Separation at Crossing Waypoints Under Wind Uncertainty in Urban Air Mobility

Todd A. Lauderdale *
NASA Ames Research Center, Moffett Field, CA, 94035

Priyank Pradeep †
Universities Space Research Association, NASA Ames Research Center, Moffett Field, CA, 94035

Kay-Martin Edholm ‡
Crown Consulting Inc., NASA Ames Research Center, Moffett Field, CA, 94035

Christabelle S. Bosson § ¶
Joby Aviation, Santa Cruz, CA 95060

To enable high-density operations in major metropolitan areas, urban air mobility networks are anticipated to have air traffic management with higher levels of autonomy. The focus of this research paper is to understand how trajectory prediction errors affect separation and scheduling services and to understand how these services can work together to mitigate the effects of these errors. Using both analytical and simulation methods, we look at conflict-detection-only scenarios to understand how wind errors and network properties affect required minimum temporal separation between crossing flights. Next, we study how trajectory errors affect conflict resolution and explore different combinations of scheduling and separation assurance to mitigate the effects of uncertainty between crossing flights. The detection study shows that the minimum temporal separation at a crossing point is dependent on several factors including inbound crossing angle, wind heading, and wind-magnitude uncertainty. The separation and resolution study compares the qualitative properties of three different scheduling/separation concepts and shows that using a combination of strategic, flow-based scheduling, tactical scheduling at crossings, speed control near crossing points, and separation management leads to a system that is insensitive to trajectory prediction errors while maintaining high network-throughput and flexibility for aircraft away from shared resources.

I. Introduction

Urban Air Mobility (UAM) can alleviate transportation congestion on the ground by utilizing three-dimensional (3D) airspace efficiently, just as skyscrapers allow cities to use limited land more efficiently [1]. The envisioned concept of UAM involves a network of small electric aircraft that takeoff and land vertically (eVTOL). These new aircraft will enable rapid and reliable transportation between suburbs and cities and within cities [1–3]. Some of the anticipated services using UAM operations include passenger transportation, cargo delivery, emergency medical evacuations, and rescue services [3]. Conventional helicopters are capable of vertical takeoff and landing, but the noise they generate has been significant enough to compel communities to take legal action on their usage in UAM [3]. Recently, technological advances have made it possible to build and flight test eVTOL aircraft that are quieter than helicopters. Over a dozen companies (for example, Airbus A3, Aurora Flight Sciences, EHang, Joby Aviation, Kitty Hawk, Leonardo, Lilium, Terrafugia, Volocopter, etc.), with many different design approaches, are working to make eVTOL aircraft a reality [2].

The Federal Aviation Administration (FAA), National Aeronautics and Space Administration (NASA) and industry partners have envisioned mature UAM operations characterized by high-tempo and high-density flights in a network with orders-of-magnitude more eVTOL aircraft than are seen in current day airspace operations[3, 4]. Although strategic

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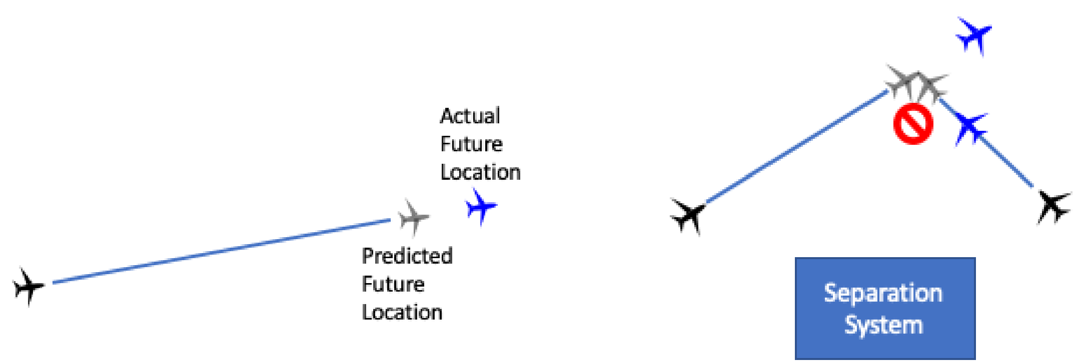
* Aerospace Engineer, Aviation Systems Division, NASA Ames Research Center.
† Aerospace Engineer, Universities Space Research Association, NASA Ames Research Center, AIAA Senior Member.
‡ Senior Software Developer, Crown Consulting Inc., NASA Ames Research Center, AIAA Member.
§ Senior Advanced Airspace Services Engineer, Joby Aviation, AIAA Member
¶ Christabelle contributed to this work when she worked at USRA/NASA Ames Research Center

conflict and flow management services are envisioned to be an essential component for enabling safe and efficient UAM operations, they may not be sufficient due to uncertainty in UAM flight trajectories, environmental conditions (e.g., wind), and other factors. Therefore, an en-route spatial separation management service with a look-ahead time between strategic conflict management and on-board tactical collision avoidance may also be needed to mitigate uncertainty and to safely handle off-nominal situations.

To enable autonomous airspace operations at high density, one of the critical steps from a safety and efficiency perspective is understanding various real-world factors that may impact the spatial separation between airborne flights and to understand ways to mitigate their effect. The current research's motivation is to understand how trajectory prediction errors due to wind uncertainties affect separation and scheduling requirements, especially at crossing points between routes (see Fig. 1). It is important to note that wind uncertainty produces only along-track prediction errors. To truly understand how to handle all real-world prediction uncertainties, both cross-track and vertical sources of uncertainty must be dealt with.

