Retrofitting Simulation Systems with Adaptive Learning to Personalize Training

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ABSTRACT

Current modeling, simulation, and training (MS&T) systems lack adaptive training functionality, which limits MS&T system training effectiveness for individuals and units. Adaptive training technologies support skill development through scaffolding – the structured instructional approach of guiding learners as they gain proficiency and confidence and reducing that support as they demonstrate skill and competence – and can evaluate skills and decision-making contexts. Incorporating adaptive training capabilities to existing MS&T systems has the potential to transform how trainees learn and receive feedback and how instructors teach and provide feedback without redeveloping the core system functionality, thereby reducing instructor manpower requirements and increasing development return on investment through tailored feedback and remediation. Although adaptive training technologies offer significant potential for effective, engaging, and personalized training experiences, they have not yet been widely applied to legacy MS&T training systems. To demonstrate this potential, we have recently integrated an open-source adaptive instructional system (AIS) architecture with a modular M1A2 Abrams tank training system. We describe an M1A2 Abrams Mixed Reality (MR)-based training station with virtual representations of crew stations that allow crew members to perform gunnery skill training to include target acquisition, designation, and engagement sequences. We discuss how we used the Generalized Intelligent Framework for Tutoring (GIFT), an open-source AIS, to retrofit the MR training station and automatically evaluate performance for simulated training events. We discuss the potential for integrating AIS capabilities in disparate systems and best practices integrating adaptive training in existing simulation systems to increase learner skill acquisition and retention with fewer resources.

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INTRODUCTION

The demand for realistic, accessible, and cost-effective training is driving the adoption of mixed reality (MR) solutions in the modeling, simulation, and training (MS&T) community. These technologies offer significant potential for effective, low-cost individual and collective training. Given growing pressure on defense budgets and an increased focus on demonstrating return on investment, maximizing the capabilities of existing training systems is of critical importance. Many existing systems have provided functional and fully fledged capabilities across strategic, tactical, and mission rehearsal contexts. This paper explores the benefits of extending the lifespan and enhancing the effectiveness of existing systems by integrating Adaptive Instructional Systems (AIS) capabilities to provide personalized training to individuals and teams as they perform critical training exercises.

The Department of Defense (DoD) invests significant resources into MS&T systems to ensure the readiness of its warfighters. These systems are used to train skills ranging from equipment maintenance, planning and operations to skill enhancement and tactics, and mission rehearsal. The MS&T training capabilities have advanced to maintain parity with our evolving battlespace since legacy systems like the Close Combat Tactical Trainer (CCTT) and One Semi-Automated Forces (OneSAF) debuted. While these legacy systems have been the standard bearers in virtual and collective simulations for the better part of two decades, new MS&T systems are being developed and fielded to address evolving threats and tactics. Newer systems such as the Synthetic Training Environment (STE) aim to move the state of training capabilities into a new technological training age, with an emphasis on integrating advanced M&S tools in MR-based environments. However, as STE continues to mature, legacy simulation systems may still have a role to play in preparing the warfighter for new and novel threats and tactics.

Legacy training systems offer exceptional functionality, well-defined features, and a history of providing meaningful training for the warfighter[1, 2, 3]. As these systems age, new technologies are needed to meet evolving training needs. One solution supports extending the life of legacy training systems through integrations with new and novel capabilities such as AIS and MR. Researching, developing, and integrating AIS and MR into existing systems offers several potential benefits including enhanced efficiency and accuracy in training scenarios and assessments as well as objective, data-driven insights into trainee performance. In addition, these systems can provide trainees with immediate feedback to correct misconceptions and guide performance, accelerating knowledge and skill acquisition. The US Army's training modernization strategies aim to harness advances in Virtual Reality (VR) and simulations technology and provide Soldiers with more realistic training environments at lower cost and with reduced risk.[4] Further, the U.S. Army Learning Concept 2030-2040 (U.S. Army, 2024) recommends modernizing learning technology infrastructure and integrating learning science and enabling technologies.[5] To meet these objectives, the DoD can apply AIS capabilities to existing simulation systems to close the gap between legacy capabilities and future training technologies.

