Initial Validation of a Simulation System for Studying Interoperability in Future Air Traffic Management Systems

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Future air traffic management systems will need to accommodate large numbers of increasingly diverse air vehicles with different operating paradigms. To support this trend, they will digitally share copious amounts of information via a common communication architecture. Operators will deploy programs that create and negotiate flight plans via the architecture's communication protocols. These programs will autonomously make decisions that must be arbitrated by the architecture and robust to uncertainty. To study interoperability in air traffic management, a new airspace simulation system was composed by integrating a legacy airspace simulation, an air traffic control model, and a new research communication architecture. It was used to evaluate air traffic management concepts by adapting it to handle congested arrival traffic at Newark Liberty International Airport and executing simulations. Results demonstrated the ability of the simulation system to model in detail strategic traffic flow management, predeparture flight planning, and air traffic control working in concert. Subsequent studies can use the simulation system to study interoperability, autonomy, digital communication, and uncertainty in future air traffic management systems.

I. Introduction

Airlines need flexibility to plan their flights. A flight plan contains (among other information) route, cruise speed, cruise altitude, scheduled departure time, and estimated arrival time. Airline planners set scheduled departure and estimated arrival times to meet their business plan, and they design routes, cruise speeds, and cruise altitudes to satisfy these times and minimize costs.

The FAA accommodates airline flight plans to the extent that the safety of operations in the National Airspace System (NAS) can be assured. During specific times and at localized places in the NAS, demand for operations exceeds capacity, potentially adversely affecting safety and air traffic control workload. To reduce traffic flows into the affected places, the FAA uses strategic Traffic Flow Management (TFM) programs. Some commonly used TFM

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programs are Miles-In-Trail, Ground Delay Program, Airspace Flow Program, and Collaborative Trajectory Options Program [1]. These change the flight plans of the involved flights. An amendment to a flight plan can be a delayed departure time or an altered route, cruise speed, or cruise altitude, all of which affect the flight's arrival time. These can adversely affect the airline's business plan.

When a flight is included in a TFM program, the change to its flight plan is prescribed by the FAA, and its airline has limited options, depending on the type of program, to redress the change. Many times, the airline does not learn about the change until close to the flight's gate departure time. This can put the airline in the undesirable position of either operating the flight at a business loss or cancelling it.

This paper builds a foundation to study the efficacy of providing airlines the ability and authority to self-plan and negotiate changes to flight plans in response to congestion problems in the NAS. The self-planning and negotiation would occur in real-time as congestion problems are detected, as opposed to today where flight plan changes are prescribed only when TFM programs are instantiated, which can be well after the problem was first detected.

There are many challenges to self-planning and negotiating changes to flight plans in response to congestion problems in the NAS. This paper focuses on those challenges associated with a stakeholder's ability to communicate and distribute information and make decisions in an effective and timely manner.

Communication among airlines and with the FAA is necessary for self-planning and negotiation. Airlines need to communicate flight plan and schedule information for each flight in their fleet, and the FAA needs to communicate times and places in the NAS where demand exceeds capacity, which includes, among other things, setting constraints on airport departure and arrival rates and setting limits on airspace flight counts. Furthermore, this information needs to be updated as deviations from plans and schedules are detected.

Given the size and diversity of the NAS, the number of flights operating in it, and the amount of information in a flight plan, a scalable architecture is required for efficiently communicating information between airlines and the FAA. The communication needs to be digital, machine-to-machine, and machines need to autonomously make more decisions. Many different machines and programs deployed by diverse stakeholders will participate, making a wide variety of decisions affecting many different flights and resources. Hence, the system will need to be interoperable, and decisions will need to be robust to uncertainty.

NASA's recent Unmanned Aerial System (UAS) Traffic Management (UTM) project [2-4] developed a prototype operational communication architecture based on scalable, secure, and digital protocols for operators collaboratively planning and controlling UAS vehicles. The present work leverages this architecture to create a similar architecture, for research and simulation, that supports planning of traditional flights operating in controlled airspace, as opposed to planning UAS operating in uncontrolled airspace.

For this study, a research communication architecture, named the Collaborative, Seamless Manager of Airspace Resources and Traffic (CSMART), was built. CSMART provides flight planners with a data exchange system for self-planning and negotiation that also meets congestion constraints in the NAS, i.e. TFM. The purpose of CSMART is to facilitate studying interoperability, collaboration, and uncertainty in the NAS. The prototype was integrated with a fast-time simulation of the NAS, named AutoResolverSim (ARS). ARS includes a plugin model of air traffic control named AutoResolver (AR) [5-13].

The simulation system formed by CSMART, ARS, and AR was used to conduct simulations of 54 flights in-bound for Newark Liberty International Airport (EWR). Multiple simulations enforcing different arrival rate constraints at EWR were conducted to show the effects of strategic TFM on air traffic control complexity in the arrival process. Because this is the first time CSMART in concert with ARS and AR has been used to conduct research, the simulations did not include any negotiation or uncertainty. However, the study validated the simulation system, and indicated how to update the system in the future to study self-planning, negotiation, and uncertainty.

The paper is organized as follows: the CSMART architecture is defined, the simulation system is presented, the experiment is illustrated, results are shown, and, finally, future work and summary are provided.

II. Collaborative, Seamless Manager of Airspace Resources and Traffic

Collaborative, Seamless Manager of Airspace Resources and Traffic (CSMART) is for investigating resolution of congestion problems by self-planning and negotiating flight schedules. It provides a framework for studying how flight planning and negotiation would occur in a future NAS. Flight planning will be increasingly autonomous, conducted by independently deployed programs connected by a communication architecture. CSMART is a research communication architecture. It defines and distinguishes, for developers of flight planning programs, data that is modifiable and data that is constrained. Furthermore, it specifies lines of communication, how future planning programs share and exchange information with each other.

In the following, important concepts and data structures are defined, scalable digital communication technologies are proposed, and CSMART is illustrated. Finally, CSMART is compared with NASA's Unmanned Aerial System (UAS) Traffic Management (UTM) project communication architecture.

A. Concepts and Data Structures

There are two concepts and associated data structures that are used in CSMART. The first is the concept of a resource and its schedule, and the second is the concept of a trajectory plan.

1. Resources and schedules

As a flight transits through the NAS, it uses runways and defined position fixes. The term "resource" is used to collectively describe these. A flight uses, or crosses, a resource at a single time. After a flight uses a resource, a specified interval of time must elapse before the resource may be used by another flight. This interval is called the separation parameter for that resource. The end of the interval is denoted the reservation end time.

For fix resources the separation parameter represents required spacing between flights as they cross the fix. For landing runways, the separation parameter represents the time required for the leading aircraft, which just landed, to clear the runway and for wake vortexes to dissipate before the following can land, and, for takeoff runways, it represents the time required for the leading flight, which just took off, to achieve proper separation and for wake vortexes to dissipate before the following flight can takeoff.

