Simulation Study for Interoperability of Urban Air Mobility Scheduling and Separation Services in Ideal Conditions

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Provision of strategic scheduling and tactical separation services is vital to the safe and efficient operation of vehicles in the urban airspace. This paper describes the efforts made towards the integration of two such services in a simulation environment under ideal conditions and the subsequent studies done on evaluation of system performance. The scheduling and separation services are set up to complement each other to ensure safe separation between airborne aircraft. The utility of these services will become important as the level of traffic increases. This paper describes the simulation experiments conducted to identify cases where the system performance measured by the number of observed losses of separation degrades even with the scheduling and separation services active. From the results obtained, we identify conditions under which the required maneuvers increase and when we observe airborne conflicts even with separation service active. Results obtained will inform requirements for future advancements both in these services independently and in their joint operations.

I. Introduction

Urban Air Mobility (UAM) is a new transportation concept for safe, quiet, and efficient air traffic operations in a metropolitan area based on manned and unmanned aircraft systems. NASA's Air Traffic Management – eXploration (ATM-X) project has been investigating new technologies which will be applied to UAM operations. The effort currently underway is intended to develop a set of technologies which will develop and mature a set of automated airspace services, allowing for high-density operations with minimal amount of human intervention. The operational paradigm proposed in the current UAM Concept of Operations (ConOps) released by the FAA [1] describes the roles of independent entities called the Provider of Services for UAM (PSU) in support of UAM operations. PSUs provide such support by facilitating the exchange, analysis, and mediation of information among the UAM operators, other PSUs, the FAA, and all other stakeholders in UAM.

One of the roles of a PSU is to provide strategic deconfliction based on the flight intent data shared by the operators, which is the primary method for maintaining separation between aircraft. Strategic deconfliction involves looking at a longer time horizon of a flight plan to ensure that separation is maintained throughout the mission; in comparison,

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tactical deconfliction is done over a shorter time horizon of the order of a few minutes while the aircraft is airborne. Tactical deconfliction is a responsibility of UAM operators. However, such division of responsibilities among the different stakeholders requires that the interoperability of these services is assured so as to maintain data integrity, communication timeliness, and a shared understanding of information by all systems [2]. Such advancement will have to be ensured even as the system evolves towards higher levels of autonomy, which is expected to gradually happen. For example, NASA's UAM Vision Concept of Operations [3] describes the UAM transportation system evolving through six UAM Maturity Levels (UML), with increasing levels of reliance on automation, traffic density, complexity of operations, alongside a desired increase in community acceptance; at UML-4, which is the focus of this ConOps, the airspace services collectively provide a "Collaborative and Responsible Automated System."

In this paper, we address the integration of two independently developed services for UAM airspace operations – Network Scheduler (NS) Service, which provides strategic deconfliction by assigning scheduled times of arrival at the departure and arrival fixes to UAM operations, and AutoResolver (AR) Service, which provides tactical deconfliction by maintaining spatial separation between aircraft operating in the airspace. The former provides the scheduling service which can maintain real-time, on-demand resources for UAM operations and control traffic congestion conditions across the network. The latter provides tactical separation and thereby helps mitigate the effects of uncertainty to maintain safe and efficient operations [4]. While the two services have been independently developed and validated, they have not yet been tested to work together with a common set of airspace resources and aircraft. Verma et al. [5] discussed simulation experiments that were conducted with these two services operating within the same simulation environment, but independently of each other – the two services did not directly interact with each other during the course of their operation. In this study, therefore, we try to integrate these two services to communicate with each other and jointly provide the scheduling and separation services for UAM operations. As a foundational step for this research, we focus on an ideal environment where both services can fully observe the state of the airspace and there are no uncertainties presented in UAM operational environments; examples of uncertainties would include uncertainty of departure time or error in magnitude of estimated wind speed. Thus, the research question we address in this paper is, *"How can Scheduling and Separation function together in a complex UAM network under ideal conditions?"*

From the simulations conducted to address this research question and the analyses of the results, we will develop requirements for the relationship between the spatial separation and temporal separation values used by the deconfliction algorithms when they are working collaboratively in the same simulation environment. A potential outcome of this work would be to determine the appropriate temporal spacing required for the scheduling algorithm for the separation algorithm to successfully resolve all potential conflicts efficiently, while maximizing network throughput. Thus, we can establish a foundation for understanding the interoperability between scheduling and separation services under nominal conditions.

The rest of this paper is organized as follows. Section II describes the two services and the architecture of the simulation system into which they are integrated. Then, Section III describes the experiment setup, including the assumptions made, traffic and network setup for the scenarios, and the actual scenarios evaluated. Finally, Section IV presents the simulation results followed by the conclusions in Section V.

II. Scheduling and Separation Services for UAM Operations

NASA has developed scheduling and separation algorithms to support safe and efficient UAM airspace operations. These two autonomous algorithms for UAM operations that are independently developed, Network Scheduler and AutoResolver, were integrated for a high-demand UAM traffic simulation and evaluated in a common high-fidelity simulation environment. This section describes these scheduling and separation service modules and the integrated simulation system architecture used in a joint experiment to investigate their interoperability.

