Aerial Refueling in a DMO Environment

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ABSTRACT

The Air National Guard is working with industry partners to develop the first Distributed Mission Operation (DMO) capable Boom Operator Simulator. The Boom Operator Simulator System (BOSS) is a high fidelity, fully immersive KC-135 boom pod simulator. Since Aerial Refueling has never been attempted in a DMO environment there are many issues that must be resolved. These issues include:

• Aerial Refueling DIS Standards Development – The current DIS Standards do not include PDU definitions for the transfer of data necessary for aerial refueling. This paper will discuss the data that must be passed between tanker and receiver aircraft.
• Location – Accurate positioning of the tanker and receiver models becomes more difficult in aerial refueling simulations. The tanker and receiver positions must be accurate enough to guarantee a correct visual representation of the boom aligned with the refueling receptacle.
• Dead Reckoning Limitations – When the tanker and receiver are in physical contact, the drift associated with dead reckoning cannot be tolerated. Innovative solutions will be required to balance rapid position updates with restrictions on bandwidth usage.
• Simulator Fidelity – While the BOSS will possess the fidelity to accomplish all aerial refueling tasks, many of the receiver aircraft flight simulators will not have the required fidelity. A multi-level scheme has been developed to allow receiver aircraft to accomplish various levels of aerial refueling training.
• Accurate Collision Detection – Aerial Refueling requires that the tanker and receiver physically touch each other during a mission. For this reason, traditional collision detection methods cannot be used. The simulation must be able to place the tip of the refueling boom on the surface of the receiver aircraft and cause visible damage to the receiver.

ABOUT THE AUTHORS

Ronald Kornreich a retired USAF lieutenant colonel and fighter pilot, is the Program Manager for Trainer Development within the ANG's Plans and Requirements Directorate. Much of his over 35 years of government service has involved training in one capacity or another with nine years in his present position as a SETA contractor. He has a B. S. Degree in Aerospace Engineering with a concentration in Nuclear Engineering from the University of Oklahoma. He is also a graduate of the Air War College and the Inter American Defense College.

As Program Manager, Mr. Kornreich developed the Air National Guard's initial Distributed Mission Operations (DMO) roadmap and was the inspiration and driving force behind the establishment of the Distributed Training Operations Center (DTOC) in Des Moines IA. The DTOC has developed into the USAF's premier facility for daily persistent DMO to include support for joint training as well. Mr. Kornreich also developed, and currently manages, the ANG's strategy for designing and developing simulator prototypes and technology demonstrators as a part of larger strategy to provide state of the art capability to all ANG flight and mission aircrew.

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INTRODUCTION

The concept of Distributed Mission Operations (DMO) simulator-based training for USAF aircrews has been a breakthrough capability that, although established for some years at many bases around the globe, is still in many ways, in its infancy. The ability for aircrews at dispersed locations to train in a persistent common virtual battle space with interoperable threat and visual terrain databases elevates mission rehearsal to a level not realized in the real world short of actual combat. With improved image generation, faster processors, high definition displays and a myriad of other technological breakthroughs, immersive simulators for both flight and mission crew members are approaching a level of realism not achievable just a few short years ago.

One glaring deficiency remains, however, in that aircrew cannot realistically conduct aerial refueling (AR) in a DMO environment. AR DMO presents unique challenges on a scale likely matching the sum of development in the field to date. Where in the past, the position of an entity in three dimensional space and time could be satisfactorily approximated to within a few feet without a loss of realism, AR demands accuracy down to fractions of an inch. Demands on bandwidth latency and computing power will be significant. To achieve this capability, new standards, protocols, models and processes have had to be developed.

Although AR DMO capability is intended to augment, not replace, live flying for realistic mission rehearsal, it provides an added margin of safety to train less experienced pilots and boom operators. As fewer and fewer flying hours are available for training, DMO may very well be the only viable solution available.

Background

To date, networked AR exercises have either been accomplished by "mimicking", in which the tanker and receiver aircraft go to the same approximate position and stay there for a proscribed period of time, or it has been done on a limited basis over a local network with little or no added network latency using a non-DMO standard trainer specific interface.

The Air National Guard is working with industry partners to develop the first DMO capable boom operator simulator. The Boom Operator Simulation System (BOSS) is a high fidelity, fully immersive KC-135 boom pod simulator prototype. The BOSS prototype development involves two phases. Phase 1 is development of the BOSS prototype and Phase 2 adds DMO capability to the BOSS prototype and develops a proposed aerial refueling DMO standard.

