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Evaluation of UTM Strategic Deconfliction Through End-to-End Simulation

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***Abstract*—This paper provides an initial analysis of the ability of volume based deconfliction to mitigate air risk between cooperative unmanned operations in an Unmanned Traffic Management (UTM) setting. Namely, we use high-fidelity simulation in combination with a collection of UTM services to evaluate the functional and performance requirements for strategic deconfliction that are emerging from the standards work in UTM. Our objective is to assess how well the requirements developed by standards groups can support end-to-end safety. We consider two key aspects of strategic deconfliction within our evaluation: how operational volumes are constructed and how well unmanned vehicles are able to conform to their planned operational volumes in the presence of system error. To that end, we outline an end-to-end simulation framework that can be used to evaluate system level implications of UTM requirements. We apply the framework to (1) provide quantitative guidance for the risk reduction associated with strategic deconfliction in UTM, and to (2) provide operational recommendations that would enable operators to meet safety targets prescribed by conformance rate and strategic deconfliction requirements in the UTM ecosystem.**

***Keywords*—UAS; UTM; safety; separation; deconfliction**

I. Introduction

From delivery drones to autonomous electrical vertical take-off and landing (eVTOL) passenger aircraft, modern unmanned aircraft systems (UASs) have the potential to perform a wide range of tasks efficiently, including delivering goods, performing surveillance, and transporting humans among others [1]. Forecasts indicate that within the next 20 years, demand and technological improvements will drive the ecosystem to one that can sustain millions of commercial UAS operations per day [2]. In contrast, existing Air Traffic Management (ATM) systems can support thousands of worldwide commercial daily flights, with the busiest airports having a capacity to support a few hundred operations per hour [3]. The gap is large between existing systems and those that will be necessary to support UAS operations at scale in the future.

Unmanned Traffic Management (UTM) has been proposed as a digitized and automated solution for scaling to the expected volume of operations. The UTM architecture is currently in a conceptual stage [4], [5], with early prototypes being tested through demonstrations. Many of the elements within this architecture are being developed, standardized and tested independently. However, the system-of-systems nature of the UTM ecosystem means there are inherent dependencies between different elements, leading to unexpected behaviors if the end-to-end effects are not considered. The quantification of the end-to-end performance in UTM is a critical step in advancing UTM from demonstration to operational deployment. This includes the verification and validation of performance-based requirements of individual services, as well as the assurance that the services and surrounding ecosystem meet desired safety targets.

Perhaps the largest barrier to the operational deployment of UTM is a lack of data, or quantitative support, behind the verification, validation and assurance of system-of-system requirements, standards, and eventually UTM regulation. Simulation can partially address this gap by investigating some of the more complex questions related to safety before a UTM system is fully operationalized and actual operational data is available. We can leverage high-fidelity simulation to examine what an operational UTM system may look like at scale, and evaluate the functional and performance requirements that are being implemented by standards and regulatory bodies today to ensure they are sufficiently robust, and can meet the desired safety targets required for essential UAS operations such as Beyond Visual Line of Sight (BVLOS).

In this work we aim to evaluate strategic deconfliction, which serves a critical safety function within UTM. While strategic deconfliction is a volume-based function performed pre-flight, its performance depends on requirements measured by in-flight conformance and separation from other vehicles. We place emphasis on the assumption made in this work to be valid within the requirements, and frameworks that have emerged within UTM. One of our objectives is to evaluate the quality of operational volumes as the primary data construct in the context of a high density UAS airspace, and to assess how the formation of these volumes can impact safety of the airspace as a whole. Additionally, we analyze how system error, namely noise in the navigation and guidance system of a UAS, can impact the ability of an operation to conform to its planned operation volumes. We connect the relationship between the system error and safety to a performance requirement on conformance rate, which provides a critical pathway to quantifying the risk mitigation that strategic deconfliction can provide in the UTM ecosystem. Lastly, we provide key recommendations for how operation volumes can be constructed by operators if they aim to meet a given conformance rate or safety target.