A. Network Scheduler (NS)

Network Scheduler (NS) provides a centralized, strategic scheduling service to all UAM operators. The scheduler can coordinate access of flights to the shared resources constrained by capacity, such as en-route crossing or merging waypoints, meter fixes, and vertiports. In the present implementation, the scheduler receives trip requests from operators consisting of origin, destination, desired departure time, and proposed route planning that includes travel times to constrained resources and metering waypoints along the route. It assigns scheduled times of arrival at the departure and arrival points to all UAM flights, considering temporal separation requirements for safety and other operational constraints at scheduling waypoints along the full trajectory. The schedule is periodically recalculated and adjusted as necessary to react to uncertainties in UAM operation environments. The current scheduler functionality is based on a First-Come, First-Served (FCFS) discipline and only assigns schedules to aircraft prior to their departure.

In the future, the scheduler will be modified to make use of speed control to set and change schedules at en-route waypoints and destination vertiports for airborne flights and incorporate optimization techniques to achieve a variety of system objectives such as maximization of network throughput, maximization of resource utilization, or minimization of delay.

B. AutoResolver (AR)

AutoResolver (AR) provides a tactical separation service for UAM vehicles. The simulation has a single, centralized AR, which executes three main functions: tactical scheduling, conflict detection, and conflict resolution. The AutoResolver actively monitors flight progress starting just prior to takeoff and continues throughout the duration of the flight. AutoResolver will periodically assign maneuvers to be done by the flights to conform with tactical schedules, while keeping flights spatially separated from each other in the air; the tactical scheduling function within AR adjusts the takeoff time of an aircraft as necessary to avoid a predicted conflict right after takeoff. The conflict detection function predicts future trajectories of flights and searches them for conflicts within a fixed pre-defined look ahead time. It detects any potential conflicts when two flights are predicted to violate separation criteria, and, if a potential conflict is detected, the conflict resolution function of the AutoResolver searches for any possible maneuvers to resolve the conflict. In our implementation, we used a look-ahead time of five minutes. The types of conflict avoidance maneuvers generated by AR include speed changes, horizontal deviations from a flight path, altitude changes, or a combination of speed and horizontal path changes. Among the set of successful maneuvers found, AR selects the one that would be of the preferred type for the conflict in the airspace in which the conflict occurs and that has the minimum amount of delay; in this paper, we assume speed control to be the preferred type of maneuver, which means that any other maneuver, if assigned, is considered to be a failed maneuver and counted as a conflict. These conflict resolution maneuvers allow each aircraft in conflict to return to its original trajectory once the conflict is resolved. More details about AutoResolver can be found in Refs. [6, 7].

C. System Architecture

Figure 1 shows the conceptual simulation system architecture. The base of this architecture is the NASA's Testbed simulation environment [8] within which, an autonomous operations layer has been created. Some standard services such as trial planning/trajectory generation, surveillance, and simulated UAM aircraft are added to the autonomous operations layer. This autonomous operations layer augments Testbed capabilities for enhanced communication modeling and maintaining a synchronized clock between services. The separation and scheduling services, which correspond to AutoResolver and Network Scheduler in this experiment, respectively, are integrated into this layer and interact with each other, allowing to evaluate complex scenarios. Further details of Testbed can be found in [8].

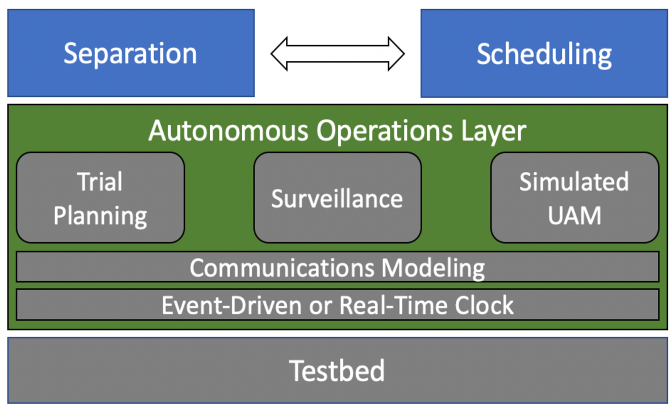


Figure 1: Simulation system architecture

III. Experiment Setup

This section describes the joint experiment to investigate the interoperability and data exchange between scheduling and separation services for mature state UAM operations [1] in ideal conditions, specifically UML-4, without considering any uncertainties in real operations such as weather impact and departure time perturbation. This section presents the experiment setup including assumptions, traffic scenarios, route network, and a test matrix.

A. Assumptions and Limitations

We make the following assumptions in the simulations for the study about the interoperability between NS and AR in ideal conditions.

1) Nominal operational conditions
   a. Good weather condition (Visual Meteorological Condition (VMC); no wind effect)
   b. No operational constraints for traffic flow management; no interaction with ATC
2) A simplified route structure modeling a congested intersection area

