A STANDARDS-BASED APPROACH TO DISTRIBUTED AIR TRAFFIC MANAGEMENT SIMULATION

Patricia A. Liguori, The MITRE Corporation, Egg Harbor Township, New Jersey, 08234

Dr. Glenn F. Roberts, The MITRE Corporation, McLean, Virginia, 22102

Abstract

Organizations across the aviation domain are currently defining and developing a standards-based environment for sharing simulation capabilities and conducting joint experiments to meet the challenges that lie ahead for global aviation.

This paper discusses an aviation community research project to define an open, standards-based set of object models, protocols, and software designed to let simulations connect via the public Internet for research and development in Air Traffic Management (ATM). Known as AviationSimNet, this environment builds on existing aviation and distributed simulation standards to simulate ATC voice and data communications. It enables distributed evaluation of concepts at reduced time and cost and lowered risks.

This paper begins with some historical context on the evolution of distributed simulation and then describes the AviationSimNet research results, architecture, performance characteristics, and applications. Two specific applications of the technology are discussed: a multi-organizational demonstration of airborne precision spacing and a multi-organizational experiment for defining future traffic flow management and en route interoperability requirements.

Introduction

The world's Air Navigation Service Providers (ANSPs) face a global challenge to safely and efficiently increase the capacity of the air transportation system to meet expected growth, forecasted to be two to three times current levels by the year 2025[1]. To meet this challenge agencies such as the United States (U.S.) Joint Planning and Development Office (JPDO) [2], the U.S. Federal Aviation Administration (FAA) [3], the Advisory Council for Aeronautics Research in Europe (ACARE) [4, 5], and Eurocontrol [6] have been actively developing visions of future air transportation needs and operations along with the associated research required to determine their feasibility and how to incrementally make these visions real.

Laboratory simulation plays a critical role in analyzing, validating and socializing these new and complex concepts. Today, laboratories at the FAA, the U.S. National Aeronautics and Space Administration (NASA), The MITRE Corporation's Center for Advanced Aviation System Development (CAASD) and various industry, research, and academic institutions are being used to analyze and depict elements of the future global air transportation system [7, 8, 9]. The Aviation community uses these simulations to explore how people and systems might work together to carry out new functions, to test operational feasibility, to gain an understanding of the robustness of concepts, and to obtain stakeholder acceptance.

At the same time as these simulation tools have been maturing, the world has seen a revolutionary emergence of global connectivity brought on by the omnipresence of the global Internet. These two concurrent phenomena: global connectivity, and widespread application of simulation to air traffic management, present a unique opportunity to bring together knowledge and tools on a global scale to address the substantial challenges ahead for JPDO, ACARE, and others as they define the future of world wide aviation.

Out of this opportunity was born the AviationSimNet research effort. Begun as MITRE-sponsored research, the project defined a set of standards and a specification for conducting distributed Air Traffic Management (ATM) simulations via the public Internet. The research elements of this work included definition of the object model, the protocols for real-time simulation monitoring and control, distributed real-time voice and data communication, and network quality-of-service assurance and performance analysis. The objective was to demonstrate end-to-end performance through a set of real-world exercises.

A Brief History of Distributed Simulation

Military Standards Paved the Way

Early work in distributed human-in-the-loop simulation was pioneered by the U.S. Department of Defense (DoD). In the 1980s, the SIMulator NETwork (SIMNET) program proved that local area network (and later wide area network) technology could be used to connect significant numbers of simulators, allowing operators to take part in joint simulations through a common synthetic environment [10]. SIMNET demonstrated the viability of using distributed simulations to create virtual worlds for training soldiers in military engagements [11].

In 1989, a semiannual workshop series was begun to expand on the SIMNET concept and explore standards to support the interoperability of defense simulations. These workshops led to the development of the Distributed Interactive Simulation (DIS) standard, first published in June 1990 [10]. By 1995, the DIS Communications Services standard and the second version of the Protocol Data Units (PDU) standard (the format and semantics for the exchange of simulation data between simulations) were formally adopted as an Institute of Electrical and Electronics Engineers (IEEE) standard.

In 1995, the U.S. Defense Modeling and Simulation Office (DMSO) initiated a new development to establish standards for modeling & simulation, called the High Level Architecture (HLA) [12]. HLA was created to address several shortcomings of the DIS standards, to enable the interoperability of simulators with widely different architectures, and to further promote the reuse of existing simulation assets [13]. This standard was designed to support a broad range of modeling and simulation activities beyond training including research and development, acquisition, test and evaluation, concept and demonstration.