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[1] Hartmann, 2021
[2] National Training and Simulation Association, 2011
[3] Nielson, 2024
[4] *Army of 2030,* 2022
[5] U.S. Army, 2024

instructional system AIS architecture with a modular MR-based crew gunnery training station allowing crew members to perform gunnery skill training. We discuss how we used an open-source AIS, to retrofit the MR training station and automatically evaluate performance for simulated training events. We discuss the potential for integrating AIS capabilities in disparate systems and best practices integrating adaptive training in existing simulation systems to increase learner skill acquisition and retention with fewer resources.

Adaptive Instructional Systems Fundamentals

AIS are "computer-based systems that guide learning experiences by tailoring instruction and recommendations based on the goals, needs, and preferences of each learner in the context of domain learning objectives".[6] The goal of AISs is to optimize learning, performance, retention, and training transfer by offering personalized instruction, feedback, and remediation.[7, 8] Examples of AIS include intelligent tutoring systems (ITSs), intelligent mentors and coaches, and AI-driven recommender systems.[9] Common components of AISs include a domain model, which contains information about the subject matter and learning objectives, a learner model, which includes information on student competence, progress, and needs; an instructional model, which facilitates guided learning experiences; and an interface model, which serves as the components that the learner or student interacts with. AIS interfaces can range from simple web pages to MR-based training systems. A key affordance of AIS's is their ability to observe a learning environment, identify changing conditions and intervene to provide guided learning experiences.

In traditional Instructor Led Training (ILT) and self-paced Computer Based Training (CBT) trainees typically act as receivers of information and are evaluated on their ability to retain, remember, and recall that information. In instructional design, Bloom's Taxonomy [10], a framework for classifying and categorizing learning objectives into classes, is one of the most used and recommended taxonomies during course and training needs analysis. Instructional design and learning objective taxonomies remain applicable when developing training capabilities with an AIS and support defining structured learning sequences through scaffolding and identifying learner proficiency levels (can a trainee remember facts, use information in context, or evaluate potential courses of action). Our use case specifically addresses how AISs are used to evaluate performance in an MR scenario-based training context and provide tailored feedback to trainees based on their actions.

A key objective of our research was to integrate the capabilities of an AIS with an MR-based training system that included physical and virtual controls to support crew gunnery training. For the AIS, we used the Generalized Intelligent Framework for Tutoring (GIFT) an open-source AIS architecture offering tools for performance measurement and instructional intervention. GIFT facilitates integration with existing training systems and provides developers with a suite of tools including a course editor to define automatic and observed assessments, a decoder for simulation data, a map visualizer, and a real-time observer panel with Observer Controller (OC) features to show the status of assessments and provide post exercise After Action Reviews (AAR)s. We integrated GIFT with the Mixed Reality Tactical Trainer (MRTT), and MR-based training test bed that realistically models the components of an M1A2 Abrams tank. The MRTT replicates the controls and interfaces for the driver, commander, and gunner positions, supporting comprehensive crew gunnery training, as shown in Figure 1. Successful crew gunnery performance relies on each member fulfilling their unique roles to eliminate opposing force (OPFOR) as quickly and effectively as possible. Previous work has demonstrated the potential of integrating AIS with low fidelity crew training systems (Smith et al., 2022). We aimed to expand this line of research to high fidelity MR raining station, supporting adaptive training in a more immersive environment with existing combat simulation engines.

[6] Sottilare, Stensrud, et al., 2019
[7] Sottilare, Barr, et al., 2018
[8] Sottilare, Brawner, 2018
[9] Sinatra, 2024
[10] Bloom, 1956

Gunner Position Physical Controls/Indicators | Gunner Position Webpage Controls/Indicators

Figure 1: MR Controls and Indicator Examples

APPROACH

Our research and development approach leveraged systems engineering, learning sciences, and agile development best practices to implement and test real-time performance monitoring within an MR environment. This methodology leverages adaptive technologies, an existing Army system, CCTT, and a modular open system architecture (MOSA) to provide real-time evaluation and feedback to a crew gunnery engagement. Using an agile development methodology, we rapidly iterated through our analysis, design, development, and integration. Throughout the effort, we met with system experts, research stakeholders, and AIS experts. Our initial concept of operations focused on using the existing form factor hardware in addition to a VR head-mounted display (HMD) for visualization, and a browser-based control system for crew positions without physical crew. We selected a VR headset for its compatibility, performance, and integration capabilities, ensuring that we could leverage existing integrations, hardware, Unity-based virtual environments, and expertise with specific devices. An Augmented Reality (AR) HMD could be used to enable learners to see the real-world controls as well as the virtual world; however, additional experimentation and prototyping is needed to ensure a smooth and seamless experience between virtual and real visuals.