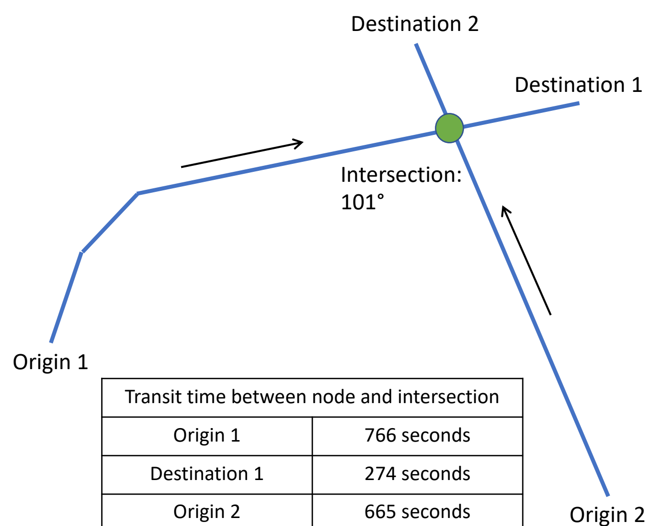
    a. Two one-way routes, both at the same altitude of 1100 ft. AGL, that have origin and destination vertiports and a crossing waypoint where two routes intersect
3) A single UAM vehicle model with nominal cruise speed of 130 kt
4) Spatial Separation
    a. Default spatial separation: 1,200 ft. lateral, 500 ft. vertical
    b. Excludes separation rules within 1 nmi. of vertiports
5) Network Scheduler
    a. Controls departure times for pre-departure flights only (ground delay only; no airborne delay assigned)
    b. Schedules the flight departure times on the First Come, First Served basis
6) AutoResolver
    a. Monitors flights within a 5-minute planning horizon. This means that AR detects potential conflicts within five minutes of current time and assigns maneuvers to avoid them.
    b. Predicts conflicts and issues resolutions whenever the minimum spatial separation is predicted to be violated
    c. Only speed control and path stretch maneuvers applied for conflict resolution
    d. When a resolution is issued, a 20% margin is added to the required minimum spatial separation to account for uncertainties (i.e., an aircraft is maneuvered such that the closest approach distance is 1.2 times the default spatial separation or greater.)

These assumptions are made to simplify the conditions in UAM operation environments and concentrate on investigating the impact of temporal and spatial separations on the system performance under ideal conditions, without considering any uncertainty factors.

B. Traffic Scenarios

In our simulations, we consider a simple network with just two routes which intersect at a single crossing waypoint. Figure 2 shows the route network developed for these experiments, which was extracted from the route structure used in Ref. [5]. Both routes have one-way traffic for all results presented in this paper and cross at 1100 ft. AGL (see Intersection in Figure 2). Though simple, simulations using this network can capture the complexities of scheduling and maintaining separation at a shared resource (crossing) to maintain safe operations.

The traffic scenarios are set up as a fixed number of aircraft departing from each origin vertiport at equally spaced intervals; in all our experiments, we modeled a total of 40 aircraft in a scenario, 20 on each route. We refer to the spacing between consecutive aircraft as "inter-departure spacing," where a lower value of inter-departure spacing corresponds to higher traffic density and vice versa. For example, 'inter-departure spacing' = 30 seconds means that flights depart from the origin vertiport every 30 seconds throughout the scenario. Figure 3 shows this value as "spacing." Figure 3 also s hows an additional parameter called "offset." Since the experiments we conduct are under the conditions of no uncertainty, we carefully set up the departure times such that the spacing between two consecutive aircraft arriving at the intersection is controlled, and this value is called the offset. In these experiments, the offset at the crossing is defined as the minimum temporal spacing between the flights passing by the crossing waypoint alternating between the two routes, given the equally spaced flights on the same route. Figure 3(a) shows a situation where all aircraft at the crossing are arranged to have equal spacing (offset = inter-departure spacing / 2), while Figure 3(b) shows a situation where the offset is specified by adjusting the departure times to evaluate the impact of the offset time at a crossing waypoint on the safety and performance of UAM route network.



Transit time between node and intersection	
Origin 1	766 seconds
Destination 1	274 seconds
Origin 2	665 seconds
Destination 2	173 seconds

Figure 2: Route structure used for simulation runs

Since all aircraft operate at a fixed common cruise speed, we can calculate the minimum temporal separation at the crossing waypoint required to ensure that the spatial separation constraint is not violated as:

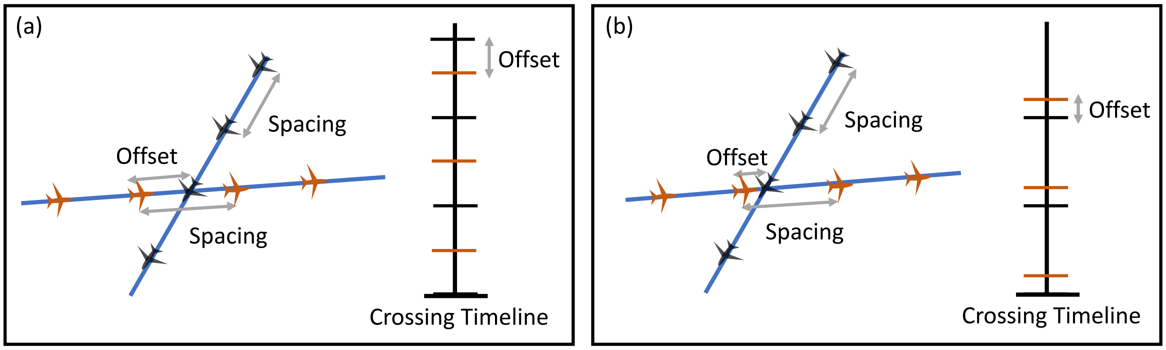


Figure 3: Spacing and offset at a crossing waypoint

$$temporalSep_{min} = \frac{spatialSep}{speed * \cos\left(\frac{\theta}{2}\right)} \tag{1}$$

where *spatialSep* is the desired spatial separation, *speed* is the cruise speed of aircraft, and θ is the crossing angle between two intersecting routes. Figure 4 shows the relation between temporal separation and crossing angle, given the cruise speed of 130 knots with two spatial separations, 1,200 ft. and 1,440 ft.; the latter value indicates the separation assigned by AR during conflict resolution after accounting for the 20% buffer over the minimum requirement. The figure clearly shows that the minimum temporal separation between crossing flights depends strongly on the inbound crossing angle, i.e., increases non-linearly as a function of crossing angle. Note that, this figure assumes that there is no cross-track error. In this figure, 0° and 180° crossing angles correspond to in-trail and head-on flight conditions, respectively.

