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ARMOUR X: Augmented Reality Mission Operations UseR eXperience

Robert A. Berardino and Arthur O. Tucker IV

AR VR MR

ABSTRACT

When developing ARMOUR X (Augmented Reality Mission Operations UseR eXperience), a Johns Hopkins University Applied Physics Laboratory (APL) team set out to explore whether mixed reality technologies can help military space professionals realize a common operating picture. Through an independent research and development (IRAD) grant from APL's National Security Space Mission Area, the team sought to address the present-day problem of communicating large quantities of data and information with outdated presentation and visualization modalities. Through the use of mixed reality technologies (e.g., augmented reality and virtual reality) to create immersive experiences, the system aims to facilitate effective decision-making in operational environments with narrowing tactical timelines, such as space. During its three consecutive years of funding (FY2017–2019), the ARMOUR X team accomplished most of its engineering objectives, created a portable demonstration system for stakeholder engagement, and acquired stakeholder community feedback to inform system design decisions and future directions.

INTRODUCTION

In his 2016 white paper, "Space Mission Force: Developing Space Warfighters for Tomorrow,"[1] General John E. Hyten, who at the time of publication was commander, Air Force Space Command, wrote:

> Today, our space operators are trained to mitigate environmental and manmade risks to complex and capable space systems. As the military threats to these systems grow, our training must shift to counter these threats. **Our space forces must demonstrate their ability to react to a thinking adversary and operate as warfighters in this environment and not simply provide space services** [emphasis added].

To achieve this goal, military space professionals must contend with the broad software and systems engineering challenge of reconciling data volume and velocity with ever-narrowing tactical timelines. They are inundated with a deluge of information affecting their mission but, almost paradoxically, must now move beyond passively observing data to experiencing data more interactively, in mission context, so that they can "operate as warfighters in this environment."

Despite these changing realities and requirements, military space professionals—and computer users in most other professions—have relied on display technology and input modality (i.e., a computer monitor, a keyboard, and a mouse) that has not fundamentally changed in over four decades.[2] It is dated and insufficient for the advanced data visualization and interaction needed to achieve General Hyten's vision.

With the availability of commercially viable augmented reality (AR) head-mounted display (HMD) technology like the Microsoft HoloLens,[3] an APL team sought and was awarded independent research and development (IRAD) funds to investigate AR technology as a possible solution to these near-term challenges. The result is ARMOUR X (Augmented Reality Mission Operations UseR eXperience).

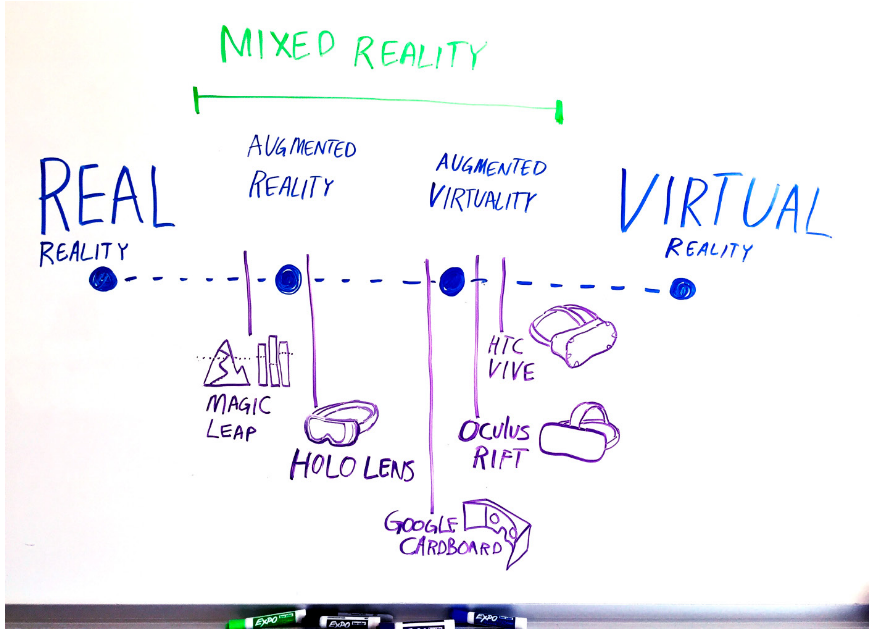

Figure 1. MR scale with recently released HMDs. (Reprinted with permission from Ref. 5.)