The focus of this paper is to discuss a methodology to perform high fidelity AR training over DMO which will accommodate exercises involving training devices at multiple distributed locations. The goal will be to use this methodology to develop a package general enough to be a candidate for extending the current DMO standards.

AR DMO CONSIDERATIONS

Many issues must be considered when adding a high fidelity boom operator trainer such as the BOSS into a distributed training environment. The technical considerations are determined based on the training objectives. These objectives define the added training value that will be achieved beyond just AR training in a stand-alone simulator. Interoperability issues with other training devices must also be considered. Can a reduced set of training objectives still be achieved with "receiver" training devices with no planned DMO AR specific upgrades?

The defined set of training objectives determines the data transfer between the devices. For example, if fighter towing is a training objective, then actual forces between the refueling boom and the receiver aircraft must be included in the DMO interface. The training objective considerations for AR training then define the data that needs to be exchanged between the tanker and the receiver aircraft.

Once the AR specific interface data is defined, the next step is to determine if existing DMO data packet definitions can accommodate the required data, or if AR specific extensions are required to the standards. If extensions are required, these extensions must be defined and submitted for approval. This step also includes definition and resolution of all the technical issues, since it may impact the content and the required transfer rate of the data over a long haul network. These technical issues include accuracy, latency, jitter, coherency, bandwidth considerations, and missing messages.

The close proximity and physical connectivity of two DMO entities requires implementation of new physical models on both the receiver and tanker simulations. The aerodynamic effects due to the tanker wake and the receiver bow wave must be considered. An innovative approach to collision/contact detection must also be considered that is not dependent on specific system implementation, i.e., image generator. Finally there may need to be consistent models added to both devices that maintain coherency among the devices without excessive data transfer.

The boom operator simulator will also have to address the dual role it will have in a distributed environment. It will need to function as a complete tanker (including the responsibilities of the front flight deck, e.g., communications and other emissions) and as a boom pod simulator that will interact with another training device (e.g., OFT) that represents the tanker flight entity.

DMO AR TRAINING GOALS AND OBJECTIVES

The Air Force has recently fielded two Boom Operator Weapon System Trainers (BOWST) to the KC-135 ATS in Altus, OK to be used for initial qualification training. The BOWSTs are high fidelity training devices that instruct initial qualification students on the procedures and mechanics of aerial refueling operations. The Air National Guard has completed development of its prototype Boom Operator Simulation System (BOSS), which is a high fidelity, fully immersive, squadron level trainer used for continuation, upgrade and mission rehearsal training. In order to fully meet the goals and requirements of DMO AR training, the specific training objectives must be defined. These objectives must identify the DMO training we are trying to achieve that cannot be obtained in the respective stand alone boom operator trainers. Can this training be used to reduce or augment live training missions?

Adding aerial refueling capability to a DMO network will provide a capability for basic and mission qualification training, special mission rehearsals, test and evaluation of new operation concepts, tactics and capabilities, and realistic training in virtual Joint force exercise environments. Understanding these training requirements is important in determining the acceptable performance of the technical issues.

Capability of Receiver Simulators

DMO capable simulators range from desktop trainers to high fidelity weapons system trainers, each with a different aerial refueling training requirement. Few, if any, receiver aircraft training devices will initially be capable of high fidelity AR training. Required modification to these devices to achieve high fidelity AR training may include visual system hardware upgrades, visual model upgrades, aerodynamic model upgrades, audio system upgrades, and various other systems model upgrades.

There are numerous Air Force training devices that are DMO capable, most with varying levels of existing AR fidelity (in a stand-alone environment). A boom operator trainer in a DMO environment must be able to accommodate these varying levels of fidelity, meeting a defined set of training objectives with each level. We have defined five levels of receiver capability that define the training fidelity.

- Level 0 – No AR Training
- Level 1 – AR Familiarization
- Level 2 – Limited DMO AR Training
- Level 3 – Partial DMO AR Training
- Level 4 – Full DMO AR Training

These five levels of training fidelity, including training objectives, system requirements, and data transfer requirements are fully described in Table 1. The higher levels will inherit the capabilities of the lower levels and will be backwards compatible with the lower levels. These levels will be automatically negotiated when the receiver and tanker exchange handshake information.