Since the two routes in our network cross at the intersection with an angle of 101°, given cruise speed of 130 knots (= 219.415 ft/sec), the minimum temporal separation value associated with 1,200 ft lateral separation is 8.60 sec, which becomes 10.32 sec with an additional 20% buffer.

Figure 5 shows that when Network Scheduler (NS) schedules departure times, it leads to controlled flow rate and offset at a crossing waypoint. This conceptual diagram considers the two routes crossing at an intersection A. In, Figure 5 the first timeline in the left-hand side shows the initial departure timeline at the origin 1. In a high traffic condition, it is assumed that new flights are requested for takeoff every 14 seconds; this corresponds to a traffic level of over 250 flight requests every hour. Then, NS adds temporal separation before takeoff by assigning ground delay so as to make enough spacings at the crossing waypoint (intersection), considering the other flights from the other origin 2 on the right-hand side, for which NS schedules the departure times as well at the same time. In this way, NS tries to make the sufficient separation between crossing flights in the pre-departure phase before takeoff.

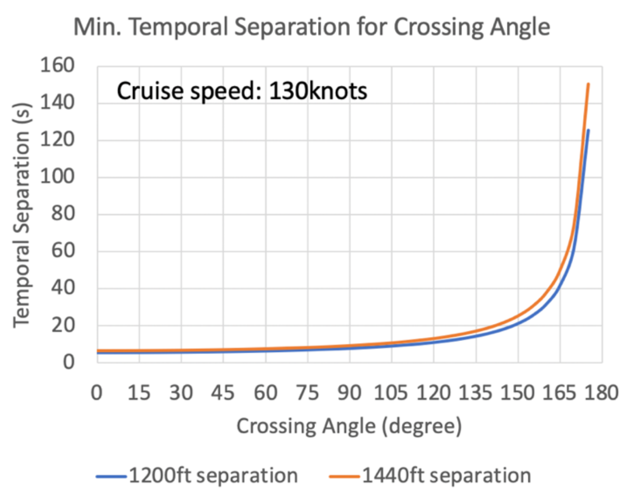


Figure 4: Relation between crossing angle and minimum temporal separation

C. Test Matrix

In this study, we set up two experiments to explore the impact of varying temporal separations on system performance. The test matrix in Table 1 below shows the main variables used in the simulation runs.

In our setup, NS assigns pre-departure schedule times. Prior to departure, NS and AR interact with each other by sharing information about scheduled times and actual times of arrival of all operations, and sequentially control an aircraft, with NS assigning and revising schedules as necessary from the time an operation is requested until a few

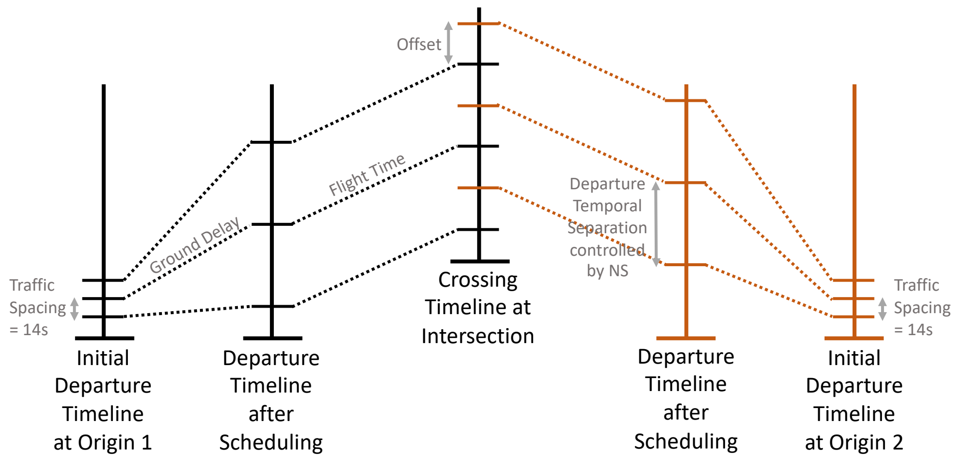


Figure 5: How Network Scheduler schedules departure times

minutes prior to take-off, at which time AR assumes responsibility to ensure tactical separation. Once an aircraft takes off, AR ensures tactical separation is maintained, but NS no longer issues new schedules to airborne aircraft. We run a series of simulations with either only the NS active or both NS and AR active. This allows us to compare the effects of the services acting together on system performance. Note that, in this paper, we only discuss the effects of varying temporal separation provided by NS on AR performance. Hence, we first run a scenario with NS only to establish comparison with the case where both NS and AR are active. Studies of the effects of varying spatial separation on NS performance are not reported in the present paper, and hence runs with AR only active are not shown. The settings for the rest of the variables are dependent on the experiment, described below.