We developed initial storyboards in collaboration with U.S. Army Combat Capabilities Development Command (DEVCOM) Soldier Center (SC) Simulation and Training Technology Center (STTC), to describe the general functionality, assessment and evaluation, and outlined our minimum viable product (MVP) – a minimum number of automated performance evaluations, a realistic terrain, navigation locations, and number and types of engagements. We established these criteria to ensure that our research and development yielded a prototype that could support meaningful interactions and demonstrate technology reuse and retrofit. In similar simulated crew gunnery engagement training, crews typically engage multiple targets at varying distances; we configured five (5) engagements, which required trainees to determine and select the appropriate gun and ammo type for the target and account for short- and long-distance targets.[11] For this effort, we relied upon learner interaction data from the simulation to evaluate trainees. Using this data provides crucial performance-related insights and confirms whether trainees have demonstrated the

[11] Smith, et al 2022

skills needed to engage and destroy targets. However, a novel component of effective AIS is the ability to tailor feedback, remediation, and the sequence of training content based on the collection of performance-based data and learner data.[12] Other simulation systems, as a part of a larger course of instruction, may be able to leverage existing course content, Learner Record Stores (LRSs), Experience API (xAPI) data, and pre-test data to tailor training scenarios and feedback and remediation.[13] An AIS with access to diverse, accurate, and well-structured content can provide relevant and tailored After Action Review (AAR).

Implementing the AIS Architecture

A typical AIS architecture has three primary components: the external training environment, the AIS, and the learner. Intelligent Tutoring Systems, which are a subset of AIS, connect to external training environments to send and receive actions and observations. Learner actions affect the training environment and are observed by the AIS.[9] This architecture, Figure 2, is the foundation and basis for the research and development we applied. We modified this architecture to enable the legacy non-adaptive simulation system, CCTT, to automatically assess performance and provide crews with structured feedback after each engagement in the MRTT test bed.

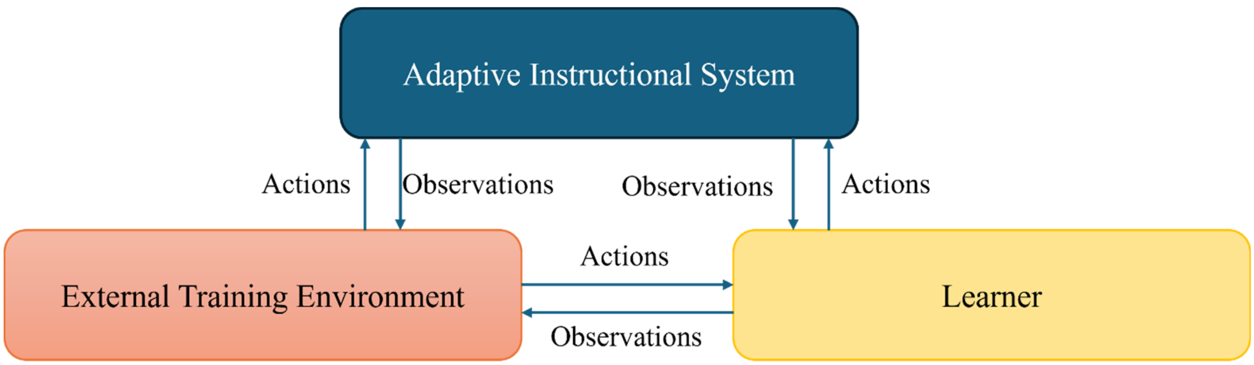

Figure 2: General Adaptive Instructional System Architecture

For this effort, additional system components were needed to translate data from the MRTT physical hardware Arduino-based signals to message traffic that affects the simulation state and stimulates the visual interfaces. The MRTT equipment contains multiple stations that are designed to emulate limited physical features of the M1A2 Abrams's internal stations in a modular way. The purpose of this is to provide physical controls for elements that are hard to meaningfully train via computer simulations, and to integrate with computer simulations and VR for other controls. In our case, we used the physical MRTT stations for the gunner and commander positions.[14]