The HLA standard promotes reuse of simulations and their components. It specifies the general structure of the interfaces between simulations without making specific demands on the implementation of each simulation. The HLA defines the rules, interface specification and object model template to support reusability and interoperability among the simulation components known as federates. The object model is developed in a cooperative, consensus-based forum of developers. The Runtime Infrastructure (RTI) software supports and synchronizes the interactions among different federates conforming to the HLA standard [12].

HLA is being used today in the military and other domains as the standard for distributed simulation.

Distributed Simulations in the United States

In 1988, the U.S. Congress recognized the role of modeling and simulation in the research development process as part of the Aviation Safety Research Act of 1988. It called for the FAA to undertake *"a research program to develop dynamic simulation models of the air traffic control system… which will provide analytical technology for predicting airport and air traffic control safety and capacity problems, for evaluating planned research projects…."* This led to a set of FAA investments in operations research and modeling & simulation, including the creation of the National Simulation Capability (NSC) program [14].

There were two thrusts to this early work, one based at the FAA's William J. Hughes Technical Center (WJHTC), and one at MITRE CAASD. WJHTC had capabilities to simulate real-world, operational equipment and CAASD had a robust set of simulations of future capabilities. The NSC was intended to be a place where researchers could go and test their ideas using a repository of simulation capabilities. It would not exist in isolation and would not duplicate capabilities at other organizations, but rather it would provide two-way links to labs at other organizations for simulating the National Airspace System (NAS) [15].

At the 39th annual Air Traffic Control Association conference in Arlington Virginia, held in 1994, the NSC program successfully demonstrated its capability as a multi-laboratory interoperable environment. However, the vision of a broader set of interoperable capabilities remained largely unachieved at that time.

The NSC was a forward looking idea, but it was before its time in a number of ways:

- Simulation capabilities within organizations were immature or non-existent.
- The Internet had not yet emerged as a global connectivity medium, and as a result

simulations relied on expensive point-to-point high speed connections.

- The protocols used were based on the DIS standard, which was relatively inflexible and heavily rooted in its DoD origins.
- The computing power of the day was expensive and slow by today's standards, limiting the sophistication and complexity of real-time simulation.

In the late 1990's, the Joint FAA, Army, NASA Federation (JFAN) project was created to evaluate HLA as a technology for use in networking large numbers of simulations. That work integrated a number of cockpit simulation facilities using a mixture of local- and wide-area networks including the Internet. It demonstrated the basic feasibility of an HLA approach but had some technical difficulties that proved difficult to resolve. For example, federates stopped receiving updates when using cross-country interconnections. A lesson learned from this project was that a federation control capability should exist to improve the organization of the federation execution [16].

More recent years have seen a growing interest in performing distributed simulation. In September 1999, the FAA, NASA, and the Volpe National Transportation Systems Center (TSC) conducted an integrated, high fidelity, real-time, human-in-the-loop simulation to examine the effect of shared separation authority on flight operations when both pilots and controllers had enhanced traffic and conflict alerting systems. Denoted the Air-Ground Integration Experiment (AGIE), it was conducted over a four week period using simulation facilities located at the FAA William J. Hughes Technical Center (WJHTC) on the east coast and NASA Ames Research Center on the west coast, and an infrastructure built and designed specifically for the experiment. Participating laboratories were linked across the country via a dedicated high speed circuit (fractional T1 line) built specifically to support the AGIE experiment [17].

Distributed Simulations in Europe

In the mid to late 1990's the Eurocontrol Simulation Capability And Platform for Experimentation (ESCAPE) capability was being developed and deployed to support real-time simulations at the Eurocontrol Experimental Center (EEC). Eventually it was split into two separate platforms to provide: (1) a platform aimed at providing a simulator specifically for research and development (R&D) and pre-operational validation (live trial) and (2) a platform that provided a stable and reliable simulator for real-time simulation and training activities. ESCAPE was regularly used for pre-operational trials (validation exercises for testing new tools and concepts in the ATC domain) [18].

In the late 1990's, a standard was launched to provide a way to join multiple simulation capabilities into a single simulation environment. This standard, the ATM Validation Environment for Use towards European Air Traffic Management System (AVENUE), was defined by stakeholder consensus and contained a set of interfaces and an ATC data dictionary. This project was driven by a need to facilitate the definition of next generation air traffic management systems and to alleviate the insufficient interoperability of system components [22].

