Initial Study of Tailored Trajectory Management for Multi-Vehicle Uncrewed Regional Air Cargo Operations

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***Abstract*—The primary contribution of this paper is an evaluation of the potential value of a tailored trajectory management (TTM) capability for uncrewed aircraft (UA) operators that is proactive in detecting conflicts and developing trajectory-based solutions for UA prior to air traffic control (ATC) performing conflict resolution. The experiment matrix is composed of one baseline simulation that models current air traffic operations without such a capability and four test simulations with different configurations of such a capability. In each simulation, five UA operations into Fort Worth Alliance airport were modeled in the presence of recorded tracks for about 4700 flights on January 18, 2022. The analysis focused on the extent to which such a capability was able to preclude an event that could spike UA operator workload. More specifically, in this study, the emulated UA operator TTM capability for multi-vehicle regional air cargo operations was able to reduce the number of instances of concurrent UA conflicts in the modeled ATC conflict resolution timeframe of 8 minutes or less from three to as low as one.**

Keywords—uncrewed aircraft, regional air cargo, tailored trajectory management

I. Introduction

Significant challenges must be overcome to conduct remotely piloted uncrewed aircraft (UA) cargo operations safely at scale. Operational challenges include flight route planning, separation and flow management, traffic pattern integration, contingency management, taxi/takeoff/landing, and communications [1]. Among the many challenges to utilizing remotely piloted large UA in m:N operations in which m number of remote pilots (RP) are responsible for N number of flights (m < N), one major potential challenge is excessive UA operator workload, which could detrimentally affect safety. Although operating UA under present-day Instrument Flight Rules (IFR) is a path towards initial airspace integration without a dependency on new flight rules or segregated airspace constructs, a UA operator responsible for multiple UA will likely experience excessive workload if required to respond to instructions by voice, especially concurrent communications with different air traffic controllers on different radio frequencies that could lead to missed communications and delays in maneuvering UA.

UA operators are interested in increasingly autonomous solutions that allow one RP to control multiple flights at a time. This has been the subject of numerous prior, ongoing, and planned research efforts [2]. In a cognitive walkthrough study of ground control station (GCS) concepts for m:N operations with small uncrewed aircraft systems (sUAS), UA pilot subject matter experts recommended that the UA GCS provide options for controlling UA without overloading operators [3]. In a follow-on remote human-in-the-loop (HITL) simulation study of m:N sUAS operations, automation support tools were found to result in faster response times, lower levels of perceived workload, and more efficient maneuvers around UAS volume reservations [4]. In addition, in a HITL simulation study in which a UAS Detect-and-Avoid (DAA) system was adapted from 1:1 to 1:3 and 1:5 operations, RP effectively utilized DAA systems to maintain safe separation for simulated MQ-9

Reaper aircraft, but they were less efficient in achieving mission objectives as the number of vehicles for which they were responsible increased. RP feedback indicated that the use of automation support tools would be appropriate and desired for completing and managing mission tasks [5].

By comparison, the primary contribution of the present study is an evaluation of the potential value of a tailored trajectory management (TTM) capability for UA operators that is proactive in detecting conflicts and developing trajectory-based solutions for UA prior to air traffic control (ATC) performing conflict resolution. More specifically, this capability detects traffic, weather, and other types of conflicts and generates closed-form trajectory-based solutions for UA operators to request of ATC. Each UA operator TTM solution maneuvers a UA flight to resolve a conflict and returns it back to its original flight plan. Whereas prior studies [3]-[5] focused on DAA systems, which operate on a tactical timeframe of a few minutes at most, the present study is focused on a TTM capability that operates on a longer timeframe of up to 20 minutes to maintain safe separation for UA while also achieving mission objectives.

The remainder of this paper is organized as follows. Section II provides background information on present-day operations and envisioned future operations, the challenges associated with voice communications in multi-vehicle UA operations, and the fast-time simulation technologies and algorithmic capabilities utilized in the present study to explore and assess one potential enabling technology: a UA operator TTM capability. Section III details the methodology utilized in this study to investigate the value of such a capability. Section IV presents the results. Section V discusses the results and potential follow-on fast-time simulations that would be valuable to run to further analyze the performance and value of a UA operator TTM capability and verify the findings of this paper. This section also discusses the need to further study and model the trajectory uncertainties that are involved in conducting regional air cargo operations and presents mitigation ideas. This section also discusses the importance of conducting follow-on research to ensure interoperability of the UA operator TTM capability with ATC and DAA systems and acceptability by UA operators and ATC. Lastly, Section VI summarizes the findings of this study.

II. Background

The present study is focused on TTM for multi-vehicle UA regional air cargo operations of 500 nmi or less. This use case is included in the FAA's Info-Centric NAS (National Airspace System) [6]-[7] and NASA's Sky for All [8] visions of the future airspace that includes an increasingly diverse set of emerging aircraft, missions, and operations (Section II.A).

The present study is complementary to the wide-ranging efforts by RTCA SC-228 to enable seamless integrated UAS operations in the NAS (Section II.B). It utilized NASA's Air Traffic Management (ATM) Test Bed simulation platform (Section II.C), NAS-Digital Twin simulation capabilities (Section II.D), and Autoresolver research ATM service that develops coordinated and comprehensive closed-form trajectory-based solutions for enroute operations, dense arrival management, and terminal area operations (Section II.E).