Table 1: Variables and their corresponding factor levels used to define experiment scenarios

Variables	Factor levels
Services	NS-only, AR+NS
Traffic demand level (expressed in inter-departure spacing in seconds)	14
AR spatial separation (ft)	1200
NS temporal separation (sec)	30, 28, 26, 24, 22, 20, 19, 18
Route offset at crossing waypoint (sec)	One second intervals from 0 to 15 seconds

Experiment 1: Varying departure separation

In this first experiment, we wish to evaluate the system performance while varying departure temporal separation which the Network Scheduler assigns to aircraft at both departure vertiports. The simulations are conducted, first, only with strategic scheduling service and no tactical separation service, and second, with both scheduling and separation services. In the former case with scheduling service only, since, in its current form, the scheduling service assigns a scheduled time of departure at the departure vertiport, with no control over the aircraft once they are airborne, we expect that the number of losses of separation (LOS) will increase as the traffic density increases. This case provides a reference level from which we can evaluate the benefit of providing tactical separation service. In the latter case, we compare the effect on system performance when both services are active.

Experiment Objective: *For evenly spaced aircraft arrivals to a crossing waypoint, measure the system safety and efficiency observed for different temporal separations*

- Case 1: NS is active, but AR service is inactive (NS-only); Case 2: Both NS and AR services are active (NS+AR)
- Traffic demand level: uniform distribution; inter-departure spacing = 14sec
- Offset = 0.5 * NS temporal separation
- All aircraft cross the crossing waypoint separated by equal time intervals.

Accordingly, all the scenarios run in this experiment differ only in their temporal separation values, which vary from 30 seconds to 18 seconds. The traffic level and spatial separation remains fixed in all scenarios.

Experiment 2: Varying offset at a crossing waypoint

In this experiment, we evaluate system performance for a situation where aircraft arrivals to a crossing waypoint are not evenly spaced. Though the current work does not explicitly model uncertainties, in real-world situations, arrivals to the waypoints can deviate from the ideal. Hence, we evaluate how the scheduling and separation services affect system performance when the offset is not equal to half of the in-trail temporal separation value. In other words, we emulate uneven arrivals at a crossing waypoint due to uncertainty by adjusting departure times at the origin vertiports.

Experiment Objective: *Measure the number of resolutions required to be issued by AR to prevent LOS when aircraft arrivals at a crossing waypoint are not evenly spaced*

- Both NS and AR services are active (NS+AR)
- Traffic demand level: uniform distribution; inter-departure spacing = 14sec
- Various offset values at crossing waypoint (i.e., aircraft cross the crossing waypoint separated by unequal time intervals), ranging from 0sec to 15sec

D. Performance Metrics

The performance metrics that can be measured from the simulations are listed below; a subset of these metrics is presented in the next section, according to the objectives of the simulation scenarios.

- Safety
    - Total instances of Loss of Separation (LOS)
    - Total number of aircraft that encounter LOS
- Efficiency
    - Flight delay (total, by route, per flight)
- NS scheduling
    - NS iteration length
    - NS ground delay
- AR maneuvers (total, by maneuver type)
    - Speed change
    - Horizontal path stretch
    - Total maneuver counts

Besides these metrics, we also evaluated other metrics such as the duration of a simulation run, or a breakdown of delay assigned by the different services; however, these additional metrics are not presented in this paper.

IV. Simulation Results

We ran 101 simulations by controlling two parameters, viz. departure temporal separation (ranging from 30 sec to 18 sec) and offset at the crossing waypoint (from 0 to 15 sec), while keeping the spatial separation requirement fixed at 1200 ft. In this section, we discuss the results from the scenarios described above.

Before starting the experiments, we conducted a series of verification and validation studies with only NS operational, only AR operational, and both NS and AR working together. For each of these, we validated that all inputs and outputs were as required, verified that there were no errors in simulation behavior, and validated that the two services functioned as intended. For example, some of the questions we answered for the verification and validation of simulation software for each of the three categories included, "Do the flights takeoff and land at designated vertiports and follow their routes?," "Does NS assign scheduled times to maintain desired temporal separation?," and "Does AR assign maneuvers correctly?" Over the course of these simulations, we uncovered a number of errors in the simulation software and corrected these errors before proceeding with the experiments.

A. Results and Analysis

We will now present the results of both experiments and describe the takeaway messages from analysis of results obtained. To get a baseline for comparison, we ran a simulation with neither the separation nor scheduling services active. With no services, the total flight time on each of the segments is shown in Figure 2. If we reduce the departure separation values, all pairs of aircraft from the two routes that cross the intersection get involved in a loss of separation since neither of the two services are active. We expect that, with the services active, the average flight times will increase and there will be no losses of separation.

1. Experiment 1: Comparing effects of varying departure separation

We present results from scenarios run under two paradigms, viz., with NS only and with both AR and NS services. NS does not monitor aircraft for spatial separation violations and hence allows conflicts to occur if the temporal separation values are set too low. AR, on the other hand, provides the detect and avoid service which means that it monitors aircraft for any possible separation violations and issues appropriate resolutions. However, this means that, in cases with dense traffic, the simulation can slow down as AR searches for resolutions to issue.