This study is divided into two parts. First, a study with only conflict detection is performed to understand how network design and wind uncertainty affect conflict detection and separation requirements. The performance of conflict detection is analyzed in two different ways: 1) analytical studies are performed using a temporal separation equation derived using nominal flight state propagation in look-ahead time, and 2) simulation studies in a fast-time simulation environment are performed using a highly autonomous spatial separation assurance Autoresolver algorithm [5, 6] for conflict detection. This study shows that conflict detection at crossings is complex function of crossing geometry, aircraft states, and wind characteristics.



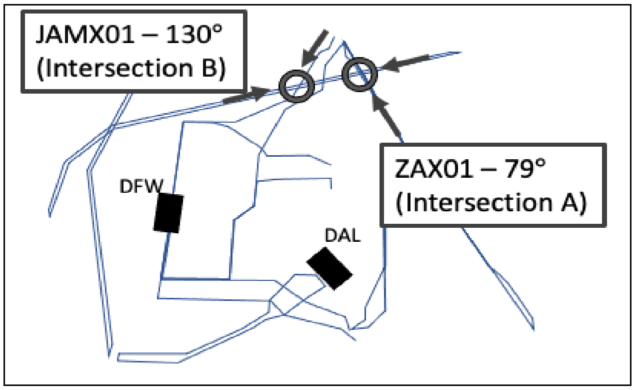
(a) (b)

Fig. 1 (a) Errors result in incorrectly predicted future locations. (b) These bad predictions may result in missed or false alerts. In this case, we have a false alert and unnecessary conflict resolutions.

The second part of the research is to understand how scheduling and separation management can work together to mitigate the effects of this uncertainty while maintaining both safety and throughput. Three different concepts for scheuduling and separation assurance are analyzed. The results show that using a combination of just-in-time scheduling, required-arrival-time management, and separation can lead to a high-throughput system that is independent of wind uncertainty.

II. Simulation Environment and Traffic Demand

Both the conflict-detection-only study and the scheduling and resolution study were conducted using the Autonomy Development Kit (ADK) toolbox for the NASA TestBed simulation platform [7]. The ADK toolbox is a set of algorithms and tools for TestBed that allow for the simulation of many different types of airspace operations, including UAM flights. ADK simplifies the process of creating new services and algorithms and of integrating them together in a common environment. The toolbox was designed to facilitate integration of new algorithms at nearly any Technology Readiness Level and to perform discrete-event based and real-time simulations.



(a)

(b)

Fig. 2 (a) UAM - X2 route structure [9]. (b) Depiction of traffic on two static intersecting routes.

In the studies for this paper, conflict detection and resolution services were provided by the Autoresolver [5, 6] algorithm. This algorithm was originally developed to handle traditional air traffic control issues, and it was modified to provide separation between UAM aircraft [8].

The basis for the traffic scenarios used in this study are the routes used for the real-time X2 study performed in Ref. [9]. These routes were created for UAM operations over the Dallas-Fort Worth Metroplex, and they were largely designed to avoid conventional operations and restricted airspace except in special instances. The routes are shown in Fig. 2(a).

The traffic flow is assumed to be in a steady-state with a single, constant cruise airspeed. Each traffic scenario is constructed such that the route of flight will alternate at the crossing point. Fig. 2(b) shows a close up view of two flows of aircraft at an intersection. For this research all flows are assumed to be at the same altitude because of airspace restrictions above and below the routes. This follows the route structure used for the X2 simulation in Ref. [9].

The simulation set-up and assumptions made for these simulation studies are shown in Table 1. These assumptions are made to simplify the UAM simulation environment and isolate the investigation to the impact of wind magnitude, wind direction, and wind magnitude uncertainty on the required temporal separation between crossing flights at various crossing points to maintain spatial separation. Similar to the route structure, the spatial separation values of 1200ft lateral and 500ft vertical are used because they were used for the X2 simulation and not with an specific safety value in mind. The ADK toolbox is set up in such a way that the simulated wind is different from the predicted wind to simulate the effect of wind uncertainty on separation services between flights at various crossing points.

Table 1 Simulation Set-up

Routes	UAM - X2 route network in the DFW metropolitan area (Fig. 2(a)) [9]
Vehicle model	UAM - X2 vehicle model with nominal cruise airspeed of 130 kts [9]
Spatial separation standards	1,200 ft lateral, 500 ft vertical
Look-ahead time	5 mins
Conflict detection cycle	10 seconds
Simulated wind conditions	Uniform wind field (13 kts) in lateral plane
Simulated wind magnitude uncertainty	various values between ± 50% of 13 kts = ± 6.5 kts

III. Detection in the Presence of Wind Uncertainty

Trajectory prediction errors can complicate conflict detection as errors result in incorrectly predicted future locations of aircraft (see Fig. 5(b)). These bad predictions may result in missed or false alerts [6]. The presence of wind magnitude uncertainty may create a false conflict detection alert, and if the system responds to it, it might create a real issue that would have to be resolved. This part of the research aims to understand the fundamental properties of conflict detection at intersections in the presence of wind magnitude uncertainty (E). In both analytical and simulation studies, the uniform wind with the magnitude of W is used in actual scenarios; however, in the trajectory prediction (state propagation) context, the uniform wind with magnitude W(1 + E) is used.

