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Networked Mixed Reality (MxR) Infrastructure for Collaborative Decision-Making

Theron T. Trout, Stephen Russell, Andre Harrison
Battlefield Information Processing Branch
US Army Research Laboratory
Adephi, Maryland 20783
{theron.t.trout.ctr@, stephen.m.russell8.civ@, andre.h.harrison.civ@}mail.mil

Mark Dennison
Battlefield Information Processing Branch
US Army Research Laboratory West
Playa Vista, California 90094
mark.s.dennison.civ@mail.mil

Ryan Spicer, Evan Suma Rosenberg, Jerald Thomas
Institute for Creative Technologies
University of Southern California
Playa Vista, California 90094
{suma@, spicer@, jthomas@}ict.usc.edu

Abstract
Collaborative decision-making remains a significant research challenge that is made even more complicated in real-time or tactical problem-contexts. Advances in technology have dramatically assisted the ability for computers and networks to improve the decision-making process (i.e. intelligence, design, and choice). In the intelligence phase of decision making, mixed reality (MxR) has shown a great deal of promise through implementations of simulation and training. However little research has focused on an implementation of MxR to support the entire scope of the decision cycle, let alone collaboratively and in a tactical context. This paper presents a description of the design and initial implementation for the Defense Integrated Collaborative Environment (DICE), an experimental framework for supporting theoretical and empirical research on MxR for tactical decision-making support.

Keywords: *Mixed Reality, Virtual Reality, Augmented Reality, Decision Making, Collaboration, Networking*

1. Introduction

The need for computers to support decision-making has been a requirement since the inception of computation. The advent of the Internet and ubiquitous computing has only pushed the need for such capabilities to additional limits. The advancement of decision science is similarly accelerating at the pace of the technology being developed to support it. Nonetheless, collaborative decision making still remains a focus of continuous study and is still not fully understood. Interesting questions regarding decision science remain in the intersection of contemporary information interaction, distributed computing, and complex problems (Russell & Moskowitz, 2016). New technologies in these domains create many new opportunities to explore the underlying theory of collaborative decision-making. However, before proper study can be begun it is necessary to have decision support environments where theoretical and empirical experimentation can be undertaken. Moreover, the complexities of doing any type of distributed computational study can be further complicated by computer and network security considerations.

Distributed, collaborative decision-making requires innovation at all architectural levels of technology-supported problem solving. Shared cognitive models are necessary for human interactions: the system-

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interface must support and maintain this shared representation, the data store must persist the representation at a fundamental data-level, and the network must allow data and information to flow freely and fluidly between all of the collaborative decision makers (Galegher, Kraut, & Egido, 2014; Tu & Sayed, 2014). Mixed reality (MxR) is one technology that has shown promise, for meeting these requirements in many settings, by integrating real-world observations and information with an immersive environment (Jacob et al., 2008). The immersive nature of MxR and the additional degrees of spatial freedom that MxR environments provide may prove to yield transformative benefits that enable collaborative, real-time decision-making.

Though already widely accepted for simulation, training, and gaming, mixed reality (MxR) (Kriz, Eiselen, & Manahl, 2014; Ricci, Piunti, Tummolini, & Castelfranchi, 2015; Stevens, Kincaid, & Sottilare, 2015) has received little focus as a decision aid that can improve collaboration in support of all phases of Simon's (1960) decision theory. In this paper, we present an experimental platform that enables the creation of instrumented, collaborative MxR environments and describe an early capability demonstration built on the platform. Finally, we offer some initial findings and observations on mixed-reality-enabled decision making in the military context.

Unlike simulation and training approaches that are documented in the literature, the proposed framework focuses on engendering a collaborative environment that can be used to study theoretical and empirical methods to enrich and improve tactical decisions. Further, we approach our investigation from the perspective of U.S. Department of Defense (DoD) laboratory research, where computer security is a paramount concern and thus restrictive of common, more direct, implementations. Therefore, the primary contribution in this work is focused on addressing security and confidentiality requirements relating to MxR transport and interconnection in the DoD research environment. The paper is organized as follows. The next section provides some background on mixed reality and its relationship to decision making. The subsequent section presents the architecture for what we call the ARL Defense Integrated Collaborative Environment (DICE). This is followed by an example use-case for the environment. We conclude with a discussion of our observations, a summary of our conclusion and our future plans.