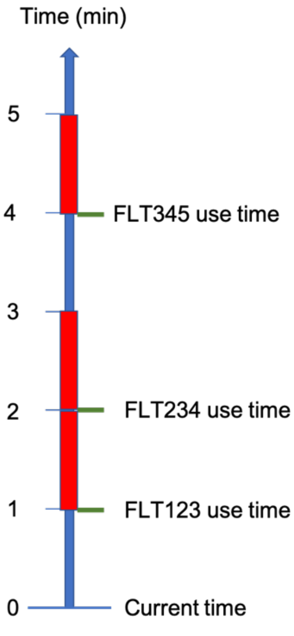

Fig. 1 Notional Resource Timeline

Figure 1 illustrates a notional timeline for a resource. Time is relative, so it is zero at the bottom of the timeline, and it increases as the timeline goes up. Three flights (FLT123, FLT234, and FLT345) have scheduled a use time on the timeline. The use times are represented by green horizontal hash marks that extend to the right of the timeline. The red boxes on the timeline are the time intervals, determined by the separation parameter, during which the resource must be clear before another flight may use it. Flights FLT123 and FLT234 consecutively use the resource with no space left in between the two. There is a minute of open interval in-between FLT234 and FLT345. The separation parameter value being used is one minute, so another flight could fit in that open interval.

For simplicity, we consider the separation parameter a constant for a given resource. However, in future work, the separation parameter can be allowed to vary so as to model real separations between flights which are generally determined by their weight classes or other performance characteristics.

The constraint imposed on the resource schedule is that no other flight can use the resource during the intervals represented by the red boxes, i.e. the red boxes cannot overlap. Thus, a resource's separation parameter value determines the maximum limit on its use rate. For example, if the separation parameter is one minute, as in Fig. 1, then the max rate is one flight per minute. A use rate bound is an example of a strategic TFM constraint.

There are many resources in the NAS. Not all are in high demand and get congested. For example, generally, the resources around high demand airports get congested during high demand periods, while some high-altitude airspaces in sparsely traveled areas do not receive much traffic. In this study, resources are categorized as either scheduled or nonscheduled. Scheduled means that a schedule containing the use times and separation parameters for all flights using the resource is compiled, stored, tracked, updated, and analyzed for congestion. Nonscheduled means that no schedule is computed for the resource. Thus, no use rate constraint is enforced on non-scheduled resources.

2. Trajectory Plan

CSMART requires a trajectory plan for each flight that operates in the simulation. A trajectory plan contains the same information as today's flight plan with additional information. The four parts of a trajectory plan are static flight information, route, schedule, and vertical profile. The outline below shows the information each part contains.

1. Trajectory Plan
    a. Static Flight Information
        i. Flight Id
        ii. Callsign
        iii. Aircraft Type
        iv. Departure Airport
        v. Arrival Airport

- a.
  - vi. Original Scheduled Departure Time
  - vii. Entry Status (simulation only)
- b. Route
  - i. List of:
    - 1. Route Point
      - a. Resource Id
      - b. Waypoint
        - i. Latitude
        - ii. Longitude
- c. Schedule
  - i. List of:
    - 1. Resource Reservation
      - a. Scheduled Resource Id
      - b. Use Time
      - c. Reservation End Time
- d. Vertical Profile
  - i. List of:
    - 1. Vertical Segment
      - a. Start Scheduled Resource Id
      - b. End Scheduled Resource Id
      - c. Cruise Altitude
      - d. Cruise Speed

Static data includes flight id, callsign, aircraft type, departure airport, and arrival airport. Flight id is unique to the flight and assigned by the simulation. Original scheduled departure time is assigned to the flight in the scenario file. It represents the time that the flight's airline planned to have the flight depart, as would be printed on a passenger's ticket. The simulation will depart the flight at the original scheduled departure time unless it is assessed a departure delay, in which case the departure time was changed during predeparture planning. Entry status is a simulation-only parameter that specifies whether the flight is entering simulation in the air or on a takeoff runway. Because the simulation system is set up for United States domestic flights, international flights begin simulation in the air at the border of United States' airspace. If an international flight is departure delayed, it enters simulation after the delay has elapsed at the edge of the airspace.

Route is an ordered list of route points that the flight is planning to use. A route point consists of the id of a resource (runway or fix) and its waypoint, defined by latitude and longitude. Route defines the lateral path of the flight, and it can include nonscheduled resources.

Schedule consists of an ordered list of resource reservations. A resource reservation consists of a scheduled resource id, a use time, and a reservation end time (based on the separation parameter). Schedule can only have scheduled resources.

Vertical profile is a list of vertical segments. A vertical segment contains a start scheduled resource id, an end scheduled resource id, a cruise altitude, and a cruise speed. The cruise speed and altitude apply to the flight segment denoted by the start and end resource ids. Although flight segments are always bounded by scheduled resources, there can be nonscheduled resources, which produce lateral turns, inside a flight segment. Cruise altitudes and speeds specify the target altitudes and speeds during climbs and descents, but not detailed vertical profiles (speed and altitude schedules) for the climbs or descents. The simulation determines detailed vertical profiles as a function of aircraft type for each flight. This applies to the simulation environment, not the operational environment, where each aircraft determines its profile.

Figure 2 notionally illustrates schedule and vertical profile portions of a trajectory plan. There are four scheduled resources: Departure Runway, Fix 1, Fix 2, and Arrival Runway. For each of these, scheduled use time and separation parameter are shown on the timelines. For clarity, the timelines only show these for a single flight. The yellow time intervals are unavailable due to other flights having already scheduled their use times and separation parameters. The vertical profile has three vertical segments. The segments specify cruise speeds and altitudes between Departure Runway and Fix1, Fix1 and Fix2, and Fix2 and Arrival Runway.

Four scheduled resources were chosen for Fig. 2 for illustration purposes. A trajectory plan can have more or fewer scheduled resources. In this study, departure runways and the EWR arrival runway were selected as the only scheduled resources. Thus, each flight in the simulations has only one flight segment bounded by a departure runway and the EWR arrival runway.

B. Scalable, Digital Communication Technologies

There are thousands of resources in the NAS, and there are tens-of-thousands of flights, run by many different airlines, that operate in the NAS each day. An architecture for communication needs to be scalable and federated. Scalability is needed to enable the system to accommodate the entry of new flights, operators, or scheduled resources. Federation is to give new participants a clear set of procedures for participating and an understanding of their responsibilities. A dictionary definition of federated is "set up as a single centralized unit within which each state or division keeps some internal autonomy." CSMART is centralized in the sense that it is a single architecture for communication and planning and that it enforces use rate constraints on resources. However, it provides each airline (state or division) autonomy for creating trajectory plans for each of their flights.