For both the simulation and the analytical results discussed below, the effect of wind on the ground-speed of an aircraft (aircraft A) is given by

$$V_{gs}^{A} = V_{tas} + W\cos\left(\psi - \psi^{A}\right), \tag{1}$$

where V_{gs} is the ground-speed, V_{tas} is the true aispeed, W is the wind magnitude, ψ is the direction of the wind, and ψ^{A} is the ground-track of the aircraft. This is a first order approximation of how aircraft move through wind in that a crosswind will not change the ground-speed in this approximation, but in reality an aircraft would need to adjust its heading to maintain its ground-track and would therefore fly a slower ground-speed.

A. Analytical Studies

Let's say in the trajectory prediction (state propagation) context, flight on route A (flight A) is at the crossing point (Fig. 3(a)) at time t = τ (i.e., the look-ahead time of the conflict detection algorithm). Assuming the ground-track of flight A to be the same as the bearing of route A, at t = 0, flight A would be at the following along-track position ($d_{initial}^{A}$) with respect to the crossing point:

$$d_{initial}^{A} = -\tau(V + W(1+E)cos(\psi - \psi^{A})) \tag{2}$$

where V is the nominal cruise airspeed of UAM vehicles, W is the wind magnitude, E is the absolute value of the ratio of the wind magnitude uncertainty to the actual wind magnitude, ψ is the wind direction w.r.t the north, and ψ^{A} is the bearing of the route A. Since flight A is actually flying in the wind field of magnitude W, therefore, it would actually cross the intersection (crossing point) at the time:

$$t_{actual}^{A} = \frac{-d_{initial}^{A}}{V_{gs}^{A}} = \frac{\tau(V + W(1+E)\cos\left(\psi - \psi^{A}\right))}{V + W\cos(\psi - \psi^{A})}. \tag{3}$$

Let's say the temporal separation between crossing flights on route A and route B is T^{A-B}. When flight A is actually at the crossing point flight B would be at the following along-track position (d_{actual}^{B}) with respect to the crossing point on route B (assuming the ground-track of flight B to be the same as the bearing of route B):

$$d_{actual}^{B} = -T^{A-B}V_{gs}^{B}. \tag{4}$$

Using equations 2, 3, and 4, the actual along-track position of flight B on route B at t = 0 is given by:

$$d_{initial}^{B} = -(T^{A-B} + t_{actual}^{A})V_{gs}^{B}. \tag{5}$$

Therefore, in the trajectory prediction (state propagation) context, the along-track position (d_{pred}^{B}) of flight B on route B from the crossing point at time t = τ is given by:

$$d_{pred}^{B} = \tau(V + W(1+E)cos(\psi - \psi^{B})) + d_{initial}^{B}. \tag{6}$$

Substitution for variables and simplification of this equation gives:

$$d_{pred}^{B} = -T^{A-B}(V + W\cos\left(\psi - \psi^{B}\right)) + \tau VWE\frac{\cos\left(\psi - \psi^{B}\right) - \cos\left(\psi - \psi^{A}\right)}{V + W\cos(\psi - \psi^{A})}. \tag{7}$$

As given in Ref. [10], in order to avoid conflict detection in the trajectory prediction context, the absolute value of d_{pred}^{B} should be as follows when flight A is at the crossing point:

$$\left|d_{pred}^{B}\right| \geq d_{min}\frac{\sqrt{1 + r^{2} - 2r\cos(\psi^{B} - \psi^{A})}}{r\sin\left|\psi^{B} - \psi^{A}\right|}, \tag{8}$$

where r is the ratio of the predicted ground speed of flight on route B to the flight on route A, and d_{min} is the minimum lateral separation requirement between any two flights in the UAM environment. The above equation 8 is derived using one aircraft's movement relative to another, i.e., the relative coordinate system instead of the absolute coordinate system.

Using equations 7 and 8, the required minimum temporal separation between crossing flights (Fig. 3(a)) for avoidance of conflict detection using state propagation in look-ahead time is given by [10]:

$$T^{A-B} = \frac{d_{min}}{V + W\cos(\psi - \psi^B)} \frac{\sqrt{1 + r^2 - 2r\cos(\psi^B - \psi^A)}}{r\sin\left|\psi^B - \psi^A\right|} + \tau VWE \frac{\cos\left(\psi - \psi^B\right) - \cos\left(\psi - \psi^A\right)}{(V + W\cos(\psi - \psi^B))(V + W\cos(\psi - \psi^A))}. \quad (9)$$

From equation 9, it can be seen that the minimum crossing temporal separation between crossing flights at an intersection (crossing point) to avoid conflict detection in the presence of uncertainties due to differences between predicted and simulated winds:

- Increases linearly as a function of the magnitude of the wind error.
- Is highly sensitive to the magnitude of wind error for certain wind directions relative to routes.
- Is a nonlinear function of the inbound crossing angle between routes at an intersection.

It is important to note again that this analysis is only for wind prediction errors, and it does not include cross-track or vertical prediction errors.