2. Background

The notion that "two heads are better than one" is the core belief to support collaborative decision-making. In a time of overwhelming information, multiple "heads" addressing a decision problem is a best-case scenario. Of course, this is grounded in many assumptions, e.g. the heads are knowledgeable, allied, have the requisite expertise/experience, etc. Setting those assumptions aside, investigation into the theories of collaborative decision-making is still an important research area, one that when combined with technology becomes more complex and interesting. As reflected in the literature, collaborative performance of any type depends heavily on effective use of the tools to support the engagement (Dickinson & Sullivan, 2014). However, typically the use of technology precedes full comprehension of its effects and impact (Martin, 2017). As the U.S. Department of Defense (DoD) begins to explore broadly popular augmented and virtual reality technologies, it is important to study its uses, implementation, and impact. These technologies have seen some measure of success in applications for simulation and training. However, in the decision-support domain, the literature is quite sparse. This might lead one to believe that the technology may not be able to support the real-time nature of tactical decision-making. Yet, when the possibilities of mixed reality are considered in the context of the activities in all phases of decision making (i.e. intelligence, design, and choice), it would seem that the benefits and capabilities of augmented and virtual reality would be directly applicable, and likely to provide significant benefit.

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Mixed reality (MxR) lies in the Reality-Virtuality Continuum between the physical world and the digital world (Milgram, Takemura, Utsumi, & Kishino, 1995). Augmented Reality (AR) and Virtual Reality (VR) further subdivide this spectrum, as shown in Figure 1. AR provides a simultaneous, superimposed view of both real and virtual objects. Implementations of these technologies include heads up displays (HUDs), Google Glass, and monitor-based systems where virtual objects appear to coexist with real world objects captured by a camera and rendered on a display. On the other hand, in a broad and convergent context, MxR, includes AR and VR as shown in Figure 1, but ensures a connection to the physical world. In this sense, MxR may have the potential to bridge and integrate physical observations, such as from sensors, cameras, and actuators with digital data or information needed to effect tactical decisions.

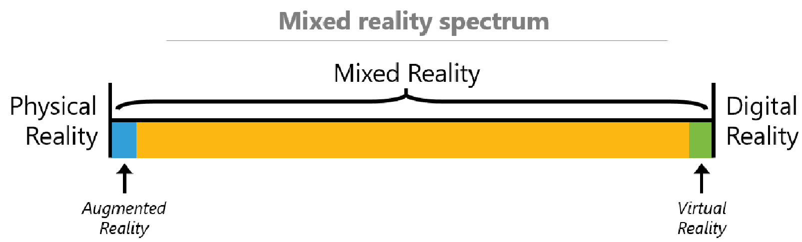

Figure 1. Mixed reality technology spectrum. Adapted from Milgram (1995)

MxR implementations often include a head-mounted display that renders a real-time visualization from the user's point of view, where virtual objects are anchored to the real world in a meaningful way (Jacob et al., 2008). To illustrate this utility, imagine a modern battlefield with geospatially diverse information sources and actuators (i.e. devices that can affect the physical world such as door openers, lighting, or motion sensing). Now consider a group of soldiers who are connected to an MxR-equipped support analyst operating in a forward tactical environment. Using a head mounted MxR display, the analyst would have access to information, such as unattended ground sensors, drone feeds, satellite imagery, and actuators/autonomy that are not readily available to the forward soldiers. In this manner, virtualized MxR battlefield information of tactical significance may be accessed, assessed, and operationalized faster than traditional methods that have spatial constraints. Through interaction with MxR representations and analytics of real battlefield resources, the analyst thus may be able to accelerate tactical decision-making on behalf, or in collaboration with, the forward soldiers.

