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Distributed Simulation Infrastructure for Researching Implementation of Evolving Concepts in the NAS

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Nomenclature

ACS	=	Airborne Control Station
ADRS	=	Aeronautical Data link and RADAR Simulator
ADS-B	=	Automatic Dependent Surveillance-Broadcast
Ames	=	Ames Research Center
AOP	=	Autonomous Operations Planner
API	=	Application Interface
ASAS	=	Airborne Separation Assurance Systems
AMSTAR	=	Airborne Merging and Spacing for Terminal Arrivals
ARINC	=	Aeronautical Radio INC
ASTOR	=	Air Simulations for Traffic Operations Research
ATM	=	Air Traffic Management
ATM-X	=	Air Traffic management eXploration
ATOL	=	Air Traffic Operations Lab
ATOP	=	Advanced Technologies and Oceanic Procedures
ATOS	=	Airspace and Traffic Operations Simulation
ATS	=	Advanced Trajectory Services
AvBus	=	Avionics Buss
AVS	=	Aviation SimNet
CMF	=	Cockpit Motion Facility
CMU	=	Communication Management Unit
CNS	=	Communications Navigation and Surveillance
ConOps	=	Concept of Operations
CPDLC	=	Controller-Pilot Data Link Communications
CSAOB	=	Crew Systems and Aviation Operation Branch
DAIDALUS	=	Detect and Avoid Alerting Logic for Unmanned Systems
DDS	=	Data Distribution Service
DRNAV	=	Dynamic Area Navigation
DSR	=	Display System Replacement
EFB	=	Electronic Flight Bag
EFIS	=	Electronic Flight Instrument System

EICAS	=	Engine Indication and Crew Alerting System
EPP	=	Extended Projected Profiles
eVTOL	=	electric vertical takeoff and landing
FAA	=	Federal Aviation Administration
FDM	=	Flight Dynamics Model
FIM	=	Flight deck Interval Management
FIS-B	=	Flight Information Services Broadcast
FOM	=	Federation Object Model
FPM	=	Flight Path Management
GNC	=	Guidance, Navigation, and Control
GUI	=	Graphical User Interface
GWP	=	Glareshield Window Panel
HITL	=	Human-In-The-Loop
HLA	=	High Level Architecture
ICAROUS	=	Independent Configurable Architecture for Reliable Operations of Unmanned Systems
IDL	=	Interface Description Language
IMAC	=	Interval Management Alternative Clearances
JSB	=	Jon S. Berndt Simulation
Langley	=	Langley Research Center
LaSRS++	=	Langley Standard Real-time Simulation in C++
LNAV	=	Lateral Navigation
MACS	=	Multi Aircraft Control System
MCDU	=	Multi-function Control and Display Unit
MCP	=	Mode Control Panel
MIXR	=	Mixed Reality Simulation Platform
NACCL	=	NASA ATM Common Communication Library
NAS	=	National Airspace System
ND	=	Navigation Display
NLR	=	National Aerospace Centre of the Netherlands
NTP	=	Network Time Protocol
PDS	=	Paired Dependent Speed

PFD	=	Primary Flight Display
QML	=	Qt Modeling Language
RPFMS	=	Research Prototype Flight Management System
RTA	=	Required Time of Arrival
RTCA	=	Radio Technical Committee for Aeronautics
SBX	=	Scenario Batch eXecution
SimMan	=	Simulation Manager
STARS	=	Standard Terminal Automation Replacement System
StringDefGUI	=	String Definition Graphical User Interface
SUA	=	Special Use Airspace
SWIM	=	System Wide Information Management
TAP	=	Traffic Aware Planner
TASAR	=	Traffic Aware Strategic Aircrew Requests
TBO	=	Trajectory Based Operations
TDCP	=	Traffic Display Control Panel
TIGAR	=	Toolkit for Integrated Ground and Air Research
TMX	=	Traffic Manager eXecutable
TP	=	Traffic Procedures
UAM	=	Urban Air Mobility
UAS	=	Unmanned Aerial Systems
VNAV	=	Vertical Navigation
VTOL	=	Vertical Takeoff and Landing

Abstract

The National Airspace System (NAS) is evolving; it is becoming more crowded, and new vehicles with different capabilities are starting to utilize airspace. Increased capacity, new vehicles, and their varying performance and equipage profiles will require changes in how we operate in the NAS. The Crew Systems and Aviation Operations Branch (CSAOB) has actively supported crew systems and aviation research contributing to the safe evolution of the NAS. As the NAS continues to evolve to meet the needs of the nation, CSAOB has the history, infrastructure, and tools to support needed research for the introduction of new technologies and understand their impact on the NAS . This paper describes the software infrastructure and tools supported by CSAOB, lists how the tools have been used in the past, how researchers can integrate into our infrastructure, and how these tools are evolving to support research into the future of the NAS.

1.0 Introduction

The National Airspace System (NAS) is continually evolving and becoming increasingly more diverse as air traffic not only increases but diversifies as new air vehicles with different capabilities engage in travel [1, 2]. Nontraditional vehicles vying for room in the NAS include but are not limited to Supersonic Transport [3, 4], Unmanned Aerial Systems (UAS) [5], and Urban Air Mobility (UAM) vehicles [6]. Each of these vehicle types bring new challenges due to their different operational capabilities and constraints [3, 4, 5, 6]. Operations need to become more flexible to safely adapt to continually evolving changes due to increased volumes and new vehicles with varying capabilities [2]. Policies and rules of flight need to be reviewed and updated to meet the needs of a multi-class airspace as some new vehicles will likely be unmanned automated systems [7], and some vehicles will have wider variability in take-off and landing locations [2]. As traffic increases, predictive modeling of the effects of weather and other unexpected obstacles needs to be performed to learn how to manage sudden changes within local high-volume traffic.

New infrastructure for traffic management is already moving forward as the Federal Aviation Administration (FAA) works towards implementing four critical infrastructure programs across eleven portfolios [5]. Three key principles are involved in meeting FAA goals [5]:

- *Delivering improved services while maintaining the highest levels of safety*
- *Ensuring seamless integration*
- *Meeting new challenges*

These changes and updates enable support of Trajectory Based Operations, Automatic Dependent Surveillance-Broadcast (ADS-B) services, Automation, System-Wide Information Management (SWIM), and other concepts as they move from distance-based to time-based separation of aircraft [5].

Figure 1 from reference [8] shows the types of vehicles that are expected to operate within the NAS in the near future. The Air Traffic Management eXploration (ATM-X) project at NASA is researching and developing solutions that will support anticipated transformational demands on the NAS: UAM, High-Altitude Pseudo-Satellites, supersonic transport, and autonomous aircraft for cargo operations [8].

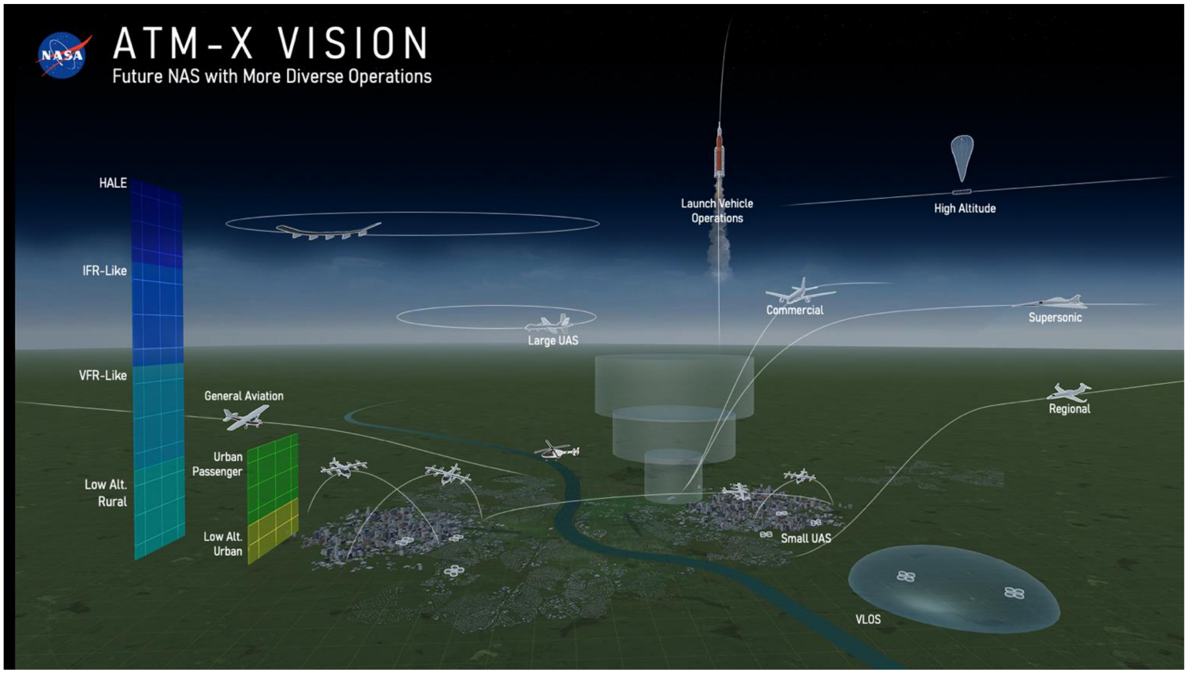

Figure 1. ATM-X Vision [8], Image Credit: ATM-X Fact Sheet, NASA

Research and simulation are required to determine what changes are needed within the NAS and the rippling effects of the changes to the NAS system of systems. One of the best ways to predict the effects of changes is through modeling and simulation of the changes to be implemented. The Crew Systems and Aviation Operations Branch (CSAOB) at NASA Langley has developed distributed simulation systems that enable modeling and simulation of many different types of vehicles and scenarios within the NAS. These simulation systems have enabled research that has contributed to policy and decision making in the past and will continue to evolve to enable new research moving forward. This paper describes simulation capabilities within CSAOB that have been used in the past or are being used currently for conducting research. Additional thoughts on how these simulation capabilities could support future research are also addressed.