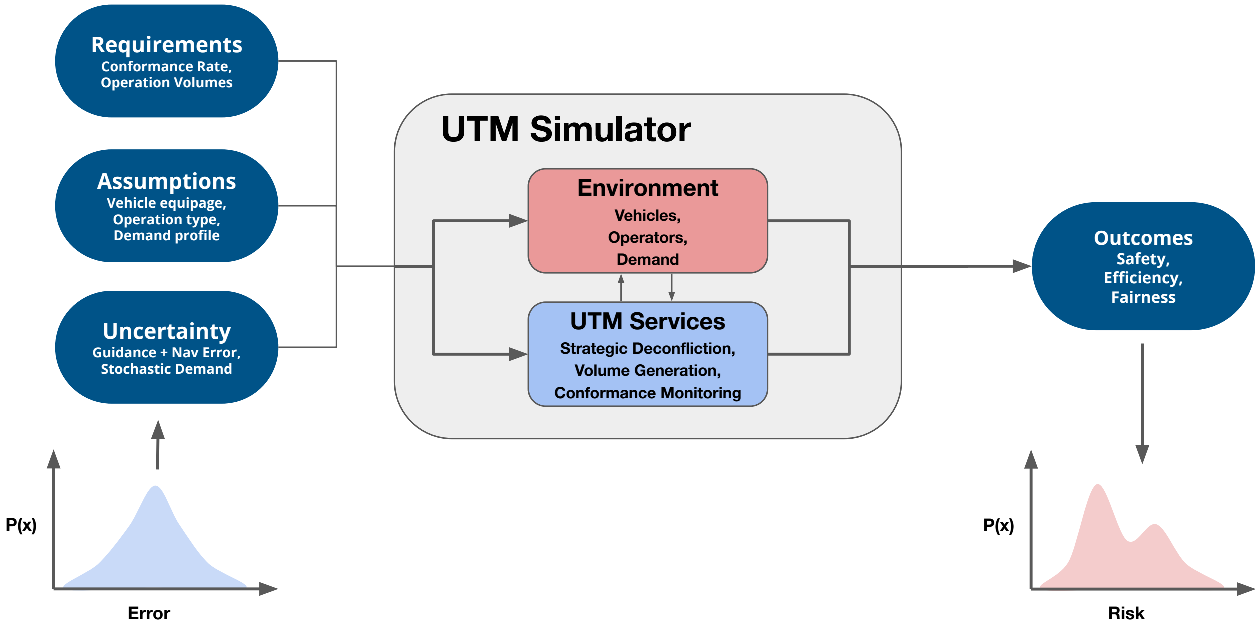

Figure 1: Architecture for Monte Carlo analysis of UTM requirements

To perform the necessary evaluations we first formalize the problem of end-to-end Monte Carlo analysis for UTM. We adopt an end-to-end analysis in lieu of an analysis that examines each individual subsystem in order to capture the complexity of UTM as a whole. By simulating all the UTM and UAS sub-systems simultaneously, we are able to extract meaningful results that are more representative of what can be expected once the systems are operationalized. Additionally, we are able to extract one-to-one relationships between a configuration in our simulation such as the system noise or the size of volumes to a safety measure. To our knowledge, this is the first work that presents a quantitative link between operation volumes, system error, conformance rate, and safety. We believe that the quantitative relationships outlined in this paper can be readily applied to fill a critical gap in standards and regulations around the safety benefits of strategic deconfliction in UTM.

The remainder of this paper is organized as follows: Section II provides an overview of existing literature on UTM, simulation based validation of autonomous technologies, and how simulation has been previously used in aviation. Section III provides an overview of the Monte Carlo simulation framework used in this work. Section IV outlines volume based strategic deconfliction that has been proposed as a means of mitigating risk between cooperative traffic in the UTM ecosystem. Section V provides a summary of the simulation configuration used in this work. Section VI summarizes the results, and Section VII provides concluding remarks.

II. Related Literature

Strategic airspace management has a critical safety function in traditional ATM, and is responsible for conflict mitigation over extended time horizons [6]. A number of tools and capabilities exist to help facilitate deconfliction in ATM [7]–[9] However, they are designed to function with humans in the loop and are not expected to scale with the projected traffic demand in UTM. A number of frameworks have been proposed for strategic deconfliction in UTM [10]–[12], with the most widely accepted and demonstrated being a federated volume based solution.

The scope of strategic deconfliction in UTM covers conflict mitigation during the pre-flight planning stage of an operation. Prior work has explored a number of research topics in the strategic deconfliction domain such as those tied to efficiency [13], fairness [14], and safety [15], [16]. However, that research was generally abstracted from the current state of the UTM ecosystem, making it difficult to relate to forthcoming standards and regulations. A large body of literature has also covered emerging topics of interest in the broader UTM domain that go beyond deconfliction, such as those related to dynamic airspaces [17], high operational densities [18], and services necessary for multiple beyond line of sight operations [19]. However, these studies also lack a clear connection to a functional system that is implementable within the current UTM framework.

A body of work that is implementable in the near term comes from recent standards, specifically Remote Identification [20]. While the standard itself provides a pathway for Remote ID in UTM, the exact nature of the safety benefit and risk reduction that the standard could provide for the ecosystem is unclear. While work has been done to address the potential gaps [21] and broader application of the standard [22], there is not an immediate path forward to assist regulators and other stakeholders in making decisions regarding standard adoption.

Evaluating the ability of a standard, a concept, or a technology to meet the needs of stakeholders through a validation and verification process can be difficult in aviation. System

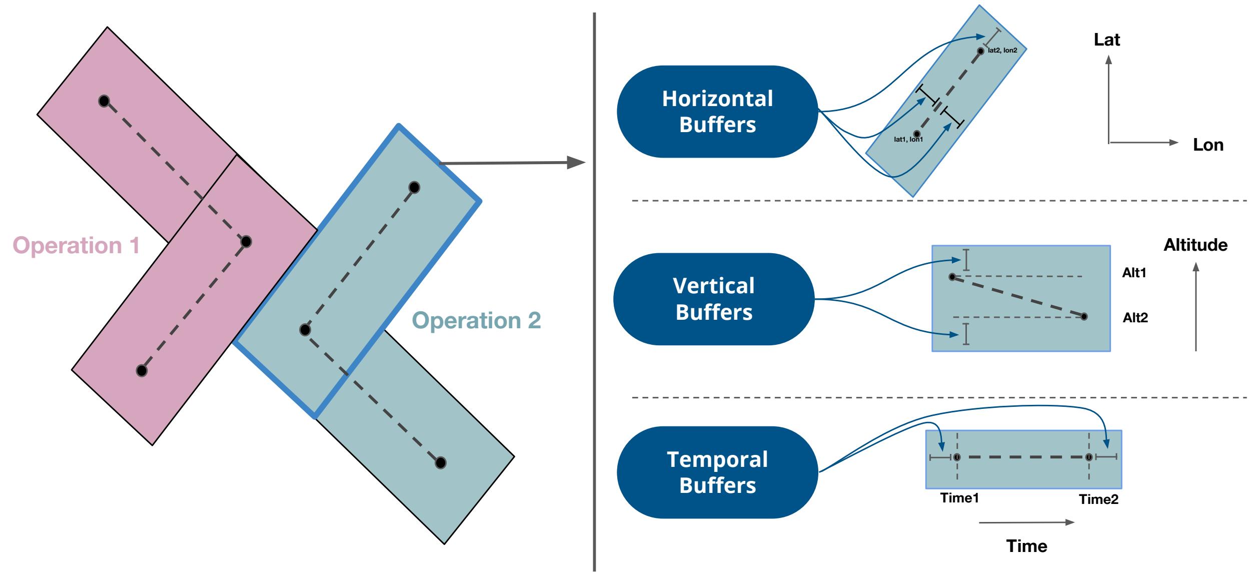

Figure 2: Operation volumes and buffer configurations used to generate them around a planned 4D trajectory

level risk analysis has been commonly used in traditional ATM [23], [24]. Simulation driven approaches have also been used to verify onboard and remotely situated collision avoidance systems in manned aviation like the Airborne Collision Avoidance System (ACAS X) [25], [26] and its variant for small UAS known as ACAS sXu [27]. In both cases, simulation enabled a more efficient and timely path towards certification of these systems [28]. More recently, simulation driven verification has been applied to UTM as a form of stress testing [29], but that work focuses on verification of algorithmic correctness for autonomous systems that may exist in UTM rather than considering the quality of a performance or functional requirement.