MxR has demonstrated advantages for training and simulation. Examples of MxR training and simulation systems include Rockwell Collin's Coalescence mixed reality system, Northrop Grumman's Adaptive Learning & Performance Support (ALPS) system, and many other systems that provide MxR training and simulation in other industries (Gauglitz, Nuernberger, Turk, & Höllerer, 2014; Gardner & Sheaffer, 2017). In each of these systems the MxR capability provides access to both the physical world and the virtual world, allowing users to balance the benefits of each to achieve system goals (Hughes, Stapleton, Hughes, & Smith, 2005; Kirkley & Kirkley, 2005; Roo & Hachet, 2017). We do not delve into the details of these systems here because there is ample exemplars in the literature. Despite the "coolness" and promise of these capabilities, and to underscore the need for additional decision-making related research, novel interfaces for decision support have traditionally been challenging for decision-makers to understand and interpret (Livingston, Russell, Decker, Leadbetter, & Gilliam, 2015). Further, there is little documentation in the literature of the quantitative benefits of MxR in an operational decision-making context. It is largely unknown which display platform is best for any given scenario, and the field has yet to determine a set of tasks and validated measures for assessing optimality. Nonetheless, the performance gains shown in training and simulation suggest that there is reason to be optimistic that MxR may provide value in decision contexts.

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As noted, the literature on MxR for decision-making is surprisingly sparse. The work by Lenuik et al. (2015) provides one example of MxR employed for decision making in the context of the DoD. This research employed a web-based MxR environment to support decision-making in the acquisition cycle. This research used the U.S. Marine Corps' trade space analysis tool, known as Framework for Assessing Cost and Technology (FACT), to allow users to view new designs ("to be") overlaid on existing systems ("as-is") in order to understand proposed design options and implications. While their work did have a contribution as a decision-support system, it was neither collaborative nor tactically oriented. Our work in intended to extend Lenuik's effort in examining requirements for immersive collaboration and the potential for real-time (potentially tactical) decision making. To this end, our effort is focused on investigating the feasibility of what we call the Defense Integrated Collaborative Environment (DICE). In the following section, we describe the generalized DICE architecture that addresses the concerns of DoD security policies, while providing an environment where experimental research on collaborative decision-making can be conducted.

3. Defense Integrated Collaborative Environment (DICE) Architecture

DICE is intended to provide a secure, policy-compliant network environment in which scientists and engineers can performance research, run experiments, and test and evaluate prototype systems. Critical to the success is ubiquitous access to telemetry capture, analysis, and reporting capabilities. To put the research in this paper in context, we spend a bit of space describing the general complexities of DoD research computing environments. Many of these requirements are available in the literature, so we do not go into great detail here.

The struggle between adversaries and the operators of information systems and networks is well known and ongoing. The size and complexity of US DoD networks and systems necessitates homogeneity of systems in order for administration and maintenance to be viable within existing manpower and technology constraints. Policies and procedures have been implemented to ensure compliance with the established security best practices and adherence to trusted baselines. The concept of least privilege is applied with the goal of restricting the operations available to a system user to the minimum set necessary required to complete their assigned responsibilities. This methodology can be applied effectively in many operational environments with common, well-understood operational activities. However, this approach is often a poor fit in research and development environments.

One common approach for information assurance (IA) in the DoD is to control user capabilities and to block, format, and rebuild any system that is found deviating from approved baselines operations. The mission of DoD scientists and engineers is to investigate and develop new capabilities and create novel systems. This science and engineering mission may be at odds with the IA approaches that have been found to be effective in non-research DoD computing environments. Information assurance in a research and development context may require adjustment of operational security methodologies. Network segmentation and boundary monitoring for anomalous activity is one method for providing the type of flexibility needed for research work. A key goal of DICE is to provide networking capabilities tuned for the requirements of researching MxR systems and (through emulation) tactical environments that are highly reliable. Engineering a secure and reliable implementation is critical to obtaining DoD IA approvals required to operate the network.