The first instance of an AVENUE-compliant system was based at the EEC and was built with existing ATC components provided by European ATC players. The collaboration between European partners to produce a common, flexible, configurable platform enables essential validation activities to be readily set up and the results from different validation exercises to be directly compared, hence greatly reducing the time required to gain acceptance for a new tool on a European rather an individual civil aviation authority basis. ESCAPE eventually became AVENUE compliant and was renamed AVENUE-Compliant ESCAPE (ACE).

A recent use of ACE was by AENA (Spain). Two two-week en-route simulations were conducted in Seville (in June 2005 and January/February 2006) concerning the evaluation of Dynamic Re-sectorization and/or Multi Sector Planner concepts (with/without other supporting ATM enablers such as SYSCO, Data Link, Medium Term Conflict Detection) [19].

The Emergence of AviationSimNet

To remedy some of the problems seen in past efforts, such as single use simulation environments and point to point connections, in 2003 MITRE began as a research project to investigate the possibility of developing an open, standards-based set of object models and protocols coupled with software designed to let simulations connect via the public Internet for aviation research and development [20]. This work was funded through MITRE's internal research and development program and became known as AviationSimNet.

From the start, this work was designed to follow an open, collaborative development process. The project established a network of organizations across the aviation community to define and implement these standards, and to facilitate a world-wide collaboration capability. The intent was to establish a specification for participants to adhere to. This would lead to a set of AviationSimNet-compliant simulation capabilities that could be readily connected in order to run complex, networked aviation simulations, as well as smaller individual or pairwise simulations. This would enable a new range of simulation capabilities that otherwise would not be feasible within the confines of any single research laboratory.

Built largely on top of existing standards for aviation and distributed simulation, AviationSimNet is a specification for conducting distributed ATM simulations among organizations in aviation. It is an environment that enables ATM simulation labs anywhere on the global Internet to be joined into an integrated simulation environment. This environment for sharing voice and data communications bridges laboratories across industry, academia, government and research organizations.

To date, organizations participating in defining and applying AviationSimNet include:

- The Air Line Pilots Association (ALPA)
- The Boeing Corporation
- The Center for Applied ATM Research (CAAR) at Embry-Riddle Aeronautical University (ERAU)
- Crown Consulting
- Eurocontrol
- The Federal Aviation Administration
- Lockheed Martin Transportation and Security Solutions
- MITRE's Center for Advanced Aviation System Development
- The NASA Ames and Langley Research Centers
- The National Center for Atmospheric Research (NCAR)
- The National Oceanic & Atmospheric Association (NOAA)
- Raytheon
- UPS

AviationSimNet

This section of the paper provides details on AviationSimNet including (1) the AviationSimNet architecture, (2) the underlying HLA-based data communications network and the RTI used to facilitate data communications, (3) the AviationSimNet SimCenter for simulation management and monitoring, (4) the Federation Object Model (FOM), and (5) performance in the AviationSimNet environment.

AviationSimNet Architecture

Figure 1 depicts the AviationSimNet architecture. It consists of a HLA-based distributed simulation environment enhanced with three additional elements:

- A simulation coordination component known as the AviationSimNet SimCenter, encompassing the simulation management and monitoring functions
- An aviation-aware FOM
- A distributed voice communications capability