III. UTM Validation & Verification with Monte Carlo Simulation

Monte Carlo methods are a form of experiments which use repeated random sampling to gain an understanding about a problem that is difficult to constrain due to uncertainty or having many degrees of freedom [30]. While these types of approaches have been successfully applied in aviation [25], [28], [31], they typically consider constrained parameter and scenario sets, because a comprehensive analysis of the whole system is infeasible. A big challenge in applying Monte Carlo methods within UTM is that it may require simulating a complex system of systems. In this setting, it is critical to concretely define and understand the assumptions being made in the simulation in order to properly interpret the outcomes. In this work, we apply the Monte Carlo approach to perform end-to-end evaluations of UTM requirements. Specifically, we perform the evaluation by simulating the system of systems nature of UTM in order to extract quantitative measures that would be representative of a real operational system. Figure 1 outlines the simulation architecture adopted in this work. The UTM Simulator in the figure consists of two key components: the simulation environment and the set of UTM services necessary to test the requirements of interest. In this work, the environment includes the models necessary to simulate a UAS, from an onboard guidance system to flight physics. The environment includes the demand profiles and operator logic associated with the simulation. The environment is based on the Complex Assured Autonomous Systems (CAAS) framework, which is a testbed for evaluating multi-agent autonomous algorithms. CAAS provides a holistic test environment capable of simulating autonomous agents, with agents controlled by various scheduling, navigation, and deconfliction algorithms. The CAAS framework has been previously used to explore performance of autonomous algorithms for UAS applications [32], [33].

In this work, the operation planning stage that exists within the simulation environment relies on volume generation and strategic deconfliction UTM services. The volume generation services ensure that each operation is planned with a valid set of four dimensional operation volumes, and the strategic deconfliction service ensures that any new volumes created in the system are conflict free (see Section IV for a more detailed description of strategic deconfliction or Figure 2 for an overview of operation volumes).

In this framework, we can group all configurable parameters within the simulation into three categories as outlined in Figure 1. The first group of parameters represents requirements, which are parameters we are seeking to validate in this study. Examples include a performance requirement associated with a conformance rate, and a functional requirement to use four-dimensional operation volumes for strategic deconfliction. The second group of parameters represents the uncertainty configuration in the simulation. It is used to configure the probability distributions relevant to our evaluation, such as the standard deviation of the navigation errors a UAS operation may experience during flight. The last group of pa-

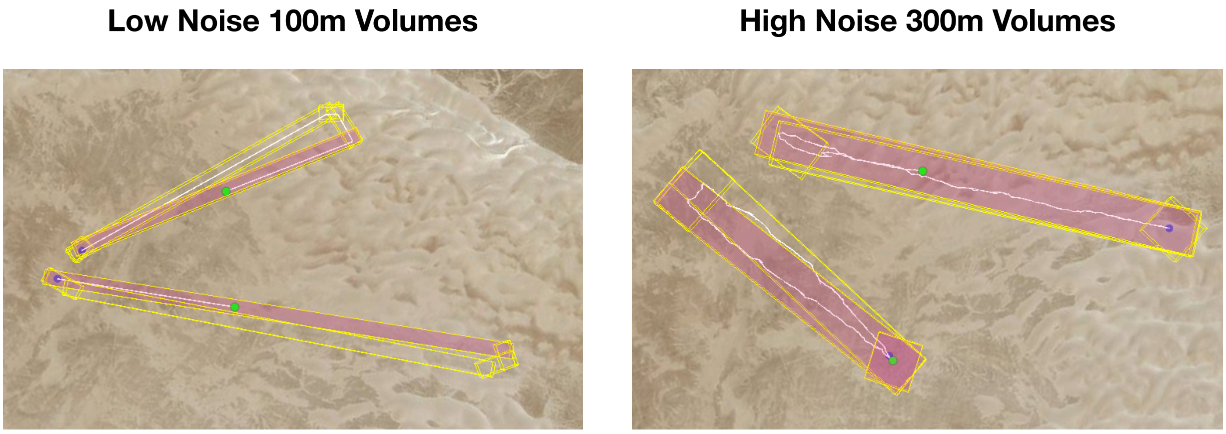

Figure 3: Example out-and-back operations with the white completed flight track and green vehicle position shown within the yellow planned operation volumes, and red active volumes.

rameters is the group representing the necessary assumptions for our analysis. Typically, this group of parameters can be difficult to fully identify due to the subtle nature of some assumptions in complex systems such as UTM. However, it is critical to do so in order to ensure that hidden assumptions do not influence the results.

The outcomes of Monte Carlo simulation are probabilistic. Given that each simulation is configured using both fixed and random variables, it is natural to expect a distribution of outcomes from any given set of evaluations. Practically, this means that if we have a methodology for quantifying risk within our simulation, each measure of risk will fall within a distribution. In this work, we are focused on evaluating risk, but any number of metrics can be evaluated this way, such as those related to efficiency or fairness in the system. While the distributions produced by the outcomes of the Monte Carlo simulation can take on a number of forms, in this work, our risk measures follow an approximately normal distribution.