2.0 Distributed Simulation Capabilities Within CSAOB

The CSAOB can model and simulate a wide variety of capabilities and aspects of the NAS. A diagram of CSAOB software that can be connected in a distributed simulation is shown in figure 2. It features several data transport mechanisms and types of simulation that can be used separately or in conjunction with each other according to requirements of the simulation experiment. Communication infrastructures include High-Level Architecture (HLA), Data Distribution Services (DDS), and TestBed. Software components include Airspace and Traffic Operations Simulation (ATOS), Aircraft Simulations for Traffic Operations Research (ASTORs), UAM Flyers, Traffic manager eXecutable (TMX), Multi Aircraft Control System (MACS), Independent Configurable Architecture for Reliable Operations of Unmanned Systems (ICAROUS), and other research software. The components outlined in red represent three different places within the infrastructure where researchers can insert their own simulation software.

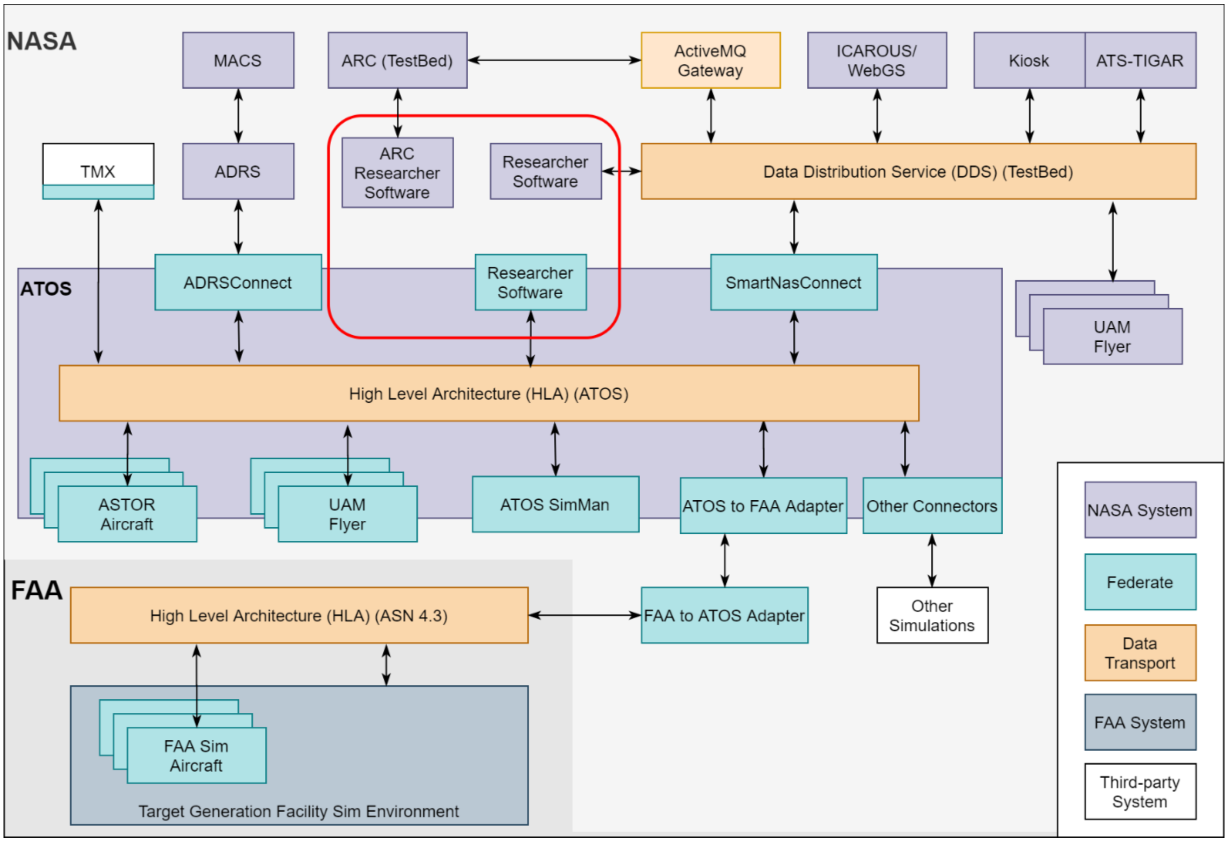

Figure 2. CSAOB Distributed Simulation Architecture

2.1 Communication Infrastructure

The ATOS implementation of the HLA is the predominant method for communication between distributed simulation components shown in figure 2. Each simulation component that communicates via HLA is a federate [11]. Federates exchange data via a Federation Object Model (FOM). The FOM defines the data to be exchanged via a publish and subscribe scheme. An Application Interface (API) wrapper called the NASA Air Traffic Management (ATM) Common Communication Library (NACCL) has been developed to interface with HLA. The NACCL enables the software developer to communicate with other software components without needing to understand the HLA transport layer. Should the transport layer need to be changed in the future, this can be done without affecting interfaces using the NACCL. The NACCL is composed of an ApiExecutive to enable initialization, triggering of cyclical processing and termination of the software, publishers that send information, subscribers that receive information, and models that provide mediated access to other simulation information. The NACCL includes features such as input handler callbacks and dead reckoning to manage messaging and reduce bandwidth required.

DDS is also used for communication between simulation components. Three versions of message formats have evolved that utilize Interface Description Language (IDL) to define the data passed between the simulations. A generic message format is available for information that does not readily fit into previously defined formats. A wrapper, set of classes, and user guide have been developed to minimize developer effort.

In addition to DDS, the NASA TestBed services could be used to communicate between the NASA Ames and Langley Research Centers. This communication service utilizes an ActiveMQ messaging infrastructure to send and receive messages. TestBed utilizes wizards to enable users to architect the connections of a distributed simulation [12, 13] as well as to develop some of the adapter code used for interfaces to send and receive messages.

CSAOB has a tested connection to enable integration with the FAA Tech Center simulation environment using Aviation SimNet. Aviation SimNet (ASN) uses HLA but has a different FOM than ATOS. Data is converted from the ATOS NACCL FOM to formats utilized by Aviation SimNet. A message update rate of 1 Hz is maintained for a minimum of 50 unique federates.

Other simulations at NASA that have connected to ATOS via the HLA infrastructure include the Cockpit Motion Facility (CMF) in the Simulation Development and Analysis Branch [14]. The CMF provides motion characteristics for full-mission-capable aircraft simulators with large cross-cockpit display systems and reconfigurable cockpits.

2.1.1.1 Software Simulations

The ATOS simulation infrastructure enables a multitude of simulations and simulation tools to run in a distributed fashion across many computers supporting complicated modeling and simulation of the NAS [9, 15].

2.1.2 ATOS

The ATOS simulation infrastructure has been in use for over 20 years [10]. The original six requirements and concepts defined as needed for ATM research and implemented in ATOS are listed in reference [10] and include:

1) The ability to support multiple human operators
2) Flexibility with variable fidelity
3) Simulation repeatability
4) Support for modes of operation
5) Component error modeling
6) Simulation execution control

ATOS continues to support all of the above features and has been used in many different research activities and experiments to include but not limited to the following:

- ADS-B performance modeling and traffic management [16]
- Comparing ground-based and airborne function allocation concepts for NextGen [17]
- Flight deck Interval Management (FIM) [18]
- Interval Management Alternative Clearances (IMAC) [19]
- Traffic management advisories with terminal metering [20]
- Controller-managed spacing [20]
- Extended Projected Profiles (EPP) trajectory error estimations for Trajectory Based Operations (TBO) [21]
- Estimation of separation buffers for wind prediction errors [22]
- Operational Concepts such as self-separation [23]
- In Trail Procedures (TP) [24]
- Advanced trajectory-based operations [25]

- Time-based flow management [15]

ATOS can be run in Batch mode or with Human-In-The-Loop (HITL). ATOS has tools to support running multiple scenarios in batch mode. In HITL mode, subject pilots, subject controllers, and/or subject dispatchers interact with the simulators to support research needs. ATOS supports distributed analysis of runs, gathering of distributed data, gathering and scanning of log files, and execution of processing analysis of gathered data [26]. Timing for all data and computers is synchronized using a Network Time Protocol (NTP) client to keep machines synchronized within 20 milliseconds.