We expanded our system architecture as shown in, Figure 3, to support interactions with MRTT. The labeled elements are as follows:

- Driver Controls, Gunner Controls, and Commander Controls represent the three standalone modules being used, which emulate the physical controls of their respective vehicle stations.
- The "Host Device" is a computer that runs the simulated scenario and runs critical components such as the:
    - CCTT simulation via virtual machines that run the semi-automated forces (SAF), simulated vehicles, and scenarios.
    - Software-centric Immersive Virtual Environment (SIVE) Socket Server. This server collects and routes information through the components of the training system to enable modular software simulation training through physical and virtual controls and to prevent the need for complicated webs of connections between each component.
    - Packet Translator. This software component reads information from the various crew position controls and translates it into the format used by the SIVE Socket Server. This allows the MRTT controls and the Web-based Crew Position Controls to be used as part of the same system.

[12] Goodwin, 2017
[13] Owens, et al., 2022
[14] Cambata, et al 2024

    - AIS collects data that is routed through the SIVE Socket Server to perform assessments and track trainees' actions.
- The "Client Device" enables trainees to interface with the simulation. The MRTT system, as integrated, does not provide visualization of the simulated environment; each Client Device provides the visual scene, and enables the use of virtual controls that are not represented by MRTT controls though:
    - Web-based Crew Position Controls is an interface visible in a web browser, and allows users to interact with mouse, keyboard, and connected game pads. This enables a more complete (though less tactile) set of controls than the MRTT equipment, allowing trainees to access controls which are not physically represented in the current equipment.
    - Unity Virtual Environment is a visualization software created using the Unity game engine, which reads data from the SIVE Socket Server to display the simulated vehicles and terrain. This Unity Virtual Environment can be run simultaneously on multiple networked computers (including the Driver, Commander, and Gunner stations used for this scenario). It is also able to display that data on either a computer monitor or VR headset. The latter can be used for trainees sitting in the MRTT stations to provide an immersive experience.