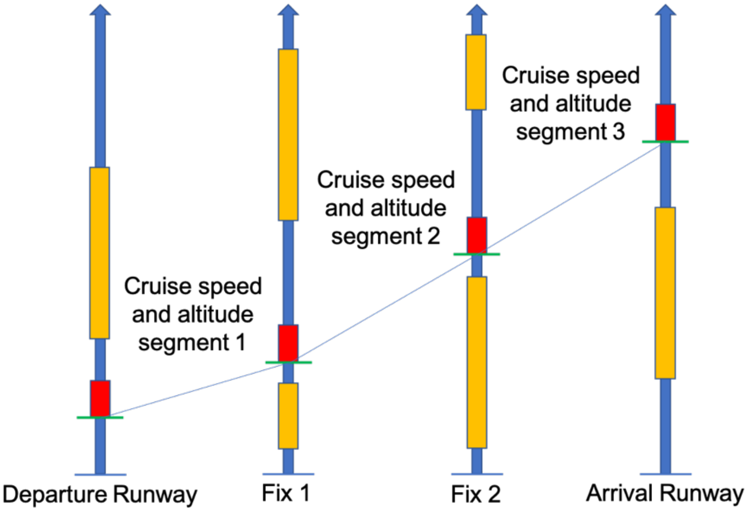

Fig. 2 Trajectory Plan Schedule and Vertical Profile

The CSMART architecture is designed to connect flight planners (e.g., airlines) and resource managers (e.g., FAA traffic flow managers) so that they can collaboratively design trajectory plans that meet resource use constraints (e.g., TFM constraints) and airline business constraints. CSMART in part achieves this by conforming to the software design principles of Service-Oriented Architecture (SOA). According to [14], SOAs provide services that are "independent of vendors, products, and technologies. A service is a discrete unit of functionality that can be accessed remotely and acted upon and updated independently." In CSMART, the "discrete unit of functionality" is scheduling resource use times, which can be done independently across the Internet by flight planners.

SOAs are being applied to new air traffic management systems that are being proposed for UAS [2-4] and urban air mobility (UAM) [15-16] vehicles. NASA's UTM project designed a system for managing UASs based on SOA. Their approach to satisfying SOA principles was to use so called RESTful Web Services. According to [17], "Representational State Transfer (REST) is an architectural style that specifies constraints, such as a uniform interface, that if applied to a web service induces desirable properties, such as performance, scalability, and modifiability, that enable services to best work on the Web."

In practice, this means that the UTM system is comprised of web services that can be deployed anywhere on the Internet, including the cloud. The web services communicate with each other through the HTTP protocol. Precise Interface Control Documents (ICDs), using the Open API version 2 standard, define messages that each web service can send and receive. Furthermore, a specification document defines actions web services must take in response to receiving messages.

C. CSMART Architecture

CSMART follows the UTM project and uses the RESTful web services approach. Furthermore, it leverages the UTM architecture by carrying over pieces of it that apply to traditional air traffic operating in controlled airspace. Figure 3 illustrates the four types of web services that comprise the

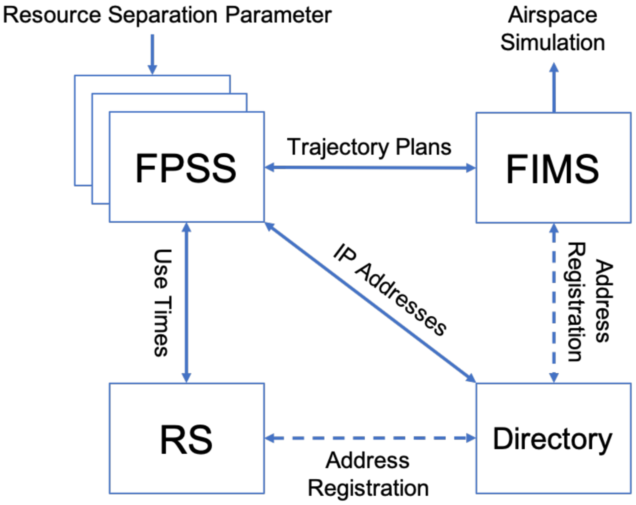

Fig. 3 CSMART Architecture

CSMART system. They are Flight Information Manager System (FIMS), Flight Plan Service Supplier (FPSS), Directory, and Resource Schedule (RS). Each of these has a clearly documented Application Protocol Interface (API), and there is a specification that defines how the four interact with each other.

1. Flight Information Management System (FIMS)

FIMS exchanges information with an airspace simulation. FPSSs send trajectory plans through FIMS to the simulation. Although not done for this paper, the simulation can return to CSMART through FIMS state and intent information.

2. Directory

Directory facilitates communication between FPSSs and RS and FIMS. FPSSs communicate directly with RS and FIMS, so they need RS's and FIMS's addresses, which consist of Internet Protocol (IP) addresses and port numbers. RS and FIMS register their addresses with Directory. Directory stores the addresses, and FPSSs get the addresses from Directory. Although the current version of CSMART has only one RS, Directory facilitates adding more RSs for scalability. In addition, Directory stores FPSS addresses so that a FPSS can use it to find other FPSS addresses.

3. Resource Schedule (RS)

RS is where resource utilization schedules are stored and analyzed to make sure that they do not violate resource use rate limits (TFM constraints). RS stores a schedule for each scheduled resource. For FPSSs planning new trajectory plans, RS calculates open intervals, which are available for reserving new use times and associated separation parameters, and sends them to FPSSs. Once a FPSS has determined a use time and separation parameter for a particular flight, it reserves them with RS. RS rejects any use time and separation parameter that is not bounded within an open interval.

4. Flight Plan Service Supplier (FPSS)

FPSS interactively generates trajectory plans by communicating with RS. It gets RS's address from Directory. For a prospective trajectory plan, FPSS gathers from RS open intervals for each scheduled resource in the plan. It selects use times and associated separation parameters that fit inside the open intervals and conform with estimated travel times, based on aircraft performance, between scheduled resources. Then, it reserves them with RS.

CSMART supports planning by one or more FPSS. Although NASA created a single FPSS for this paper, FPSSs are meant to be designed and deployed by multiple research partners participating in a simulation study. To participate, a new partner would develop a new FPSS containing their flight planning logic and conforming to the CSMART specification and API.

For this paper, NASA built a prototype FPSS based on Refs. [18, 19]. It uses multi-point scheduling to select use times and separation parameters that fit within open intervals of scheduled resources and meet flight travel time constraints between scheduled resources. Travel time constraints are formulated as min and max bounds on travel times, which can be used to model variations of flight cruise speed.

D. Comparison of CSMART and UTM Architectures

This section compares and contrasts the CSMART and UTM architectures. Whereas both support flight planning and management of air traffic, a key difference between the two is that the UTM architecture is an operational system for UAS, whereas the CSMART architecture is part of a simulation system for traditional air traffic. Other differences occur in two areas: web services and flight plans. Table 1 lists the corresponding CSMART and UTM architecture web services.