ATOS uses the concept of a "string" to decouple scenario definitions from the particular population of computers used to run the scenario. This provides tremendous flexibility in deploying scenarios to varied development and production network environments without modifications. A String Definition Graphical User Interface (StringDefGUI) provides a convenient interface for defining the pool of computer resources comprising the string and specifying the deployment of simulation federates across those resources as shown in figure 3. Scenario files store information about the configuration of each software instance: what aircraft are flown, navigation database, weather, etc. A string file stores distributed simulation information about which computers are to be used, what software is to be run on each computer, the scenario files to be used by each computer, and other deployment-specific configuration information. StringDefGUI reads in a string definition file selected by the user, enables the user to edit the file, then sends the information to the computers that will participate in the simulation execution.

ATOS has a DataCollection facility that contains DataLogger and DataReader to manage writing and reading of data files produced by the simulation event. The data is gathered using the Scenario Batch eXecution (SBX) system. The SBX tool combines the running scenario with the additional steps needed to perform initial post-run data analysis and to gather data into a single run-specific data repository. A PostAnalysis tool facilitates creation of data analysis programs that read and process the *.dat file generated and is invoked by SBX. A configuration file is used to tailor data collection to be specific to the ongoing research.

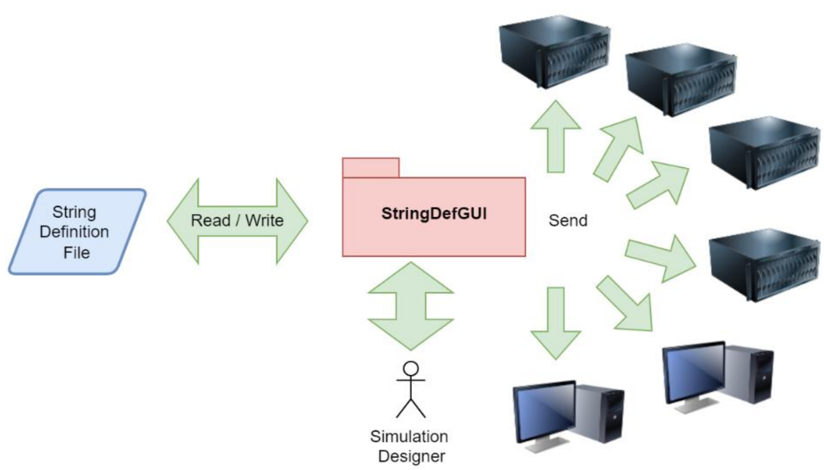

Figure 3. CSAOB Distributed Simulation Architecture - StringDefGUI

ATOS has a simulation manager (SimMan) that reads in a scenario file, either selected by the user or specified in the SBX system configuration file. The SimMan combines information about what simulation roles need to be executed from the scenario file with the role deployment information specified in the string definition to determine which federates need to be launched, where each is launched, and when each is launched. The SimMan then monitors federates and sends mode control transition information to the federates [9, 10, 26]. Transition modes include reset, hold, operate, and terminate. Each simulation connects according to its technology and needs while ATOS coordinates and manages the interactions. Each simulation described in the following sub-sections model specific aspects of the NAS.

2.1.3 ASTOR

An Aircraft Simulation for Traffic Operations Research (ASTOR) is a representative state-of-the-art transport class aircraft implemented with a six-degree-of-freedom aircraft data model, multi-function displays, autopilot, auto-throttle systems, Research Prototype Flight Management System (RPFMS), multi-function control display unit, mode control panel, Flight Information Services Broadcast (FIS-B), and ADS-B [9, 26].

The architecture for the communication of the high-level components within the ASTOR is shown in figure 4. The Avionics Bus (AvBus) simulation software was specifically modeled after existing standards such as the Aeronautical Radio Inc (ARINC) 429 and ARINC 700 series documents [26, 27, 28, 29]. AvBus is the central communication network for all of the ASTOR internal systems [26, 27, 28].

The pilot interface package contains all the graphical user interfaces (GUIs), panels, and displays for the pilot [26]. A sample cockpit display is shown in figure 4. ASTORs have a rule-driven pilot model used during batch studies that mimics the decision making of a pilot [26]. The pilot model monitors the AvBus channels used by the displays to obtain information needed about situations, rules used for decisions, actions based on the decision, and the “personality” of the pilot: normal, lazy, alert. The pilot model “personality” defines the timing distribution used for the delay between the simulation and the response by the pilot.

Each ASTOR has a software based RPFMS that includes expanded 4D flight guidance capabilities [26] to enable testing of NextGen TBO. 4D trajectories may include a Required Time of Arrival (RTA) at specific waypoints [26]. Guidance and control within the RPFMS encompass trajectory generation, horizontal guidance, and vertical guidance [26]. Areas of expanded research capability in the RPFMS include time error management, spacing guidance, and constraint management and relaxation described in more detail in reference [26].

On the ASTOR, the Autonomous Operations Planner (AOP) obtains information from the AvBus and utilizes the AvBus for all communication with the RPFMS and displays [29]. Additional information about AOP can be found in section 2.1.7.

The airframe and performance model are based on an early version of the NASA Langley Standard Real-time Simulation in C+ (LaSRS++) [26, 30] and models all but type-specific components for the airframe: mass properties, aero, propulsion systems, equations of motion, landing gear, and control system. There are several specific aircraft models and specific equipage available. Aircraft model and equipage information is determined by the following configuration files read by the ASTOR: framework configuration file, simulation initialization file, navigation database, and navigation database initialization file. Additional information can be found in reference [26].

The Communication Management Unit (CMU) manages all incoming traffic information and passes data to subsystems and broadcasts ownship information. It is modeled to process the data which drive the Communications, Navigation, and Surveillance (CNS) functions within the ARINC 660A compliant Avionics [25]. The CNS functions include Voice, Controller-Pilot Data Link Communications (CPDLC); ADS-B; and FIS-B. The FIS-B implementation distributes weather and Special Use Airspace (SUA) information. None of the communication models incorporate transmission layer effects such as range limits, noise, or dropped messages.

ASTORs have record and playback features to enable visual review of a simulation [26]. A Bus Recorder reads data from the AvBus. All data needed to drive ASTOR displays are also recorded [26].

Each ASTOR is a federate [28] and initially was on a different computer. A concept called a multi-ASTOR has been developed which enables multiple ASTORs to run on the same computer; however, only one ASTOR has displays on each computer. The remaining ASTORs are flown by the Pilot Model and do not have display graphics. Sample display graphics are shown in figure 5.

The number of ASTORs that can be instantiated has increased significantly with the updates to the NACCL. Prior to the updates, up to 150 could be instantiated at a time. Now up to 353 have been instantiated simultaneously in an experiment with up to 1200 throughout a single scenario [15].