The extensive growth and adoption of cloud service providers in recent years has led to the creation of Federal Risk and Authorization Management Program (FedRAMP). FedRAMP establishes policies and

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procedures for government and commercial entities to accredit and operate systems in commercial cloud environments for the benefit of the US Government. The basic philosophy is that the cloud service providers obtains and satisfies an extensive set of security compliance and auditing requirements. Once completed and approved they are granted an Authority to Operate (ATO). Users of FedRAMP-approved cloud services then inherit the security controls satisfied in the FedRAMP ATO and concentrate on implementing the remaining controls as applicable to their system's operational requirements.

Interaction with collaborators outside of the DoD is a core requirement for DICE. It is essential that no external collaborators or participants in DICE are able to gain access to DoD internal resources. Consequently, DICE requires that any data, services, or resources to be shared must be pushed into the DICE server space and access policies modified to grant access explicitly to authorized participants. Figure 2 shows a generalized example of the DICE deployment.

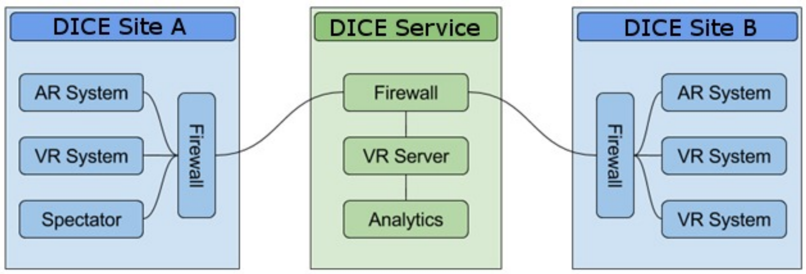

Figure 2 - DICE Deployment Diagram

3.1. A Secure Mesh Network

Integrity, confidentiality, and reliability are key elements of network security. Integrity ensures that the message received is free of unauthorized alterations and tampering. Confidentiality prevents access to data by those not authorized to receive it. Reliability provides confidence that a transmitted message will reach its destination. One common mechanism for achieving acceptable levels of network security requirements is through the use of encrypted mesh networks. The Open Virtual Private Network (OpenVPN) protocol emerged as an acceptable mechanism for use in DICE. Some characteristics supporting its adoption are its broad acceptance in the commercial networking space and its ability to transport UDP packets; the latter being necessary to establish a shared MxR environment using the Unity engine's standard networking features.

3.2. Policy Based Security

Policy based security allows for the creation of rules that grant privileges and impose restrictions on different categories systems and users. DICE uses the concept of security groups to implement policy-based security in relation to network traffic control. A dedicated OpenVPN server is configured for each participating organization. One or more security groups are associated with each server thereby establishing network access rules that define the access granted to members of each organization. If finer-grained access control is required then additional OpenVPN servers can be instantiated and associated with groups within each organization as necessary.

A legitimate concern exists for DoD network administrators when outbound VPN access is available to users of their networks. Traffic that flows through the VPN tunnel will be encrypted and is generally not accessible to intrusion detection systems (IDS), intrusion prevention systems (IPS), and other network security stack elements. DICE is configured to deny access to the Internet from OpenVPN servers thereby preventing users from bypassing their local security stack.

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3.3. Instrumentation and Telemetry Capture

The DICE infrastructure incorporates instrumentation and telemetry capture backed by Elasticsearch, Logstash, and Kibana (ELK). Collectively these capabilities are called an ELK stalk. Elasticsearch is a NoSQL database engine designed for large data analytics and machine learning. Logstash is a modular and configurable data import engine. It includes an extensive array of data input, filtering, and output plugins. This makes it suitable for collecting experimental data in environments composed of heterogeneous systems and data formats. Kibana is a web application that provides access to powerful querying and analytical tools as well as data visualization and graphing tools. The ELK stack provides a capable toolset for collecting and analyzing telemetry from experiments performed in DICE.