Table 1 Comparison Between CSMART and UTM Architecture Web Services

CSMART	UTM
FIMS	FIMS
FPSS	USS
Directory	Discovery
RS	

FIMS performs the same function, data exchange, in both architectures. However, the UTM FIMS communicates with FAA systems, whereas the CSMART FIMS communicates with an airspace simulation. The service supplier in UTM is named UAS Service Supplier (USS) because it is a service supplier for UAS. On the other hand, the service supplier in CSMART is named FPSS because it is a service supplier for flights with traditional flight plans. Both are service suppliers responsible for building flight plans, albeit for different types of air vehicles with different operating paradigms. Directory is named Discovery in UTM because it assists a USS with "discovering" other USSs participating in the system. In the UTM architecture, flight planning is primarily accomplished through communication among USSs. The CSMART Directory acts as a RS directory for FPSSs. In the CSMART architecture, flight planning is primarily accomplished through communication between FPSSs and RS. There is no analogue between RS and a web service in the UTM architecture.

Another place where there is an important distinction between the UTM and CSMART architectures is flight plan. In the UTM architecture, each flight plan consists of an ordered list of three-dimensional volumes each having a start and end time. A UAS must operate within both the time and the space of one or more of the volumes in its flight plan for the duration of its operation. UAS are anticipated to operate in uncontrolled airspaces, and, therefore, the UTM architecture needs to possess a strategic separation assurance capability. Strategic separation assurance is achieved by de-conflicting in both time and space the volumes contained in each flight plan. On the other hand, CSMART is designed for managing traditional flight traffic operating in controlled airspace. Air traffic controllers provide strategic separation assurance services for these flights. Therefore, assuring that flights operate within deconflicted volumes for all times is not necessary. The CSMART flight plan is named trajectory plan and is defined above. It does not contain spatial volumes, but it preserves time parameterization, i.e. flights using airspace resources at scheduled times.

III. Simulation System

The simulations in this study were conducted using a simulation system that combined multiple NASA airspace simulations and tools. This section introduces the simulations and tools and how they are connected together.

A. Block Diagram

Figure 4 shows a diagram of the simulation system. The system consists of two main parts connected by NASA's ATM-X Testbed. The two parts are CSMART and AutoResolverSim (ARS). CSMART creates trajectory plans that satisfy resource rate constraints, and ARS simulates flights operating according to their trajectory plans and being managed by air traffic control.

B. Testbed

CSMART and ARS are connected using NASA's ATM-X Testbed system [20-22]. Testbed is a software framework for connecting airspace simulation systems. Testbed supports fast-time and real-time systems, and it can connect simulations to live operational systems. In addition, Testbed contains tools for analysis, visualization, and scenario generation. In this study, trajectory plans were passed through Testbed from CSMART to ARS, and Testbed was used to generate the scenario.

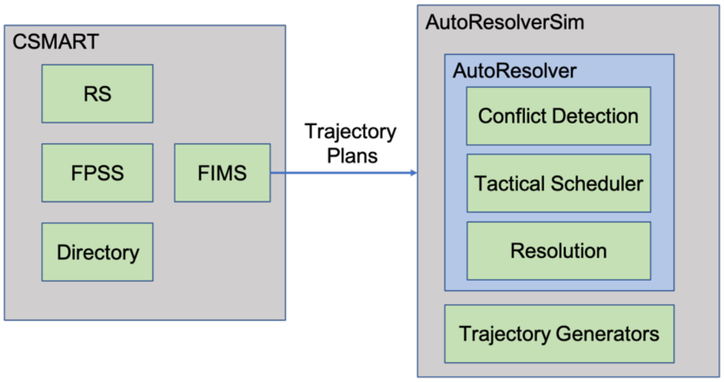

Fig. 4 Simulation Diagram

C. AutoResolverSim (ARS)

The function of ARS is to simulate flights operating in the NAS. ARS's predecessor was NASA's Airspace Concepts Evaluation System (ACES) [23-29]. ARS was created by refactoring ACES's software to work with Testbed and creating an API for connecting ARS to a multitude of airspace simulations and real-time operational systems. ARS preserves the ACES trajectory generators, Multi Pseudo Aircraft Synthesizer (MPAS) [26] and Kinematic Trajectory Generator (KTG) [30], which have a history of use in NASA research. KTG is used to simulate flights as they are traveling through high-fidelity modeled Terminal Radar Approach CONtrols (TRACONs), and MPAS is used to simulate flights as they are traveling through low-fidelity modeled TRACONs and en route airspace. Both MPAS and KTG get aircraft performance parameters from Base of Aircraft DAta (BADA) [31]. In addition, AutoResolver (AR), NASA's automated strategic separation assurance system, plugs into ARS.

D. AutoResolver (AR)

AR [5-13] serves as a model of air traffic control. It executes three main functions: tactical scheduling, conflict detection, and resolution. These functions are automated versions of duties and responsibilities performed by human controllers in the NAS.

1. Tactical Scheduling

The AR tactical scheduling function builds arrival schedules for arrival meter fixes and runways, similar to the present-day Time-Based Flow Management (TBFM) system. The schedules satisfy configurable time separations between flights as they use arrival fixes and runways.

Tactical scheduling performed by AR is not strategic scheduling performed by CSMART. Although similar in principle, tactical and strategic scheduling differ in time horizons, enforcement, and operational purpose. These are described in more detail in the following.

Time Horizon

Tactical and strategic scheduling differ in the time horizons over which they are applied. Tactical schedules are built and solidified as flights cross the freeze horizon (~20 minutes from the arrival meter fix) or as the flight crosses the arrival fixes (~10 minutes before landing on the runway). In contrast, strategic schedules are generated pre-departure. Strategic schedules use predictions of landing times (possibly hours in the future depending on the length of the flight) to build schedules at arrival and departure airports. The longer time horizon used in strategic scheduling exposes its schedules to more uncertainty.

Enforcement

Tactical and strategic scheduling are enforced differently. Closed loop control is applied to tactical schedules. AR actively monitors flight progress and periodically maneuvers flights to conform with tactical schedules. On the other hand, open loop control is applied to strategic schedules. CSMART strategic scheduling is accomplished as part of predeparture flight planning. No modifications are made to flight plans while they operate in the air.

Purpose

Tactical and strategic scheduling have different purposes. Tactical scheduling assists AR with keeping flights in merging arrival streams properly separated. In cases where a particular flight needs a large delay (greater than five minutes) in the TRACON, it assists AR with applying the delay to the flight when it is located upstream of the TRACON in en route airspace where there is more available airspace. In contrast, the purpose of strategic scheduling is to prevent arrival and departure rates at airports from exceeding their limits.