Figure 1

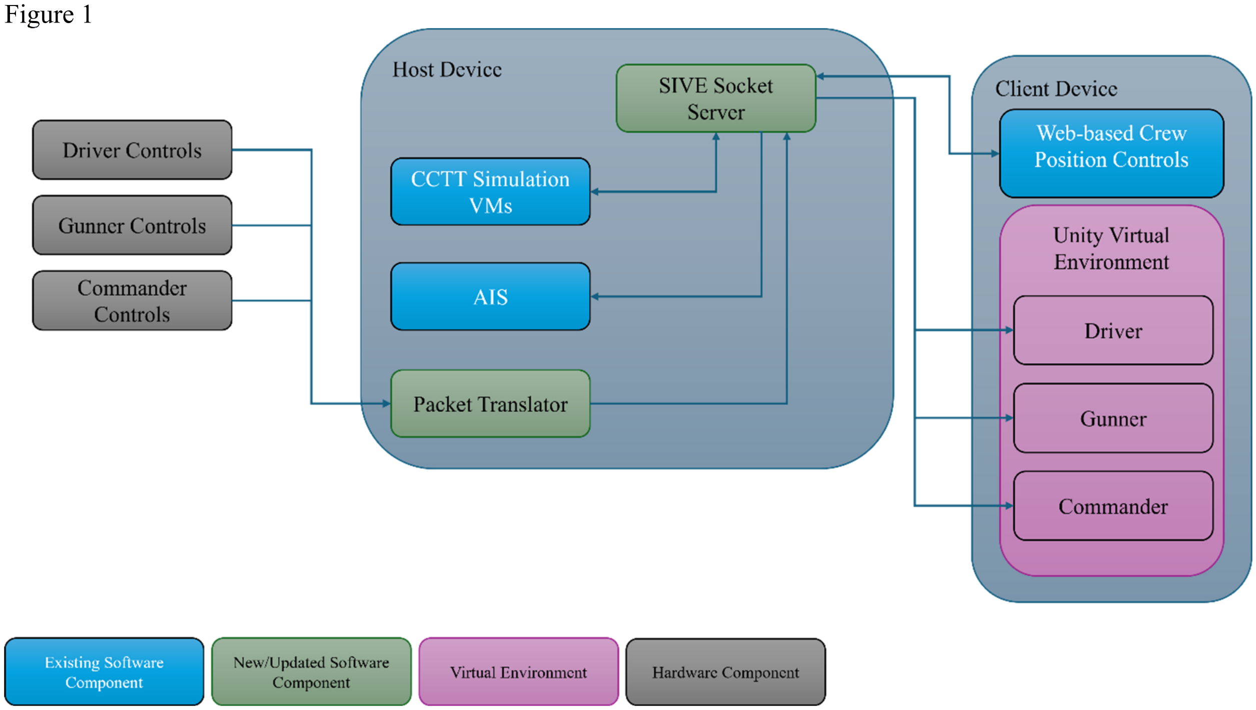

Figure 3: Retrofitted Simulation System Components

As shown in Figure 2, two software components were developed and updated for this effort: the Packet Translator provides a communication pathway between the state of controls from the physical hardware or the web-based crew controls and the Unity virtual environment. Without this component, the virtual environment would not reflect the state of the controls that trainees are interacting with (E.g., steering wheel rotation direction). The SIVE Socket Server, by contrast, shares data with the AIS for the current state of controls and Distributed Interactive Simulation (DIS) Protocol Data Units (PDUs).

INSTRUCTIONAL DESIGN CONSIDERATIONS

In instructional design, there are principles that guide media selection, media type, and interactivity recommendations. During our initial analysis of the training system integration, our team of engineers and instructional designers worked together to define the experience – how will potential trainees interact with the system and how will leveraging this collection of systems meet existing training goals? What feedback is useful to the whole team; is there specific feedback for each role? We answered these questions, in collaboration with DEVCOM SC STTC, and expanded on previous work that required crew members to detect, identify, and engage targets using Virtual Battlespace 3 (VBS3) and DIS messages.[15]

Specifically, we defined crew duties and tasks and interactions that could take place in this MR environment along with strategies for assessing crew performance. Automated assessments for this effort were only possible for simulation-based events, but this gave us access to a variety of data, including vehicle positions, orientations, firing events, and OPFOR health status. We used these data sources to define our domain model, assessment rules and thresholds for assessing crew duties and individual tasks. Current efforts are investigating expanded functionality through sensors, video, and audio to extend real-time, or near-real-time, evaluation in individual and team performance in MR experiences.[16,17]

Learning Objectives and Mapping within AIS

Learning objectives in traditional training equate to the outcomes that leaners are expected to have knowledge of and skill to perform after participating in training. Within our use case, our learning objectives connect to tasks trainees can perform within CCTT that generates DIS message traffic; our AIS already supports automated real-time assessments using DIS data.[18] Therefore, we triggered our evaluations using navigational waypoints, specifically driving the M1A2 within a specific area of a terrain and for OPFOR that spawn in specific locations. Our evaluations used the DIS data generated from performing sector scans, detecting each entity, acquiring targets through laser designation (lase), and destroying each identified target. As a part of this effort, we developed support within our AIS to read the designator PDU, thus adding the capability to evaluate laser designation, which is triggered by using the gunner or commander position to track and lase a target.

ASSESSMENT APPROACH

The training context we integrated with was limited to crew gunnery tables to scan, detect, acquire, and engage targets. Each of these tasks have a clear alignment between the gunnery table and a set of actions with the simulation system that can be evaluated using data standards described below. We can evaluate crew performance by analyzing turret orientation, laser designator usage, firing lines, entity locations, and entity health from the DIS PDUs being sent through the system. By setting timers in the AIS, we can determine how long it took crews to perform relevant tasks and factor this information into our assessment model.

Using DIS message traffic and AIS evaluation logic, the AIS automatically evaluates whether the trainees have completed each task, defined within the domain module, or not and to what degree.

In our current use case, crew teamwork, cohesion, and communication can be evaluated by an external OC using web browser-based OC tools provided by the selected AIS.

Evaluations from the OC tools are a dataset supporting the overall evaluation scheme and AAR. Therefore, by automatically evaluating whether the crew succeeded at scanning, detecting, acquiring, and engaging targets and augmenting with OC expert observations of crew teamwork, we extrapolate and develop a broader picture of evaluations of the crew's performance. In addition, capturing OC observations using the AIS can help better-inform the assessment models and thresholds that are used for automated assessment.