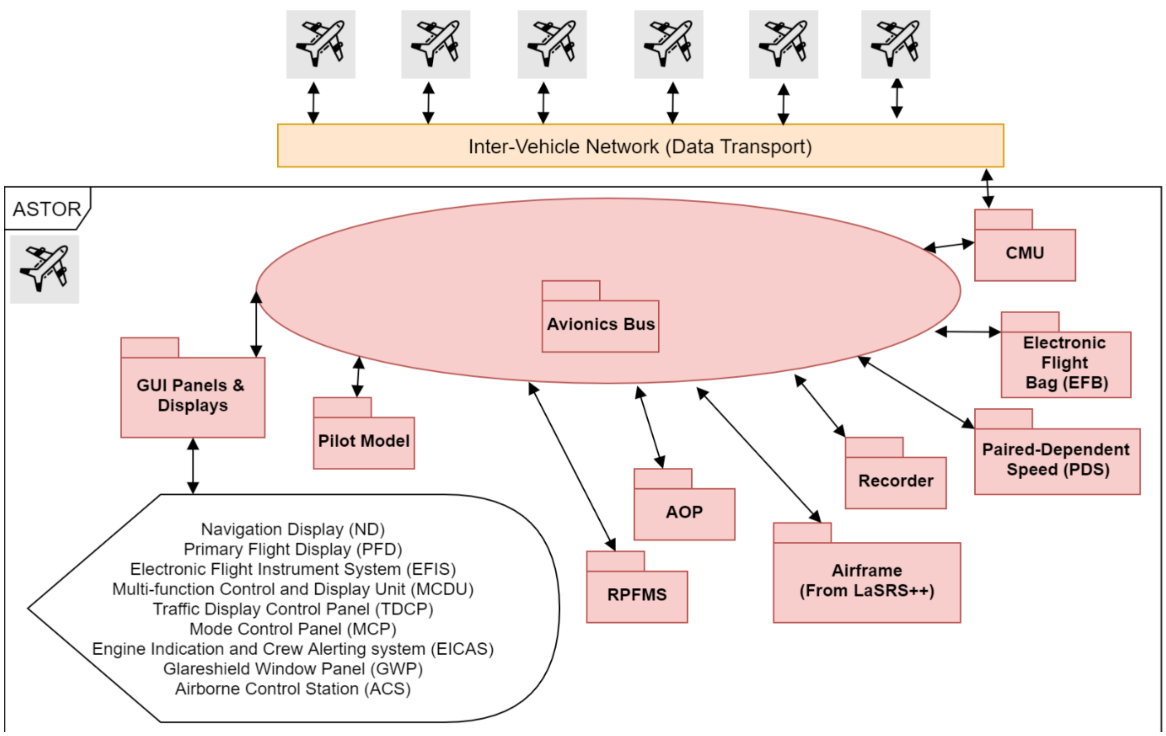

Figure 4. ASTOR Architecture

Figure 5. Sample ASTOR Cockpit Displays [31]

2.1.4 UAM Flyers

The FAA published a concept of operations (ConOps) for UAM vehicles [6]. These vehicles are expected to support flight operations in and around urban areas [6]. UAM vehicles are expected to include vertical takeoff and landing (VTOL) vehicles with varying capabilities to include electric propulsion [6]. Flights are expected to be between 10 and 100 miles and will enable on-demand mobility through the air to nearby destinations potentially using mobile applications for access [32]. Currently in an infant stage [32, 33], this complicated system will likely take decades to evolve, and its evolution may be measured according to a UAM Maturity Level (UML) scale [32]. This system like other air traffic systems will require rules and regulations for safety and simulation for testing ideas prior to implementation. CSAOB has developed UAM vehicle simulators that can be used for research [34] and that will be able to utilize many of the communication, navigation, and surveillance technologies described in reference [33]. These Flyers can operate within a distributed simulation in the same manner as the ASTORs, except that in addition to using the NACCL with HLA, they can also communicate directly via TestBed using DDS. Many different aircraft technologies will emerge within the UAM market [33], and the CSAOB Flyers are built to enable different configurations to be used without changing the Flyer architecture.

The Flyer is a modular, configurable air vehicle model that can be readily configured or extended to simulate many different types of air vehicles. Currently implemented models include two notional NASA reference six-passenger electric VTOL (eVTOL) vehicles: a quadrotor and a lift+cruise configuration described in reference [35]. Integration of a Flight Dynamics Model (FDM) that was code generated from a MATLAB/Simulink model has also been demonstrated.

A high-level view of the Flyer is shown in figure 6. The open-source Mixed Reality (MIXR) Simulation Platform forms the core of the Flyer framework. The two six-passenger eVTOL FDMs and their inner control loops were developed using the Jon S. Berndt Simulation (JSBSim) FDM package. The outer Guidance and Navigation functions were developed in C++. Pilot displays use a mixture of Qt Modeling Language (QML) and MIXR/Open GL components. Flyers can be configured and initialized using command-line parameters or using ATOS scenario configuration files and SimMan just like ASTORs. While only two are currently implemented, the architecture was built to enable easy integration of any C++ callable models. Like the ASTORs, the Flyers can utilize AOP. The Simulation Executive manages the MIXR components. Runtime selectable components provide the FDM; inceptor interfaces; displays; network interfaces such as TestBed, ATOS, and out-the-window displays; and Flight Path Management (FPM)/AOP interface. In addition to modified instrument panels and out-the-window displays, the ability to view a street map has been added to aid in navigation as a part of the instrument panel. Multiple Flyers can be run on a single computer, much like the ASTORs, but only the displays from one Flyer can be shown. Also, a single Flyer can be used to simulate hybrid human/automated operations. The Flyers have data recording capabilities that are part of the MIXR framework and are built upon Google Protocol Buffers (protobuf) libraries used for data record definition and serialization/deserialization. The definition of data to be stored is defined in language-independent *.proto files, which allows data to be analyzed in several programming languages including Java and Python in addition to C++. A sample Flyer display is shown in figure 7. Simulations have been run with up to 180 distinct Flyer federates in a single execution, not including background traffic, consistent with UML-4 described in reference [32].

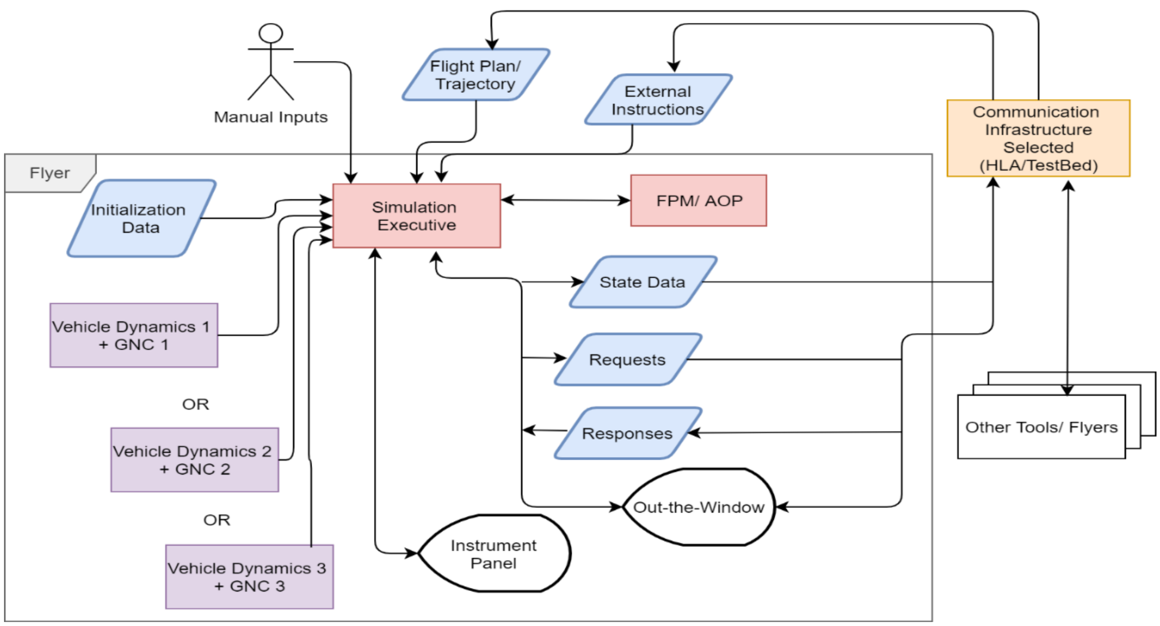

Figure 6. Flyer Architecture

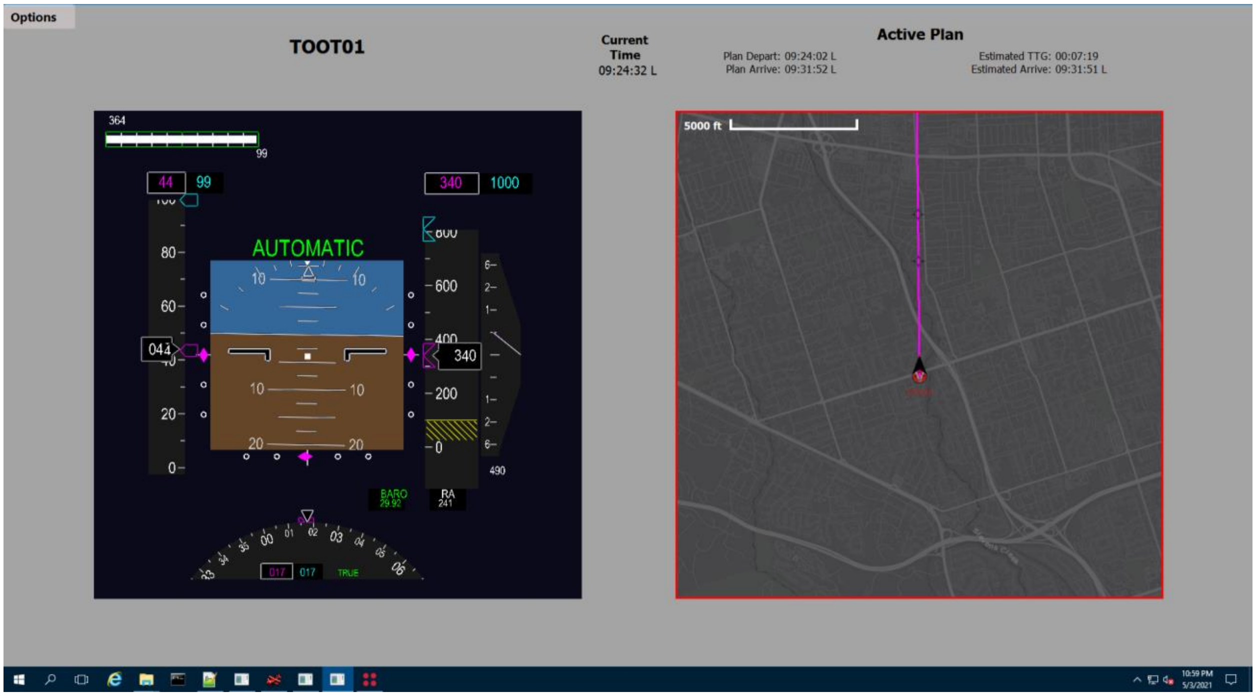

Figure 7. Sample Flyer Display

Some experiments within CSAOB have already started to test ideas for the Flyers:

- CSAOB has used the Flyers to demonstrate the FAA UAM ConOPS in the Atlantic City area
- Feasibility of self-separation is being tested in a simulated urban environment (ongoing)

Much simpler and more modular than ASTORs, the Flyers shown in figure 8 have been designed to enable simple adaptation and extension to meet experiment needs. An example of such is an interface module that integrates the Flyer into a Unity-based virtual reality environment with headset and eye tracker for crew systems research.

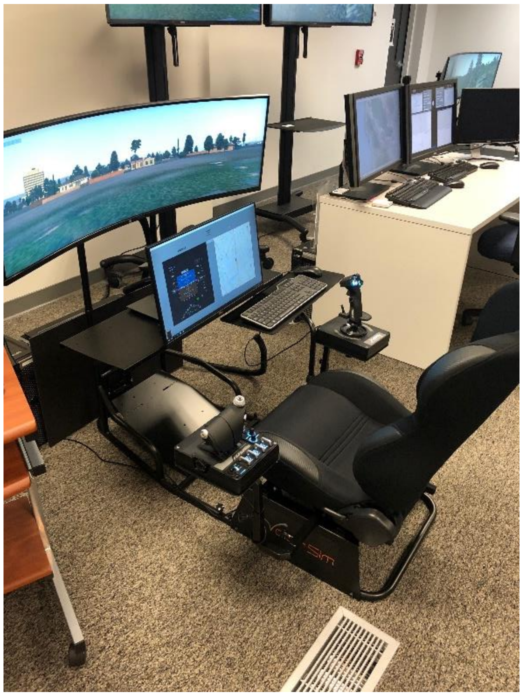

Figure 8. Flyer

2.1.5 TMX

The TMX was independently developed by the National Aerospace Centre of the Netherlands (NLR) for use in research of distributed traffic management concepts such as free flight. TMX has been used by CSAOB as a traffic generator for scenarios that require a large number of aircraft as well as for simulating parts of the NAS. A screenshot from TMX is found in figure 9. TMX has the following capabilities [36]:

- Over 200 different 6-degree-of-freedom aircraft performance models
- Basic altitude, heading, and speed modes
- FMS coupled Lateral Navigation (LNAV) and Vertical Navigation (VNAV) modes with auto throttles for auto flight
- Airborne Separation Assurance Systems (ASAS) such as conflict detection resolution and prevention systems selectable among 10 variants
- Gate to gate operations that include ILS approach and taxi control
- A pilot model
- ADS-B model
- Wind model
- Weather models that include moving weather cells

TMX has been used both standalone and with ATOS and ASTORs in past experiments that include but are not limited to the following:

- Researching concept of operations for overland supersonic flight [3, 4]
- Airborne self-separation [23]
- Distributed air traffic management research [[9, 17, 37]

- In-Trail Procedure Validation [24]
- Simulations of future Trajectory-Based Operations Environment [15]
- Airborne Merging and Spacing for Terminal Arrivals (AMSTAR) [36]
- Pairwise Trajectory Management [38]

While up to 1200 ASTORs have been simulated within an experiment with 353 simultaneously, TMX enables additional background traffic beyond the ASTORs. In reference [15] there were an additional 400 flights run in TMX, and the maximum traffic limit was not reached for TMX.

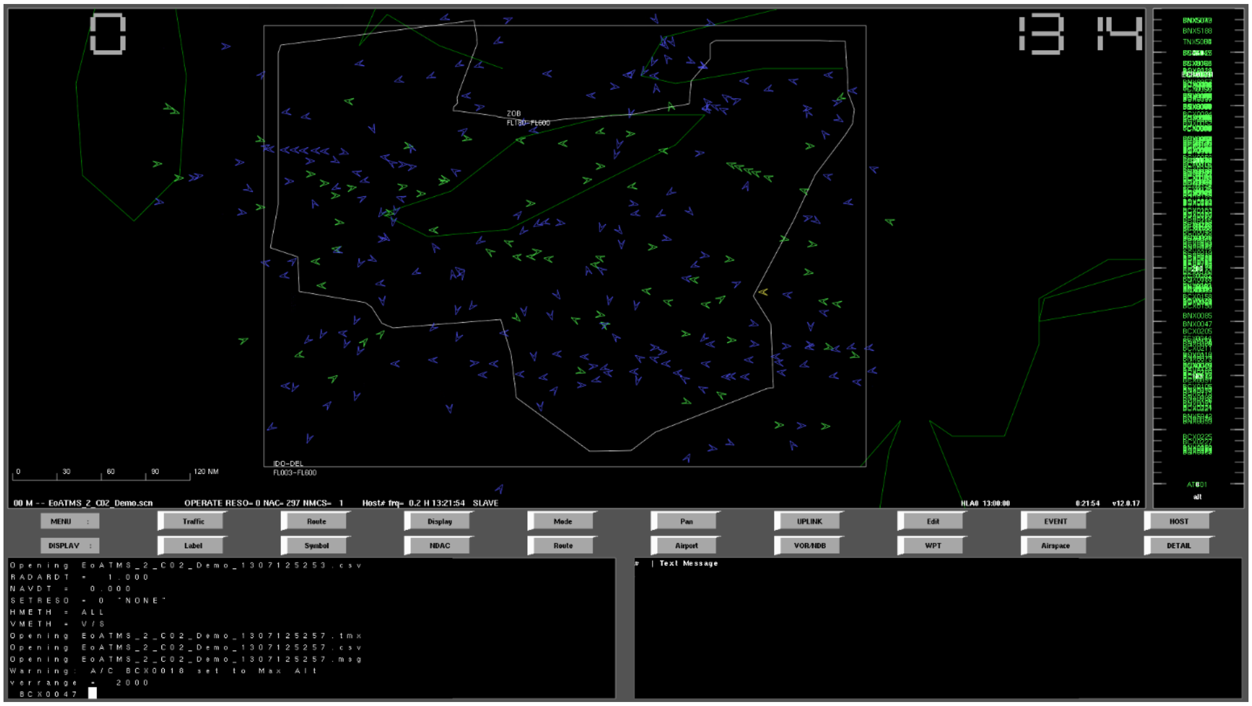

Figure 9. TMX Display [31]

2.1.6 MACS

The Multi Aircraft Control System (MACS) is an environment created by NASA Ames for developing and running real-time controller and pilot-in-the-loop simulations. It includes high-fidelity emulations of current air space systems and enables envisioned capabilities to be rapidly prototyped [39]. MACS can be run in different modes to simulate different parts of the NAS: it can serve as a cockpit for a pilot, a pseudo-pilot control station, or as one of several types of air traffic control stations [39]. Pilot modes include single and multi-aircraft pilots. Controller workstations include but may not be limited to en route controllers (display system replacement (DSR)), approach controller (standard terminal automation system (STARS)), or oceanic controllers (Advanced Technologies and Oceanic Procedures (ATOP)). MACS receives data from the Aeronautical Data Link and RADAR Simulator (ADRS) which can link other computers running MACS in different modes enabling a distributed simulation of MACS instances running in different modes [39]. The MACS simulation can incorporate winds and convective weather cells, and it supports data collection. CSAOB primarily utilizes the controller modes during experiments. Figure 10 shows a sample MACS configuration with ADRS instances used to communicate between each of the MACS stations. Figure 10 also shows use of the different MACS modes such as simulation manager, pilot, and ATC stations. Other software such as radios, audio, etc., may also be loaded to enhance each workstation (not shown).