Tactical scheduling is fine-tuned to keep flights separated; strategic scheduling is coarse to keep airspaces and airports from getting too congested, moderating workload for AR. The two work in concert together. The experimental simulations demonstrate that this simulation system is a valid model of the two scheduling processes and their interactions.

2. Conflict Detection

The conflict detection function predicts, using MPAS and KTG, future trajectories of flights and searches them for conflicts. For this study, conflicts are categorized into two types. The first type, called Loss Of Separation (LOS), is between flights, i.e. when two flights are predicted to violate separation criteria. The separation criteria are that flights must be separated by at least 1000 ft in altitude and at least 5 nm in lateral distance. The lateral distance limit is reduced to 3 nm for flights in the TRACON. The second type, called schedule, is between a flight and its arrival schedule. It occurs when the flight is predicted to use its arrival fix or runway at a time other than its scheduled time.

3. Resolution

The resolution function searches for maneuvers that resolve conflicts. The search space of maneuvers tried is tailored to the initial conditions of the conflict and patterned after maneuvers commonly used in practice by air traffic controllers. All maneuvers in the search space are tried, even after solutions are found. From the set of successful maneuvers found, AR selects the one that has the preferred type for the conflict and airspace it occurs in and has the least amount of delay.

Many types of maneuvers are included by AR in the search space. In this study, only four types (path stretch, speed, temporary altitude, and combined path stretch and speed) were used because they are the ones commonly applied to flights approaching the arrival airport. Path stretch maneuvers lengthen the flight's path with the intent that a specified amount of delay or advance is achieved. Speed maneuvers incrementally change the speed profile of the flight. This is done differently depending on whether the flight is in cruise, descent, or climb. Updates to speeds and altitudes are checked against performance data to ensure that they are within the aircraft's performance envelope. Temporary altitude maneuvers are commonly used for LOS conflicts where at least one flight is in descent. They resolve these conflicts by holding the descending flight at a specified altitude while the other un maneuvered flight passes by separated by altitude.

In this study, the resolution function did not utilize holding patterns. This limited the amount of delay that AR could achieve with maneuvers. The limits were approximately 5 minutes for schedule conflicts and 7 minutes for LOS conflicts. These numbers are approximate because AR used buffers. Discussion of the buffers is beyond the scope of this paper. When traffic in the simulations increased to the point where airborne delays greater than these limits were needed to maintain separation, AR failed. The fix was to use CSMART to departure-delay flights. AR has a holding pattern function that can be used in future studies.

IV. Experiment

To validate the simulation system, a series of simulations were executed. They demonstrated the capability of the simulation system to model and analyze interactions between strategic and tactical scheduling and air traffic control. Although these simulations advance the simulation system, they do not directly include negotiation, arbitration, and uncertainty. The future work section will discuss how the simulation system can be extended to study these. This section presents the scenario, simulation setup, and experiment matrix.

A. Scenario

All the simulations presented in this work were initialized by one scenario. Key parameters of the scenario are listed in Table 2. The numbers in parentheses next to domestic departure airport codes denote the count of departures greater than 1 for that airport.

Table 2 Scenario Parameters

Parameter	Value
Flight Count	54
Simulation Duration	~ 7 hours
Domestic Flight Count	42
International Flight Count	12 (4 south, 2 north, 6 east)
Arrival Airport Code	EWR
Arrival Runway	22L
Domestic Departure Airport Codes	SJC, STL, CLT, DFW, BUF, PBI, CMH, SFO(2), AUS, ROC, MYR, BOS(2), PDX, RDU, GSO, MSN, MKE, RIC, IAH, SEA, RSW, CVG(2), ATL(2), ITH, CHA, CLE, PIT, SAN(2), IND(2), SNA, FLL, TPA, BTV, LAX, DTW(2)

Figure 5 displays the flight routes. The scenario has domestic flights departing from large airports dispersed across United States. It also has international flights that begin simulation at cruise altitude and speed where their routes intersect the boundary of United States' airspace. Table 2 lists the international flight counts that entered the airspace from the south, north, and east.

All flights approach EWR through one of three arrival meter fixes. Table 3 lists the fixes and the counts of flights using them.

Table 3 Arrival Fix Flight Counts

Arrival Meter Fix	Flight Count
SAX	15
METRO	17
SWEET	22

Fig. 5 Routes

Figure 6 illustrates the layout of the airspace surrounding EWR. EWR shares its TRACON, N90, with LaGuardia Airport (LGA) and John F. Kennedy International Airport (JFK). N90 is blown up in the right side of Fig. 6. The three arrival meter fixes and the Standard Terminal Arrival Routes (STARs) that pass through the them are shown. The fixes terminate the STARs. The approach fixes for runway 22L are GIBTE and IDACE. GIBTE is labeled. IDACE,

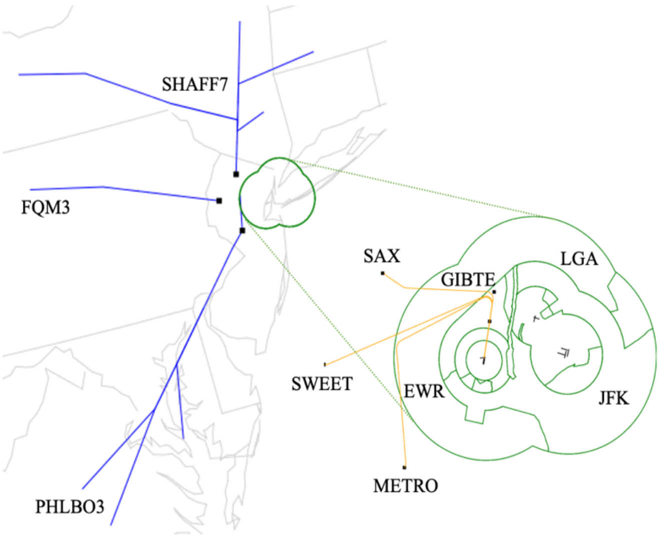

Fig. 6 Layout of EWR Airspace

the black dot under GIBTE, is not labeled due to limited space in Fig. 6. The paths drawn in orange are the nominal flight trajectories from the arrival meter fixes to 22L. During simulations, AR used maneuvers to modify these to resolve conflicts. The proximity of EWR to LGA and JFK and the sharp right turn into GIBTE, limited the maneuvers available to AR.

The scenario was created using operated flight plans recorded on April 26, 2018. Flights that landed on 22L at EWR between 18:30 and 20:00 UTC were selected for the scenario. The actual flight plans did not produce an arrival rate at EWR that was high enough to require strategic scheduling. To create a time period with an increased arrival rate, departure times were adjusted by dividing 18:30 to 20:00 into 3 30-minute bins, see Table 4. Flights from the first and last 30-minute bins were moved to the middle bin. The movement process preserved the original landing order at EWR.