B. Simulation

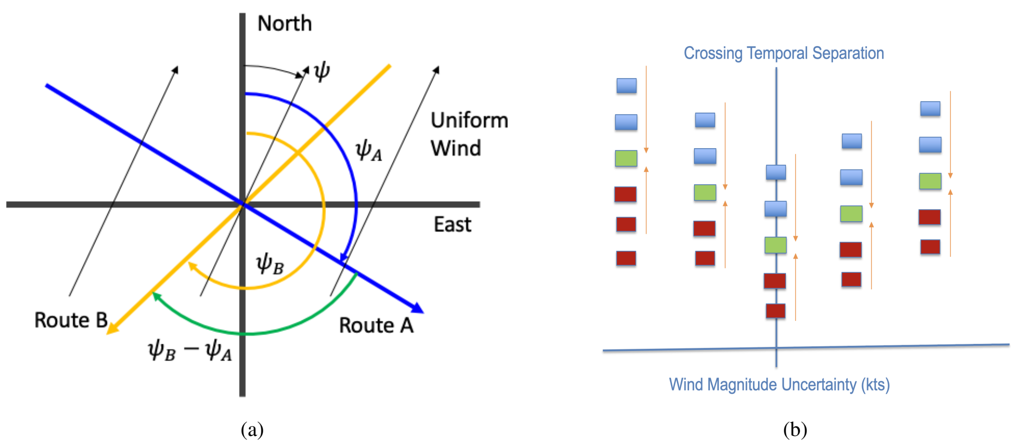


Fig. 3 (a) Depiction of relative angles between wind and crossing routes. (b) Process of finding minimum crossing temporal separation.

These analytical results were evaluated in simulation using ADK and Testbed. The underlying traffic demand scenarios were created such that, for any two chosen routes and a corresponding crossing point (under a given wind conditions), there are 10 flights per route. The departure temporal separation (in-trail) between flights on the same route is twice the crossing temporal separation (offset), and the temporal separation between crossing flights at the chosen point is equal to the desired offset between flights on alternating routes.

The following process is used to determine the simulation prediction of the minimum crossing temporal separation for a crossing point and wind condition:

- Run the traffic scenario in ADK including wind errors for conflict prediction trajectories and check for detected conflicts
  - If conflicts are found, then: recreate the traffic scenario with increased crossing temporal separation
  - If conflicts are not found, then: recreate the traffic scenario with decreased crossing temporal separation
- Run ADK with updated traffic scenario file
- Repeat the process until the minimum crossing temporal separation that results in zero predicted conflicts is found

This processes is represented pictorially in 3(b) where blue squares indicate simulations with no conflicts, red squares indicate simulations with conflicts, and the green squares indicate simulations on the boundary without conflicts.

At the crossing point ZAX01 (79 deg crossing angle, see figure 2(a)), four different wind directions are simulated with wind magnitude uncertainty ranging from -30 % to +30 %, as shown in Fig. 4(a). The dashed lines in Fig. 4(a) show analytical results, whereas the markers show empirical results from simulation. From Fig. 4(a), the following can be observed: i) The required minimum temporal separation between crossing flights at a crossing point to ensure no false-alerts increases linearly as a function of the absolute value of wind magnitude error. ii) The simulation results are validated using analytical results. Some simulation runs have a slight difference (1 or 2 seconds) in the results from analytical results for the following reasons: i) Flight track data are recorded at a 1-second cycle rate in the TestBed/ADK simulation (unlike the continuous results using analytical equation). ii) The analytical results are obtained assuming crossing routes with constant bearing (unlike UAM-X2 routes).

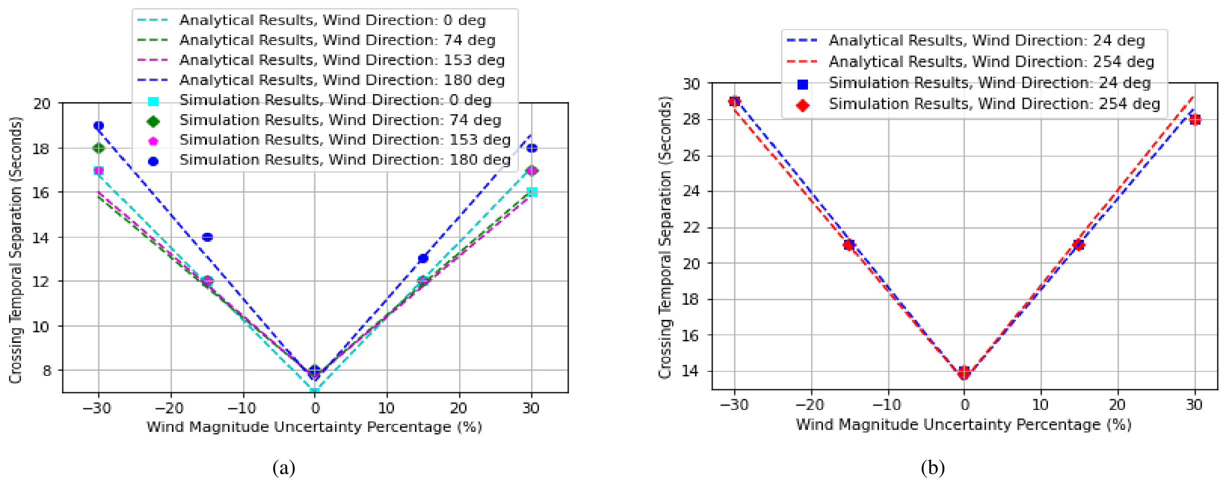


Fig. 4 Variation of minimum crossing temporal separation for 13 kts wind magnitude and various wind uncertainties at (a) ZAX01 (Intersection A) and (b) JAMX01 (Intersection B)

At the crossing point JAMX01 (130 deg crossing angle, see figure 2(a)), two different wind directions are simulated with wind magnitude uncertainty ranging from -30 % to +30 %, as shown in Fig. 4(b). From Fig. 4(b), it can be seen that the required minimum temporal separation between crossing flights at a crossing point to avoid false-alerts increases linearly as a function of the absolute value of wind magnitude error.