4. DICE Proof-of-Concept Demonstration

To assess the feasibility of DICE, a demonstration scenario was created that had soldiers as analysts in the "rear" to support and virtually interact with soldiers in "forward" environment. The demonstration scenario consisted of three human participants along with simulated AI entities. The first participant was an operator in the forward area who wore a Microsoft HoloLens optical-see-through display. The second was a VR-enabled support analyst in the rear, utilizing an HTC Vive headset and integrated motion tracking system. The third was an additional support analyst, also in the rear, who was equipped with third-person visibility of the scenario via conventional computer displays. Finally, the synthetic actors consisted of three virtualized soldiers patrolling the forward area. All three participants were connected with audio that simulated radio communication. The forward soldier was tasked with monitoring the movements of the virtual actors and two support analysts were to help maximize the situational awareness of the soldier in the field.

US Army Reservists stationed at ARL were invited to experience the system and consider how the virtual presence capability might be employed to support collaborative decision-making in the context of the scenario presented. The soldiers were asked to patrol the hallways and to communicate to each other about the movements and activities of the synthetic soldiers in the environment. No specific mission objectives were identified, rather the participants were asked to freely explore the system and to provide their thoughts and observations. The participants were also asked to consider to what degree they felt that the system assisted them in communicating effectively with remote participants.

The purpose of this demonstration was to perform an initial evaluation of the viability for DICE to enable mixed- and virtual-reality interactivity between geographically separated participants in a DoD-networked tactical setting. Preliminary anecdotal assessment was informal and based on user feedback yielded positive system responsiveness and performance. This included qualitative comments on both the visual experience relating to the MxR and VR elements, as well as the quality of the audio communications operating over the same VPN links.

4.1 Initial Observations

The soldier participants provided feedback that indicated they were in favor of the capabilities demonstrated by the system. The participants commented on the limitations of the equipment used in the test: specifically the narrow field of view provided by the headset employed in the evaluation. This negative issue did not seem to reduce the participants' level of enthusiasm for the potential DICE demonstrated. They expressed a consistently favorable opinion that the capability could be leveraged to support various missions which they performed previously under traditional conditions. It is unclear to what degree any of the participants' past experiences with video games and/or science fiction media may have resulted in a biased perspective on the technology. The presence of such a bias factor may be worthy of consideration in the design and implementation of experiments to evaluate the performance impacts of

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MxR systems in the tactical environment with respect to traditional visualization systems. We do not consider these results to conclusively prove anything, besides the feasibility of DICE to address the DoD operational concerns and for the implementation to be used in experimental evaluation of MxR-augmented tactical decision-making. However, these preliminary observations underscore that the design and development of structured experimentation to test these tactical decision augmentation would be valuable. It will be important to determine if the perceived enhancements to situational awareness expressed by the soldiers would manifest in measurable decision performance improvement. Additionally, careful steps must be taken to ensure that MxR environments are designed to maximize user comfort and that systems are in place, when possible, to track changes in behavior and physiology that are indicative of motion sickness (Dennison, D'Zmura, & Wisti, 2016).

5. Conclusions and Future Work

In this paper, we have shown an experimental network to enable the development of an MxR collaborative decision-making framework that is capable of addressing performance, transport, and security considerations in a DoD research context. While the initial evaluation of the systems was qualitative, it did demonstrate that the DICE architecture performed adequately in a controlled situation, illustrating feasibility. Moreover, DICE demonstrated the viability of collaborative MxR decision support concept, while operating in compliance with DoD Information Assurance policies and regulations. Our planned future work will include additional instrumentation of DICE, e.g. network and application performance monitoring to include link utilization, tactical network emulation, and participant behavior logging. It is expected that this instrumentation will provide quantitative performance data that can be used for controlled measurement during experimentation and subsequently for evaluation. Once the instrumentation is implemented in the framework, we plan to conduct an empirical evaluation to assess the efficacy of MxR in tactical decision-making situations by measuring decision outcome accuracy, speed and confidence. It may also prove beneficial to assess real-time changes in individual's cognitive load, attention, and comfort through non-invasive cortical measures like electroencephalography (EEG) and cardiovascular measures such as impedance cardiography (ICG).

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