TECHNOLOGY SELECTION

The first step in developing ARMOUR X was determining which technology to use. Paul Milgram and Fumio Kishino were some of the first researchers to consider the relationship between AR and virtual reality (VR). They and their team built a taxonomy for describing display technologies that fit in the world of AR and VR and influenced future thinking on the subject by defining the reality–virtuality continuum, also known as the mixed reality (MR) scale.[4] See Figure 1 for a sketch showing where modern-day HMDs fit along the continuum.

Charlie Fink, who writes about VR and AR for *Forbes*, *Medium*, and other outlets, defines the terms in his 2018 book:

- VR is "an experience that requires a headset to completely replace a user's surrounding view with a simulated, immersive, and interactive virtual environment."[6]
- AR is "overlaying or mixing simulated digital imagery with the real world as seen through a camera and on a screen. Graphics can interact with real surroundings (often controlled by users)."[6]
- MR is "an experience that always gives the user a view of their real surroundings, but uses a headset to overlay graphics that are interactive with actual reality (augmented reality), and/or incorporates elements from actual reality into a virtual environment (augmented virtuality)."[6]

AR devices were selected for the ARMOUR X system implementation. Potential use cases, such as planning and analysis in operations environments with a variety of mission-critical legacy technologies, influenced this decision. In addition, the diversity of skill sets and job functions in the operations environment limits the usefulness of HMDs. The ability to demonstrate rich collaboration among users who may or may not be equipped with an HMD requires alternative device form factors that support AR technology. Additional advantages of AR include:

- When used as part of a collaborative virtual environment, it can improve communication among team members who are geographically distant.[7]
- It provides a medium that can fundamentally change the way complex spatial concepts and content are understood.[8]
- Integration of AR technologies in applications has been shown to improve productivity in the performance of tasks.[9]

RESEARCH GOALS AND HYPOTHESIZED BENEFITS

The ARMOUR X team sought to understand how AR technology could best be leveraged to provide immersive experiences to mission operators and space situational awareness analysts. Additionally, with the assumption that the technology will become ever-present in many information technology (IT) environments, the team sought to identify the architectural components and integration pathways that space missions and enterprise IT systems would need to adopt to make use of the technology. Other questions that bounded the research effort include:

- How can we achieve a space common operating picture in an AR immersive experience?

- Can AR experiences solve battlespace management visualization challenges and identify points of intersection with other domains, such as air and missile defense, for multi-domain battlespace management command and control?

Beyond the aforementioned benefits of AR technology, the ARMOUR X team hypothesized it could deliver an AR user experience that stimulates thinking and approaches to problem solving that could possibly improve reaction time, produce new data products, inform higher-fidelity spacecraft courses of action, and result in a framework of core software components that can be reused to create derivative experiences and tools.

REQUIREMENTS DEVELOPMENT PROCESS

Software development for ARMOUR X followed an Agile workflow. In addition, because the application largely involves human interaction, there were multiple iterations of interacting with users and subject-matter experts (SMEs), eliciting feedback, and developing new features for future demonstrations. Major demonstrations to SMEs or at workshops and conferences defined the length of a development sprint. The team met weekly to discuss development and design decisions.

The team determined initial system requirements based on feedback from an early stage in the development process. Specifically, it was critical to implement a portable prototype to facilitate stakeholder engagement. The prototype system needed to be able to be taken outside of APL for demonstrations where others used the system and the development team captured meaningful feedback from users. Because of this requirement, the system could not rely on constant internet access. In addition, SME feedback indicated that multiple users would need to be able to interact with the system, experience the visualizations, and collaborate with each other in a physical environment.