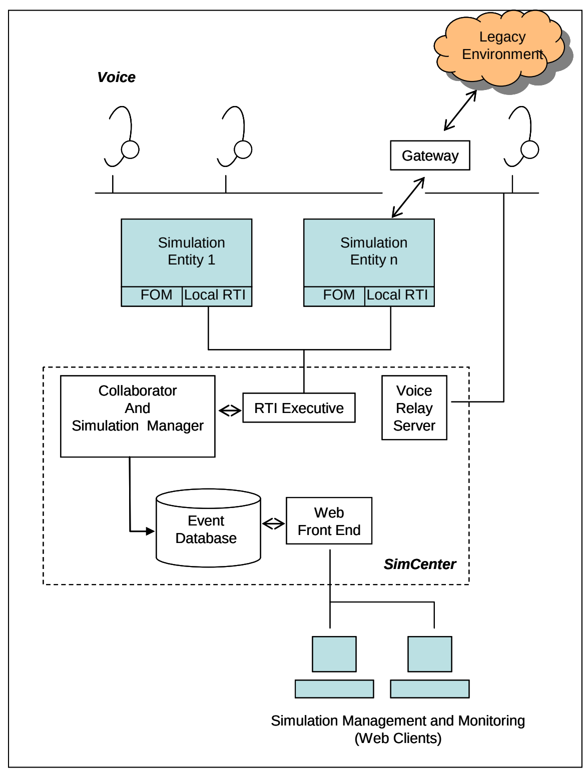

Figure 1. AviationSimNet Architecture

The Data Communications Framework

The underlying data communications framework is based on the HLA standard. The framework makes no assumptions about how the connected simulation entities process data internally.

To accommodate interconnection of existing, often non HLA-based environments, simulation entities can be interfaced to a gateway to link in legacy simulation capabilities to the broader AviationSimNet environment. Gateway federates perform the necessary real-time translation of data and simulation protocols between the HLA federation and another, possibly proprietary, set of simulation protocols embedded in the legacy environment [21]. The core HLA functionality is implemented through the RTI, consisting of a central RTI Executive and a local RTI component embedded in each of the simulation entities. The RTI executive is a commercial software component that implements the core HLA functionality.

There are a number of commercial RTI offerings, however, for successful Internet operation, the RTI must be capable of operating across multiple Internet subnetworks and through boundary protection systems. The AviationSimNet community has successfully employed the RTI from MÄK Technologies to meet these requirements [25].

The architecture implies that any participant's network has to be capable of establishing a TCP/IP socket connection to a computer outside its protected laboratory network, thus, TCP/IP connectivity is visible to a specific host and port on the public internet. This implies a firewall policy that does not allow "inbound" socket connections, or any socket connections on hosts or ports that may differ from federation to federation. This policy is secure provided that the participant trusts the host to which it is connecting, and the host server trusts each of the participants connecting to the RTI.

The AviationSimNet SimCenter

AviationSimNet relies on a server, called the SimCenter, to aid in the distributed simulation. Only a single organization participating in a simulation is required to host a SimCenter, which contains the following elements:

- An RTI executive
- A voice relay server
- The simulation manager
- The collaborator server

As previously mentioned, the RTI executive is a commercial software component that implements the core HLA functionality.

The voice relay server provides a mechanism for distributing voice communications among the simulation participants. Voice communication is based on the 1278.1a DIS standard. The architecture allows for mixed use of commercial and custom-built solutions. MITRE's implementation has successfully used the SMx Digital Audio System from SimPhonics [23], however any 1278.1a-compliant component will work.

Commercial off-the-shelf systems have the advantage of allowing for integration with other audio networks and tools such as voice-over-IP and standard telephone networks. Simulation systems from Advanced Simulation Technology, Inc. [13] and real hardware such as SINCGARS [24] radios can also be interfaced to the voice environment. Most off-the-shelf voice components are designed for use on a local area network. The AviationSimNet voice relay server takes care of wide-area re-transmission of packets to remote participants, thus eliminating this restriction.

The simulation manager component orchestrates distributed management of the simulation entities, including start-up, pause, shutdown and runtime health monitoring. Figure 2 shows the underlying state machine.

The start-up process allows for a two-phase initiation. During the first phase, simulation entities initiate their internal state and prepare for communication with the rest of the federation. During the second phase, simulation entities can exchange necessary data in preparation for start-up. Once all entities have passed through these two phases, the simulation is ready to begin.

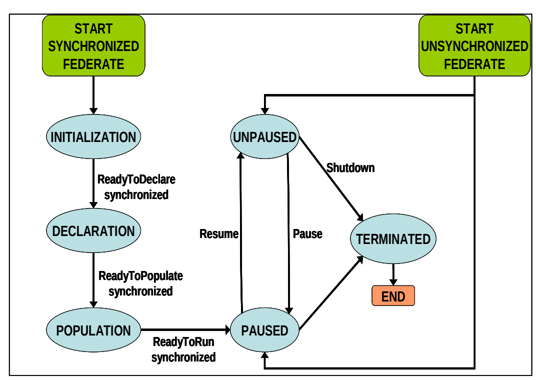

Figure 2. State Machine

The AviationSimNet specification details the simulation procedures to be used at runtime, but since the participants are widely distributed, additional coordination among the human operators is necessary. This helps to ensure that proper procedures are followed, and that the participants are equally aware of each others' facility status before, during, and after a simulation exercise. The AviationSimNet collaborator is intended to satisfy this need.