A. Increasingly Diverse Aircraft and Airspace Operations

The FAA's Info-Centric NAS vision describes how the FAA will build on the Next Generation Air Transportation System and trajectory-based operations by developing an integrated information environment that provides data for future information services to enable an integrated airspace with both legacy and emergent aircraft and operations in the 2035 timeframe [6]. The FAA's complementary Info-Centric NAS initial concept of operations documents how this vision will be achieved from an operational perspective and includes expected changes in infrastructure, operations, and safety assurance [7].

Complementary to the FAA's Info-Centric NAS vision, NASA's Sky for All vision [8] provides a research and development (R&D) framework that incorporates the aspirations, goals, and challenges of aviation stakeholders in the 2045-2050 timeframe. It includes a 30-year R&D roadmap progression of R&D investment needs in five-year increments that aligns R&D and incremental capability development to maximize investment across stakeholders towards: 1) integrated and synchronized outcomes, 2) measurable progress, and 3) flexibility to evolve and adapt in response to discoveries during the development process.

B. Multi-Vehicle Uncrewed Aircraft Operations

Towards the FAA's Info-Centric NAS vision and NASA's Sky for All vision, there is a need for solutions that enable seamless integrated UAS operations in the NAS [9]. RTCA SC-228 has supported this goal by developing standards for DAA [10]-[12], Command and Control (C2) data link [13]-[15], and other UAS systems for operating UA under present-day IFR as a path towards integration of UA operations without a dependency on new flight rules or segregated airspace constructs. NASA [16], MIT-Lincoln Laboratory [17], and many other organizations have contributed to this goal as part of RTCA SC-228.

This type of airspace integration will require UA operators to communicate with ATC and respond to instructions by voice. This could lead to excessive workload when a UA operator is supervising multiple UAs, especially when those flights are operating in different airspace sectors and require UA operators to simultaneously monitor different radio voice frequencies. Excessive pilot workload can result in missed ATC communications and delays in UA maneuvering, which could detrimentally affect safety. For instance, Bulusu, et al [18] found that the probability of loss of separation (LOS) increases as a function of increased response time to ATC commands for maintaining separation.

The mitigation approach investigated in the present study is to have a UA operator capability that is proactive in performing TTM for UA prior to ATC performing conflict resolution. This capability is designed and configured to operate on a longer time horizon than ATC so that the UA operator overseeing multiple UA flights can acquire situational awareness, assess TTM solutions, and communicate flight plan change requests to ATC. It also provides time for ATC to review and approve or modify the requested changes and to communicate with the UA operator. It also provides time for the UA operator to review and send the changes to the UA. The configuration of the UA operator TTM capability should be based on factors such as trajectory uncertainties, the expected ATC time horizon, and the expected UA operator response time, which depends on the m:N ratio under which the UA operator is working and other factors.

C. *ATM Test Bed*

The NASA ATM Test Bed (or simply Test Bed) [19]-[20] was the ATM simulation platform utilized to perform the present study. It provides a foundational environment that enables multi-fidelity, real-time and fast-time, human-in-the-loop and automation-in-the-loop simulations of current and proposed future air traffic concepts. It includes a configuration panel, traffic viewer, interfaces for input data (e.g., airspace and airport models, arrival and departure procedures, historical and live flight tracks and flight plans), and other capabilities. It is an integration middleware that connects both physical and software aircraft simulators, ATM services (e.g., scheduling, conflict detection, conflict resolution, polygon avoidance such as for hazardous airspace), and other technologies. It has been utilized to conduct studies with components hosted locally, remotely, and in the cloud.

D. *NAS-Digital Twin*

Built on the NASA ATM Test Bed simulation platform, the NAS-Digital Twin (NAS-DT) simulation capabilities were utilized to perform the present study. NAS-DT can and has been utilized to simulate and quantitatively evaluate changes to the NAS, uncover unintended consequences and risks of introducing new concepts and technologies, and perform verification and validation of new algorithms. Leveraging decades of R&D, it contains a set of capabilities that enable a Live, Virtual, and Constructive environment with historical and simulated airspace service providers, operators, aircraft, and weather. Its modular architecture facilitates the process of developing new algorithms and services and integrating them in a common environment.

NAS-DT can and has been set up and configured in various ways to explore different concepts in enroute flight, dense arrival management, and terminal area operations for both existing and emerging aircraft types and operations. It has been utilized to study operations in different timeframes ranging from the present-day through the far-term, including increasingly complex airspace with increasingly diverse aircraft and increasingly autonomous operations. It can be run in real-time and fast-time modes as desired and has been utilized in the lab [18], [21]-[24] and in the field [25]. It is continually being extended to new use cases, including wildfire management, persistent contrail formation avoidance, transonic truss-braced wing aircraft, and regional air cargo operations with UA as in the present study.

E. *Autoresolver*

The Autoresolver (AR) is a research ATM service that detects conflicts and develops coordinated and comprehensive closed-form trajectory-based resolutions [21]-[28] such as TTM solutions. It contains algorithms for pre-departure scheduling, air traffic separation, arrival management, and polygon avoidance (e.g., weather) on a longer timeframe than DAA (a few minutes) and collision avoidance (seconds) and on a shorter timeframe than traffic flow management (hours). All AR capabilities except polygon avoidance were utilized in the present study to maneuver UA flights that were simulated using NAS-DT to maintain separation from each other and from recorded flight tracks that were played back using NAS-DT (more details in Section III). Since AR was and is being developed in conjunction with NAS-DT, it has a similar range of applications as described in the prior section.

