much greater risk reduction for parallel intents. Assuming the total flight duration is one hour, the collision per flight hour becomes 3.5×10^{-6} and 9.5×10^{-10} for these two cases, respectively.

(a) SCD_0, collision risk = 2.1×10^{-4}

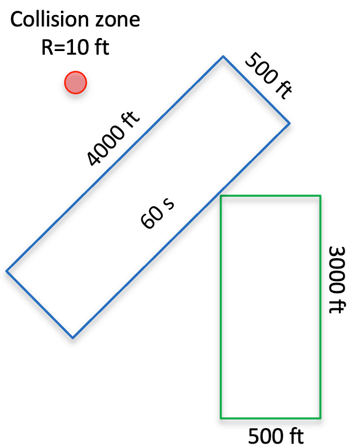
(b) SCD_{buf}, collision risk = 5.7×10^{-8}

Fig. 5 Impact of the layout of operational intents

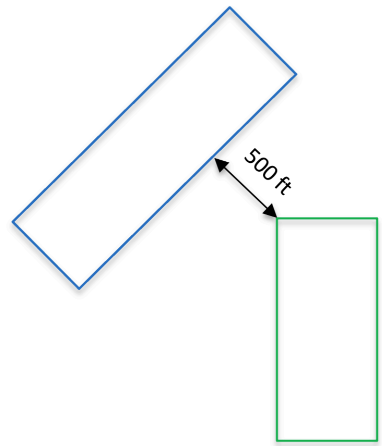
C. The Size of Operational Intents

The size of operational intents is affected by aircraft trajectory performance, mission type, and even human factors, especially at the current stage where there is no regulatory guidance for how to model operational intents. According to the only existing ASTM specification, which requires that an operational intent of a flight shall capture 95% of its possible positions within the specified time window, when the size of operational intents increases, the tail part of the distribution, or the remaining 5% of possible aircraft positions, will expand. Such expansions increase the likelihood of overlap between the collision zone and intents, but they may also reduce the collision risk due to the increased intent as the size of the collision zone is fixed.

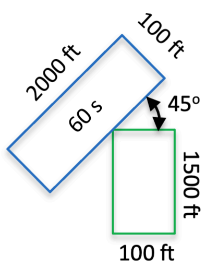
Fig. 6 shows operational intents with different sizes from Fig. 4. In Fig. 6(a), when no buffer is considered in the SCD, the collision risk is 4.36×10^{-6}, which is similar to the case in Fig. 4(b). When incorporating the same 500-ft buffer in the SCD (Fig. 6(b)), the risk is less: 1.04×10^{-6}, which is higher than 7.5×10^{-7} in Fig. 4(c). This result means when the size of operational intents increases, the buffer between intents needs to increase to maintain the same level of collision risk. Fig. 6(c) and 6(d) present smaller operational intents than the ones in Fig. 4. In Fig. 6(c), with SCD_0, the collision risk is 1.12×10^{-5}, which is higher than the case in Fig. 4(b). However, when incorporating a 500-ft buffer in the SCD, the collision risk is less: 4.48×10^{-7}, which is lower than 7.5×10^{-7} in Fig. 4(c). This result shows a similar trend: as the size of operational intents decreases, the buffer needed to maintain the same level of collision risk decreases as well.



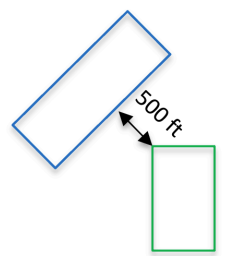
(a) SCD_0, large intents, no buffer, (collision risk = 4.36×10^{-6})



(b) SCD_{buf}, large intents, with buffer, (collision risk = 1.04×10^{-6})



(c) SCD_0, small intents, no buffer, (collision risk = 1.12×10^{-5})



(d) SCD_{buf}, small intents, with buffer, (collision risk = 4.48×10^{-7})

Fig. 6 Impact of the Size of Operational Intents

V. Discussion

Sensitivity analysis revealed that both layout and size of operational intents play important roles in assessing an SCD service, which implies that test cases need to be carefully selected in a test process. The examples in the previous section (Sec. IV) show that the collision probabilities differ by a factor of about 100. Test cases must be representative and sufficiently complex for a valid evaluation of an SCD service.

Additionally, the sensitivity analysis also showed that, to achieve the TLS, an SCD service needs to include extra buffers to account for the additional separation demanded by the tail part of the distribution and the nonzero size for the collision zone. The examples in the previous section show that the risk reduction varies from several to several hundred times depending on the target level of safety and the geometry of the operational intents. That is the rationale for why new requirements like *SCD001x* (Sec. III.C) should be proposed.

When the operational tempo/complexity is high in a test case, the SCD service will reduce the operational tempo/complexity to mitigate the UA-to-UA collision risk. Therefore, it essentially compromises the tempo of sUAS operations for safety. The MOC in this work is proposed for when conflict of operational intents is not permitted, but it can only support low-tempo/low-density sUAS operations from the efficiency perspective.

This MOC can serve as proof while providing guidance on test harness and data collection: Once proposed requirements are satisfied and the SCD service passes the tests, the MOC shows that the operations will meet the target level of safety. Additionally, the MOC suggests that the telemetry data of sUAS positions and the history of operational intents must be collected to ensure the requirements are adhered to.

VI. Conclusions

This work proposed a method of compliance for the situation when an overlap between operational intents is not permitted to ensure that the UA-to-UA collision risk meets the TLS. This method of compliance was developed based on the current ASTM requirements. First, a volume-based collision risk model was developed to calculate the UA-to-UA collision risk between two operational intent volumes. Then a testing strategy was presented to assess if an SCD service can mitigate the UA-to-UA collision risk and meet the TLS. Through this process, two new requirements were identified to fill a gap in current ASTM standards. Finally, a sensitivity analysis was conducted to understand the main factors contributing to the collision risk calculation. The results showed that the size and layout of operational intents affect the collision risk, and buffers must be considered in the SCD services.

This MOC is the first MOC for sUAS operations to show how to achieve the acceptable UA-to-UA collision risk. It provides what is needed, including new requirements, a volume-based collision risk model, and a test strategy to prove that a strategic conflict detection service can achieve the target level of safety in situations when conflict between operational intents is not permitted. It also specifies the types of operational data that should be collected to examine the requirement compliance.

Future work will focus on developing a method of compliance for another situation where conflict between operational intents is permitted. Other advanced services will be involved, such as the detect and avoid service. Its development will allow high-tempo and high-complexity operations, thus improving operational efficiency while meeting the TLS.

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