The collaborator provides for a web-based front end for interaction with the simulation manager and monitoring of simulation status. The collaborator monitors all events in the simulation and records them in a database. A service-oriented architecture (SOA) back end connects this database to a web-based host to respond to web client queries. By using web services, the collaborator remains lightweight, and the users are relieved of issues related to vendor licensing, software installations, patches, or version-matching.

This architecture makes for an open, extensible user interface. Using this framework, MITRE has developed a prototype tool that includes a 2-dimensional plan view display of current aircraft location, listing of joined participants, listing of HLA-level federates, and simulation-control interface (Figure 3).

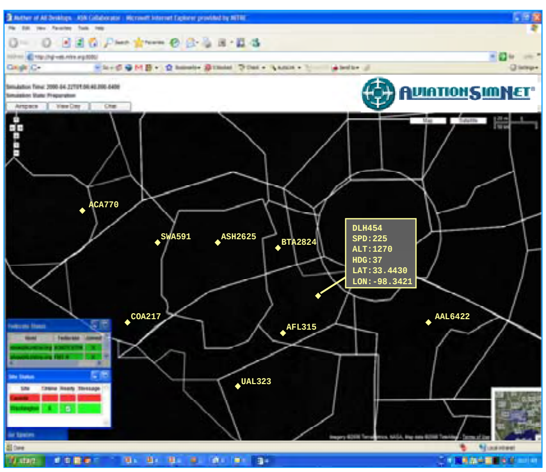

Figure 3. Collaborator Interface

Additional planned features include the ability to tune in to voice channels to hear streamed controller/pilot dialogue, the ability to inject test objects into the simulation, and an instant messaging capability.

The AviationSimNet Federation Object Model (FOM)

While the HLA, RTI and SimCenter components orchestrate the simulation execution, the FOM defines the underlying aviation domain objects in the federation. The FOM effectively defines the domain-specific information exchange that can occur among participating simulation entities. The number of objects and their associated object values will grow as the FOM matures.

The objects and interactions supported by the current FOM were identified by the AviationSimNet Standards Working Group. The role of this working group is to define the requirements and standards for AviationSimNet including requirements to access the environment, federation state, timing and synchronization [25] among others. This working group is also responsible for defining the object model, and published Version 2.0 of the FOM in August 2006 [26].

Version 2.0 of the FOM is largely focused on aircraft state data and intent information. The FOM is being extended to support a flight object as well as weather data. Figure 4 depicts the classes and interactions in the upcoming version of the FOM as well as those in version 2.0. The interaction Flight Specific Reroute is being added to support the organizations looking into automation tools to provide communications between traffic flow managers and ultimately the ATC controllers. And, Rapid Update Cycle (RUC) [27], which is a data structure of wind, temperature and pressure observations, is being added as many of the organizations involved in AviationSimNet have simulators that need and understand RUC.

Classes and Interactions	*Description*
AircraftState	*The truth representation of the aircraft in the simulation*
Flight Specific Reroute	*This interaction contains aircraft specific reroute information and is currently limited to lateral maneuvers.*
Notification of Rapid Update Cycle (RUC) file	*Link to updated short-range weather forecast*

Figure 4. Sample of FOM

Performance in the AviationSimNet Environment

One of the key issues in operating a distributed simulation via the Internet is performance. The performance specification is experiment-dependent, and system and network performance characteristics should be carefully analyzed to ensure that sufficient resources will be available for a successful experiment.

Several factors can have an impact on simulation performance when using AviationSimNet over the Internet, including the Central Processing Unit (CPU) speed and loading of the participating computer systems, the available network bandwidth, and the number of simulation objects being modeled and shared. The varying impact of these factors makes it difficult to accurately predict the peak capability of any particular distributed simulation configuration without taking direct measurements.

As a means of bounding the problem, however, the AviationSimNet research team has analyzed nominal performance expectations based upon connection specifications and some general assumptions.

The greatest limiting factor for experiments using AviationSimNet over the Internet is likely to be bandwidth. Insufficient bandwidth can impact the operation of the distributed simulation over the Internet.