AR can be set up and configured in many ways, including a centralized form in which a single instance of AR manages all flights, a federated form with multiple instances of AR in which each instance manages a subset of flights and operates in coordination with each other, and a fully distributed form with one instance of AR per flight in which all AR instances operate in coordination with each other. In addition, AR can operate in a wide range of modes from decision support tool to fully autonomous.

F. *Adapting and Extending Autoresolver*

In the present study, AR was adapted and extended to model a UA operator TTM capability for regional air cargo operations. For example, AR as a UA operator TTM capability was configured to only maneuver simulated UA flights to resolve predicted conflicts. In addition, AR was modified to perform conflict detection and resolution for flights that did not have a filed flight plan (e.g., most VFR flights). Also, AR was modified to develop conflict resolution maneuvers that would resolve the primary conflict involving a simulated UA aircraft, even though doing so would generate a secondary downstream conflict that would require AR to issue a subsequent maneuver. This was done to allow AR to have additional time and opportunity to find a completely conflict-free resolution.

III. METHODOLOGY

In the present study, a set of fast-time simulations was conducted utilizing the NASA ATM Test Bed simulation platform, NAS-DT simulation capabilities, and AR research ATM service to evaluate the potential value of a UA operator TTM capability that is proactive in detecting conflicts and developing closed-form trajectory-based solutions for UA prior to ATC performing conflict resolution. In each simulation in this study, four instances of AR were run to emulate: 1) Terminal Radar Approach Control (TRACON) ATC, 2) Center ATC, 3) UA operator TTM capability in TRACON airspace, and 4) UA operator TTM capability in Center airspace. To focus this study on the behavior of the four AR instances, each was provided complete and perfect flight information (i.e., no trajectory uncertainties).

A. *Traffic Scenario*

Figure 1 is a plot of the simulated UA flight routes into Fort Worth Alliance airport (KAFW) in Texas. They were based on recorded Cessna 208 Caravan (C208) flights into KAFW on

January 18, 2022—three flights from Austin airport (KAUS) in Texas, followed by one flight from Lubbock airport (KLBB) in Texas, and then one flight from Wichita airport (KICT) in Kansas. KAFW was selected as the airport of focus because it is a cargo carrier hub for FedEx Express and Amazon Air that has complex operations as a Class D airport underneath a Class B shelf of Dallas-Fort Worth International airport (KDFW) in Texas and Dallas Love Field airport (KDAL) in Texas [29]. It also has various features that could facilitate future regional air cargo operations with UA, such as a continuously operating control tower and two 11,000 ft runways with Instrument Landing System (ILS) approaches, including one with a Category II/III approach.

January 18, 2022 was selected as the simulation date due to having minimal convective weather in Fort Worth Center as indicated in the NASA Sherlock ATM Data Warehouse [30]. The simulated UA were scheduled such that they would arrive at KAFW at intervals of about 20 minutes based on discussions with industry regarding the tempo of initial remotely piloted regional air cargo operations with UA.

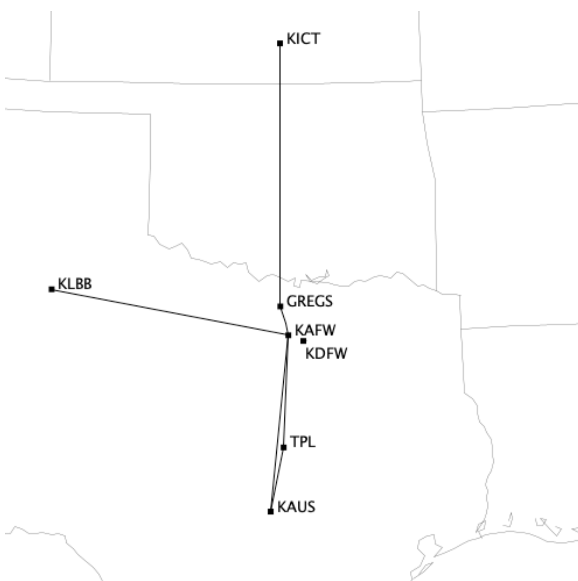

Fig. 1. Simulated UA Flight Routes into KAFW.

In each simulation, recorded tracks for about 4700 flights from Fort Worth Center, adjacent Centers (Albuquerque, Kansas City, Memphis, and Houston), and their respective major TRACONs (D10, ABQ, MCI, T75, and I90) on January 18, 2022 from around 1400 to 1630 UTC (0800-1030 local time) were played back as background traffic that the AR instances performing conflict detection and resolution needed to maneuver the simulated UA flights away from to maintain safe separation. This specific period was selected due to the high density of departing and arriving flights in 2022 as illustrated in Figures 2 and 3; alternatively, other busy periods could have been selected. The red dots are C208 flights, the yellow dots are Regional Transport Airplanes 72 (ATR72) flights, the orange dots are flights that squawked 1200, and the blue dots are other flights in the area.

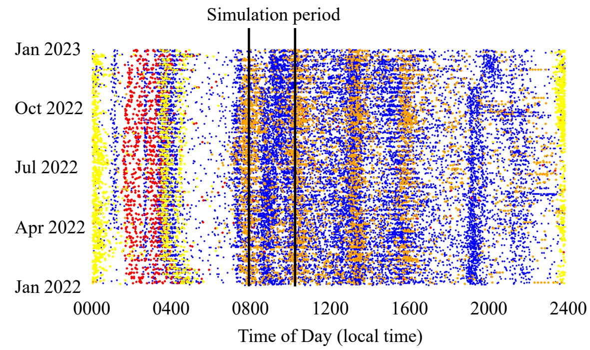

Fig. 2. KAFW Departing Flights (2022).