While the architecture and assessment system framework described above represents a significant step towards a more integrated AIS-driven training environment, the path to implementation was not without its hurdles. The integration of disparate technologies – the physical fidelity of the MRTT stations, the complexities of the CCTT simulation, and the data management needs of the AIS – presented a unique set of challenges. The following section details these implementation difficulties, outlining both the technical obstacles encountered during development and the valuable lessons learned regarding system integration, data synchronization, and the practical application of instructional design

[15] Smith, et al. 2022
[16] Teo, et al. 2024
[17] Vatral, et al. 2022
[18] Ragusa, et al, 2013

principles within a mixed-reality training context. These insights will be valuable for informing future iterations of this system and similar endeavors seeking to blend physical and virtual training components.

IMPLEMENTATION AND LESSONS LEARNED

Technical Constraints

Our initial task was to analyze the existing equipment, an existing MR hardware software system, from which we only leveraged the physical hardware. The hardware included three M1A2 Abrams crew positions: driver, gunner, and commander, with moderate fidelity. Each crew position was networked via ethernet to share data between them; each position provided realistic physical controls similar to an M1A2. To analyze network traffic and messages from each position, we used network diagnostic tools such as Wireshark. We evaluated network connectivity and firewall constraints, inspected throughput, and verified the integrity of data packets. This data is critical to share across the network so that as each position performs their job function, the shared virtual environment between them updates to match the current simulation state. We relied on hardware and network experts to perform initial physical system analysis and engineers to interpret target system interface control documents.

Hardware/Software Integration

As shown in Figure 3, we integrated several disparate architecture components, each one with a unique set of communication, network, and performance requirements. We faced significant challenges in networking due to the volume of virtual machines required to run CCTT and all its dependencies. The host machine alone required three IP addresses, and each client machine required a unique IP address as well – for a crew of four this is manageable. As the simulation system and number of client machines increase, this challenge grows in complexity, especially if each station can, or will, change crew positions throughout the course of training or experimentation. In addition, there were physical and virtual networks to contend with; each physical or virtual network has unique IP addresses and can be a source of errors. While we were able to solve this for the purposes of our research through clear documentation, configuration guides, and minimizing client-machine role changes, to support broader system needs, we recommend collecting system design documents early, establishing a standalone sandbox environment for testing, and engaging system experts early in analysis and design to clarify specific network requirements early so that the network architecture is defined prior to prototyping or testing.

We were limited within the virtual environment for the types of evaluations that we could perform due to the data generated within the simulation, the amount of development required to support additional DIS data, and value to the specific research use case. One limitation is related to the DIS PDUs that are generated. The selected AIS includes a library of pre-existing evaluation condition logic using DIS PDUs; this condition logic enables real-time evaluations and supports DIS PDUs for detonations, collisions, and entity state. While our AIS has the capability to send injections to simulation systems, those injections can only be sent if the external software can receive and respond to those injections. Because of how the software was set up, it would have been a major development task to send injections from the AIS to the simulation. Therefore, we could evaluate interactions and events that occurred within OneSAF/MRTT/CCTT, but we could not (within the scope of this project) adjust the scenario in real-time as an automatic response to those evaluations. With two-way communication between the AIS and external simulation, that is possible. We address this in the use case extension and future research possibilities section below.

Another limitation was the fact that, while our AIS could read data from the simulation system, we were limited in how we could send data back to the simulations from our AIS. In other cases, it may be possible to send real-time adaptations to the simulation as an automatic response to an evaluation from the AIS and subsequently assess the users' response to that adaptation. That was, however, outside the scope of the development performed in this case.

Access (Physical and Software)

With respect to physical access, we faced a challenge in integration due to the physical nature of the MRTT system. With our goal to integrate an AIS with an existing simulation system and a set of physical hardware, it was incumbent upon us to connect to the physical hardware for analysis, to determine network configuration settings and communication protocols and later to test and debug the system. This was a trivial challenge for us given the static state of the MRTT system and limited operational use, but other systems may have more significant access challenges including in-use operational systems, classified systems, or data that cannot leave a secure room or facility. For systems that have regular training use or that require scheduling with instructors to gain access, close collaboration and pre-planning will likely be the best form of mitigation.