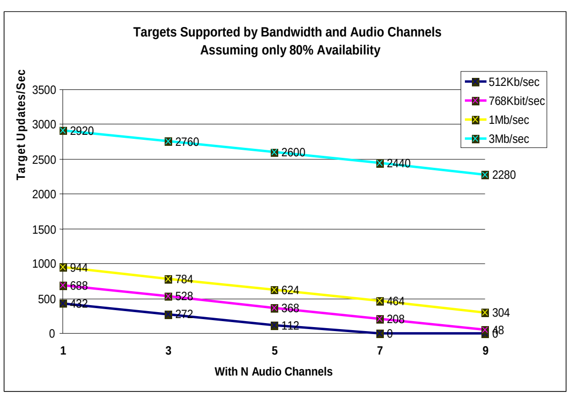

Figure 5. Theoretical Limits for Bandwidth

The best measure of performance is the number of simulation objects that can successfully be supported during an experiment, such as the number of aircraft targets propagated and voice channels in use. Figure 5 shows computed limits for a given bandwidth and number of voice channels. These results are based on the following assumptions:

- No more than 80% of the maximum bandwidth is available.
- Target packet size is estimated at around 100 bytes (800 bits).
- Targets are updated once per second (0.8 kbits/sec per target).
- Each voice channel uses about 64K bits per second.

For example, a site with a T1 (rated at around 1.5Mbps) connection to the Internet that is shared by others at the site, could comfortably expect to support an experiment with approximately 700 active targets and three radio channels simultaneously in use [28].

Applications of AviationSimNet

Demonstration of Airborne Precision Spacing

The first multi-organizational application of AviationSimNet was performed in 2005 in an exercise between MITRE CAASD and NASA's Langley Research Center. The focus of the demonstration was the Airborne Precision Spacing (APS) concept [29, 30]. APS is an Automatic Dependent Surveillance-Broadcast (ADS-B) enabled procedure in which the flight crew manages their speed in order to control their aircraft's spacing relative to another aircraft. The goal is to increase runway throughput by precisely spacing aircraft to the runway threshold at the ATC-specified interval.

AviationSimNet allowed the organizations to bring the necessary simulation capabilities at each site together into a single environment. MITRE provided the simulated ATC ground system via CAASD's integrated ATM laboratory. NASA provided the flight simulators via their Aircraft Simulation for Traffic Operations Research (ASTOR) [33] capabilities and their high-fidelity flight simulators that incorporate the algorithms and tools defined in the concept. Only together could these two organizations demonstrate APS from a high-fidelity, end-to-end perspective.

Demonstration of Execution of Flow Strategies

A second application of AviationSimNet was a demonstration of the execution of flow strategies.

Under this concept, reroutes from Traffic Flow Management (TFM) are automatically sent to the appropriate En Route automation. Today, such reroutes are handled via voice communication. The automatic transmission of reroutes is expected to significantly reduce the workload of traffic managers and controllers, and to reduce potential transmission errors. In addition, it will allow for better use of automation and decision support tools in each of these systems.

This multi-organizational demonstration, illustrated in Figure 6, involved laboratories at MITRE CAASD and Lockheed Martin Corporation's Transportation and Security Solutions (LMTSS) business unit. The MITRE CAASD Collaborative Routing Coordination Tool (CRCT) was used to implement the TFM functionality. The LMTSS implementation of the User Request Evaluation Tool (URET) was used to implement the en route functionality. During the experiment, data was exchanged via AviationSimNet. Airborne flights were rerouted by CRCT and the reroutes were sent via AviationSimNet to URET via Lockheed's System-Wide Information Management (SWIM) prototype infrastructure. After receiving the reroutes, URET converted them to amendments and displayed the new routes. The SWIM infrastructure was also able to distribute the updated flight object to any subscribers on the network.

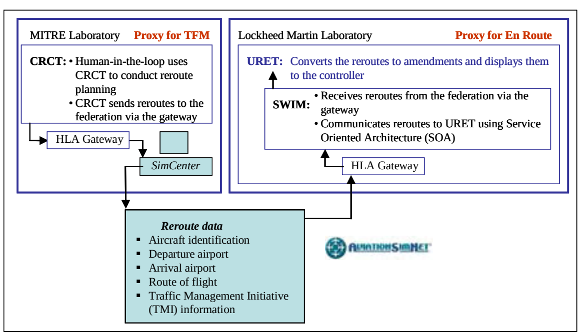

Figure 6. Execution of Flow Strategies Demonstration

AviationSimNet enabled the two organizations to work jointly in establishing initial requirements for connecting TFM and En Route domains.