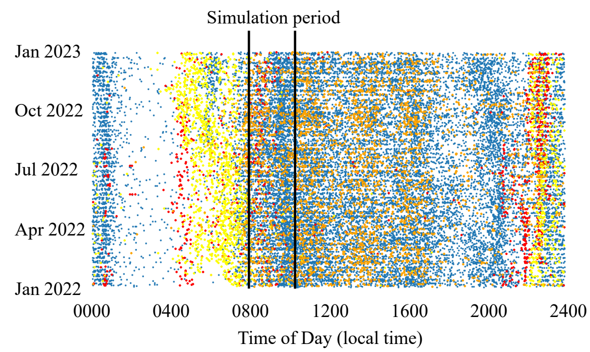

Fig. 3. KAFW Arriving Flights (2022).

B. *Simulation Configurations*

The experiment matrix is composed of one baseline simulation and four test simulations. The baseline simulation (Table I) was configured to model current air traffic operations, which does not include a UA operator TTM capability that is proactive in detecting conflicts and developing closed-form trajectory-based solutions for UA prior to ATC performing conflict resolution. More specifically, in the baseline simulation configuration, the ATC TRACON AR and ATC Center AR performed both conflict detection and resolution, and the UA operator TRACON AR and UA operator Center AR only performed conflict detection.

The four test simulations (Table 2) were configured to model potential air traffic operations with a UA operator TTM capability that is proactive in detecting conflicts and developing closed-form trajectory-based solutions for UA prior to ATC performing conflict resolution. In these test simulation configurations, the responsibilities were reversed from the baseline simulation. That is, the ATC TRACON AR and ATC Center AR only performed conflict detection, and the UA operator TRACON AR and UA operator Center AR performed both conflict detection and resolution.

In all simulations, all instances of AR ran once per simulation minute. In addition, in all simulations, the ATC TRACON AR identified conflicts with less than 3.0 nmi of horizontal separation (HorzSep) and less than 1000 ft of vertical separation (VertSep). Also, the ATC Center AR identified conflicts with HorzSep < 5.0 nmi and VertSep < 1000 ft. (See FAA Order JO 7110.65 5-5-4.) In the baseline simulation only, when the time to LOS was 8 minutes or less, the ATC TRACON AR developed conflict resolutions for simulated UA flights to maintain HorzSep ≥ 4.0 nmi and/or VertSep ≥ 1000 ft for at least 10 minutes, and the Center AR did so to maintain HorzSep ≥ 7.0 nmi and/or VertSep ≥ 1000 ft for at least 12 minutes. The required conflict-free duration for conflict resolutions must be greater than the time to LOS at which to start the conflict resolution process to preclude conflicts from reoccurring.

In the baseline simulation and in the standard test simulation, the UA operator TRACON AR identified conflicts with HorzSep < 3.0 nmi and VertSep < 1000 ft, and the UA operator Center AR identified conflicts with HorzSep < 5.0 nmi and VertSep < 1000 ft. In the baseline simulation, the UA operator ARs only performed conflict detection. In the standard test simulation, when the time to LOS was 10 minutes or less, the UA operator TRACON AR developed conflict resolutions for simulated UA flights to maintain HorzSep ≥ 4.0 nmi and/or VertSep ≥ 1000 ft for at least 12 minutes, and the UA operator Center AR did so when the time to LOS was 12 minutes or less to maintain HorzSep ≥ 7.0 nmi and/or VertSep ≥ 1000 ft for at least 16 minutes.

Three additional test simulations were also run with the UA operator TRACON AR configured as described in the prior paragraph and the UA operator Center AR configured differently with: 1) larger horizontal separation, 2) longer time horizons, and 3) both larger horizontal separation and longer time horizons.

TABLE I. BASELINE SIMULATION (ATC TRACON AR AND ATC CENTER AR PERFORM BOTH CONFLICT DETECTION AND RESOLUTION; UA OPERATOR TRACON AR AND UA OPERATOR CENTER AR PERFORM CONFLICT DETECTION ONLY)

	Horizontal Separation for Detection [nmi]	Horizontal Separation for Resolution [nmi]	Vertical Separation for Detection [ft]	Vertical Separation for Resolution [ft]	Time to LOS to Start Conflict Resolution Process [minutes]	Required Conflict-Free Duration for Conflict Resolutions [minutes]
ATC TRACON AR	3.0	4.0	1000	1000	8	10
ATC Center AR	5.0	7.0	1000	1000	8	12
UA Operator TRACON AR	3.0	N/A	1000	N/A	N/A	N/A
UA Operator Center AR	5.0	N/A	1000	N/A	N/A	N/A

TABLE II. TEST SIMULATIONS (ATC TRACON AR AND ATC CENTER AR PERFORM CONFLICT DETECTION ONLY; UA OPERATOR TRACON AR AND UA OPERATOR CENTER AR PERFORM BOTH CONFLICT DETECTION AND RESOLUTION)

	Test Simulation	Horizontal Separation for Detection [nmi]	Horizontal Separation for Resolution [nmi]	Vertical Separation for Detection [ft]	Vertical Separation for Resolution [ft]	Time to LOS to Start Conflict Resolution Process [minutes]	Required Conflict-Free Duration for Conflict Resolution [minutes]
ATC TRACON AR	All	3.0	N/A	1000	N/A	N/A	N/A
ATC Center AR	All	5.0	N/A	1000	N/A	N/A	N/A
UA Operator TRACON AR	All	3.0	4.0	1000	1000	10	12
UA Operator Center AR	Standard	5.0	7.0	1000	1000	12	16
UA Operator Center AR	Larger Horizontal Separation	7.0	9.0	1000	1000	12	16
UA Operator Center AR	Longer Time	5.0	7.0	1000	1000	16	20
UA Operator Center AR	Larger Horizontal Separation and Longer Time	7.0	9.0	1000	1000	16	20