Data

As part of the DMO AR Standard development, the AR unique data that needs to be shared over the DMO network must be compared to the existing data constructs within the current DMO standard to determine if new data constructs are required.

Table 1. Levels of AR Capability and Fidelity

Level	Description	Training Objectives	Receiver Training Device System Requirements	Data Transfer Requirements
0	No AR Training	None	No AR specific capabilities	No AR specific data transfer requirements
1	AR Familiarization	• Visual rendezvous training • Pre-contact positioning training	• Basic tanker visual model (boom articulation not required) with basic aircraft exterior lighting • Comm/Nav simulation compatible with rendezvous and communication	• High fidelity positioning data • Exterior lighting data • Full DMO compatible digitized voice for all communications systems
2	Limited DMO AR Training	• Contact positioning training • Simulated contact training • Emergency separation training	• Detailed tanker visual model with articulating boom and pilot director lights • Receptacle door control simulation • AR related external light controls, i.e., receptacle lights, slipway lights, etc.	• Boom azimuth and elevation data • Pilot director light data • Receptacle door data • AR specific lighting intensities
3	Partial DMO AR Training	• Basic contact training • Fuel transfer training	• Geometrically compliant tanker model with fully articulating boom, fuel tube (with multiple segments) and fuel nozzle, tail mounted AR floodlight, and boom nozzle light • Geometrically compliant and fully articulating boom drogue adaptor (BDA) model with defined segments (U.S. Navy & NATO) • Fuel management system model capable of fuel on-load via AR • Boom interphone communication • Basic AR malfunction simulations	• Fuel tube extension data • Fuel tube bending data • Tanker AR lighting intensity and direction • BDA positioning data • Fuel quantity transfer data • Point-to-point digitized voice communication data through the boom interphone link • Basic malfunction activation data

4	Full DMO AR Training	• Full contact training
		• Full boom/nozzle interaction training
		• Full transfer of forces through the boom
		• Flying qualities changes (while in contact) due to weight and balance changes
		• EMCON communications
			• Force and moment transfer due to impacts and connectivity
			• Full mass (fuel) transfer effects on flight performance
			• Tanker generated wake and turbulence effects on flight performance
			• Special effects
			  o Fuel spray
			  o Damage simulation
			  o Audio cues
			• Advanced AR malfunction simulations and damage response
				• Contact forces while connected
				• Impact location and severity data
				• Temperature compensated fuel mass transfer data
				• Special effects related data
				• Advanced malfunction data and secondary effects data
				• EMCON signals

In many cases the data can be packaged in such a way that it can be added as either a new data type or an extension of an existing type. Data that is addressed by existing constructs must also be evaluated to ensure proper implementation and accuracy for the intended task. The major data components identified as part of the aerial refueling task are:

- Location of tanker and receiver
  - Position
  - Velocity
  - Acceleration
- Boom data
  - Azimuth
  - Elevation
  - Fuel tube extension data
  - Fuel tube bending data
  - Boom Drogue Adaptor (BDA) and/or Multi-Point Refueling System (MRPS) hose and drogue segment data
- Navigation
- Radio Communications
  - Tanker radios
  - Boom interphone (to receiver)
  - Tanker intercom
- Tanker external lights
  - Navigation lights
  - Underbody lights
  - Underwing lights
  - Tail mounted flood light
  - Boom marker lights
  - Boom nozzle light
  - Nacelle lights
  - Tanker beacon
  - Pilot director lights
- Receiver surface / Receptacle locations
- Contact interaction
  - Boom tip forces
  - Impacts and damage data
  - Signal system
- Fuel transfer
- Handshake data

Based on our initial investigations, from a Distributed Interactive Simulation (DIS) perspective, none of this data will require a new type of Protocol Data Unit (PDU) but many will require either an extension to an existing PDU or additional special handling.

TECHNICAL ISSUES

The issues associated with physically connecting two DMO entities in a virtual environment present a unique set of technical challenges. These challenges include accuracy, latency, jitter, coherency, network bandwidth, and missing messages. However, prior to a presentation of the technical issues, a basic background in "real-world" aerial refueling is in order.

The main objective of the receiver aircraft when approaching the tanker in an AR maneuver is to reach the contact point and maintain zero velocity and acceleration relative to the tanker. While it is obvious that the receiver will not have zero inertial (earth-relative) velocity, inertial acceleration may also not be zero due to turns, toboggan maneuvers, etc. The low (ideally zero) tanker-relative velocity and acceleration of the receiver aircraft can be used to our advantage for positioning accuracy in a DMO environment.