IV. UTM Strategic Deconfliction

In this section, we outline the key functional components of volume based strategic deconfliction. In UTM, strategic deconfliction is responsible for mitigating conflicts prior to the start of an operation. This is in contrast to tactical deconfliction, which aims to respond to safety hazards in-flight. In tandem with collision avoidance, these three components create the separation stack of UTM, which is responsible for mitigating safety hazards at various time horizons within the UTM ecosystem. It is likely that UTM services will enable strategic deconfliction by providing digital and automated tools to either assist or fully facilitate the process of hazard mitigation during the pre-flight planning stage for an operation. While UTM services may support or receive information regarding other separation layers, we focus this work on strategic deconfliction. Specifically, we consider the risk benefits of strategic deconfliction between cooperative traffic within UTM.

Within the operation planning phase, there are two primary tasks that are attributed to deconfliction — conflict detection and conflict resolution. Because we make the assumption that operations are allocated on a first-come, first-served basis, the conflict detection phase involves detecting overlaps between the set of operation volumes that are being planned and the set of operation volumes that already exist in the system. Conflict resolution involves adjusting the set of volumes being planned in a way that eliminates conflicts in the system. The goal of strategic deconfliction is to ensure that all sets of operation volumes that are being planned are conflict free from all the volumes that already exist in the system, or free of overlap in four dimensions. Note that strategic deconfliction may have goals and requirements that consider the efficiency of the airspace as well, but we do not address them in this work.

In this work, we used an automated conflict resolution service that is based on scheduling. The service computes an optimal departure delay by solving a linear program formed by overlaps between the set of operation volumes that exist in the system and the set of operation volumes proposed by the operation being planned [29]. The departure delay is propagated to all the volumes of a planned operation, and guarantees that the proposed set of operation volumes is conflict free from any volumes that already exist in the system. This approach allows us to ensure that regardless of the underlying operation, the size of volumes used, or the mechanism for allocation, a planned operation will always be conflict free prior to take-off.

There are other approaches that can ensure operation volumes are free of conflict in the UTM settings. Specifically, modifying the locations of a given flight path and its subsequent volumes is another method of conflict resolution. A hybrid approach that utilizes both scheduling and flight path modification could also be used for conflict resolution. Each of these approaches can be implemented in a way that guarantees the volumes created during the pre-flight planning process are free of conflict. For simplicity, we use only schedule based conflict resolution in this work, and leave other forms of conflict resolution for future work.

The operation profile considered in this work is an out-and-back operation that could resemble a package delivery or a surveillance mission. In this operation, a UAS begins its flight from one location, flies to a location of interest, and returns to the location where the flight began. Two examples of out-and-back operation types are shown in Figure 3 with different noise and volume size configurations. We note that the operation profile chosen in this work will likely impact the risk outcomes presented. We leave the sensitivities of risk to a given operation profile for future work, and assume a single operation type in all our simulations. To create the volumes for these operations, we assume that the UAS has the ability to navigate along a four dimensional planned centerline associated with its operation. The volumes can be then created assuming a geospatial buffer in the horizontal and vertical planes and a temporal buffer in the time dimension.

There are two key factors that ultimately dictate the safety benefit of strategic deconfliction for cooperative traffic. They are as follows:

1) **Volume sizing**: or how an operator creates volumes relative to their intended flight path. These volumes can be sized along four dimensions — two horizontal, one vertical, and one temporal. In this work we focus on the impact of sizing in the horizontal and time dimensions.
2) **Volume conformance**: or how well an operation can conform to the planned operation volumes during the flight. A number of factors can influence the ability of a vehicle to conform to the planned volumes, and in this work we focus on system error that comes from onboard guidance and navigation, while leaving external disturbances such as weather conditions for future work.

The impact of both of these factors on operations is shown in Figure 3, where example flight tracks and corresponding operation volumes are shown for low noise, 100m buffer operations, and for high noise, 300m buffer operations. The operation buffer values shown are for the horizontal dimensions only. The figure also shows an example of how large errors due to high noise in the system impact the ability of the UAS to stay within its planned volumes.

V. Simulation Setup

A series of Monte Carlo simulations were designed to evaluate the performance of strategic deconfliction in highly utilized airspace, exploring the impact of noise models on various safety metrics.

A. Airspace

The airspace is $3\,\mathrm{km} \times 3\,\mathrm{km}$ in size with UAS operating in a single horizontal layer (i.e. all platforms are co-altitude). We assume the airspace is free of constraints and obstructions, so flight trajectories can be planned in an unmitigated way. We also assume that access to the airspace is authorized when the operation volumes submitted into the UTM system are free of conflict with any other existing operation. In order to receive authorization to fly, operations must be conflict free. We do not consider any other requirements for flight authorization for simplicity.

B. Mission Planning

Each simulation contains a fixed number of operations, with each operation consisting of a plan from a randomized origin to a randomized destination and back to the origin. A path planner then produces a series of intermediate waypoints to reach those mission goals, while heeding to dynamic constraints such as turn radius.

The Rapidly-Exploring Random Tree Star (RRT*) algorithm [34] was used for path planning, designed to provide an asymptotically-optimal, motion-based solution. Constraints on turn rate were applied via the Dubins model to match the dynamic constraints of the UAS [35], and to allow for better recovery from unplanned disturbances like guidance error. No deconfliction is done during the path planning stage, and all plans are initially scheduled to begin at simulation start. Delays may be enforced using volume based strategic deconfliction after operation volumes are created from the planned trajectory.

C. Strategic Deconfliction

In this study, we used a schedule based strategic deconfliction approach that relies on solving a linear program as outlined in Section IV. This method of strategic deconfliction ensures that operations are scheduled in a way that guarantees that any set of volumes for a given operation is free of conflict from any other existing operation volumes in the system. By specifying an appropriate spatial buffer for the volumes, the strategic deconfliction service ensures that configured nominal separation criteria are met for any given simulation. We use the configuration without strategic deconfliction as the unmitigated baseline against which we compare safety results, enabling us to directly measure the safety benefit of UTM strategic deconfliction under the assumptions considered in this work. This work considers simulations along a fixed altitude, and the single source of events that could break nominal separation happen in the horizontal plane. We thus base the horizontal buffers used to create volumes on the nominal separation values. Additionally, for any given simulation run, the buffer values used to create operation volumes are held fixed across all segments of the planned trajectory and all operations in the simulation run.