C. *Evaluation Metrics*

Several metrics were calculated to evaluate the UA operator TTM configurations in the prior section. The first metric was the number of losses of separation, which should be zero and was utilized to: 1) verify the effectiveness of the enhancements that were implemented to adapt and extend AR to emulate a UA operator TTM capability (Section II.F), and 2) demonstrate the validity of the simulations. In Center airspace, LOS occurs when HorzSep < 5.0 mi and VertSep < 1000 ft. In TRACON airspace, LOS occurs when HorzSep < 3.0 nmi and VertSep < 1000 ft. (See FAA Order JO 7110.65 5-5-4.)

The second metric was the number of conflict resolution maneuvers. Since the concept of operations that was simulated in the present study was of the UA operator utilizing the TTM capability to develop conflict resolutions that would be sent as flight plan change requests to ATC, this metric was one indication of UA operator workload.

The third metric was the inter-resolution time (i.e., the amount of time between conflict resolution maneuvers). Since the concept of operations that was simulated in the present study was of the UA operator managing multiple UA flights concurrently, this metric was one indication of potential spikes in UA operator workload.

The fourth metric was the number of UA conflicts in the ATC conflict resolution timeframe of 8 minutes or less that was modeled in the present study, the fifth metric was the number of instances of concurrent UA conflicts in this timeframe, and the sixth metric was the maximum number of non-UA flights involved in those instances. These metrics were also indications of potential spikes in UA operator workload.

IV. Results

This section presents the evaluation metrics described in the prior section that were calculated to characterize the performance and potential benefits of a UA operator TTM capability. Section IV.A presents the number of LOS that occurred in the baseline simulation and four test simulations. Section IV.B presents the number of conflict resolution maneuvers that were issued, and Section IV.C presents the average and minimum inter-resolution times. Section IV.D presents the number of UA conflicts in the modeled ATC conflict resolution timeframe of 8 minutes or less, Section IV.E presents the number of instances of concurrent UA conflicts in this timeframe, and Section IV.F presents the maximum number of non-UA flights involved in those instances.

A. Losses of Separation

In the baseline simulation in which only the ATC TRACON AR and ATC Center AR performed conflict resolution, there was one LOS. This case was analyzed and determined to be the result of simulation artifacts that have been investigated and are being worked on. In all four test simulations in which only the UA operator TRACON AR and UA operator Center AR performed conflict resolution, there were zero LOS. In the test simulations, conflict resolution maneuvers were issued earlier upstream in less complex, less dense airspace. In the test simulations with larger separation parameters, conflict resolution maneuvers were also larger and resulted in greater separation between flights, which reduced the probability of downstream conflicts.

B. Number of Conflict Resolution Maneuvers

As illustrated in Figure 4, the number of conflict resolution maneuvers issued was similar across the baseline and test simulations. In the baseline simulation in which only the ATC TRACON AR and ATC Center AR performed conflict resolution, there were ten conflict resolution maneuvers. In the standard, larger horizontal separation, and longer time test simulations in which only the UA operator TRACON AR and UA operator Center AR performed conflict resolution, there were also ten conflict resolution maneuvers in each simulation.

By comparison, in the test simulation with larger horizontal separation and longer time parameters, there were two fewer conflict resolution maneuvers. This was because those conflict resolution maneuvers were issued earlier and were larger, which resulted in greater separation between flights for longer periods of time that prevented downstream conflicts from occurring to a greater extent than the conflict resolution maneuvers that were issued in the other simulations.

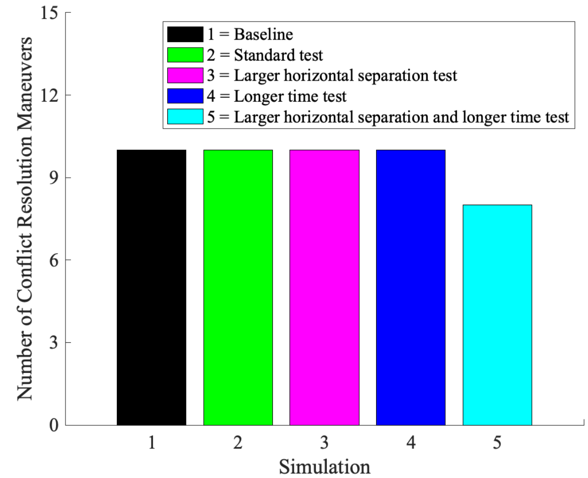

Fig. 4. Number of Conflict Resolution Maneuvers.

C. Inter-Resolution Time

The inter-resolution times—that is, the amount of time between conflict resolution maneuvers—were also calculated for all simulations. As illustrated in Figure 5, the average inter-resolution time was similar across the baseline and test simulations at between 9 and 11 minutes.