Table 4 Actual and Adjusted EWR Arrival Counts in 30-Minute Bins

Time Bin UTC	Actual Arrival Count	Adjusted Arrival Count
18:30 – 19:00	19	10
19:00 – 19:30	19	29
19:30 – 20:00	16	15

Figure 7 shows the actual and adjusted arrival rates as landing counts in sliding 15-minute bins at EWR. Using 70 seconds as the average spacing limit between flights as they cross the runway threshold, the average maximum arrival rate is 12.8 arrivals per 15-minute bin. The adjusted arrival rate peaked at 19 arrivals per 15-minute bin, which was well above 12.8. Furthermore, it was sustained above 12.8 from 19:05 to 19:25. The adjusted scenario challenged the strategic and tactical schedulers and was used in the simulations.

B. Simulation Setup

The simulations executed in two phases. In phase 1, CSMART generated, predeparture, trajectory plans and passed them to ARS. In phase 2, ARS simulated the flights operating according to their trajectory plans. Only one pass was made through the two phases per simulation. Hence, CSMART strategic planning was open loop.

Only departure and arrival runways were selected as scheduled resources. All other fixes were non-scheduled resources. Because only one or two flights departed from the same airport, departure runways were not congested, and there were no or few constraints on use times for these resources. On the other hand, all flights arrived at EWR, and, to stress the

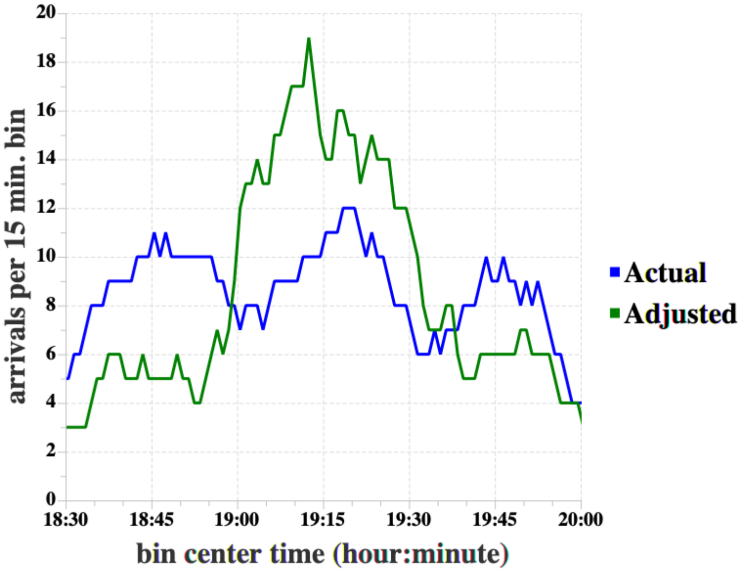

Fig. 7 Actual and Adjusted Arrival Rates and EWR

schedulers, the scenario was adjusted to congest the EWR runway. CSMART found for each flight a use time on the EWR runway that did not conflict with previously scheduled use times and then inferred a departure time from the arrival use time and flight's transit time. This process is similar to operational Ground Delay Programs, which allocate slots at the arrival airport to flights and then calculate corresponding Expect Departure Clearance Times (EDCTs).

Whereas the strategic scheduler executed during phase 1, the tactical scheduler executed during phase 2. As part of AR, the tactical scheduler scheduled flights during simulation as they crossed the freeze horizon and the arrival meter fix. There were four independent tactical schedulers, one for SAX, METRO, SWEET, and 22L. The time separation constraint for the arrival meter fix schedulers was 60 seconds, and the time separation constraint for the 22L scheduler was 70 seconds. Because the arrival meter fixes are located near the border of N90, the arrival meter fix schedulers affected flights operating in en route airspace and headed towards the meter fixes, whereas the 22L scheduler affected flights operating in N90 and approaching 22L.

C. Experiment Matrix

Six simulations were executed for this study to be an initial validation of the system. Table 5 lists the simulations and the parameters that were varied. Simulation 0 was the baseline simulation with CSMART and AR resolver both turned off. It was used to calculate unimpeded transit times between departure and arrival runways. The transit times were stored in a file and later used by the FPSS for simulations 1 through 5. The FPSS used the transit times in the calculation of trajectory plans for each flight. This process eliminated transit time uncertainty between the FPSS planning process in phase 1 and the simulation in phase 2.

Table 5 Experiment Matrix

Simulation	CSMART Sep. Param. (sec)	AR Resolver	AR Arrival Fix Sep. Param. (sec)	AR Runway 22L Sep. Param. (sec)
0	off	off	60	70
1	120	on	60	70
2	110	on	60	70
3	100	on	60	70
4	90	on	60	70
5	80	on	60	70

Although AR resolver was turned off in simulation 0, AR conflict detection and tactical scheduling were turned on. Conflicts were counted for simulation 0. Because AR resolver was turned off, no maneuvers to resolve conflicts were generated. The conflict count was a measure of the scenario's difficulty for AR when CSMART was turned off. In en route airspace, there were 8 LOS conflicts and 11 schedule conflicts, and in N90 there were 45 LOS conflicts and 30 schedule conflicts. These numbers of conflicts appear to be high because when a new simulation, not listed in Table 5, was run with AR resolver on and CSMART turned off, AR could not find maneuvers that resolved some conflicts because they needed too much delay.

The conflicts in simulation 0 are different from those appearing in simulations 1-5 because AR resolver and CSMART are turned off. With AR resolver turned on, maneuvers are used, and events downstream of maneuvers are altered by it. Also, CSMART strategic scheduling and departure delay alter conflicts.

In simulations 1-5, both AR resolver and CSMART are turned on. The CSMART separation parameter was varied from 120 to 80 seconds. Because of the relation between separation parameter and use rate described in section IIA, the arrival rate at EWR increases as the separation parameter is lowered.

V. Results

The results of the simulations are shown using three metrics: delay, workload, and throughput.

A. Delays

Figures 8 and 9 show box and whisker plots of the departure and airborne delay statistics, respectively. Observed departure delays were greatest for simulation 1, decreasing through simulation 5 as the CSMART separation parameter was reduced. On the other hand, airborne delays were greatest for simulation 5, decreasing through simulation 1 as the CSMART separation parameter was increased.

Airborne delays in simulations 1-3 were mostly zero because most flights were not maneuvered. Negative airborne delays arose as AR gave flights speed up (time advance) maneuvers. These maneuvers have either speed increases or short cuts in the route. AR can prescribe them as resolutions for either a schedule or LOS conflict.

In general, departure delays are much larger than airborne delays. This is partially due to AR’s limitation in finding maneuvers with large delays. It is also consistent with delay observations in actual operations, where ground delays are larger than airborne delays.