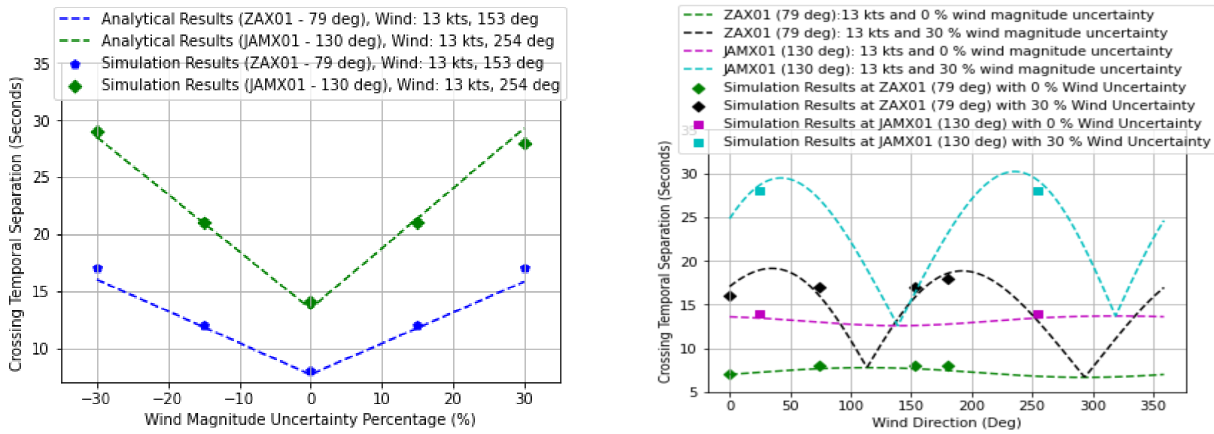
A comparison of results for the two different intersections is shown in Fig 5(a). It can be seen that different crossing points can have significantly different characteristics. Also, comparatively larger temporal separation is required to maintain the spatial separation with the increase in crossing angle. The difference in the lines' slopes at the two crossing points ZAX01 and JAMX01 can be attributed to the relative angle between the crossing routes and wind direction apart from the crossing angle.

From Fig. 5(b), it can be seen that the required crossing temporal separation between alternate flights at the crossing point is highly sensitive to the wind magnitude uncertainty, i.e., wind error for certain wind directions. From the analytical results, it is noted that the crossing temporal separation is insensitive to the wind magnitude uncertainty only when the wind direction bisects (in either direction) the headings of the two routes.

Across a large network with different intersection angles, the dynamic nature of the separation requirements in real world conditions may need to be considered when scheduling aircraft.

IV. Scheduling and Resolutions in the Presence of Uncertainty

The focus of this portion of the research is to understand how trajectory-prediction errors can be handled effectively by a combination of a scheduling and separation assurance. Since both scheduling and separation assurance rely on predictions of future states of aircraft, the effects of trajectory prediction errors need to be understood, and ways to efficiently handle those errors must be developed. Fig. 1 shows an example of how prediction errors can lead to false



(a) (b)

Fig. 5 (a) Comparing the two crossing points. (b) Impact of wind uncertainty and wind direction on crossing temporal separation for two crossing points.

alerts. They can also lead to unnecessary resolution maneuvers and to conflicts being detected much later that would be desirable.

The effects of errors on scheduling can also be significant, and the presence of these errors is one of the reasons that the management of flights through the network is divided into different systems that function at different time-scales, with some looking at least tens of minutes into the future and some focusing only on the next minute or so.

To understand different concepts of operations for scheduling and separation assurance in the presence of trajectory-prediction errors, we will analyze three different schemes in the presence of wind prediction errors: 1) perfect scheduling and separation assurance, 2) flow-based scheduling and separation assurance, and 3) flow-based scheduling with just-in-time scheduling for separation at crossings. We will define these three scenarios in more detail in the following sections.

A. Setup and Crossing Scenario

In this portion of the research, scheduling services are approximated by crafting the input scenarios to have particular characteristics. Separation services are provided by the Autoresolver.

To distill the UAM airspace management problem into a single, characteristic problem, we will focus on a single crossing of two routes over the Dallas-Fort Worth metroplex. These two routes were adapted from those used for the previous, real-time, X2 UAM study. Fig. 2(b) shows an image from the simulation platform showing aircraft on the two routes. The angle of incidence of the two routes at the crossing point (JAMX01) is approximately 130°.

In all simulation runs, there is a uniform, constant wind field with a magnitude of 13 knots and blowing as a direct tailwind for the west to east route (Fig. 6(a)). As seen in Fig. 6(b), the wind error comes in the form of a magnitude error where a positive error indicates that trajectory predictions will include a larger predicted wind magnitude and a negative error indicates use of a smaller predicted wind magnitude.

B. Experiment Procedure

To determine the maximum system throughput for a specific concept and level of wind prediction error, the following procedure was followed.