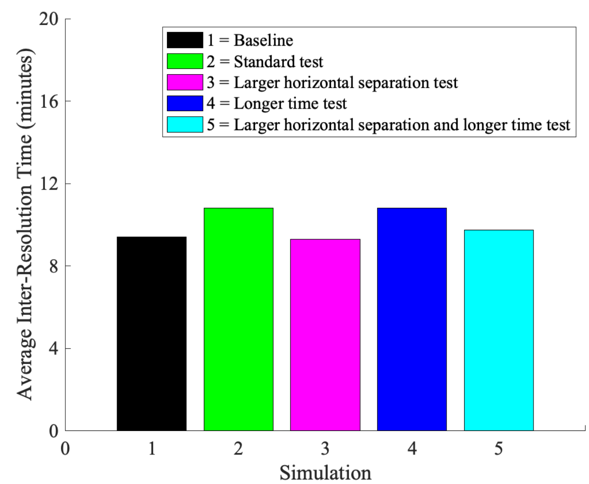

Fig. 5. Average Inter-Resolution Time.

As illustrated in Figure 6, the minimum inter-resolution times were also similar across the simulations, except for the test simulation with both larger horizontal separation and longer time parameters. In the baseline simulation in which only the ATC TRACON AR and ATC Center AR performed conflict resolution, the minimum inter-resolution time was one minute. In the standard, larger horizontal separation, and longer time test simulations in which only the UA operator TRACON AR and UA operator Center AR performed conflict resolution, the minimum inter-resolution time was also one minute. (All instances of AR ran once per simulation minute.) These included cases in which AR issued a maneuver to resolve a primary conflict involving a simulated UA aircraft, even though doing so generated a secondary downstream conflict that required AR to issue a subsequent maneuver. This was done to allow AR to have additional time and opportunity to find a completely conflict-free resolution.

By comparison, in the test simulation with both larger horizontal separation and longer time parameters, the minimum inter-resolution time was three minutes. This was because the conflict resolution maneuvers in that simulation were issued earlier and resulted in greater separation for longer periods of time, which reduced the probability of downstream conflicts.

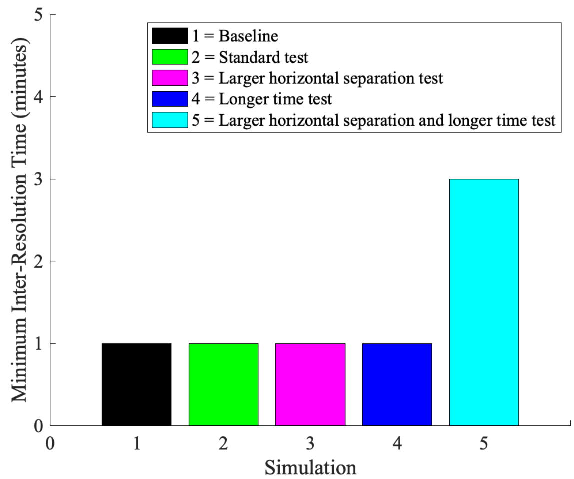

Fig. 6. Minimum Inter-Resolution Time.

D. *Number of UA Conflicts in the ATC Conflict Resolution Timeframe*

As illustrated in Figure 7, the number of UA conflicts in the ATC conflict resolution timeframe of 8 minutes or less that was modeled in the present study decreased between the baseline simulation in which only the ATC TRACON AR and ATC Center AR performed conflict resolution and the four test simulations in which only the UA operator TRACON AR and UA operator Center AR performed conflict resolution.

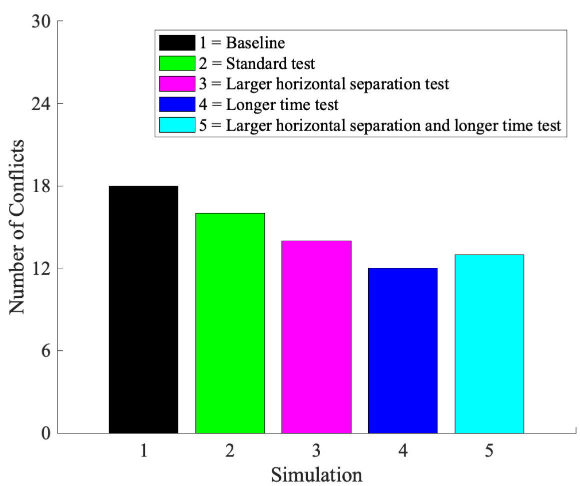

Fig. 7. Number of UA Conflicts in the ATC Conflict Resolution Timeframe.

In the baseline simulation, there were 18 UA conflicts in the modeled ATC conflict resolution timeframe of 8 minutes or less. By comparison, across the four test simulations, there were between 12 and 16 UA conflicts in this timeframe. These results indicate that a UA operator TTM capability can reduce UA operator workload.

E. *Number of Instances of Concurrent UA Conflicts in the ATC Conflict Resolution Timeframe*

As illustrated in Figure 8, the number of instances of concurrent UA conflicts in the ATC conflict resolution timeframe of 8 minutes or less that was modeled in the present study decreased by one between the baseline simulation that had three instances and the standard, larger horizontal separation, and longer time test simulations that had two instances. Utilizing both larger horizontal separation and longer time parameters resulted in an additional decrease to one instance.

These results indicate that a UA operator TTM capability can reduce the number of instances of concurrent UA conflicts in the ATC conflict resolution timeframe that could spike UA operator workload. However, as discussed in Section V, additional research efforts (e.g., expanded fast-time simulations and complementary HITL simulations) are needed to further explore and ensure UA operator and ATC interoperability and acceptability in more realistic scenarios with more flights and more aircraft types at other airspaces and airports with representative trajectory uncertainties.