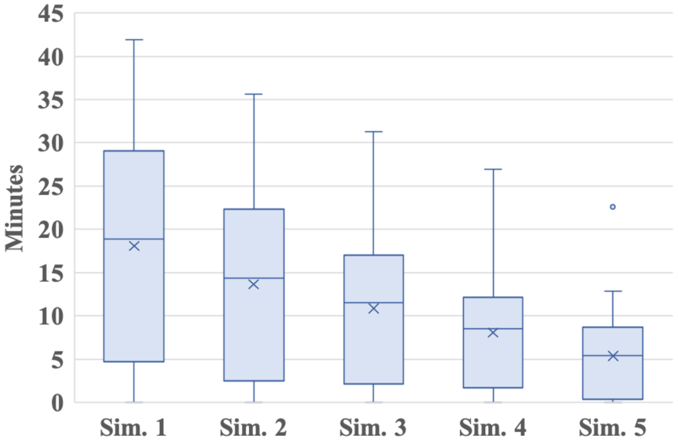

Fig. 8 Departure Delay Box and Whiskers Plot

B. Workload

AR applied maneuvers to flights as they descended and approached the airport. Counts of these maneuvers were used as a metric for workload. Table 6 lists these counts for the simulations. As the CSMART separation parameter was decreased, the counts increased. The total AR maneuver counts for a single flight produced its airborne delay. There were no other phenomena in the simulation that gave rise to airborne flight delays.

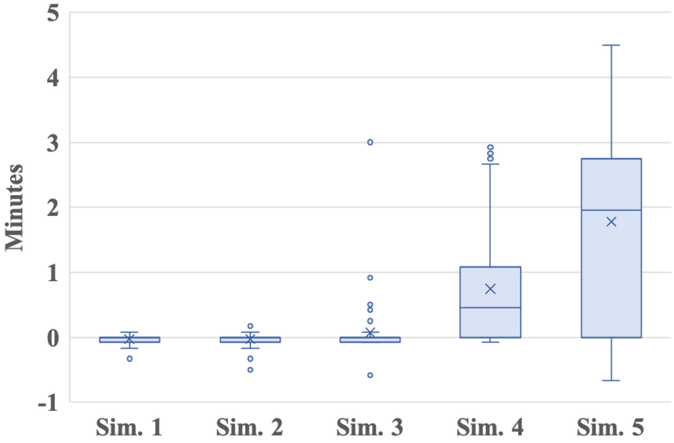

Fig. 9 Airborne Delay Box and Whisker Plot

Counts were broken out into maneuvers given in en route airspace and in N90. En route counts were lower than N90 counts. This indicates that the AR tactical scheduler separation limit on the arrival meter fixes was small. By increasing this limit, more maneuvers could have been given in the en route airspace alleviating the need for maneuvers in the N90.

Maneuver counts were broken out into four types: speed, path, temporary altitude, and combined speed and path. In en route airspace, path maneuvers are used more frequently than speed maneuvers. In N90, speed maneuvers are used more frequently than path maneuvers. However, in the simulations with a high count of maneuvers, 4 and 5, combined maneuvers are used as frequently or more than speed. The prevalence of path over speed maneuvers in en route airspace is due to en route airspace having more available airspace for path stretching. In N90 where space is highly limited, AR used speed and combined maneuvers before resorting to path. The only altitude maneuver occurred in en route airspace.

Maneuver counts were also broken out by purpose (conflict type). The two purposes are LOS and schedule, see Table 6. In en route airspace, the frequency of schedule and LOS maneuvers is approximately equal. However, in N90, all maneuvers are for schedule. This is because merging of the three final arrival flows occurs in N90, see Fig. 6.

Table 6 Count of Maneuvers Provided by AR to Flights

	Sim. 1	Sim. 2	Sim. 3	Sim. 4	Sim. 5
Total	3	6	12	37	46
En Route	2	4	4	5	5
Type	(1 speed, 1 path)	(1 speed, 3 path)	(1 speed, 3 path)	(1 speed, 3 path, 1 altitude)	(2 speed, 3 path)
Purpose	(1 LOS, 1 schedule)	(1 LOS, 3 schedule)	(1 LOS, 3 schedule)	(2 LOS, 3 schedule)	(3 LOS, 2 schedule)
N90 TRACON	1	2	8	32	41
Type	(1 speed)	(2 speed)	(5 speed, 1 path, 1 combined)	(16 speed, 5 path, 11 combined)	(6 speed, 1 path, 34 combined)
Purpose	(1 schedule)	(2 schedule)	(8 schedule)	(32 schedule)	(41 schedule)

Another measure of workload is the count of flights that were maneuvered more than once. Table 7 lists counts of flights with two maneuvers. In all cases where a flight was maneuvered more than once, the flight was maneuvered only twice: once in en route airspace and once in N90. This is because there were no uncertainties modeled in the simulations and each flight was acted on by two AR tactical schedulers (the arrival meter fix scheduler and the 22L scheduler). Once AR gave a maneuver to a flight to resolve a conflict, there was no uncertainty to cause the conflict to reappear.

Table 7 Count of Flights with Two Maneuvers

Simulation #	Count
1	0
2	0
3	2
4	4
5	5

C. Runway Throughput

Figure 10 displays the runway throughput at EWR in landing counts per sliding 15-minute bin for the simulations. Simulation 1 had the lowest peak rate of 8 landings per bin, whereas simulation 5 had the highest sustained peak rate of 11 landings per bin. All simulations except 5, to some extent, starved the runway, meaning that the runway could have accommodated more landings per bin during times of peak demand and that the ground delays were too restrictive. On the other hand, simulation 5 had a reasonable mix of ground delay and airborne delay that fully utilized the runway. Evidence supporting this is that the original landing rate, shown in Fig. 7, peaked at 12 landings per bin. Even though the original rate peaked at 1 landing per bin higher than the rate in simulation 5, the original rate was sustained for only 3 minutes, whereas the peak rate in simulation 5 was sustained for over 45 minutes, not counting a few minor downward spikes.

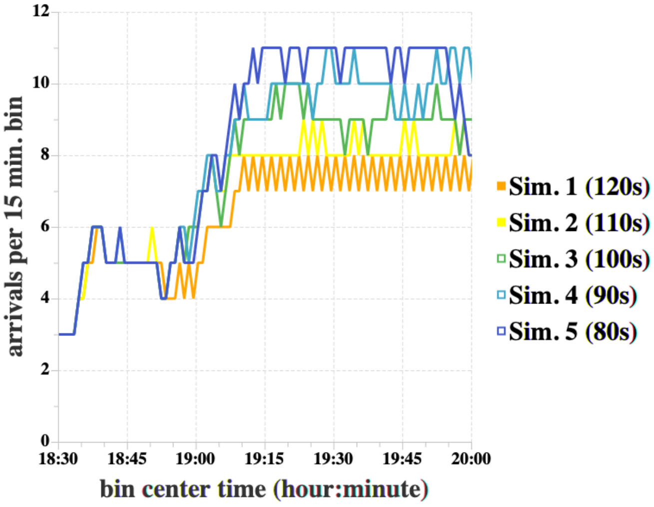

Fig. 10 KEWR Runway Throughput for each Simulation (Separation Parameter)

VI. Future Work

This study was designed to be an initial validation of the simulation system. Additional studies, adding realism and models of future air traffic management concepts, can be done with the system. Some ideas for future studies are included here.