Real-world AR consists of multiple man-in-the-loop systems. Response of the receiver aircraft to directions given by the boom operator can take on the order of hundreds of milliseconds. This real-world latency is automatically compensated for by experienced boom operators who tend to get a feel for the closing rates of the receiver aircraft and respond with appropriate anticipatory commands. This presents quite a different training device latency requirement from a typical pilot training device where any response latency is critical and can lead to pilot induced oscillations of aircraft motion or simulator sickness. Based on this, latency introduced into a boom operator trainer associated DMO network delays will have less detrimental effect on boom operator training than in pilot training and may not even be perceivable until it reaches a high level.

In a DMO environment, coherency among the scenarios that are presented to each entity is critical to the proper response from each player. This coherency must be extended to a DMO AR scenario, where the relative positioning between the tanker aircraft and the receiver aircraft must be consistent between the boom operator device and the receiver aircraft device to within a high degree of accuracy. However, high fidelity accuracy for the boom/nozzle position when approaching the receptacle is only required for the boom operator entity. Many U. S. Air Force receiver aircraft have AR receptacles located in areas that are not visible to the pilot, e.g., C-5B, C-17, B-2, etc. Some aircraft have receptacles located in areas that are not easily seen, such as the F-15, F-16, and the F-22. Even the aircraft with receptacles in the nose, such as the A-10, the B-1B, and the E-4B, have their receptacles partially obscured by the HUD or glare shield. The need to present a highly accurate boom/nozzle position to the receiver aircraft entity that is matched within fractions of an inch to the position presented to the boom operator is greatly reduced due to the fact that in most, if not all, training devices, the closer the nozzle gets to the receptacle, the less the receiver pilot can see the boom nozzle, due to aircraft/trainer configuration or limitations with dome and collimated display systems. This reduces the strict coherency requirement for the boom and nozzle articulations between the boom operator entity and the receiver entity. The only requirement being that when connected, any visible portion of the boom appears stable to the receiver entity. For multiple fighter aircraft in refueling formation the receivers in the observation or reform positions are not likely to actually have the primary (in contact position) receiver aircraft within their visual field of view even with a full dome visual display system since the primary receiver will be positioned aft and below. Quickflow formation is the only likely scenario where a second receiver aircraft entity would notice any inaccuracies with the boom nozzle positioning on the primary receiver.

In all real-world AR scenarios, one entity acts as the refueling "lead", while the other acts as the refueling "observer" or "monitor". In typical boom refueling, the boom operator takes the lead by "putting the pole in the hole", while the receiver pilot maintains the optimal positioning and monitors/observes the actions and commands of the boom operator. In drogue refueling via the BDA (or MPRS), the receiver pilot takes the lead by plugging into the drogue, while the boom operator monitors/observes the procedure. This lead/observer relationship lends itself to the DMO concept of single ownership of the data. During boom refueling, the boom operator entity will "own" the data for exact boom/nozzle positioning, while during drogue refueling, ownership of exact drogue positioning will transition from the boom operator entity to the receiver aircraft entity as the receiver approaches the astern or pre-contact position.

One of the fundamental concepts in reporting an entity position over a DMO network (both DIS and HLA) is through the use of a construct called "dead-reckoning". Dead Reckoning (DR) is a method in which position and motion are combined and described through the use of a parametric equation usually involving a position in a chosen coordinate system at some time t along with a velocity and acceleration. Hence at some future time, all another system has to do is apply the time difference to the velocity and acceleration to calculate a new position valid for that current time. The originating entity in turn compares its current actual location to the current DR location and when the error is greater than a defined threshold value, the entity sends updated equation parameters for use by the other systems. DR is typically utilized in an Earth Centered Earth Fixed (ECEF) coordinate system, whereas all entity motion is relative to the ECEF system. Th**e** use of DR does two things for the DMO network. It helps reduce bandwidth requirements for an entity update as well as gives a method for accommodating a certain amount of system latency. The threshold value for requiring a new update determines the level of accuracy needed for the exercise, impacting bandwidth as well as the accuracy to accommodate for latency.