D. Study Parameters

With the above framework, a series of Monte Carlo studies were simulated by performing a sweep over the study variables of interest. Where applicable, the variables apply to all UAS in that simulation. The study variables examined in this paper are outlined in Table I, while key simulation parameters are shown in Table II. We note that the speed and heading errors are uncorrelated in this work, but higher-fidelity UAS noise models may include correlated uncertainties.

VI. Results

This section presents the results of Monte Carlo experiments performed in this work. The experiments outline the relationships between parameters used to create operation volumes, error that can emerge from navigation and guidance systems on a UAS, operation volume conformance rates, and

TABLE I. Study variables used in this work.

Study Variable	Values
Nominal separation	$[1, 5, 10, 50, 100, 300, 600, 1200]$ m
Volume time buffer	$[0, 1, 5, 10, 15]$ s
Speed error Std Dev	$[0, 5, 10, 15]$ $\mathrm{m\,s^{-1}}$
Heading error Std Dev	$[0, 5, 10, 15]$ °

TABLE II. Key simulation parameters used in this work.

Parameter	Value
Operations per simulation	9
Cruise speed	$15\,\mathrm{m\,s^{-1}}$
Maximum linear acceleration	$2.5\,\mathrm{m\,s^{-2}}$
Maximum UAS turn rate	$45\,°\,\mathrm{s^{-1}}$

absolute and relative risks within the UTM ecosystem. The critical set of relationships that we highlight are those related to the risk reduction that comes from strategic deconfliction when error is present in the UAS system, under a given set of assumptions about how the operation volumes in the system were created.

To generate the baselines for our safety analysis, we also considered a configuration where strategic deconfliction was off. In total, our simulations consist of $\sim$ 18 million hours of UAS flight time, with each configuration of the parameters above consisting of $\sim$ 28 thousand UAS flight hours. To ensure that our results were statistically significant, we used an adaptive sampling method along with variance reduction [36] to obtain 99% C.L. for the metrics of interest in this work, namely conformance rate and risk ratios.

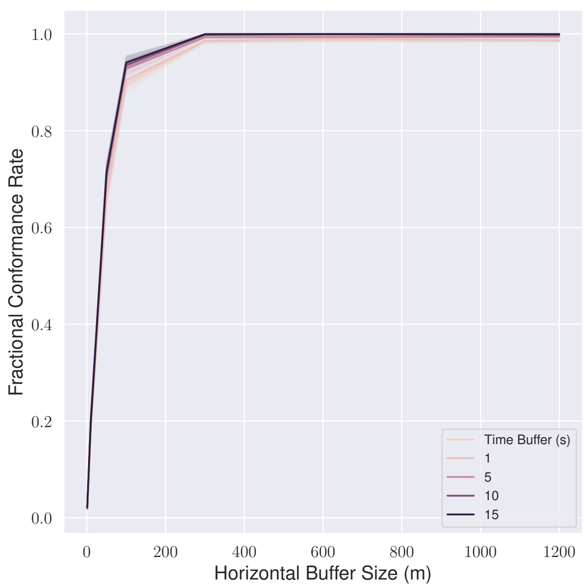

Figure 4: Conformance rate as a function of the volume horizontal buffer across a variety of volume time buffers.

Figure 4 shows the relationship between the conformance rate of an operation for a given set of nominal separation values and time buffers which were used to create the operation volumes. The nominal separation values were used to determine the horizontal buffers around the planned trajectory centerline. Each point on the curve was generated using $\sim$ 2000 individual operations with varying levels of navigation and guidance noise, as outlined in Section V. The relationship between conformance rate of an operation and the size of the horizontal buffer used to generate the volumes follows a logarithmic curve. Specifically, we see a significant drop in conformance rate as the size of the horizontal buffer used to create volumes decreases. We note that in the figure, conformance rate is averaged over all of the noise parameters examined in this work, and that configurations with lower noise approach unity at lower horizontal buffers. A more detailed relationship between noise, conformance rate and buffers is outlined in Figure 10.

To evaluate the safety implications of the Monte Carlo analysis, we first consider the distribution of all pairwise distances within a single parameter configuration. The distribution of pairwise distances between all active vehicles provides an in-depth view of the separation profile within a given simulation configuration, from which more insightful metrics can be extracted. We compute these distances between all active vehicles during a single simulation at 1 Hz. An example of these distributions for three configurations is shown in Figure 5 with their corresponding cumulative distribution functions. The figure additionally shows the state of the operation when the separation values were measured. The states are as follows:

1) **Activated**: operation is in-flight and in a nominal state, within its active planned volumes
2) **NonConforming**: operation is in-flight and is not within any of its active planned volumes
3) **Intruding**: the operation is in-flight, has left its active planned volumes, and is within an active volume of another operation

The left sub-figure demonstrates the emergent distribution of separations for a noiseless and strategically deconflicted setting. The large buffers are set to 300m and the small buffers are set to 1m. We observe that the left and center distributions have similar shapes, with the large buffer distribution shifted towards larger values of separation. The right figure shows the impacts of noise on the separation distributions when horizontal buffers are configured to 300m. The low noise plots are completely noiseless, while the high noise plot is generated with 15 m/s standard deviation of speed noise and 15 degrees standard deviation of heading noise. The distributions for high (right) and low noise (center) configurations are generally similar in shape, with the high noise distribution shifted towards a separation of zero. The high noise distribution has an additional residual bump between 0 and 100 meters, indicating that there is a higher risk in the system despite the strategic deconfliction service generating conflict free operation volumes prior to the start of any given operation.