Under both paradigms, we initially start with the departure temporal separation set to 30 seconds and gradually reduce this separation in each successive run, as shown in Table 1; that is, we reduce the temporal separation from 30 seconds down to 18 seconds. Our intent was to find minimum possible separation values that could be achieved with both services active that would not violate safety. We observed that the traffic at departure temporal separation of 18 seconds was so dense that AR could not resolve all predicted conflicts. For each of these runs, the traffic level remains constant at one flight request every 14 seconds and the spatial separation is 1,200 ft. At this spacing, there would be over 250 flight requests on each route per hour, which corresponds well with the expected level of traffic at UML-4.

As explained in Figure 5, NS adds an aircraft's ground delay to the original departure time based on the required departure temporal separation from the preceding aircraft. From both origins, the first aircraft take off at their scheduled times. Thereafter, every successive aircraft receives an increasing amount of ground delay which is proportional to the departure separation. Equation 2 shows the ground delay assigned by NS to aircraft *i* as a function of traffic spacing and the departure temporal separation of the scenario. The total ground delay, therefore, is the sum of ground delays of all aircraft on a route and proportionally increases as the total number of aircraft increases.

$$ground\_delay_i = (departure\_separation - traffic\_spacing) * (i - 1) \quad (2)$$

Based on the above formula for ground delay, the mean ground delay per route is a function of the total number of aircraft we simulate in an experiment. Equation 3 gives the value for mean ground delay, where N is the total number of aircraft on a route.

$$ground\_delay = (departure\_separation - traffic\_spacing) * (N - 1)/2 \quad (3)$$

Figure 6 shows the mean and standard deviation of assigned ground delay for each of the departure separation scenarios, and the blue line shows the expected mean ground delay based on Eq. 3; the actual ground delay values observed from the simulation are close to the expected values. Here, the small differences between the actual and expected values are due to numerical truncation of time to integer values done by the simulation software. Also note, that since we imposed no limit on the amount of delay that can be assigned to an aircraft, increasing trend observed in Figure 6 is expected.

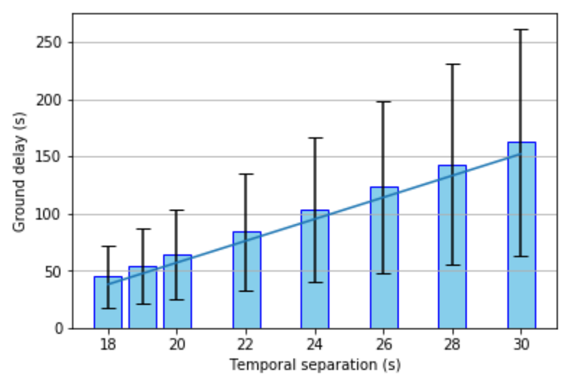


Figure 6: Mean and standard deviation of assigned ground delay for various departure temporal separations

Consequently, higher departure separation values will lead to higher total and mean ground delay but decrease the likelihood of conflict at crossing. On the other hand, lower departure separation values would result in lower ground delay, higher throughput, but also lower temporal and spatial separation at the crossing, resulting in higher likelihood of a conflict. In our current simulation setup, the crossing waypoint is far enough from the origin vertiports that it lies beyond AutoResolver's lookahead horizon, and as a result, AR does not assign any ground delay.

When only NS is operational, we expect that below a certain temporal separation threshold, we will observe losses of separation (LOS). While there were no observed conflicts for temporal separation value of 19 seconds or greater, there were two LOS when the separation was set to 18 seconds. We note that the simulation software currently handles time in integer seconds such that any intermediate values are rounded off. As a result of this, separations of successive aircraft departing from the origin vertiport alternate between 18 seconds and 19 seconds, leading to a mean value of 18.6 seconds, which is slightly larger than the user specified value. From NS assigning departure times, the mean crossing separation at the crossing waypoint is 9.31 seconds, which is well in excess of the required minimum of 8.6 seconds. Nonetheless, in two instances, the rounding of time to integer values results in aircraft from the two routes arriving at the crossing waypoint within 8 seconds of each other, and these two are the observed instances of LOS.

Following this observation, we repeated the same set of simulations, but this time with both NS and AR active. The simulations we run are of discrete event in nature, so that while AR searches for a resolution to avoid a predicted conflict, the entire simulation pauses. We allocated a maximum of 20 minutes of run time for all simulations, at the end of which the experiment was terminated. While most scenarios completed in seven minutes, the scenario with departure separation of 18 seconds and both AR and NS services operational did not complete within the allocated run time. No LOS were observed for the duration of the run. However, this required AR to issue a speed change maneuver to an aircraft labeled "UAM107" and a path deviation to an aircraft labeled "UAM208"; these are the seventh and eighth aircraft on the two routes, respectively. These same two aircraft were involved in the first of the two instances of LOS observed when only the NS service was operational.

Thus, AR was able to successfully resolve a predicted conflict, albeit only after attempting a large number of different resolutions. In the 20 minutes duration of simulation run, AR predicted a potential conflict between UAM107 and UAM208 a total of 15 times and attempted 76 resolutions for both aircraft combined before it could successfully maneuver them. Currently, AR does not have an algorithm which can guide its search of resolutions, with the result that it searches randomly. Each search attempt for a maneuver is recorded as a resolution attempt, and, due to the lack of an algorithm to guide this search, the number of resolutions can be high. Future work will investigate additional scenarios to further understand the relation between traffic density and AR resolution attempts. Finally, when AR finishing searching, it selects a resolution maneuver which does not cause any new conflicts and leads to low delay.