SYSTEM DESCRIPTION

The ARMOUR X application consists of an interactive geocentric visualization in AR of multiple resident space objects (RSOs), simulated trajectories, information panels with representative RSO field of view, and user interface (UI) widgets, as shown in Figure 2. Hundreds of models can be visualized simultaneously, representing RSOs from low Earth orbit to geosynchronous orbit. The UI widgets allow the user to control the current date, time, and speed of scene playback. The user can select individual RSOs to toggle trajectory visualization, highlight the RSO to share in a multiuser setting, or view detailed information and field of view. Multiple users can participate in a collaborative session, including users with AR-capable devices and users with traditional computer displays. Specific actions taken by a user are reflected in the visualizations of other users, regardless of whether the users are in the same physical location.

The ARMOUR X system architecture was designed to meet the functional needs of identified use cases. As such, one of the top-level requirements was system portability. The application must be usable in a variety of settings and easily transported for demonstration purposes. The operational system needs to function completely using components that can fit inside of a duffel bag or backpack. Today, most mobile device applications rely on regular access to data made available via external cloud services, enabled by wireless networks and the internet, to function properly. This same paradigm has already been shown to be useful for commercial AR and VR applications, such as computer games.

In the case of ARMOUR X, additional constraints limited the system's ability to access data remotely. AR HMD devices are a relative novelty to enterprise IT infrastructures. Although established security policies allow many kinds of devices to interface with the typical corporate network, the limited availability and lack of standardized security management applications for these devices, as well as their real-time processing requirements, necessitated the creation of a separate

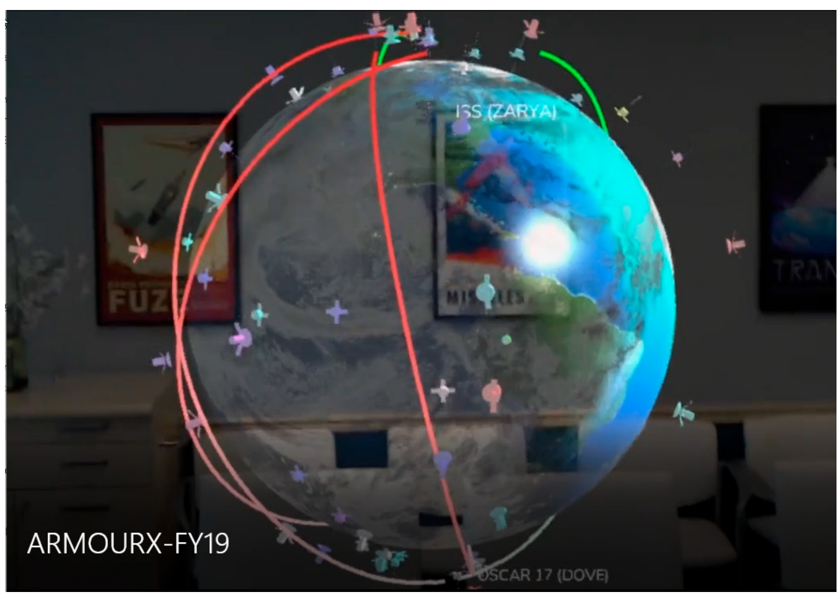

Figure 2. RSO visualization. The ARMOUR X application consists of an interactive geocentric visualization in AR of multiple RSOs, simulated trajectories, information panels with representative RSO field of view, and UI widgets.

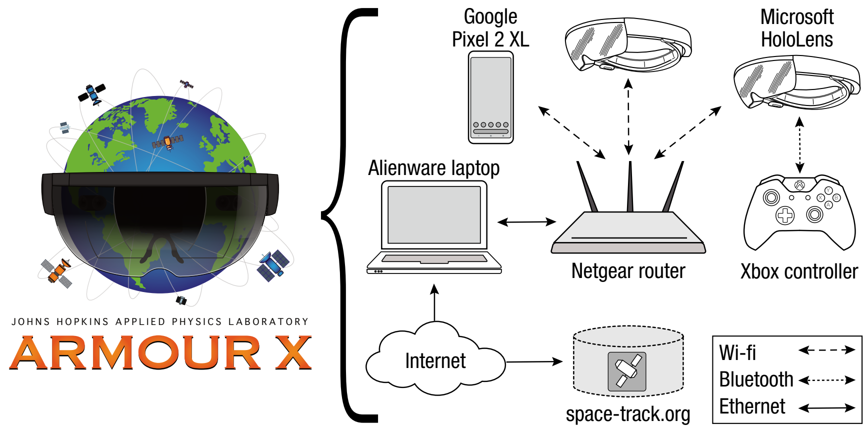

Figure 3. ARMOUR X physical architecture. The system consists of mobile viewing devices and data service applications running on a commodity laptop. Mobile clients access the data services over Wi-Fi on an ad hoc local area network, and Bluetooth-enabled Xbox controllers are configured for user input.