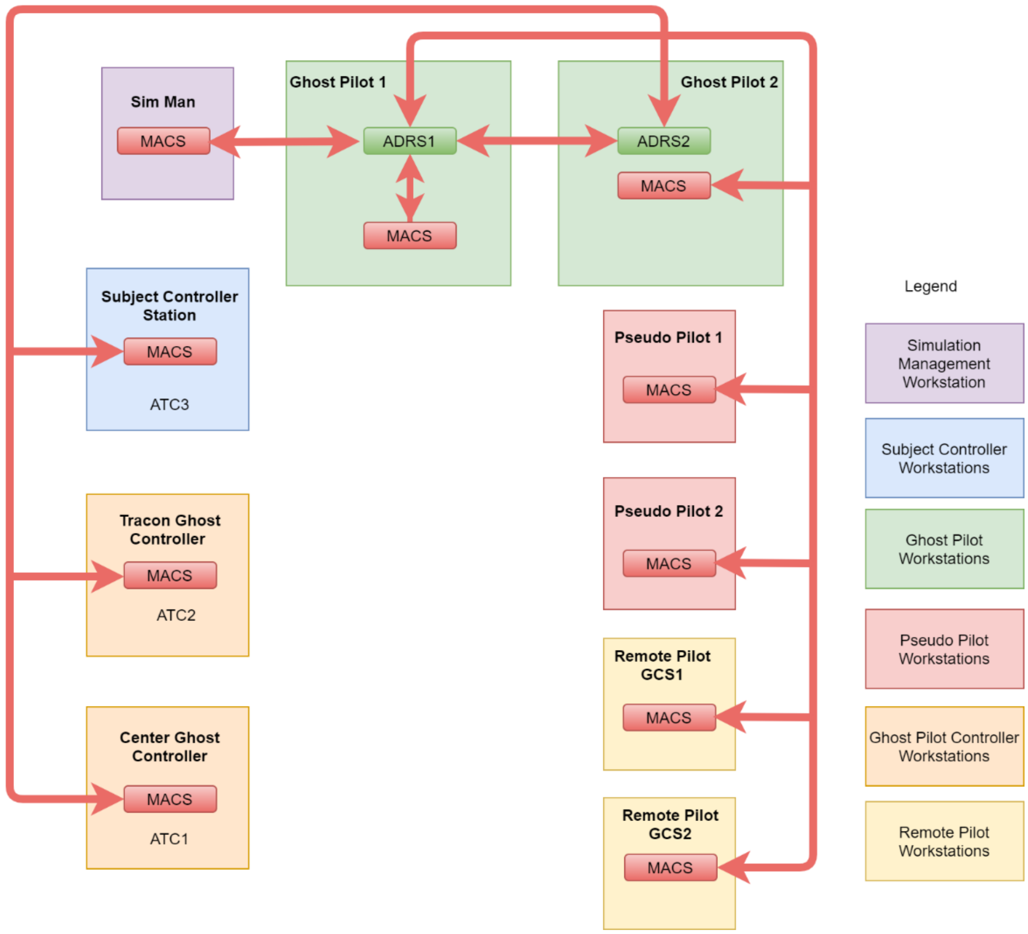

Figure 10. Sample MACS Configuration

CSAOB experiments that have used MACS include, but are not limited to the following (how MACS was used is noted in parentheses):

- Comparing Ground-based and Airborne Function Allocation Concepts for NextGen [17] (Used for ATC Workstations)
- FIM [18] (Used for ATC Workstations)
- Interval Management Alternative Clearances (IMAC) [19] (background traffic and ATC workstations)
- Traffic management Advisories with Terminal Metering [20] (ATC workstations)
- Controller Managed Spacing [20] (ATC workstations)
- Advanced TBO [40] (Traffic Displays Used)
- UAS Well Clear Alerts [41] (Used for traffic and simulation manager)

2.1.7 AOP

As early as 1995, RTCA released concepts for an operational paradigm called free flight [42]. The Autonomous Operations Planner (AOP) was designed and developed as a decision support tool for use by crew on board flights [42]. AOP supports distributed traffic management and was used in several self-separation experiments [9, 15, 17, 22, 23, 29, 37, 43]. The Traffic Aware Planner (TAP) was derived from the AOP's architecture and algorithms to research the concept of the Traffic Aware Strategic Aircrew Requests (TASAR) as an advisory tool to operate within a Class 2 Electronic Flight Bag (EFB) [44]. The TAP/TASAR software was tested onboard Alaska Airlines from July 2018 to April 2019 [45], and its success led it to be selected as one of the winners of the 2019 R&D 100 awards by R&D World Magazine [46].

Efforts utilizing AOP are active: it was used in TBO experiments [15], the AOP code base was extracted from the ASTORs to be made stand-alone, and various features and configurations have been modified to enable its use in experiments with the UAM Flyers. The prior research in decision support using AOP may provide crucial insights to research needed in application of digital flight rules [47]. A prototype display is shown in figure 11.

Figure 11. Sample AOP Display

2.1.8 ICAROUS

ICAROUS was developed to enable safe autonomous UAS operations [48]. ICAROUS utilizes a collection of formally verified core algorithms for path planning, traffic avoidance, geofence handling, and decision making that can interface with an autopilot system [48]. Sense and avoid functionality implemented within ICAROUS is provided by the Detect and Avoid Alerting Logic for Unmanned Systems (DAIDALUS) software library available under NASA's open-source agreement. DAIDALUS serves as a reference implementation of the minimum operational performance standards for UAS detect and avoid as described in RTCA FAA DO-365 [48]. The UAM Flyers have been successfully connected and tested to ensure communication with ICAROUS for future use with the CSAOB UAM Flyers. The ability to send messages from ICAROUS to Ames via TestBed infrastructure has also been tested to ensure ICAROUS can be used at Ames from Langley in distributed simulation.

2.1.8.1 Research Software

Researchers within CSAOB develop software that can interface with the distributed simulation suites. Software developed for research purposes include but are not limited to the Advanced Trajectory Services (ATS) Toolkit for Integrated Ground and Air Research (ATS-TIGAR). The Vertiport Scheduler [39], and the Stratway conflict resolution [49]. The ATS-TIGAR software dynamically generates reroutes in the form of Dynamic Area Navigation (DRNAV) routes. The vertiport scheduler creates schedules for flights to enable strategic conflict avoidance before takeoff. These tools have been used in experiments to test:

- Capacity and throughput of the UAM vertiports given first-come, first-served vertiport scheduling [50]
- Mission planner algorithms for conflict free trajectories for flights [51]

Researchers who would like to test capabilities that would interface with the current simulations can utilize the communication infrastructures available to enable interaction with the current distributed software just like these research tools.

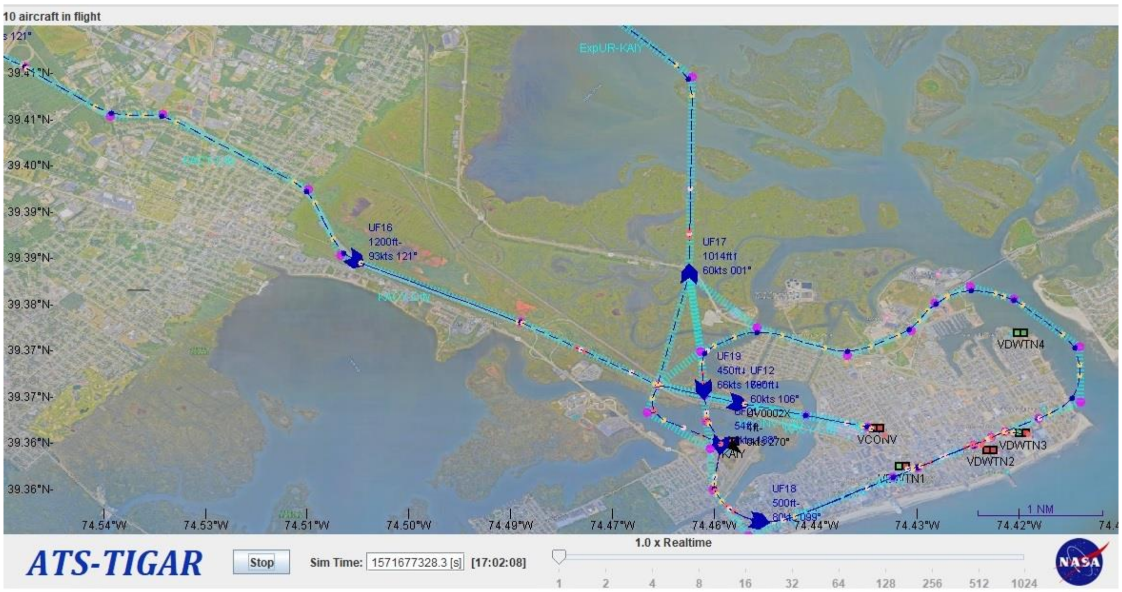

Figure 12. Display from TIGAR

2.1.8.2 Cloud Use

The CSAOB utilizes the cloud to facilitate a stable standard operating system platform and to support standard version release of software to non-developer users. The cloud instances are updated and patched weekly, and the latest software releases of ATOS, ASTOR, Flyer, and MACS are installed for researchers to use as shown in figure 13. Tutorials are available in either written instructions or video format depending upon the tool so that the researcher can learn how to access and use the software. This hands-on access is meant to enable understanding of how the software operates, helps with building requirements, and facilitates a review of changes made by the developers. Formal experiments are not conducted by researchers in the cloud.