AviationSimNet Outlook

Future Planned Uses

A joint simulation of a concept called Flight Deck-Based Merging and Spacing (FDMS) is planned for 2007 that will connect NASA and MITRE research facilities in Hampton and McLean, Virginia together via AviationSimNet. Both NASA-Langley and CAASD are part of the FAA's Merging and Spacing working group that is researching technologies and concepts to enable the early adoption of airborne spacing. The initial implementation is focused on a stream of aircraft merging onto a common route at cruise altitudes and then performing a continuous descent arrival to the runway. The Merging and Spacing operation will allow the aircraft to achieve current-day spacing intervals more consistently while gaining most of the benefits (e.g., reduced noise, fuel usage, and time) of the continuous descent arrivals. By combining these resources, the two entities will be able to use a greater number of medium and high-fidelity aircraft simulators and high-fidelity air traffic control simulators. The simulation will focus on joint air-ground interaction issues during nominal and off-nominal operations.

AviationSimNet Global Partners

To date the participation in the AviationSimNet Standards Working Group has been driven largely by partners from the United States. The time has come, however, to seek broader harmonization of simulation environments across the globe. Toward this end the Standards Working Group has already begun to incorporate elements of the Eurocontrol Flight Object Interoperability Proposed Standard (FOIPS) [31] into the AviationSimNet FOM.

The AviationSimNet community is actively seeking additional partners to help advance the state of AviationSimNet, extend its capabilities, share their experience in distributed simulation, and define an international standard for simulations in aviation. The more that international governments, researchers, and industry partners get involved in AviationSimNet, the more likely we are to achieve the goal of global harmonization of future ATM capabilities.

Conclusion

Laboratory simulation can be expected to continue playing a critical role in analyzing, validating, and socializing new air traffic management technologies and concepts. Given the pressing challenges that lie ahead for the aviation community, and recent rapid growth in global broadband connectivity, AviationSimNet offers a critical opportunity for international cooperation and harmonization.

This research demonstrated the feasibility and viability of real-time distributed simulation over the public Internet by generating a specification, building the necessary software components, and exercising the environment using two real-world air traffic management demonstrations. It also succeeded in establishing an open and growing collaborative, network of participants to foster the growth and enhancement of this capability.

The AviationSimNet specification will continue to mature, driven by the needs of real-world experimentation, and guided by an open, standards-definition process. It is hoped that increased stakeholder participation by a broadening community of interest will only help to add value to these tools, toward the ultimate betterment of global solutions for delivering safe and efficient air traffic management services.

Acknowledgments

The authors would like to thank the following contributors to this paper: Bryan Barmore (NASA Langley) for his contributions on APS, Randall Bone (MITRE) for his contributions on FDMS, Rafael Katkin (MITRE) for his contributions on flight object and execution of flow strategies, Alexander Alshtein (MITRE) for his contributions on execution of flow strategies, David Bodoh (MITRE) for his technical contributions on AviationSimNet, and Philip Brown (MITRE) for his contributions on performance in the AviationSimNet environment.

The authors would like to thank Kelly Connolly, Urmila Hiremath, and John Mack of MITRE for their invaluable review comments on this paper.

The authors would also like to thank all of the organizations participating in AviationSimNet for their commitments to this activity. Without their participation AviationSimNet would not be what it is today.

Biographies

Patricia Liguori is a Lead Information Systems Engineer at The MITRE Corporation. Her background is in developing real-time air traffic control systems and information systems and is the project leader for the AviationSimNet research effort. She holds an M.S. in Computer Science from the New Jersey Institute of Technology.

Glenn Roberts is the Chief Engineer for The MITRE Corporation's Center for Advanced Aviation System Development. He is responsible for formulating and executing CAASD's internal research and development programs, and directing strategies for technology transfer, technical publishing, information sharing, and laboratory evolution. He holds B.S., M. Eng. and Ph.D degrees from Rensselaer Polytechnic Institute.

References

[1] Borener, Sherry, et al, 2006, *Can NGATS Meet the Demands of the Future?*, ATCA Journal of Air Traffic Control, Vol. 48, No. 1, January – March 2006.

[2] *Joint Planning and Development Office, Concept of Operations for the Next Generation Air Transportation System, Draft,* July 24, 2006, Version 0.2.

[3] FAA OEP, http://www.faa.gov/programs/oep/.