siloed environment within APL's network. Because of this limitation, the system needed to be designed so that all the application data requirements could be met within the portable system, with the potential to expand to externally available data sources in the future.

Although the system architecture design accounted for the possibility for future connectivity to remote cloud services, the basic functionality of the operational system was built to be portable and self-contained. As illustrated in Figure 3, the system consists of mobile viewing devices, including the Microsoft HoloLens HMD and the Google Pixel 2 XL phone. Multiple data service applications were built to run on a commodity laptop. Mobile clients can access the data services over Wi-Fi on an ad hoc local area network. Bluetooth-enabled Xbox controllers are configured for user input. The system is bootstrapped and updated at periodic intervals by connecting to the internet to download RSO characterization data.

The AR client application was developed, built, and deployed on two AR-enabled mobile devices. The Microsoft HoloLens HMD was chosen as a target device because of its availability and extensive software development resources and support. The HoloLens provides multiple ways to interact with the device and its visualization content, including voice commands, hand gestures, and button-based interface devices such as hand clickers and game controllers. The ARMOUR X HoloLens client was developed to support all these interaction modalities. Orbit simulation calculations are performed on the device and external messaging is supported using Socket.IO. Vuforia image recognition is used to coordinate the placement of the AR scene between multiple physically colocated users and an image marker located in the physical environment. The application was modeled in Unity, and the Microsoft Visual Studio Integrated Development Environment was used to program object behavior scripts in C# and deploy the built application image to the HoloLens. The same tools were also used to develop and build the AR client application for the Google Pixel 2 XL mobile phone device, which was selected based on its availability, software development support, and screen size. Unlike the HoloLens AR application, the Pixel AR application only provides interaction with the system via the device touchscreen. Multiple HoloLenses and mobile devices can be connected simultaneously to an interactive and collaborative session, as shown in Figure 4.

A web-based client application was also developed to illustrate how the same data provided by the back-end services can be consumed and visualized using a traditional web dashboard application that is integrated into the same collaborative environment as the AR-based applications. The web client was developed in JavaScript using Angular 7. Angular Material was used for UI widgets and CesiumJS was incorporated for RSO and trajectory visualization. The application also uses the Socket.IO messaging library to send and receive session information to the back-end services.

Multiple service-oriented back-end applications were developed based on free, open-source software. Within

Figure 4. ARMOUR X collaborative experience. Two users, each wearing a Microsoft HoloLens and using an Xbox controller, interact with the system simultaneously.

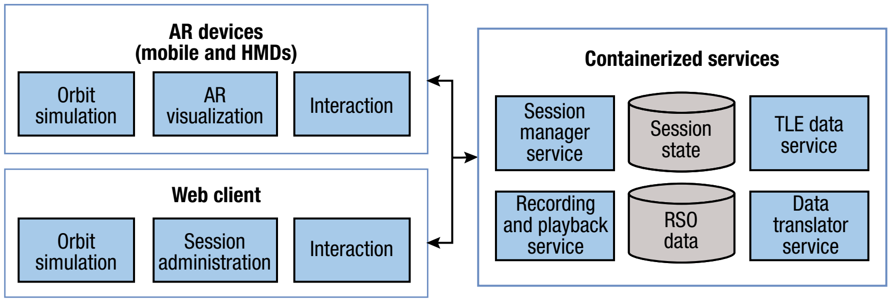

Figure 5. ARMOUR X system components. Within the microservice architecture, four service-oriented back-end applications were built and deployed in Docker containers.

the microservice architecture (shown in Figure 5), four applications were built and deployed in Docker containers, and Docker Compose was used to manage the container configuration and execution. The four applications are detailed below.