1. *Negotiation and/or Arbitration*

This study used only one FPSS in the CSMART planning, so there was no competition for resource use times. The FPSS ordered (i.e., prioritized) the flights by predicted EWR arrival times and planned them one at a time. In future research, a second FPSS can be added to CSMART. This will create competition between two FPSSs as they asynchronously plan flights. Different sets of rules meant to facilitate, moderate, and arbitrate the competition can be investigated. In addition, negotiation situations can be studied. This will occur when both FPSS are vying for the same use time for a resource. Since CSMART is machine-to-machine, the negotiation will be carried out digitally. Studying more complex and realistic flight prioritization schemes will be possible with two or more FPSSs.

2. *Uncertainty*

This study attempted to reduce uncertainty as much as possible because it was the first study with this simulation system. This was accomplished in several ways. Winds were not modeled. Flights took off from runways in ARS exactly when they were planned to in CSMART. During simulation in ARS, flights used the exact speed and altitude profiles that were used in the CSMART planning phase. In addition, the same trajectory generators used in CSMART flight planning were used in ARS simulation. None of these apply in actual operations.

Future studies can begin to reintroduce uncertainties. However, as uncertainties are added, new techniques to account for them in CSMART planning will need to be added. One such technique is to make the scheduling probabilistic instead of deterministic. In this study, planning was deterministic in the sense that use times were single values. In the future, the FPSS can reserve intervals, as opposed to times, on the resource timelines. An interval will denote a duration of time when a flight is likely to use the resource according to a specified probability density function. The RS function which enforces resource rate constraints by calculating open and closed intervals will need to be more complex and probabilistic.

Another way to account for uncertainty in CSMART planning is to build closed-loop control around the strategic trajectory plans. These simulations were open loop because the trajectory plans were generated in CSMART predeparture (phase 1), and then ARS executed the simulations (phase 2). Once ARS started simulation, no information was sent back to CSMART, and CSMART did not have an opportunity to adjust or update trajectory plans. This is not to be confused with tactical scheduling, around which AR closed the loop. A closed-loop control around CSMART trajectory planning could be built by 1) having ARS send during phase 2 state and other information back to CSMART, and 2) allowing CSMART to use that information to update trajectory plans and send updates to ARS. Part two will require flight plan amendments be sent to the flights while in the air.

3. *Multi-point Scheduling*

This study selected only departure and arrival runways as scheduled resources. Future studies can specify more scheduled resources in the NAS. Likely candidates will be any fixes that merge more than one heavy traffic flow, such as arrival meter fixes and STAR transitions. Another possibility will be to surround an airspace with scheduled fixes and use CSMART to limit the traffic flowing into it. This will simulate using an Airspace Flow Program (AFP) to protect an airspace with capacity-limiting weather.

4. *Different Scenarios*

This study simulated an EWR arrival scenario. Future scenarios can augment EWR arrival traffic with JFK and LGA arrival traffic. Another possibility will be to mix traditional traffic with UAM or UAS traffic, all arriving at the same airport. This simulation system can also be used to investigate heterogenous UAM or UAS traffic.

5. *Updates to AutoResolver*

In this study, all flights landed on 22L. EWR possesses a crossing runway, 11, that is used for overflow arrivals. A future study can have AR route some arrivals to 11. ARS has functions for multi-runway scheduling that can be used for this purpose.

In this study, AR’s tactical schedulers for the meter fixes and runway were not coordinated. As a result, AR workload was unbalanced between en route airspace and the N90, i.e. there were fewer en route maneuvers than N90 maneuvers. A future study can investigate coordinating the schedulers or adjusting the separation limits of the meter fix schedulers.

As shown in Fig. 6, AR maneuvers were limited by the layout of EWR terminal airspace. This limited AR’s ability to accommodate EWR arrival traffic without CSMART predeparture delays. A future study can investigate increasing the amount of arrival traffic AR is able to handle by adapting its resolution logic to the EWR terminal airspace or including holding maneuvers.

VII. Summary

A simulation system for studying collaborative flight planning, strategic traffic management, and air traffic control was developed. The system includes a communication architecture, a realistic model of air traffic control, and an airspace simulation, driven by proven trajectory generators. The communication architecture is named the Collaborative, Seamless Manager of Airspace Resources and Traffic (CSMART). The model of air traffic controlled is named AutoResolver (AR). Finally, the airspace simulation is named AutoResolverSim (ARS).

Leveraging NASA's Unmanned Aerial System (UAS) Traffic Management (UTM) project research, CSMART was designed to be scalable and efficient. It digitally communicates, machine to machine, flight plans and strategic traffic flow management constraints via the Internet. It was setup to be interoperable, meaning that it has clearly defined Application Protocol Interfaces (APIs) and procedures so that many different computers, deployed by different stakeholders and operators, can connect and participate in decision making, possibly using artificial intelligence. The architecture is federated. It possesses centralized rules that facilitate organized and well-defined collaboration between computers, while preventing unauthorized interactions.

AR is the detailed model of air traffic control. AR possesses tactical schedulers that build schedules that satisfy time separation constraints for arrival fixes and runways. AR predicts and solves conflicts due to multiple flights violating separation criteria and single flights not conforming to the arrival meter fix and runway schedules. AR is a prototype of a future air traffic control system that automates the functions of air traffic controllers where clearances are automatically uplinked to aircraft via FAA's data communications systems.

ARS combines AR and NASA's proven fast-time trajectory generators into a simulation for studying autonomous airspace systems and tools. It uses NASA's ATM-X Testbed to connect, and, thus, it leverages Testbed's ability to connect to a wide range of real-time systems, fast-time systems, live data feeds and systems, and tools for analysis, scenario generation, and visualization.

The simulation system was validated by running simulations of a scenario of 54 flights flying inbound to Newark Liberty International Airport. Although the scenario originated from real arrivals at EWR recorded from the NAS on April 26, 2018, the flight departure times were adjusted so that the arrival rate at EWR exceeded capacity. The scenario was simulated multiple times, varying the CSMART arrival rate limit. Results compared the delays produced by CSMART and those produced by AR. AR workloads, as measured by count of maneuvers given to flights by AR, and EWR arrival rates were presented. CSMART predeparture planning was able to successfully update flight plans and relieve arrival congestion at EWR to the extent that AR was able to safely manage the traffic. CSMART's flight plan updates were departure delays. When CSMART's arrival rate limit was too low, the runway at EWR was starved. However, when CSMART's arrival rate limit was set reasonably, delay distribution between CSMART and AR was well balanced, and the runway was efficiently used.

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