There are several factors which make AR unique from a DMO network perspective. The first factor is not only the level of close proximity the two entities (in this case the tanker and the receiver) have to each other, but also th**e** amount of time they spend close to each other. The other unique aspect about AR over a DMO network is the interaction between the boom and the receiver. Physically connecting two DMO entities in virtual space places unique requirements on how and what positioning data is sent over the DMO network. These two unique issues make it next to impossible to achieve high fidelity, realistic DMO AR training using typical DR techniques.

Our approach is to utilize a relative coordinate system that moves with the tanker aircraft. The Relative Position Measuring System (RPMS) coordinate system is centered at a point aft and below the tanker aircraft, defined to co-align with the boom fuel nozzle tip when the boom is at zero azimuth, thirty degrees down, and ten foot extension. RPMS is a right hand coordinate system with positive X defined to be in the direction of tanker motion, positive Y is outward toward the right wing of the tanker, and positive Z orthogonal to X and Y coordinates (typically downward unless the tanker is in a bank or climb maneuver). A unique feature of the RPMS coordinate system is the "bendable" nature of the X coordinate. As the tanker executes a turn or climb/descent maneuver, the X coordinate follows the path of the zero azimuth, thirty degree elevation, ten foot extension point of the boom, in effect leaving a coordinate system trail behind the tanker. This coordinate system has been used extensively in flight test of refueling operations and in the subsequent data reduction. Figure 1 shows the RPMS coordinate System.

The RPMS coordinate system is "owned" by the tanker entity. When within the refueling airspace behind the tanker entity, the receiver aircraft entity outputs RPMS position, velocity, and acceleration data for the receptacle location in addition to the normal ECEF data onto the DMO network. The boom operator device uses the RPMS data to dead reckon the receiver entity behind the tanker. As described previously, when in the optimal refueling location, the receiver entity position data will ideally be nearly constant with low relative velocity and acceleration. This allows DR within a much tighter error tolerance without saturating the DMO network bandwidth.

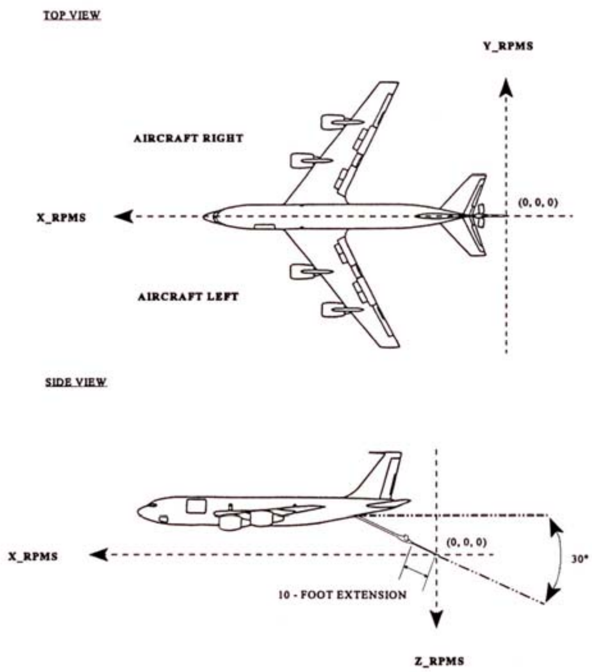

Figure 1 RPMS Coordinate System

Normally the boom operator entity will dead reckon all entities in the standard ECEF coordinate system until a receiver entity approaches the "refueling airspace" behind the tanker. At this point, the boom operator entity will "interrogate" the receiver entity and request handshaking to determine the AR capability level of the device. No response to the interrogation is assumed to be a level zero capability. If the receiver entity responds with a valid capability level (1 through 4), the handshaking is completed and the receiver will immediately start sending RPMS relative positioning data to the boom operator entity. The boom operator device will then seamlessly transition the receiver entity positioning algorithms from ECEF DR to RPMS DR. The boom operator device will also output data to the receiver entity consistent with the capability level negotiated between the two devices. Upon completion of the AR maneuver and exit of the "refueling airspace", the boom operator device transitions the positioning of the receiver back to ECEF DR.

The use of RPMS data provides several advantages. The RPMS data is, by nature, more stable than ECEF due to lower velocity and acceleration values. This allows much tighter error tolerances and higher accuracy, thereby reducing jitter related issues, without excessive bandwidth use. The significantly lower RPMS velocity reduces latency issues and dropped/missing message issues. Also, by providing RPMS data for its own receptacle, the receiver entity eliminates issues involved in centroid/center of gravity location and visual model geometric accuracy for the receptacle area.