The relationships between volume sizes and loss of nominal separation and guidance error are shown in Figure 6. We take nominal separation to correspond to twice the horizontal buffer value used to generate operation volumes around the

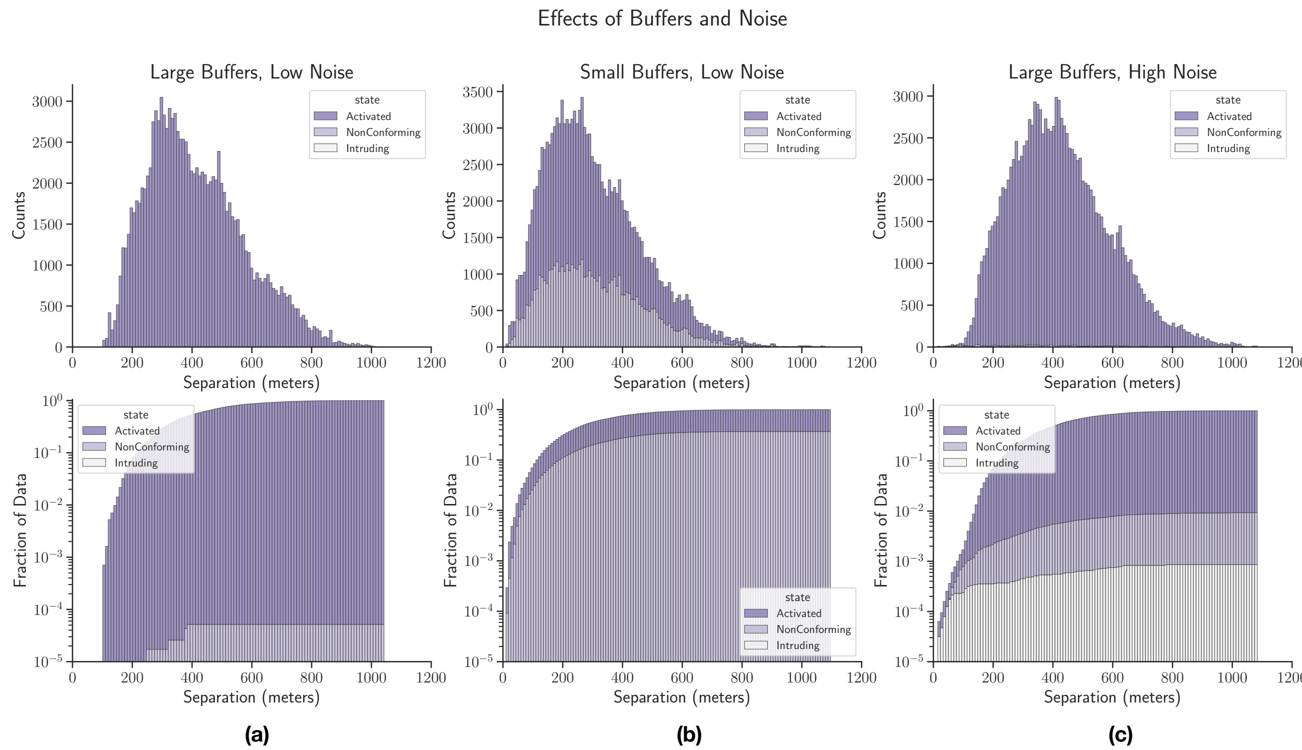

Figure 5: Distributions of separation values and their corresponding cumulative distribution functions for large horizontal buffer (300m) and low noise (a); small horizontal buffer (1m) configurations and low noise (b); large horizontal buffer and high noise (c)

planned trajectory centerline. The loss of nominal separation rate increases as the size of the horizontal buffers and the nominal separation threshold increases. Intuitively, the increase in the loss of separation rate can be attributed to separation being more difficult to maintain as its value becomes larger. This difficulty is especially apparent for configurations with large system noise, where a vehicle may deviate more significantly from the centerline. Loss of nominal separation is somewhat more sensitive to speed noise compared to heading noise.

Our objective is to determine the relationships between the parameters of interest and a metric that appropriately describes safety within the UTM ecosystem. We can leverage the separation distributions shown in Figure 5 to determine the fraction of all pairwise separation values that fall within a given threshold. A large fraction of values within a threshold that may be considered safety critical, the 15m small Near Mid-Air Collision (sNMAC) threshold for example [37], could imply that the simulation configuration associated with that separation distribution is high risk. We further expand on this concept by first considering the fractions of a given threshold for a specific set of noise configurations for a strategic deconfliction-free result. This fraction indicates the baseline risk within the system, or unmitigated risk, because no mitigation mechanisms exist in this configuration. Figure 7 illustrates the baseline absolute risk plotted against nominal separation thresholds. We note that the baseline risk is independent of noise, and we thus consider baseline risk to be only a function of the separation threshold. We then consider the fraction of separation values that fall within a given separation threshold for a configuration that uses strategic deconfliction with specific operation volume buffers horizontal buffer (or one half the nominal separation) and time buffer. Each of these fractions corresponds to the absolute risk in the system under the given configuration. The ratio of absolute risk with strategic deconfliction to the absolute risk with the unmitigated configuration provides a relative measure of risk reduction, known as a risk ratio. The risk ratio outlined above specifies the reduction in risk from strategic deconfliction.