In contrast to the physical access, we discovered that the simulation software baseline access can pose significant delays to getting started with analysis and design tasks. For example, because separate entities own or store the software simulation (e.g., CCTT), the small-footprint hardware simulation equipment (E.g., DoD research lab), and the interface that was used to connect them all together, were required to establish a Distribution Agreement (DA) (to confirm that the baseline was authorized for use in support of existing DoD research goals. Based on the experience we had with getting the DA in place, we recommend investigating this early in any project, including identifying key points of contact, specific versions of software needed, and communicating deadlines or potential delays in analysis and development.

Use Case Extension and Future Research Possibilities

In determining what other simulation systems can benefit from these capabilities, we have identified several criteria that make a system a target candidate, including systems that:

- Do not currently include automated assessment support but have reasonable "shelf-life" time remaining
- Are aged but don't currently have a suitable replacement system available
- Leverage a common simulation data standard, such as DIS
- Include a robust and well-documented communication protocol
- Require significant time to evaluate individuals or teams
- Rely solely on OC to perform evaluations
- Are not used due to complicated operation procedures

An evaluation that was not explored was the use of specific controls in sequence. For example, we did not evaluate whether the crew used the correct steps to load a particular round of ammunition or the speed at which they operated the physical controls. That level of evaluation, while feasible and possible, was not the goal of this integration and is a possible future use case: do trainees know how to operate an M1A2? Can they follow procedures for loading munitions? Those are valid questions and evaluations for training, but not the evaluation we were focused on. We set out to determine whether this system could be used to evaluate crew gunnery tables in an MR environment.

In addition to identifying more suitable simulation systems to apply AIS to, there were also threads of interest that were not explored but are related to ongoing research, including:

- Predictable OPFOR: can AIS leverage artificial intelligence to inject unique / non-traditional OPFOR actions to diversify scenarios?
- Rules-based Customization Injection: combining results from other research, to trigger customizations within a VTE with customizations such as VTE difficulty modifications, and environmental effects (e.g., jammed guns, loss of visuals, etc.)[19]
- Leverage Large-Language Models to generate unique AAR feedback based on performance and OC assessments
- Leverage existing speech-to-text software integrations, such as the Team Communication Analysis Toolkit (TCAT) to evaluate verbal coordination between team members[20]

Evaluation at Individual / Team Level and How to Personalize Instruction

A step for this research is to refine the experience over multiple training runs and outcomes and then personalize and tailor feedback for each position as they perform their function.

Personalization in AIS equates to tailoring training content and material, feedback, and/or the simulation event assigned. In our use case, we evaluated the team as a whole: did the team engage and destroy the targets? The automated and manual assessments reduced the effort required to evaluate trainees and generated objective data to support AAR: who is being evaluated; was the target detected and identified and how quickly; was the appropriate ammunition selected; and finally, was the target destroyed and how quickly?

Our experience applying AIS in similar virtual training environment (VTE) suggests that we can personalize instruction and feedback in multiple ways:

1. Provide a pre-test for the trainee or team that determines and assigns a scenario aligned with skill level

[19] Cambata, et al. 2023
[20] Paul, et al. 2023

2. Scaffold scenarios as trainees or team completes missions – automate selection of scenarios based on the trainee or team's performance metrics, such as accuracy and completion time
3. Instant feedback, which is a critical AIS capability, alerts trainees to their progress and areas needing improvement or reinforcing success
4. Dynamic environment adjustments involve real-time modifications to the virtual environment based on the trainee's actions and performance. For instance, if a trainee is excelling, the system can present obstacles and increase the complexity of the environment, making the training more challenging and realistic

While not implemented, the capability exists and further reduces workload on instructors to ensure each individual or each team is challenged but not held back by the difficulty, rewarded for success, and objectively evaluated and corrected when required.

CONCLUSION

This research and development effort successfully leveraged a small-footprint manned module simulation set, repurposing it as a valuable testbed for both AIS development and crew gunnery research. Specifically, we demonstrated how we can integrate AIS with legacy software and low-cost hardware systems to support adaptive training and demonstrate renewed value in modular training systems. Using MOSA technologies, new or existing APIs, and simulation data standards, it is possible to retrofit older systems with current technologies. By integrating with AIS technologies, we also enabled real-time performance evaluation that enables personalizing feedback, and remediation. Through these connections, we add value to leverage legacy training systems.

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