The session manager service provides a centralized hub for managing the software-based publication and subscription (pub/sub) messaging bus. The application was developed in JavaScript using Node.js. The Socket.IO library is used to pass messages containing session-based information between all the clients that subscribe to a particular session. For example, if a user selects a particular space object to view its trajectory via any of the client applications (HMD, mobile, or web), this event and the associated information (e.g., North American Aerospace Defense Command identification of RSO) is passed along to all the subscribed clients. The state of the session is also managed by this application through the use of Redis, a key-value datastore. Multiple pieces of data, such as the names of users connected, playback date and time, playback speed, and the selected RSOs, are stored on a Redis Docker container and updated during each session.

The recording and playback service records user actions during a session and plays back the actions from a recorded session. The application is based on Node.js and subscribes to messages over the Socket.IO bus. The messages from a session are recorded as comma-separated value (CSV) text files on the host computer file system. Recording and playback are initiated from the web-based client UI. A web-based client is important to the overall user experience for two reasons: it provides users with amplifying information about the task being executed and it provides those outside of the experience with valuable information about what is going on inside of the immersive experience. Another factor is the pragmatics of immersive experience design: HMDs are currently expensive, so organizations in the early years of adoption and experimentation might not have many devices.

The two-line element (TLE) data service is an application that provides a RESTful interface to a MySQL database. Data can be stored and retrieved on a MySQL Docker container via Uniform Resource Locators (URL) and various query parameters. Using this service, the client applications can download TLE data, which is the mean Keplerian orbital element at a given point in time, and from this information extrapolate RSO trajectories that can then be visualized. The application is written in the C# language.

The data translator service provides a capability to obtain TLE data from an external source and extract and translate this information into a form that can be stored by the TLE data service. Originally developed as a command line application in Java, it was converted into a servlet that runs on an Apache Tomcat HTTP web server Docker container. A web-based UI is provided for specifying the source location of TLE data (external resource or local text file), the type of TLE data to obtain (e.g., debris, communication satellites), and the destination for the data on the ARMOUR X system (TLE data service or local text file). The external data sources supported by this application include those from Space-Track.org, a US government-curated space situational awareness data repository, and the Radio Amateur Satellite Corporation (AMSAT). TLE data are obtained before system execution via an out-of-band connection to the internet.

Each of the service-oriented applications can be relocated to one or more external servers in a robust enterprise environment, within a commercial cloud environment such as Amazon Web Services (AWS) or Microsoft Azure, or across the internet. By building the microservice applications and deploying them to Docker containers, portability across compatible systems is maintained.

USER ENGAGEMENT

One of the initial goals of ARMOUR X was to create a system to engage SMEs to identify space-based battle management visualization challenges and understand how AR technologies can not only address those challenges but also be integrated into operational settings. In keeping with this goal, a top-level requirement was that the system be portable so that it could be taken into the field for demonstration and solicitation of user feedback. ARMOUR X was taken to various conferences and workshops, where the team demonstrated the system and captured feedback from distinct groups representing potential sponsors, ground system architects, and other AR/VR researchers. The key venues where ARMOUR X was presented are listed in Table 1.

Table 1. Key venues where ARMOUR X team demonstrated capability, sought knowledge, and collected feedback

Fiscal Year	Venue
2017	First mini-workshop, "Augmented, Virtual, and Mixed Realities: Creating Value across the Mission Development Lifecycle with the Application of xR Technologies," at the 6th International Conference on Space Mission Challenges in Information Technology (SMC-IT) (Alcalá de Henares, Madrid, Spain)
2018	Poster presentation at the 2018 National Fire Control Symposium (Oahu, HI)
2018	Poster presentation at the Multi-Domain BMC2 Workshop at APL (Laurel, MD)
2018	Poster presentation at the Science & Technology (S&T) Showcase at APL (Laurel, MD)
2019	Technical demonstration at the 2019 National Fire Control Symposium (Orlando, FL)
2019	Technical demonstration at the Ground System Architectures Workshop (GSAW) (Los Angeles, CA)
2019	Technical demonstration at the SPIE Defense + Commercial Sensing Conference (Baltimore, MD)
2019	Presentation (Space Track) and Technical Demonstration at xR Symposium at APL (Laurel, MD)
2019	Second mini-workshop SMC-IT (Pasadena, CA)