Geometric model accuracy is critical for high fidelity collision detection between the refueling boom and the receiver aircraft. An innovative and unique collision detection concept has been applied to the BOSS trainer that utilizes a high detailed contact "map" of the receiver surface and receptacle area built from the OpenFlight models developed for the image generator. This allows the collision detection algorithms to be removed from the image generator processing, while still providing consistency between the visual representation of boom tip/receiver surface contact and the host impact and subsequent boom force/moment response processing. Our DMO AR solution maintains this collision detection concept where the boom operator trainer determines collision events based on surface and receptacle maps of the receiver aircraft resident on the boom operator trainer host computer. The advantage of this approach is that it still provides a highly accurate collision detection scheme that is consistent with the visual model on the boom operator device. This also provides excellent impact correlation for the receiver aircraft device for areas in the vicinity of the receptacle.

Data such as tanker wake and receiver bow wave would be impractical to try to exchange across a DMO network. Effects of the tanker wake on the receiver aircraft must be computed on the receiver device based on the relative positioning and speeds of the two entities. Conversely, receiver bow wave effects must be computed on the boom operator trainer based on the same relative positions and speeds. In both cases, the models will be tightly coupled with the aerodynamic models of the respective devices with specific scaling and model parameters making it impossible for general DMO data to apply to all receiver aircraft types and aerodynamic models.

During actual connection of the boom to the receiver aircraft receptacle or the refueling probe to the refueling drogue, a consistent model will be used on both the boom operator device as well as the receiver aircraft device to maintain coherency between the visual images. These models basically provide a common means to connect the points in relative space to ensure the latched fuel nozzle does not visually move relative to the receptacle or the refuel drogue remains locked onto the receiver probe tip.

Dual Role of the Boom Operator Simulator

The BOSS trainer is designed to act as a complete tanker aircraft on a DMO network. This requires DMO only models for IFF and other required comm/nav systems that are not used during stand-alone operation. The capability to act as a complete tanker entity allows the BOSS to set up on any standard AR track and automatically fly the published waypoints or alternately fly a designated rendezvous.

A secondary mission for the BOSS device is to act as just the boom pod on a single DMO entity flown by another training device. This allows the BOSS to provide Crew Resource Management (CRM) training between the front and back ends of the same aircraft. This capability provides valuable training for emergency situations such as refueling breakaway maneuvers, tactical threat identification and avoidance, and malfunction training such as tanker directional control failure where the boom operator uses the boom to assist in steering the tanker.

In this role, the boom operator training device acts as a "child" entity on the network that is attached to the parent tanker entity. Boom positioning data originates from the boom pod entity, while tanker positioning data originates from the tanker. During refueling maneuvers, the same receiver interrogation/ handshaking operations and RPMS DR computations are still performed by the boom operator device to position the receiver entity within the boom operator visual scene with the exception that the tanker entity "owns" the RPMS coordinate system. This will not affect the relative positioning between the boom pod entity and the receiver entity since actual geographic location of the tanker is only used for positioning the boom pod within the visual terrain database. The data of consequence to the boom pod entity is the RPMS positioning data of the receiver entity.

Level 4 capability of the tanker simulation requires AR related forces and moments to be transferred to the tanker flight model. This provides boom drag and dynamic motion effects, as well as receiver bow wave effects on the tanker flight performance.

STANDARDS ACCEPTANCE

At the conclusion of the BOSS DMO program, an AR data package will be presented to the Air Force Materiel Command, 677th AESG (Simulator Management Support Group) for advocacy as a proposed standard for AR on the MAF DMO network. Once the data package is accepted for use on the MAF DMO network, it will be submitted as a proposed USAF wide standard and extension to the IEEE 1278 Standard for Distributed Interactive Simulation.

NEXT STEPS

The BOSS DMO program is currently testing the AR DMO considerations outlined in this paper using a constructive receiver aircraft simulation networked to the BOSS. Our next step will involve testing our AR solutions using a simulated long haul network. Finally, we intend to test the proposed AR data package with a distributed Air National Guard simulator over the ARCNET 0 network.

This paper is intended to be the first in a series of three papers. The next paper will describe the technical and programmatic details required to implement the approach, and will present data from actual test results on a long haul network. The final paper will describe the final operational suitability as well as lessons learned and recommendations for future efforts regarding AR in a DMO environment.

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