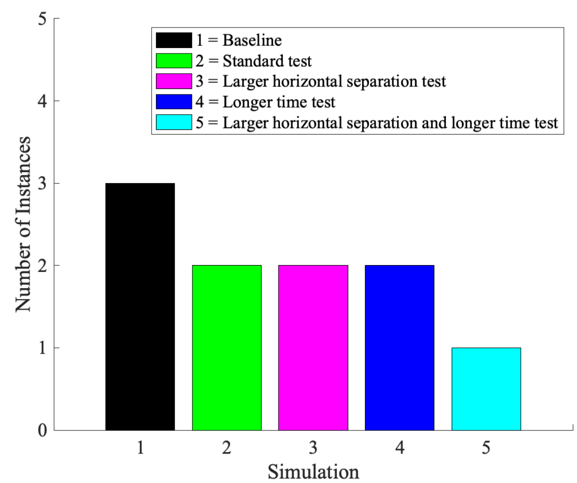

Fig. 8. Number of Instances of Concurrent UA Conflicts in the ATC Conflict Resolution Timeframe.

F. *Maximum Number of Non-UA Flights in Instances of Concurrent UA Conflicts in the ATC Conflict Resolution Timeframe*

As illustrated in Figure 9, the maximum number of non-UA flights in instances of concurrent UA conflicts in the modeled ATC conflict resolution timeframe of 8 minutes or less decreased from six in the baseline simulation to three in the test simulations. These results provide additional indication that a

UA operator TTM capability can reduce spikes in UA operator workload.

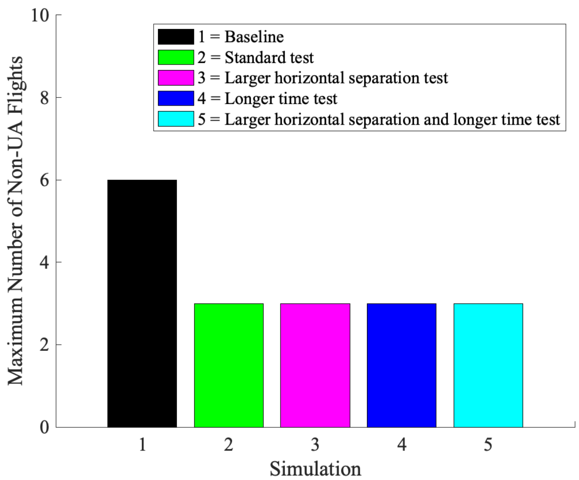

Fig. 9. Maximum Number of Non-UA Flights in Instances of Concurrent UA Conflicts in the ATC Conflict Resolution Timeframe.

V. Discussion

This paper documents an initial study of a UA operator TTM capability for multi-vehicle regional air cargo operations. It was composed of five zero-uncertainty fast-time simulations in which five UA regional air cargo flights arriving at KAFW were simulated in the presence of recorded tracks for about 4700 flights from January 18, 2022. Although the results of this study indicate that a UA operator TTM capability can be beneficial, it would be valuable to run expanded simulations to further analyze the performance and value of such a capability and verify the findings of this study (Section V.A). In addition, there is both need and value to further study, model, and mitigate the trajectory uncertainties involved in conducting regional air cargo operations (Section V.B), ensure the interoperability of the UA operator TTM capability with ATC and DAA systems (Section V.C), and evaluate UA operator and ATC acceptability of the UA operator TTM capability (Section V.D).

A. *Expanded Simulations*

There are many valuable extensions of this initial fast-time simulation study of a UA operator TTM capability for multi-vehicle regional air cargo operations. For example, simulations could be conducted for other days and time periods in addition to what was run in this study. In addition, more UA flights and more UA operators could be simulated based on recorded operations. This could include duplications of the five UA flights that were simulated in this study (with or without modifications), additional UA flights arriving at KAFW based on aircraft types other than the C208 that was simulated in this study (e.g., ATR72 that are also utilized for regional air cargo operations at KAFW), and UA flights departing from KAFW, for example. In addition, simulation studies could be performed for other airspaces and other airports (e.g., other regional cargo airports such as Visalia Municipal Airport (KVIS) in California that could be utilized for regional air cargo operations with UA [29]).

B. *Trajectory Uncertainties*

In the present study, all instances of AR were provided complete and perfect flight information (i.e., no trajectory uncertainties) to focus on the behavior of the four AR instances. With this foundational study demonstrating the potential benefits of a UA operator capability that is proactive in performing TTM for UA prior to ATC performing conflict resolution, it would be valuable to evaluate, adapt, and extend this capability in follow-on studies with realistic trajectory uncertainties modeled.

As part of this, there is a particular need to model trajectory uncertainties for VFR flights and develop mitigation solutions because VFR flights are known to have significant trajectory uncertainties due to various factors that include but are not limited to lack of VFR flight plans, lack of transponders on VFR aircraft, and gaps in surveillance coverage [31]-[32]. Initial research towards this for regional air cargo operations has been conducted by the NASA ATM-X PAAV sub-project [33], with complementary follow-on research underway. The results of these research efforts could be utilized to develop avoidance polygons for a UA operator TTM capability to manage UA flights around (e.g., high VFR density, limited surveillance, and limited communications areas).

Furthermore, the benefits of a UA operator TTM capability will depend on how well it is configured for the environment in which it is operating, especially in terms of trajectory uncertainties. For example, setting larger horizontal separation criteria in one operating environment may turn out to be detrimental because doing so makes it more challenging to find a conflict-free resolution maneuver, but setting longer time horizons may turn out to be beneficial because potential conflict situations are resolved further upstream in less dense, less complex airspace. On the other hand, the latter may be detrimental in a different operating environment due to the inherent increase in uncertainties as a function of trajectory prediction look-ahead time [34], which could result in conflict resolution maneuvers that are larger than necessary or not necessary at all. As such, additional performance metrics such as missed alerts and false alerts should be calculated in any follow-on studies with trajectory uncertainties modeled.