LESSONS LEARNED

The ARMOUR X system provides a platform to engage users and get their impressions of working with a new computing and visualization medium. Many users experienced AR for the first time when interacting with ARMOUR X. The engagement strategy of providing a highly interactive, engaging demo while querying users conversationally in situ allowed for genuine conversations and ad hoc brainstorming of ideas. It was favored over a more clinical approach to experimentation, time trials, and data capture. Whereas other research efforts sought to prove the general benefits of AR,[10] ARMOUR X focused on applying the technology to an operational warfighting context. General themes of user feedback included:

- **Manipulate points of view.** The omniscient view of Earth that drives the primary user experience is less relevant than the ability to view a specific geographic region, theater, or conflict zone.
- **Display sensor data.** In addition to higher-fidelity geographic laydown of the region, visualizing electromagnetic spectrum and other measurements from data collectors would benefit users.
- **Connect to other systems.** Have ARMOUR X interface to simulation environments with knowledge of order of battle, doctrine, or other rules engines to visualize strike and counter-strike and to play through "what-if" scenarios.
- **Display multi-domain assets.** Beyond simply displaying RSO objects, and predicated on being able to zoom in to a specific region/theater, visualize additional multi-domain Blue and Red assets (e.g., land, air, sea).

CURRENT CHALLENGES

Several things, not necessarily specific to ARMOUR X and its research focus, continue to challenge engineering teams attempting to field AR solutions. These challenges, described in more detail below, include security, rapidly maturing tools, and organizational mind-sets.

Given the novel nature and highly dynamic period of development in the HMD hardware industry, security is a paramount concern. Using HMDs in a classified setting is an unresolved challenge hampering wider adoption of the technology. The Virtual Worlds Forum (VWF) is a group of US government representatives researching, developing, testing, assessing, and using VR, AR, and MR applications to enhance various aspects of their respective mission areas.[11] The VWF meets every quarter at locations throughout the United States, giving participants an opportunity to collaborate on common interests.[11] ARMOUR X team members are active participants in the VWF and are working with the broader community to try to develop best practices for getting HMDs accredited to use in broad settings, including secure facilities.

Another challenge is the rapid maturation of tools. Creating robust and reliable immersive experiences depends on disciplined software engineers writing quality software. A software engineer's tool chain enables their productivity. The tools and software libraries that enable AR experience development are new and rapidly changing. This means having to deal with shifting interface contracts, otherwise known as "breaking changes," resulting in software that has to be rewritten to accommodate the changes. Engineering teams must budget additional time to cope with this challenge.

And, finally, organizations' attitudes about technology adoption can be a barrier. In its Hype Cycle for Display and Vision, 2020, Gartner, the world's leading research and advisory company, positioned MR, AR, HMDs, and VR in the Trough of Disillusionment phase. Gartner estimates a 2- to 5-year timeline for mainstream adoption for VR and a "moderate" benefit rating, while it estimates a 5- to 10-year timeline for MR, AR, and HMDs and a "high" benefit rating.[12] Significant benefits notwithstanding, organizations with low tolerance for risk will lag in adopting these technologies.

FUTURE WORK

Elements developed during the ARMOUR X IRAD project have avenues for further research and exploration. Although the project established a notional architecture for delivering a portable prototype system, scaling ARMOUR X to support real-time, collaborative AR for use in an operational scenario requires additional investment. A reasonable pathway toward that maturity would be to enhance the system to support modeling and simulation visualizations and to use it in war game exercises in a prototype capacity. This would raise the system's technology readiness level and help military space professionals identify data requirements and use cases for next-generation immersive environments. Aspects of this maturation are already taking place. ARMOUR X is a component of a FY2020 APL IRAD effort to conduct research into the software integration risks of a specific enterprise architecture.