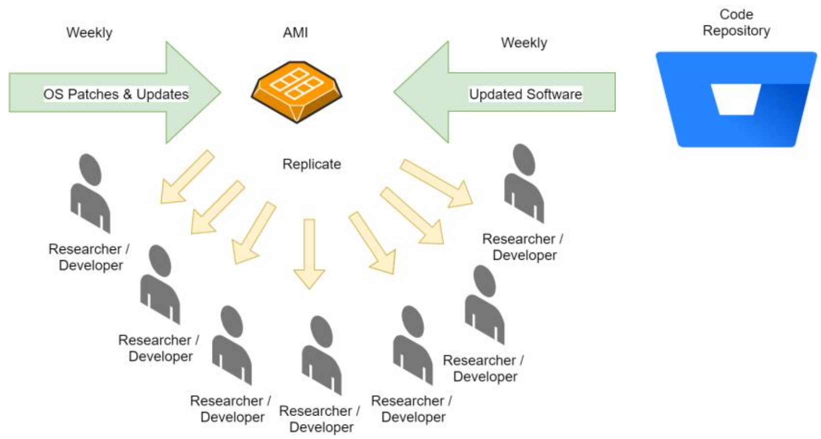

Figure 13. Cloud Instance Maintenance Cycle

2.1.8.3 ATOL

CSAOB experiments are conducted in the Air Traffic Operations Lab (ATOL) by experiment specialists. After special development and testing has been completed by the development team, and researchers have reviewed the final products, the software to be used in an experiment is delivered to the ATOL. The ATOL facilities configure strings of computers for the specific experiment, install the software, run initial tests, and conduct final reviews of data, visual displays, and other aspects of the experiment with the researchers, and then run the experiment according to predetermined schedules. Data is sent to the researchers and also stored long-term should there be a need to review data at a future date. ATOL runs both batch and HITL experiments.

3.0 Concluding Remarks

This paper describes the distributed simulation software supported by CSAOB, which is used to model the NAS and its many different vehicles. This software has been utilized for twenty years to support experiments for research of both controller-centric and distributed traffic management, separation assurance, aircraft piloting procedures, trajectory error estimations, UAS Well Clear Alerts, and many other research concepts. ATOS and associated software have an infrastructure utilizing HLA, DDS, and TestBed components for communication. Many different types of vehicles and air traffic scenarios can be simulated for research. Various tools exist to enable scenario setup and data collection across the computers used in a distributed simulation environment. In addition to using ATOS and its associated software, researchers can create new simulations that can use the existing infrastructure to connect to ATOS and other simulation software to model increasingly complex systems with new components. ATOS software is available for testing and running in the cloud so that users can concentrate on understanding ATOS and ATOS component capabilities and not worry about installation of the software or configuration of a specific release. The ATOL is a specialized simulation production facility designed for configuring, running, and delivering data to researchers. Utilizing the tools described in this report, researchers can conduct thoughtful experiments that can contribute to the evolution of policies and procedures used in the NAS environment, as increasingly diverse types of air vehicles and improvements are introduced.

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References

[1] M. G. Ballin, W. Cotton and P. Kopardekar, "Share the Sky: Concepts and Technologies That Will Shape Future Airspace Use," in *11th AIAA Aviation Technology, Integration, and Operations ATIO) Conference, AIAA*, Virginia Beach, VA, September 20, 2011.

[2] S. Roy and M. Xue, "Management of Heterogeneous Traffic in the Future National Airspace System: Decision-Support Challenges," in *AIAA*, Garden Grove, CA, June 19-21, 2012.

[3] M. C. Underwood and G. M. D., "A Preliminary Evaluation of Supersonic Tranpsort Category Vehicle Operations in the National Airspace System," in *AIAA Aviation*, Dallas, TX, June 22, 2015.

[4] M. Underwood, "Concept of Operations for Integrating Commercial Supersonic Transport Aircraft into the National Airspace System," NASA Technical Publication (NASA/TP-2017-219796, Hampton, VA, December 2017.

[5] Federal Aviation Administration, "Next Gen Implementation Plan 2018-2019," Federal Aviation Administration, Washington, DC, 2018.

[6] Federal Aviation Administration, "Next Gen Concept of Operations v1.0 Urban Air Mobility (UAM)," Federal Aviation Administration, Washington, DC, June 26, 2020.

[7] D. J. Wing, E. T. Chancey, M. S. Politowicz and M. G. Ballin, "Achieving Resilient In-Flight PErformance for Advanced Air Mobility through Simplified Vehicle Operations," in *AIAA Aviation 2020*, Reno NV, April 2020.

[8] ATM-X Project, NASA, *ATM-X Project Fact Sheet*, NASA, 2021.

[9] D. Finkelstein, L. Teh-Kuang, R. A. Vivona, J. Bunnell, D. Mielke and W. Chung, "Airspace and Traffic Operations Simulation for Distributed ATM Research and Development," in *AIAA Modeling and Simulation Technologies Conference and Exhibit*, San Francisco, CA, August 15-18, 2005.

[10] M. E. Peters and M. G. S. J. S. Ballin, "A Multi-Operator Simulation for Investigation of Distributed Air Traffic management Concepts," in *AIAA Guidance, Navigation and Control Conference*, Monterey, CA, January 1, 2002.

[11] R. M. Fujimoto, "Time Management in the High Level Architecture," *The Society for Modeling & Simulation International, Sage Journals*, vol. 71, no. 6, pp. 388-400, 1998.

[12] C. F. Lai, "Air Traffic Management TestBed Simulation Architect: User's Guide," NASA Technical Memorandum (NASA/TM-2019-220196, Ames Research Center, Moffett Field, CA, April 2019.

[13] C. F. Lai, "Air Traffic Management TestBed Data Exchange Model," NASA Technical Memorandum (NASA/TM-20205001252), Ames Research Center, Moffett Field, CA, May 2020.

[14] R. M. Smith, "A Description of the Cockpit Motion Facility and the Research Flight Deck Simulator," in *AIAA Modeling and Simulation Technologies Conference*, Denver, CO, August 14-17, 2000.

[15] T. L. Barney, K. M. Ballard, B. K. Buck, M. C. Underwood and R. C. Chartrand, "Simulation of a Representative Future Trajectory-Based Operations Environment," NASA Technical Memorandum (NASA/TM-20205006885), Langley Research Center, Hampton, VA, November 2020.

[16] R. Barhydt, M. T. Palmer, W. W. Chung and G. W. Loveness, "ADS-B Within a Multi-Aircraft Simulation for Distributed Air-Ground Traffic Management," in *23rd Digital Avionics Systems Conference, IEEE/AIAA*, Salt Lake City UT, September 13-15, 2010.

[17] D. J. Wing, T. Prevot, J. L. Murdoch, C. D. Cabrall, J. R. Homola, L. H. Martin, J. S. Mercer, S. T. Hoadley, S. R. Wilson, C. E. Hubbs, J. P. Chamberlain, R. C. Chartrand, M. C. Consiglio and P. Michael, "Comparison of Ground-Based and Airborne Function Allocation Concepts for NextGen Using Human-In-The-Loop Simulations," in *10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, Fort Worth, TX, September 13-15, 2010.

[18] B. T. Baxley, J. L. Murdoch, K. A. Swieringa, B. B. E. E., C. William, C. E. Hubbs, S. Richard and T. S. Abbott, "Experiment Description and Results for Arrival Operations Using Interval management with Spacing to Parallel Dependent Runways," NASA Tehnical Publication (NASA/TP-2013-217998, Langley Research Center, Hampton, VA, January 2013.

[19] B. T. Baxley, M. T. Palmer and K. A. Swieringa, "Cockpit Interfaces, Displays, and Alerting Messages for the Interval Management Alternative Clearances (IMAC) Experiment," NASA Technical Memorandum (NASA/TM-2015-218775), Langley Research Center, Hampton, VA, July 2015.

[20] B. T. Baxley, W. C. Johnson, J. Scardina and R. F. Shay, "Air Traffic management Technology Demonstration-1 Concept of Operations (ATD-1 ConOps), Version 3.0," NASA Technical Memorandum (NASA/TM-2016-219213, Langley Research Center, Hampton, VA, June 2016.