1) A scenario with a specific density of aircraft on each route was simulated for the level of wind uncertainty desired.
2) If the separation assurance algorithm was able to handle the scenario with no losses of separation and only using speed maneuvers, the scenario was considered a success.
3) The density of the aircraft on the routes was increased until the separation system was no longer successful at providing separation.
4) The maximum density that could successfully be managed for a specific concept of operations and wind prediction

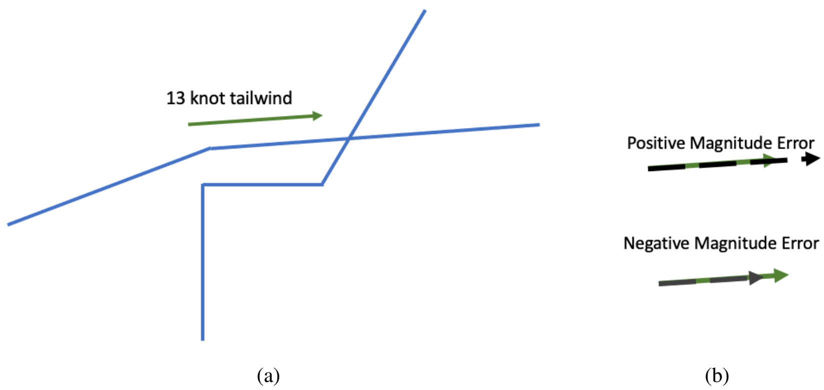


Fig. 6 (a) For these analyses the wind is a tailwind along the west/east route. (b) Wind errors add or subtract from the magnitude of the predicted wind.

error was recorded.

C. Perfect Scheduling Scenario

For the perfect scheduling scenario, it is assumed that the scheduling system (or the scheduling system combined with some conformance assurance system) can deliver aircraft precisely spaced to the crossing point even in the presence of these uncertainties. This is created by carefully crafting the input scenario such that along a given route the aircraft are evenly spaced, and at the crossing between the two routes aircraft on one route pass precisely in the middle of two aircraft on the other route.

Even though the scheduling can be performed perfectly, the separation assurance function is still subject to the wind prediction uncertainties. Using the experiment procedure outlined in Section IV.B, the results for the minimum crossing-time (offset) are shown in Fig. 7.

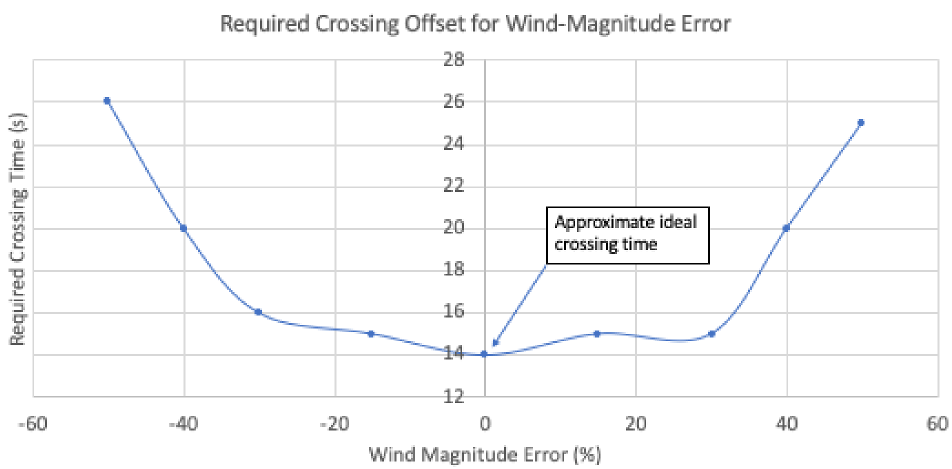


Fig. 7 Results showing the required crossing spacing as a function of wind error

An important thing to note about these results is that all increase in spacing is due to the wind errors because the scenarios are set up so that if there is no uncertainty in the prediction of winds and the resolution algorithm does not do anything, then the aircraft will cross with sufficient spatial separation. Another important thing to notice about these data is that with zero wind error, the minimum crossing-time spacing between aircraft is 14 seconds which matches analytical predictions (see Fig. 4(b)) and represents the maximum throughput for this conflict geometry.

The curve of minimum required spacing as a function of wind error exhibits two general trends. Between about -30% error and +30% error, the curve is relatively flat, indicating that the system is not extremely dependent on wind errors. For errors more than 30%, though, there is a very strong dependence on wind error. The results are generally symmetric about the y axis since the conflict detection results are symmetric with magnitude of wind (Fig.4(b)). This specific scenario would probably be relatively feasible for smaller wind errors.

D. Flow-Based Scheduling Scenario

For the second scenario, the requirement is removed that the aircraft be delivered precisely to the crossing (by scheduling and conformance assurance). The role of the scheduler in this scenario is to provide an approximate number of aircraft along a route. This is a simple scheduling problem in that it can mostly be provided by departure delay only. Any ground-speed errors that accumulate along the path or departure errors from takeoff can be handled by the separation algorithm at the crossing point.

To approximate this scenario for analysis, the input flight scenario is modified from those constructed for the ideal scenario. The ideal scenario is modified by selecting a random departure time perturbation from a uniform distribution from -8 seconds to +8 seconds. This maintains the general flow rate along the route while the exact spacing between pairs of aircraft varies. It also creates separation issues at the crossing point that the separation algorithm must resolve.

This flow-based scheduling scenario was simulated, and the minimum average crossing times required are shown by the orange line in Fig. 8. Unlike the scenario in which aircraft are delivered precisely to the crossing point (in the blue line), for this scenario there is an approximately linear increase in required separation as a function of wind error.