Another promising focus area involves the concept of digital twins. Digital twins are virtual representations of physical entities—digital replications that enable the exchange of data between the physical and virtual worlds, thus facilitating the means to monitor, reason about, and optimize a fielded operational asset.[13] While ARMOUR X displayed multiple RSOs, each distinct RSO model could be considered a digital twin instance of its physical complement. Further adaptation of the ARMOUR X prototype's immersive experience or reuse of its back-end components could enable derivative experiences and avenues for future research. Another APL project that explores the primitives of a digital twin system is underway.

Throughout the execution of the ARMOUR X IRAD project, there were many discussions about the future working environments of military space professionals. Technological innovations slowly find their way to the operations room floor. There has been a lot of original thinking and research in the domain of work spaces of the future. One example, the Future Analyst Workspace (A-Desk), was conceived after consultation with the National Geospatial-Intelligence Agency and with support from the US Intelligence Advanced Research Projects Activity.[14] While the initial prototypes for the A-Desk predate the era of lower-cost HMDs, prototype experiences like ARMOUR X reinvigorate the idea of future work spaces. Research or pilots exploring purely immersive work spaces for the military space professional, similar to offerings like Spatial,[15] would continue to unearth requirements for future systems and acquisitions.

CONCLUSION

A number of technical milestones were accomplished during the ARMOUR X IRAD execution, including APL implementation of non-colocated collaborative user sessions, service containerization, and a second-screen user experience that enhances the AR user experience while allowing users in "real reality" to collaborate without an HMD.

ARMOUR X TRAVELS TO USERS

The road show kit for the ARMOUR X prototype system consists of the following:

- Two Alienware laptops
- One NETGEAR wireless router
- One tripod
- Two to four sets of paired HoloLens and Xbox One controllers
- Two banner displays (one for ARMOUR X and one for APL)
- ARMOUR X logo stickers

The system has a minimal footprint, often taking up no more than a 6-foot folding table (see Figure 6). A HoloLens running the client application is attached to a tripod. A Windows 10 laptop runs the Connect app and, using Miracast (also known as direct Wi-Fi), projects the ARMOUR X client experience point of view, creating an attract screen to draw in users and begin a conversation. First the team talks to users to assess their experience with AR, their technical background, and their data challenges and to briefly introduce them to ARMOUR X. Then users move on to an HMD demo with the HoloLens, guided by a member of the ARMOUR X team. During the guided HMD session, users are casually asked a variety of questions to gauge their reaction to, interest in, and comfort level with the system. This formalized but casual interaction with users and SMEs provided immensely valuable feedback and informed the team's prototyping efforts.

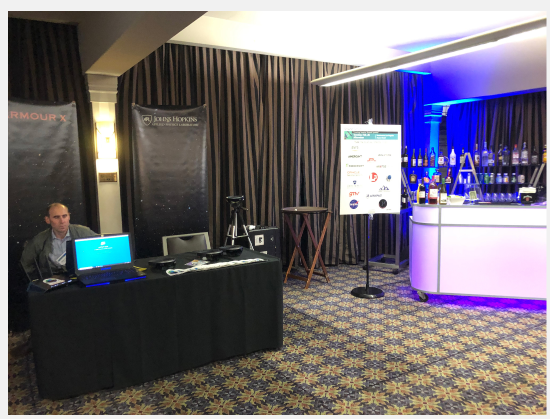

Figure 6. The ARMOUR X demonstration system. Shown here is the system set up and ready for demonstration at the 2019 Ground System Architectures Workshop (GSAW). A top-level requirement for ARMOUR X was portability so that the system could be demonstrated in the field to capture user feedback.

By providing a geocentric visualization with a representative sample of RSOs, ARMOUR X was able to prototype a reference system architecture and application demonstrating functionality that could someday enable users to effectively analyze complex relationships in a collaborative operational environment. Military space professionals, operational decision-makers, and space control analysts can benefit from having a capability that allows them to collaboratively build, visualize, and interact with space mission models and simulations in an AR immersive experience. AR technologies provide capability to collaborate beyond just sharing data—context, analysis, and experience are shared—resulting in a common operating picture that strengthens the capabilities of the warfighter.

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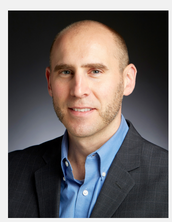

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