[21] N. M. Guerreiro and M. C. Underwood, "Understanding Extended Projected Profile (EPP) Trajectory Error Using a Medium-Fidelity Aircraft Simulation," in *AIAA Aviation 2018 and Aeronautics Forum and Exposition*, Atlanta, GA, June 25-29 2018.

[22] M. Consiglio, S. Hoadley and B. D. Allen, "Estimation of Separation Buffers for Wind-Prediction Error in an Airborne Separation Assistance System," in *Eighth USA/Europe Air Traffic management Research and Development Seminar (ATM2009)*, Napa, CA, 2009.

[23] D. J. Wing, J. L. Murdoch, J. P. Chamberlain, M. C. Consiglio, S. T. Hoadley, C. E. Hubbs and M. T. Palmer, "Function Allocation with Airborne Self-Separation Evaluated in a Piloted Simulation," in *27th International Congress of the Aeronautical Sciences*, Nice, France, 2010.

[24] J. L. Murdoch, F. J. L. Bussink, J. P. Chamberlain, R. C. Chartrand, M. T. Palmer and S. O. Palmer, "Enhanced Oceanic Operations Human-In-The-Loop In-Trail Procedure Validation Simulation Study," NASA Technical Publication (NASA/TP-2008-215313, Langley Research Center, Hampton, VA, June 2008.

[25] N. M. Guerreiro, D. R. Jones, B. E. Barmore, R. W. Butler, G. Hagen, M. J. M., N. N. Amad, L. J. Rogers and m. C. Underwood, "An Advanced Trajectory-Based Operations Prototype Tool and Focus Group Evaluation," NASA Technical Memorandum (NASA/TM-2017-219670, Langley Research Center, Hampton, VA, September 2017.

[26] Langley Enhanced IT Services (LITES) Contract, *"Airspace and Traffic Operations Simulation (ATOS) System Software Project: ATOS System Capabilities Document, Version 5.0"*, Hamton, VA: LITES Contract (NASA), October 31, 2015.

[27] M. T. Palmer and M. G. Ballin, "A High-Performance Simulated On-Board Avionics Architecture to Supprt Traffic Operations Research," in *AIAA Modeling and Simulation Technologies Conference*, Austin, TX, August 2003.

[28] D.-J. Liu and W. W. Chung, "ASTOR: An Avionics Concept Test Bed in a Distributed Networked Synthetic Airspace Environment," in *AIAA Modeling and Simulation Technologies Conference and Exhibit*, Providence, RI, August, 2004.

[29] R. Barhydt, P. M. T and T. M. Eischeid, "Development and Evaluation of an Airborne Separation Assurance System for Autonomouse Aircraft Operations," in *24th International Congress of the Aeronautical Sciences*, Yokohama, 2004.

[30] P. Glaab and M. Madden, "Benefits of a Unified LaSRS__ SImulation for NAS-Wide and High-Fidelity Modeling," in *33rd Digital Avionics Systems Conference*, Colorado, CO, October 2014.

[31] B. K. Buck, T. L. Barney, M. C. Underwood and R. C. Chartrand, "design and Implementation of a Scenario Development Process for a 2040 Trajectory-Based Operations Simulation," NASA Technical Memorandum (NASA/TM-20205006526), Langley Research Center, Hampton, VA, October 2020.

[32] K. H. Goodrich and C. R. Theodore, "Description of the NASA Urban Air Mobility maturity Level (UML) Scale," AIAA SciTech 2021, Virtual, 2021.

[33] D. Thipphavong, R. Apaza, B. Barmore, V. Battiste, B. Burian, Q. Dao, M. Feary, S. Go, K. Goodrich, J. Homola, H. Idris, P. Kopardekar, J. Lachter, N. Neogi, H. Ng and R. Oseguera-Lohr, *Urban Air Mobility Airspace Integration Concepts and Considerations,* NASA.

[34] N. J. O'Connor, K. D. Kennedy, M. C. Underwood, A. R. Harrivel, C. L. Stephens, J. R. Comstock and m. C. Last, *Development of a simulation platform to evaluate integration of UAM traffic into the NAS,* NASA.

[35] C. Silva, W. Johnson, K. R. Antcliff and M. D. Patterson, "VTOL Urban Air Mobility COncept Vehicles for Technology Development," in *AIAA Aviation Forum*, Atlanta, GA, June 25-29, 2018.

[36] F. J. Bussink, N. A. Doble, B. E. Barmore and S. Singer, "A Fast-Time Simulation Environment for Airborne Merging and Spacing Research," in *23rd Digital Avionics Systems Conference*, Salt Lake City UT, January 1, 2005.

[37] D. J. Wing, T. Prevot, J. L. Murdoch, C. D. Cabrall, J. R. Homola, L. H. Martin, J. S. Mercer, H. T. Hoadley, S. R. Wilson, C. E. Hubbs, J. P. Chamberlain, R. C. Chartrand and M. C. P. M. Consiglio, "Comparison of Airborne and Ground-Based Function Allocation Concepts for Next Gen Using Human-In-The-Loop Simulations," in *10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, Fort Worth, TX, February 7, 2010.

[38] R. Chartrand and K. Ballard, "Benefits of using Pairwise Trajecotyr Management in the Central East Pacific," in *17th AIAA Aviation Technology, Integration, and Operations Conference*, Denver, CO, June 5, 2017.

[39] NASA Ames, *Multi Aircraft Control System (MACS) User Guide,* Mountain View, CA: NASA Ames, March 5, 2012.

[40] N. G. Guerreiro, D. R. Jones, B. E. Barmore, R. W. Butler, G. E. Hagen, J. M. Maddalon and N. N. Ahmad, "Prototype Tool and Focus Group Evaluation for an Advanced Trajectory-Based Operations Concept," in *AIAA Aviation 2017*, Denver CO, June 26, 2017.

[41] R. D. Roper, A. C. Trujillo, E. T. Lewis and S. KC, "Human-in-the-Loop Flight Simulation Experiment on Unmaned Aircraft Terminal Operations," in *AIAA SciTech Forum*, Orlando FL, April 29, 2020.

[42] M. G. Ballin, V. Sharma, R. A. Vivona, E. J. Johnson and R. Ermin, "A Flight Deck Decision Support Tool for Autonomous Airborne Operations," in *AIAA Guidance, Navigation and Control Conference*, Monterey, CA, January 1, 2002.

[43] D. A. Karr, R. A. Vivona, D. A. Roscoe, S. M. DePascale and D. J. Wing, "Autonomous Operations Planner: A Flexible Platform for Research in Flight-Deck Support for Airborne Self-Separation," in *12th AIAA Aviation Technology, Integration and Operations (ATIO) Conference*, Indianapolis, IN, September 17, 2012.

[44] S. E. Woods, R. A. Vivona, D. A. Roscoe, B. C. LeFebvre, D. J. Wing and B. G. Ballin, "A Cockpit-based Application for Traffic Aware Trajectory Optimization," in *AIAA Guidance, Navigation, and Control Conference*, Boston, MA, August 19, 2013.

[45] D. J. Wing, K. A. Burke, B. K. J. Henderson and J. Woodward, "Initial TASAR Operations Onboard Alaska Airlines," in *AIAA Aviation* , Dallas, TX, June 17, 2019.

[46] D. Meade, "NASA Langley Technology Selected as R&D 100 Winner," NASA, 04 11 2019. [Online]. Available: https://www.nasa.gov/feature/langley/nasa-langley-technology-selected-as-rd-100-winner. [Accessed 12 07 2021].

[47] D. J. Wing and I. M. Levitt, "New Flight Rules to Enable the Era of Aerial Mobility in the National Airspace System," in *NASA Technical Memorandum (NASA/TM-20205008308)*, Langley Research Center, Hampton, VA, November 1, 2020.

[48] M. Consiglio, B. Duffy, S. Balachandran, G. Louis and C. Munoz, "Sense and Avoid Characterization of the Independent Configurable Architecture for Reliable Operations of Unmanned Systems," in *Thirteenth USA/Europe Air Traffic Management Research and Development Seminar* , Vienna Austria, June 17, 2019.

[49] G. Hagen, R. Butler and J. Maddalon, "Stratway: A Modular Approach to Strategic Conflict Resolution," in *11th AIAA Aviation Tehcnology, Integration, and Operations (ATIO) Conference*, Virginia Beach, VA, September 20, 2011.

[50] N. M. Guerreiro, G. E. Hagen, J. M. Maddalon and R. W. Butler, "Capacity and Throughput of Urban Air Mobility Vertiports with a First-Come, First-Served Vertiport Scheduling Algorithm," in *AIAA Aviation 2020 Forum*, Virtual Event, June 15-19, 2020.

[51] N. M. Guerreiro, R. W. Butler, J. M. Maddalon and G. E. Hagen, "Mission Planner Algorithm for Urban Air Mobility - Initial Performance Characterization," in *AIAA Aviation 2019*, Dallas, TX, June 17-21, 2019.