Given the need to carefully optimize the configuration of a UA operator TTM capability, there may be a need to optimize parameters beyond what was explored in the present study. For example, in addition to optimizing the horizontal separation detection and resolution criteria, the time to LOS at which to start the conflict resolution process, and the required conflict-free duration for conflict resolutions as in the present study, there may be a need to optimize the vertical separation detection and resolution criteria, required temporal separation between arrivals, modeled time for the UA operator and ATC to communicate and coordinate, modeled time to execute different types of conflict resolution maneuvers, and other parameters. Furthermore, in addition to optimizing configuration parameters for the UA operator TTM capability in Center airspace as in this study, there may be a need to optimize the configuration parameters for the UA operator TTM capability in TRACON airspace.

C. *Interoperability of UA Operator TTM Capability*

In the present study, one simulation was run that modeled ATC performing both conflict detection and resolution and the UA operator only performing conflict detection with a TTM capability, and four simulations were run that modeled the reverse. Although the results of this initial fast-time simulation study provided some indication of the potential benefits of a UA operator TTM capability, there is both need and value to further explore and evaluate this capability to a greater extent in follow-on fast-time simulation and complementary HITL studies in which conflict detection and resolution are performed by both the UA operator with a TTM capability and by ATC towards ensuring interoperability between them (Section V.C.1). In addition, it will be important to study and ensure interoperability between a UA operator TTM capability and other separation-related capabilities such as DAA (Section V.C.2).

1) With ATC

In the concept of operations for regional air cargo operations with UA [1] that was modeled in the present study, the UA operator would utilize the TTM capability to develop coordinated and comprehensive closed-form trajectory-based solutions that would be sent as flight plan change requests to ATC. The latter would review those requests and subsequently coordinate with the former. In a system with full knowledge of what each component is doing and will do, the UA operator TTM capability can be set up and configured to fully interoperate with ATC. However, in real-world operations with uncertainties, interoperability issues will likely arise.

As such, it is important to conduct studies that explore and develop mitigations for potential interoperability issues between the UA operator TTM capability and ATC. This can include follow-on fast-time simulation and HITL studies in which conflict detection and resolution are performed by both the UA operator with a TTM capability and by ATC. To perform follow-on fast-time simulations studies with the capabilities that were developed for and utilized in the present study, a concept of operations would first need to be developed and modeled in the NASA ATM Test Bed simulation platform, NAS-DT simulation capabilities, and AR research ATM service. It may also be necessary to simulate historical IFR and/or VFR flights so that AR can maneuver them in addition to the simulated UA flights.

2) With DAA

In addition to ensuring interoperability between the UA operator TTM capability and ATC, it is important to ensure interoperability between the former and DAA systems. This includes the UA operator's own DAA systems and other operators' DAA systems. Although RTCA has developed and published minimum operational performance standards for DAA systems [10]-[12], they can be implemented in different ways by different companies, which makes it challenging to ensure interoperability. Thus, as discussed in the prior section, it important to conduct both fast-time simulation and HITL studies that explore and develop mitigation solutions.

D. *UA Operator and ATC Acceptability.*

The results of the present initial fast-time simulation study provide some indication that a UA operator capability that is proactive in performing TTM for UA prior to ATC performing conflict resolution could benefit UA operators by reducing peak workload. However, the present study did not evaluate acceptability by UA operators or ATC, which is important to do in separate studies or as part of the fast-time simulation and HITL studies that were described in the prior section towards ensuring the interoperability of a UA operator TTM capability with ATC and DAA systems.

In addition to UA operator and ATC acceptability across different UA operator TTM configurations, other aspects should be explored and evaluated. These could include the m:N ratio that is being undertaken by the UA operator, the availability of capabilities to digitally load closed-form TTM solutions directly into UA flight management systems, and the availability of datalink capabilities that enable combined flight plan change requests to be made by the UA operator to ATC instead of multiple requests by voice that could result in simultaneous step-on communications, different interpretations of communications, time-consuming and error-prone manual entry of flight plan amendments into flight management systems, and other issues.

VI. Concluding Remarks

The demand for air cargo transportation has grown over the past decade and accelerated during the COVID-19 pandemic. To mitigate the pilot shortage challenge for conducting scaled-up regional air cargo operations, industry is seeking to utilize remotely piloted mid-sized and large UA in m:N operations. Towards this goal, this paper documents an initial fast-time simulation study of a modeled UA operator capability that is proactive in performing tailored trajectory management for UA prior to ATC performing conflict resolution. In the present study, the emulated UA operator TTM capability reduced the number of instances of concurrent UA conflicts in the modeled ATC conflict resolution timeframe of 8 minutes or less and the maximum number of non-UA flights involved in those instances. These results indicate that a UA operator TTM capability can reduce spikes in UA operator workload.

To conduct this study, existing NASA simulation technologies and research ATM services were adapted and extended for regional air cargo operations with UA. These enhanced capabilities serve as the foundation upon which to develop additional capabilities for follow-on UA operator TTM research efforts to study, model, and mitigate trajectory uncertainties, ensure interoperability with ATC and DAA systems, and ensure UA operator and ATC acceptability.

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