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LEVERAGING INDUSTRIAL MIXED REALITY SUCCESSES FOR SAFEGUARDS

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ABSTRACT

Augmented, mixed and virtual reality systems have the potential to assist International Atomic Energy Agency (IAEA) inspectors and technicians with a variety of tasks at nuclear fuel cycle facilities, decreasing the number of person-days of inspection and technician visits required to meet safeguards objectives. Although augmented, mixed, and virtual reality are closely related, this paper will define the differences between these technologies, introduce the range of hardware and software options that are commercially available, and describe potential cost-effective application of these technologies to safeguards use cases.

INTRODUCTION

Augmented reality (AR), mixed reality (MR), and virtual reality (VR) technologies are closely related technologies that describe immersive environments in which the physical and virtual world are merged. How they are merged and how users interact with each is what differentiates each from the other. In this paper we will try to use the following definitions:

Augmented reality—Typically used with smartphones or tablets. Applications overlay digital information (e.g., data or images) onto a real-time camera feed of a physical environment, which is then displayed on a screen. For example, games like Pokémon Go or home decorating apps like the Home Depot's Project Color App, which lets users virtually paint surfaces.

Virtual reality—Typically uses a headset that encompasses the user's entire field of view. The user experiences an entirely computer-generated world of imagery and sounds, which they can manipulate using hand-held controllers or hand gestures [1]. Recently VR systems from Oculus and those in the HTC Vive family have brought VR to mainstream gaming with popular titles such as Beat Saber and Half-Life: Alyx.

Mixed reality—Typically uses a headset with transparent visor that allows users to see the physical world and 3D holographic projections. Users can interact with virtual objects using hand-held controllers or hand gestures. The Microsoft Hololens 2 may be the most widely adopted headset with applications targeted primary at enterprise users. Figure 1 and Figure 2 show example mixed reality headsets.

Extended reality—AR, MR, and VR technologies often fall on a continuum, which sometimes makes it difficult to clearly define a technology as one or the other. Often the technologies are lumped together and described as *extended reality* or *XR*.

EXISTING COMMERCIAL APPLICATIONS

A variety of commercial fields have taken advantage of AR, MR, and VR technologies, including the manufacturing and repair, medical, and telecommunication domains [2–4]. In particular, VR technology has matured in recent years and is increasingly used in product development and testing, design for rapid prototyping, and virtual trainings in industries such as aerospace, agriculture, automotive, construction, consumer goods, energy, and the military [5].

Figure 1. Magic Leap 1 MR headset.[1]

Figure 2. Trimble XR10 hard hat with MR HoloLens 2 technology.[2]

Design teams often use VR to test visibility, ergonomics, and aesthetics before producing a full-size prototype. For example, the military is using VR evaluate turret viewing angles on Humvees [5]. Additionally, automotive and construction industries have used VR to assess aesthetics as well as functional subcomponents.

Industrial customers are also embracing MR and AR reality solutions. Many of these solutions tend to fall into the following general categories: remote assistance, step-by-step instructions, dynamic training, or augmented complex tasks.

Remote assistance

Industrial companies are embracing remote assistance technologies such as Vuforia Caulk or Microsoft Dynamics 365's Remote Assist. For example, Howden, a producer of industrial rotating equipment, embraced Caulk to deliver expertise to support service teams around the world. With Caulk, local service teams were able to use tablets and mobile devices to triage problems and troubleshoot issues in real time using shared audio and video with annotations anchored to the technician's view. Their customers appreciated Howdens' ability to respond faster and resolve issues, and Howden's technician's felt more confident in their assessment of the equipment and the advice they provided to the end customers [6]. Similarly, Musashi Seimitsu, an automotive parts manufacturer headquartered in Japan, was able to establish a new production line in Mexico without a single engineer leaving Japan. By leveraging HoloLens 2 with Dynamics 365 Remote Assist, the Japan based team was able to draw arrows on equipment as they guided the Mexican team through adjusting the equipment and process for the local environment. This application of remote assistance technology saved 264 work hours and

[1] Image Credit: Garner

[2] Reprinted with permission from Microsoft: Source: https://1gew6o3qn6vx9kp3s42ge0y1-wpengine.netdna-ssl.com/wp-content/uploads/prod/2019/02/TrimbleLensXR10_w_HoloLens2-1024x576.png extracted from https://blogs.microsoft.com/blog/2019/02/24/microsoft-at-mwc-barcelona-introducing-microsoft-hololens-2/

deepened the communications between the Mexican and Japanese teams to the point that the Mexican team could then apply knowledge to handle some of the work themselves [7].