[4] ACARE Vision, http://www.acare4europe.org/docs/Vision%202020.pdf.

[5] ACARE, http://www.acare4europe.org/html/strategic0.shtml.

[6] Eurocontrol Concept of Operations, http://www.eurocontrol.int/oca/gallery/content/public/docs/op_concept/ConOps.pdf.

[7] MITRE CAASD, http://www.mitrecaasd.org/work/.

[8] Prevot, Thomas, et al, 2006, *The Airspace Operations Laboratory at NASA Ames Research Center*, AIAA Modeling and Simulation Technologies Conference and Exhibit, August 2006.

[9] Barmore, Bryan, et al., 2005, AIAA 5th ATIO and16th Lighter-Than-Air Sys Tech. and Balloon Systems Conferences, Arlington, Virginia, September 2005.

[10] Simulation Interoperability Standards Organization, http://www.sisostds.org.

[11] Miller, D. C., J.A. Thorpe, 1995, *SIMNET: The Advent of Simulator Networking*, Proceedings of the IEEE 83(8): 1114-1123.

[12] Kuhl, F., R. Weatherly, J. Dahmann, 1999, *Creating Computer Simulation Systems, An Introduction to the High Level Architecture*, Prentice Hall.

[13] Advanced Simulation Technology, Inc., http://www.asti-usa.com.

[14] DEPARTMENT OF TRANSPORTATION AND RELATED AGENCIES APPROPRIATIONS FOR 1999, Wednesday, February 11, 1998.

[15] Roberts, G. F., Randall J. Stevens, 1991, *The National Simulation Laboratory: The Unifying Tool for Air Traffic Control System Development*, Proceedings of the 1991 Winter Simulation Conference.

[16] Meloche, Patrice, March 10, 1998, Joint FAA/Army/NASA Federation (JFAN) Status Update, CAE Electronics Ltd.

[17] Rehmann and Rehmann, and Krois, 2004, *Distributed Simulation: A Proposed Approach for Air Traffic Management Research*, Digital Avionics Systems Conference.

[18] ESCAPE, http://www.eurocontrol.fr/Newsletter/2003/July/Live_Trials/Live_Trials_v0_2.htm.

[19] ACE, http://www.eurocontrol.int/eec/public/standard_page/EEC_News_2006_2_G2G.html.

[20] Liguori, Patricia, Glenn Roberts, et al., 2004, *MITRE Simulation Environment*, ATCA Journal of Air Traffic Control, Vol. 46, No. 3, July – September 2004.

[21] Bodoh, Dave, Patricia Liguori, Matt Pollack, 2004, *A Model for Distributed Human in the Loop Air Traffic Management Simulations*, AIAA Modeling and Simulation Technologies Conference and Exhibit, August 16, 2004.

[22] AVENUE, http://www.eurocontrol.int/eec/public/ standard_page/ERS_avenue.html.

[23] Simphonics, http://www.simphonics.com.

[24] Sincgars, http://www.acd.itt.com/sincgars.htm.

[25] http://aviationsimnet.net/ASN/MP06W0000131.pdf.

[26] AviationSimNet FOM, http://aviationsimnet.net/ASN/AviationSimNetFOM2.0PubliclyReleased.pdf.

[27] RUC, http://ruc.noaa.gov/.

[28] Brown, Phil, et al., 2006, *AviationSimNet Integration Manual*, The MITRE Corporation, August 2006.

[29] Barmore, B. E., T. S. Abbott, K. Krishnamurthy, 2004, *Airborne-Managed Spacing in Multiple Arrival Streams*, Proceedings of the 24th Congress of the International Council of Aeronautical Sciences, Stockholm, Sweden, ICAS Secretariat.

[30] Barmore, B. E., 2004, *Airborne Precision Spacing: A Trajectory-based Approach to Improve Terminal Area Operations*, 25th Digital Avionics Systems Conference, Portland, Oregon.

[31] FOIPS, http://www.eurocontrol.int/mil/public/standard_page/newsletter_0606_art02.html.

[32] ASTOR, http://pdf.aiaa.org/preview/CDReadyMMST04_854/PV2004_5259.pdf.

This work was produced in part for the U.S. Government under Contract Number DTFA01-01-C-00001 and is subject to Federal Aviation Administration Acquisition Management System Clause 3.5-13, Rights in Data-General, Alt. III and Alt. IV (Oct., 1996).