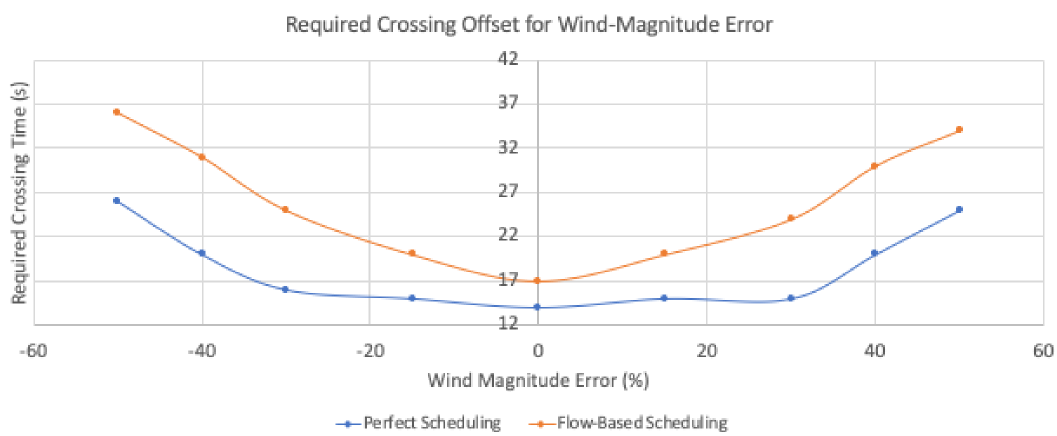


Fig. 8 Results showing the flow-based scheduling scenario and the perfect scenario

This scenario results in lower throughput compared to the ideal scenario for all levels of wind error. This is partially due to the fact that the separation algorithm requires 20% greater spatial separation between aircraft that have required a resolution than between those that do not. The linear increase in required spacing would make it difficult to ensure optimum throughput for the system as a whole because it is unlikely that the error would be a temporally static value. So, to maintain the highest possible throughput, the scheduling system would need to continually adjust the spacing between aircraft as the wind changed to provide an appropriate flow rate of aircraft at intersections to the separation management system.

E. Just-in-Time Scheduling for Separation Management

After observing the difficulties inherent in the flow-based scheduling system, a different scheduling and separation paradigm was developed. In this concept, aircraft are allowed to fly without constraint along their routes. As in the flow-based scenario, the average numbers of aircraft on each route per unit time is controlled. When they approach a location where they are within some time range of the crossing point (for this analysis, 5 minutes was chosen as the freeze horizon) a schedule is generated for aircraft to the crossing point with a minimum temporal spacing at the point (see Fig. 9). When the schedule is generated, it is communicated to the separation system, and a conflict-free trajectory is generated to hit that new scheduled time. The method for specifying the trajectory and the concept of just-in-time scheduling are related to those found in Ref. [11].

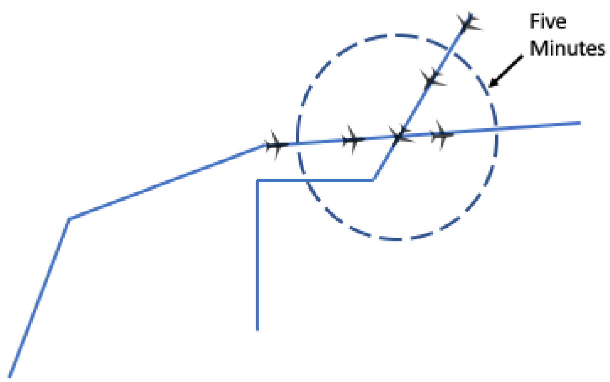


Fig. 9 As aircraft cross a five-minute freeze-horizon they are scheduled at the crossing point and a trajectory is created to hit that scheduled time

All of these trajectories contain some amount of prediction error, so if the aircraft are allowed to progress without further intervention, the schedule would not be maintained. Therefore, inside the freeze horizon, speed control is used to maintain the schedule even in the presence of trajectory-prediction errors.

Every 10 seconds a new estimated time of arrival (ETA) at the crossing point is predicted for each aircraft inside the freeze horizon. If this new ETA is outside of a specified time conformance bound, then a speed resolution is created to move the predicted ETA closer to the scheduled time. This implementation could be greatly improved by using previous estimates to determine the actual ground speed and using them to determine the speed resolution provided. This improved method will be explored in subsequent studies. Closing the loop on the scheduled time could also be performed as a flight-deck function.

1. Results

The required average crossing spacing as a function of the wind error is given by the green line in Fig. 10. From this figure, it is apparent that the required flow rate on the routes is no longer a function of the wind prediction error. The just-in-time scheduling and the speed control allow for a constant, high throughput on the routes independent of the quality of the wind predictions. An important caveat to this study is that we did not limit the minimum or maximum speed of the aircraft as they approach the crossing point. With realistic values for these minimum and maximum speeds, there will be a maximum error that can be removed by the speed control.

The insensitivity of the throughput to wind prediction error is caused by an increase in the number of resolutions for the just-in-time scheduling case as shown in Fig. 11. As the uncertainty goes up, each crossing-time prediction is worse, and it requires more changes to the aircraft speed for the simple speed control algorithm that was implemented to maintain the desired crossing time.

2. Discussion

This was just an initial analysis for just-in-time scheduling. The parameters have not been optimized, and it is expected that further development would lead to throughput approaching the maximum throughput.

For this scenario, aircraft are able to fly along the route without constraints until they approach the intersection. Once within the freeze horizon, they may be subject to speed control to ensure they can pass through the intersection, and once through the intersection they can generally resume unrestricted flow. Also, the speed control needs only be applied if there are other aircraft approaching the intersection at that time. It is very possible that the speed may be constrained in one direction or the other as well. Furthermore, since two aircraft on the same route have very low relative velocity they can safely be closer together than the 14-second minimum for aircraft on different routes, the maximum throughput of the intersection could be increased by having two aircraft on the same route pass at a time.