We illustrate the relationship of the relative risk ratio to volume sizes in Figure 9. The figure also shows how the risk ratio changes as the required conformance rate in the system increases. Recall that we also examined a wide range of guidance errors on the heading and speed of the UAS. For a given volume size and noise parameterization, it may be impossible to meet certain conformance rates. For example, when horizontal volume buffers are one meter, a heading noise of 15 degrees would cause the UAS to leave its planned operation volume when traveling at the cruise speeds considered in this work of $15\,\mathrm{m\,s^{-1}}$. By enforcing a conformance rate in Figure 9, we are effectively filtering out simulation configurations that are unable to meet that conformance rate requirement. Gray squares in the figure indicate a buffer configuration that does not meet the conformance rate within a given sub-figure. A surface plot of

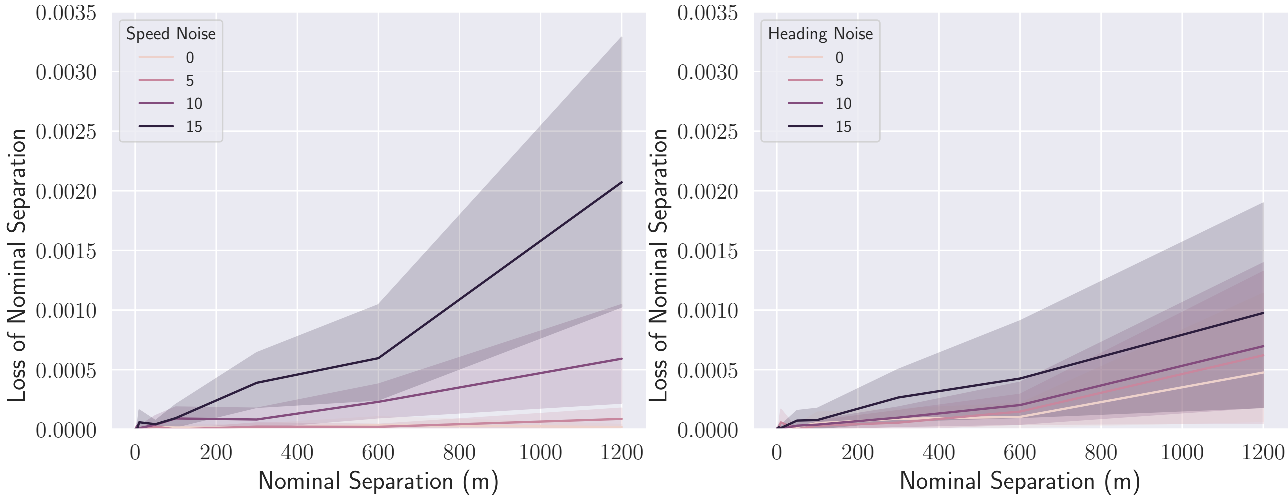

Figure 6: Loss of nominal separation rate as a function of the volume horizontal buffer size for speed noise (Left) and heading noise (Right)

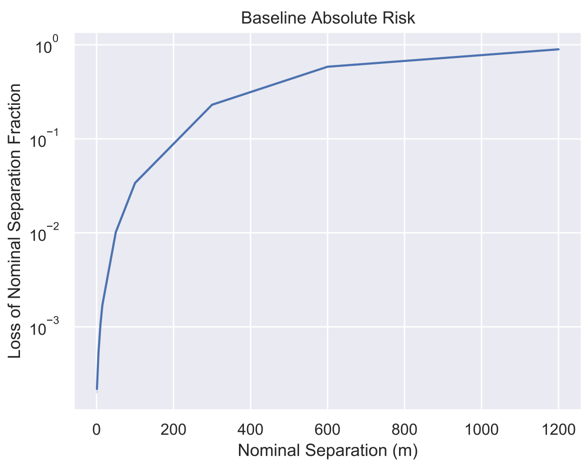

Figure 7: The absolute unmitigated risk as a function of nominal separation

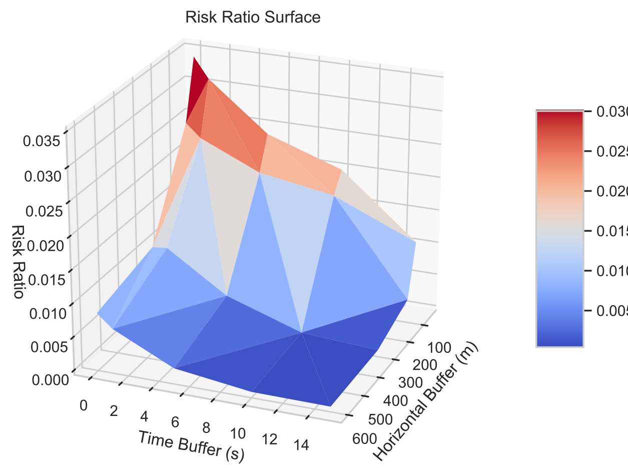

Figure 8: Risk ratio surface plot for a conformance rate of 0.90

the risk ratio is shown in Figure 8 for a conformance rate of 0.90. These results allow us to evaluate the risk of the system under the assumption that all UAS are able to conform to at least the specified rate. The figure provides a quantitative view into how much risk reduction we can expect from strategic deconfliction when a given set of buffer values is used and the specified conformance rate is adopted in the system. Our results show that significant risk reduction can be obtained by using strategic deconfliction as a risk mitigation mechanism between cooperative traffic.

Figure 10 provides a set of horizontal buffer recommendations derived from our evaluation for a variety of heading and speed noise that would be necessary to meet a given conformance rate. The figure shows that as the noise values increase, larger buffers are needed to meet a given conformance rate requirement. Additionally, the required buffer sizes are more sensitive to heading noise than to speed noise for the operational profiles and dynamics considered in this work. Note that the buffer values needed to meet a 0.99 conformance rate are relatively large under high noise conditions, while a lower conformance rate requirement would allow a significantly smaller volume sizing under the same error configuration.

VII. Conclusion

UTM performance-based standards are being drafted to define a baseline for how UTM services will be deemed worthy to safely provide a UTM function. This requires quantitative analysis to map the standards to the risk they are mitigating, as well as a means for operators to comply with the standard. For example, if a conformance rate requirement exists in the system, we must understand how much risk it mitigates, and UAS operators need to know how to size their operation volumes in order to meet it.