Network Scheduler's computational performance can be assessed by comparing the mean length of each scheduling iteration of NS for the different scenarios. Network Scheduler has a cycle time of 30 seconds, which means that it runs a scheduling iteration once every 30 seconds. As the traffic density increases, there are a larger number of aircraft that are required to be assigned schedules in each iteration. This results in a longer average length of each iteration of NS, as shown in Figure 7 below, where the mean length of each scheduling iteration increases as the departure separation decreases.

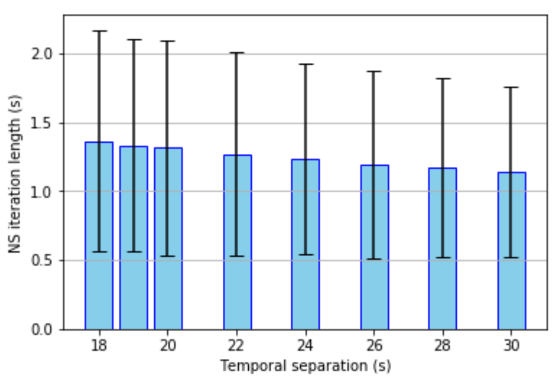


Figure 7: Average length of schedule iteration vs. departure separation

2. Experiment 2: Comparing effects of varying offset

The results presented in the previous subsection are for a single value of offset, where offset is half of departure separation. In such a case, the aircraft arrive at the crossing at evenly spaced separations which are controlled by adjusting assigned schedules at departure vertiports. In real world operations, it is unlikely that all aircraft will be able to maintain such uniform separation due to the presence of uncertainties. Thus, in this section, we compare the effects when the offset values change. For all values of departure separation, we increase offset gradually from 0 seconds, which indicates that two aircraft arrive at the crossing at the same time, to up to one second less than departure separation. Even though we are not modeling uncertainties explicitly, these scenarios will allow to estimate the effects of uncertainties indirectly by using a variation in offset.

Figure 8 shows the boundaries of No Loss of Separation cases for the various combinations of temporal separation shown in Table 1 and one second intervals of offset ranging from 0 seconds (aircraft from two routes arrive at the crossing at the same time) to 15 seconds. When the offset is large compared to the theoretical minimum separation at the given crossing waypoint (8.6 sec), there are no LOS situations as shown in green colored shaded area, and conflict resolutions are not required. Note that blue lines and dots in the graph are also included in the green shade, showing the boundary for no LOS and no resolutions needed. Once the offset is at or below the minimum separation, AR issues conflict resolutions to avoid the LOS, as shown in the yellow shaded area in the figure. However, regardless of the offset, if the departure temporal separation is too low (i.e., less than 19 sec), we could either not complete the simulation runs or could not avoid the LOS even with AR active, which is shown in the red shaded area. Incomplete runs can occur when AR cannot find feasible resolutions for potential conflicts detected due to the highly congested traffic in the airspace. However, when the temporal separation is 19 sec with a 7 or 8 sec offset, we could complete the runs without any LOS. That means NS and AR working together can increase the throughput by reducing departure temporal separation used in NS and providing conflict resolution maneuvers issued by AR.

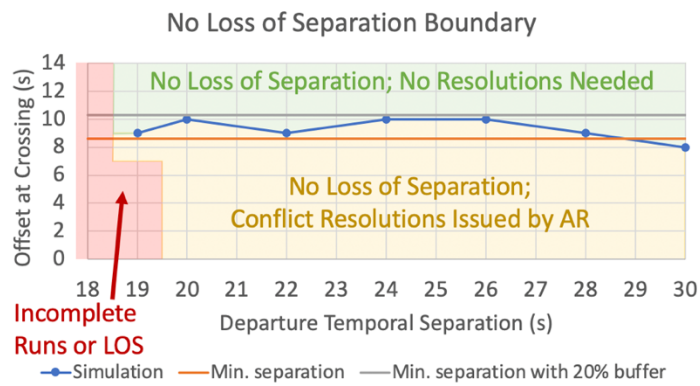


Figure 8: No Loss of Separation boundaries from simulation results

Figure 9 shows the number of conflict resolutions with different departure temporal separations ranging from 19 sec to 30 sec, for a selected value of offset of 6 seconds. These representative results illustrate that the number of conflict resolutions issued by AR increases as the departure temporal separation used in NS decreases. Since the offset of 6 seconds is less than the minimum required at the crossing waypoint, AR resolves a potential LOS by maneuvering all but one aircraft on one of the two routes for all values of temporal separation above 22 seconds. In this experiment, though AR could search for and, in some cases, apply other maneuvers besides speed control, we consider all such resolutions besides speed control to be failed attempts. With temporal separation set to 20 seconds, AR needs to perform a few additional maneuvers, which results in the aircraft maneuvering with an additional 20% separation buffer over the minimum separation required. This causes some new potential LOS to be created for which AR needs to make later adjustments. This effect becomes largely amplified at a temporal separation of 19 seconds where the number of resolutions more than doubles to 40, with four LOS. At a temporal separation of 18 seconds, the simulation did not complete because AR could not find feasible solutions.