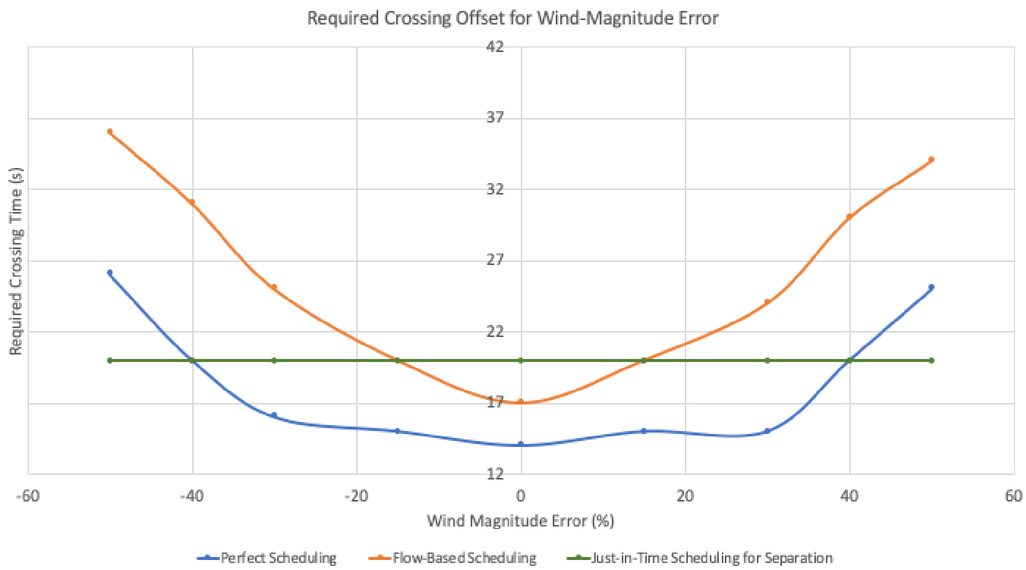


Fig. 10 Results showing the three different scenarios with the Just-in-Time scheduling having no sensitivity to trajectory prediction errors.

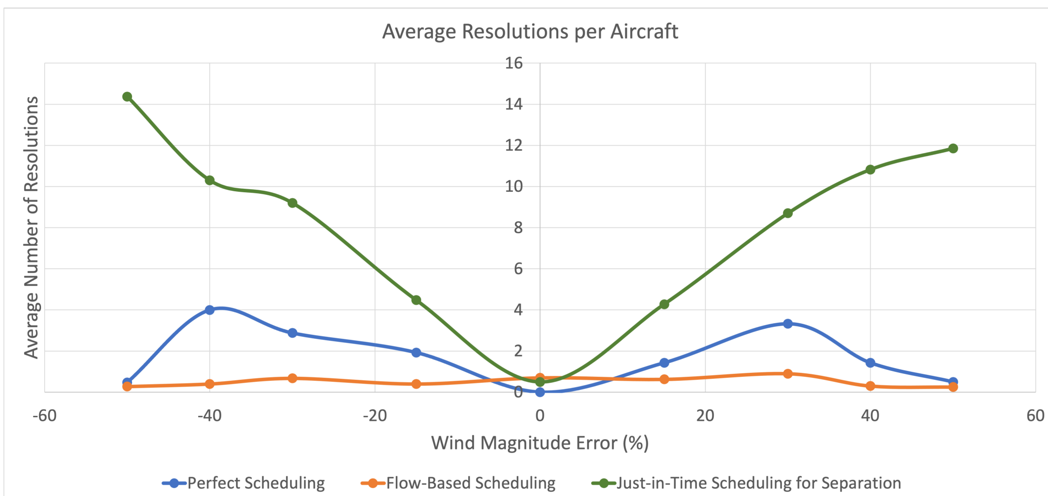


Fig. 11 The average number of resolutions executed per aircraft for the three different concepts of operations.

3. Future Work for Just-In-Time Scheduling

There are many unanswered questions surrounding the exact design of the just-in-time scheduling system. One of the important considerations will be finding a way to determine the appropriate freeze horizon. It will also be important to understand how to set the scheduling time buffers to balance the energy demand required to maintain the scheduled time with the throughput that tight buffers can enable. Furthermore, in a complex network with many different intersections, it will be important to study if intersections can be scheduled independently or if the schedules must take account of downstream constraints.

V. Conclusions and Future Work

This paper presented the results of two related studies on the effects of wind-prediction errors in high-density UAM operations. The first, detection-only study quantified the different effects of wind errors for different intersection types and different wind directions. An analytical equation (Eq. 9) was developed to understand what throughput an intersection can have in certain wind fields without false-alert conflicts. This equation was then validated using simulation of aircraft in the ADK toolbox for TestBed. The results showed that this minimum temporal separation varied widely based on many different parameters including the route-crossing angle, the direction and magnitude of the wind, the magnitude of the wind error, the cruise speeds of the aircraft, and the look-ahead time used. This could complicate the design of UAM networks and the scheduling of flights on these networks in shifting wind conditions.

The second study looked at how separation and scheduling can be combined to mitigate these errors. This study explored the qualitative differences in throughput for three different concepts of operations for combined scheduling and separation. A combination of just-in-time scheduling and aircraft speed-control where necessary resulted in a high-throughput system with no dependence of throughput on wind magnitude uncertainty. This combination of scheduling and separation allows for flexibility for aircraft to optimize their trajectories for the conditions away from constrained resources (crossings, merges, or vertiports) while maintaining robustness to uncertainty by applying temporal constraints only where necessary.

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