In this work we proposed an end-to-end simulation framework that could be used to evaluate the safety implications

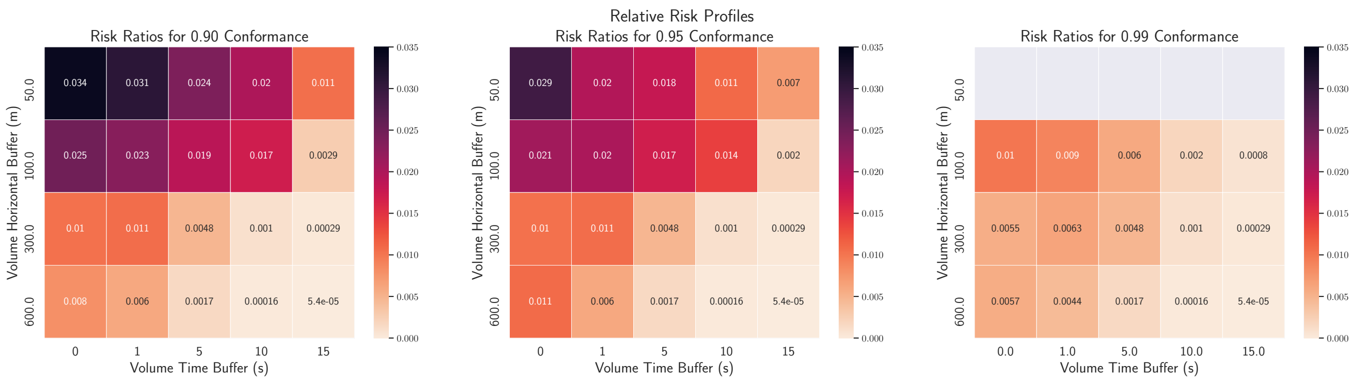

Figure 9: Risk mitigation fraction of strategic deconfliction for varying time and horizontal buffers across conformance rates of 0.90, 0.95, 0.99

of UTM requirements under a broad set of parameters and assumptions. We applied this framework to volume based strategic deconfliction in order to determine the relationships between operation volume sizing, system error, conformance rate, and system safety. We demonstrated that the framework can be used to validate and verify requirements in the context of strategic deconfliction that have emerged from recent standards work, namely those around operation volumes and conformance rate. We showed that strategic deconfliction can lead to significant risk reduction under proper volume sizing assumptions even in the presence of large system noise. We also illustrated that requiring higher conformance rates can be a mechanism of improving the quality of strategic deconfliction, and ultimately leading to reduced risk. Finally, we provided a set of guidance criteria for constructing operation volumes under a given system error that can be used to meet a desired conformance rate and ultimately a specific safety target. It is important to note that there is not a direct mapping between conformance rate and the risk ratio, so specifying just a conformance rate is insufficient to meet a desired safety target. Instead both conformance rate, and volume sizing impacts the risk mitigation form strategic deconfliction. The numerical relationships presented in this work can be used as a guide for UTM standards and regulations, and accelerate the operationalization of the ecosystem.

A number of open questions remain about strategic deconfliction in UTM. Specifically, analyzing the impact of external disturbances on operational conformance such as those related to weather could provide valuable insights for a more comprehensive safety target. Analyzing the performance of strategic and tactical deconfliction jointly would lead to a more comprehensive safety measure for applications where using both tactical and strategic deconfliction is possible. We can also explore the ability of UTM strategic deconfliction to safely scale to high densities, and the capacities that may need to be enforced to ensure a safe operational regime. The framework proposed in this work can be used to evaluate the performance of a strategic and tactical system independently and jointly. Future work could also include a more comprehensive sensitivity analysis on the impact of vehicle capability, like nominal speed and turn rate, on operation volume construction and conformance rate. Specifically, the impact of UAS dynamic constraints can be analyzed using our framework, and upper bounds on requirements can be derived that allow all vehicles to meet a specified safety target. Lastly, efficiency can also be analyzed as part of future work. Given that volume sizing can have a significant impact on the throughput and efficiency of an airspace, it is critical to understand the relationship between safety and efficiency when performing a system wide analysis. Additionally, because we measure safety through a relative risk ratio in this work, we are able to quantify the safety improvements that UTM strategic deconfliction adds over a risk unmitigated baseline. Future work may involve properly quantify relative efficiencies and inefficiencies added by UTM strategic deconfliction.

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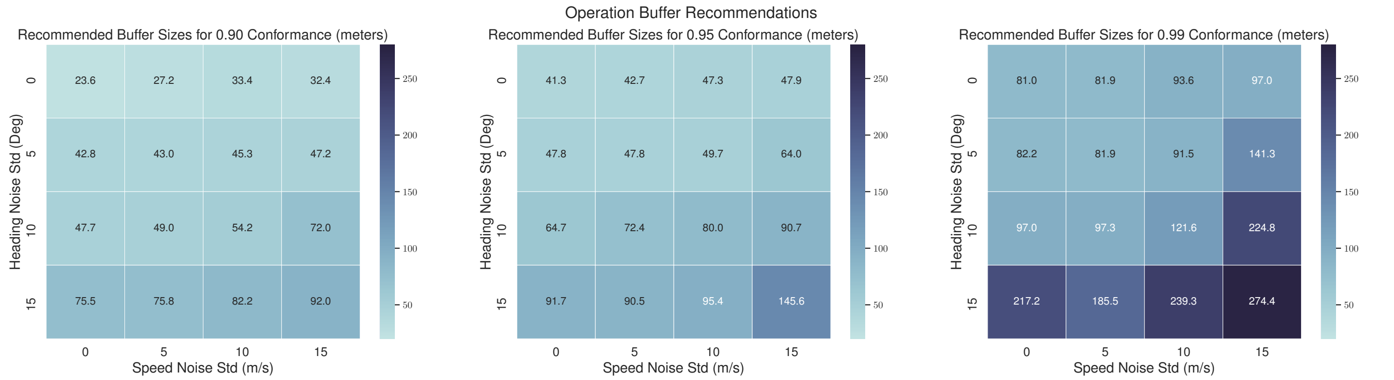

Figure 10: Horizontal buffer recommendations that would meet the specified conformance rates 0.90, 0.95, 0.99 given the expected heading and speed noise of a UAS.

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