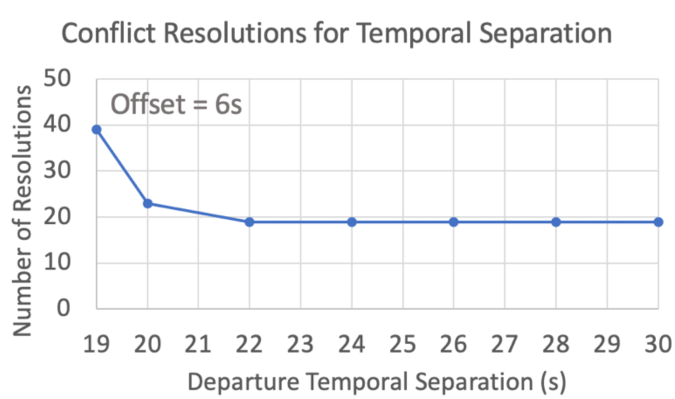


Figure 9: Conflict Resolution for Departure Temporal Separation

The NS-assigned ground delay values in the scenario with offset = 6 seconds are very close to the values when only NS was active; as noted, the simulation with the temporal separation of 18 seconds did not complete. This is to be expected because the crossing waypoint is sufficiently far from the origin that AR does not assign any ground delay. Consequently, ground delay is assigned only by NS whose behavior does not change whether or not AR is active.

We expect that the pre-departure strategic scheduling by NS-only may work well in the ideal conditions, but it cannot deal with the uncertainties in the real world. In our simulations, though there are no uncertainties, we mimicked uncertainties in the real world in the form of an offset value other than half of departure separation. Then, in case of high underlying demand (i.e., high frequency of new flight request), the temporal separation at the crossing which results from departure separation assigned by NS may not be sufficient to meet the required spatial separation standards for safety. Figure 10 shows such a case, where, by scheduling the flights at vertiports, NS alone can meet the separation requirements (shown as a red horizontal line) in the absence of any scheduling errors (blue bar in the middle of Figure 10), but when there are scheduling errors that were intentionally added to the test system, NS-only cannot satisfy the separation requirements (orange and gray bars in the NS-only group in Figure 10). To accommodate the scheduling errors or other uncertainties like departure time perturbation, NS may set a higher minimum crossing time separation (e.g., 30-second departure temporal separation), but this solution would result in the decreased throughput.

AutoResolver (AR) complements the limitation of the NS-only scheduling service. After takeoffs, AR monitors the trajectories of flights in the air and conducts the conflict detection and resolution by detecting potential conflicts and providing appropriate maneuvers to maintain safe separation and avoid any predicted conflict. In this example in Figure 10, AR is expected to control the aircraft flying in the air to ensure enough separation at crossing waypoints, which is greater than the minimum separation requirement, even with the errors in the schedule.

Figure 10: Complete scheduling and separation system moderates demand

B. Lessons Learned

Based on our simulations described above, we arrived at the following key insights.

1. The minimum temporal separation between crossing flights depends heavily on the inbound crossing angle, i.e., increases non-linearly as a function of crossing angle. This effect is especially pronounced once the crossing angle exceeds 90 degrees.
2. Scheduling and separation services working together can handle heavy traffic scenarios in which LOS would happen without these services (e.g., when offset is below theoretical minimum separation), leading to increased throughput. We observed this even with limited coordination between the two services in our experiment setup. Additional work can investigate the benefits obtained in the presence of uncertainties and with increased coordination between scheduling and separation services, for example, when both services can control aircraft which are airborne.
3. Throughput at a crossing waypoint can be increased by scheduling flights to the crossing waypoint compared to setting flow rates. In the current work, the scheduling service assigned pre-departure delays to regulate throughput over the entire route. With scheduling at the crossing, the required temporal separation at the crossing point can be obtained from the known required spatial separation, which can potentially allow for better conditioning of traffic flow.

4. The number of conflict resolutions from a separation service increases as the departure temporal separation in a scheduling service decreases. This effect occurs when the actual temporal separation gets closer to the required minimum value.

V. Conclusions and Future Work

We integrated two independently developed airspace services into a simulation environment and ran a series of experiments to demonstrate their interoperability. The two services are a strategic scheduling service which assigns departure times to aircraft and a tactical separation service which ensures that aircraft stay spatially separated to maintain safety during operation.

From our experiments, we conclude that UAM scheduling and separation services working together can handle heavy traffic scenarios in which LOS would happen without these services (e.g., when offset is below theoretical minimum separation), leading to increased throughput. As expected, we observed that as the departure temporal separation between aircraft was reduced, the number of maneuvers required to avoid conflicts increases, especially as the actual temporal separation values gets closer to the required minimum to maintain desired spatial separation. In extreme cases, the separation service is not able to resolve potential conflicts and the simulation does not complete within the assigned time.

Though the work presented in this paper describes ideal conditions, it serves as a useful foundational case for more complex scenarios with uncertainty. Related work that extends the studies conducted in this paper are already underway. Lauderdale et al. [9] have run simulations to study the effects of wind and departure time uncertainty on operations on the same route network described in this paper. They evaluate how the presence of uncertainties raises the required temporal and spatial separation values in order to ensure safety is maintained. Further work will evaluate the effects of dynamically changing separation requirement on system performance. For example, in the presence of contingencies, a sector of airspace may require aircraft to maintain higher spatial separation which can affect throughput and efficiency. Finally, future work will also investigate how the Network Scheduler and AutoResolver services can be integrated to function at higher levels of interoperability where they interact during the course of a flight operation.

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