Step-by-step instructions

Industrial companies are also embracing new MR training approaches such as Vuforia Instruct and Microsoft Dynamics 365 Guides. For example, the Suntory Group, makers of Japanese and American whiskies such as Jim Beam and Maker's Mark, has used Microsoft Dynamics 365 Guides to upskill new employees on increasingly complex procedures. Some of their production team use more than 50 different checklists a day. Suntory, like many other organizations, is being forced to revisit the way they train new employees and deliver on-the-job instruction as the majority of their workforce is set to retire in the next 10 years They have used Guide's authoring tools to convert a 200-step procedure into step-by-step instructions and have found that they can reduce the time to master tasks by up to 70% [8]. Clean Energy Fuels, operator of 550 compressed natural gas stations across the United States and Canada, reports by using Guides they were able to reduce training expenses for high turnover groups such as new technicians. Although some of the savings are short term savings with reduced travel costs due to COVID-19, Clean Energy Fuels expects it will be able to maintain a 40% savings in its training budget [9].

Dynamic enquiry based information transfer

Companies have been leveraging MR to engage audiences with context-sensitive knowledge transfer. Royal Enfield, the oldest motorcycle brand in continuous production, was able to provide more than 3,000 salesforce participants an interactive experience consisting of animated sequences about key features and technologies included in its newly released Meteor 350 motorcycle [10].

Augmented complex activities in real time

Companies are also adopting XR to augment complex activities in real time. XR has the potential for tremendous societal impact in medicine. For example, surgeons at the CHRISTUS MUGUERZA Hospital Conchita have overlayed a surgeon's field of view with 3D models built from X-rays, CT and MRI scans to optimize patient outcomes and minimize their recovery time [11]. In another example a 3D holographic reconstruction of a scapula was positioned above the patient's scapula, which helped the surgeon track his progress and view hidden components of the patient's body during the procedure. Presurgery medical data was also loaded on the headset for the surgeon to examine [12]. Aerospace applications like the one shown in Figure 3 have also been explored, which provide advanced data visualization methods for fluid and heat transfer data [5].

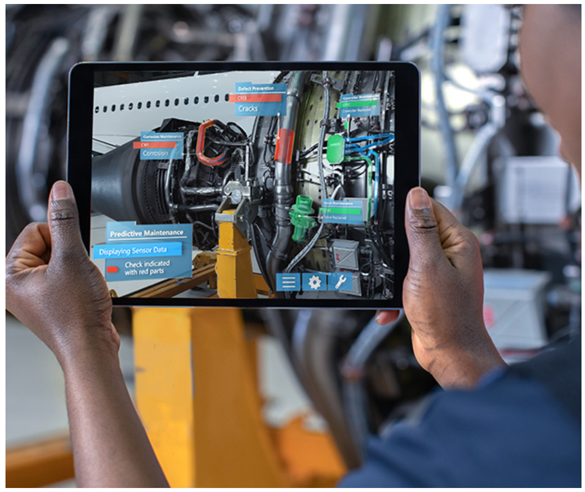

Figure 3. VR techniques can provide users advanced data visualization solutions for sensor data.[3]

ENABLING HARDWARE

XR use has been expanding as enabling hardware components and sensors have shrunk in size and been included in mainstream devices such as smartphones. For example, inertial measurement unit (IMU) sensors (i.e., accelerometer, gyroscope, and magnetometer) are now included in almost every smartphone and some smartphones (i.e., the iPad Pro and iPhone 12 Pro) are including even more advanced sensor, such as LIDAR, for improved spatial mapping capabilities [13].

AR hardware

Most smartphones and tablets can be leveraged for AR experiences, but specific devices have also been developed for professional work. For example, head mounted wearable tablets such as the RealWear HMT-1[4] and Vusix M4000,[5] include a small visor that lowers in front of one or both eyes and can be used to overlay data or images.

VR hardware

VR gaming has exploded in popularity in recent years fueled by a plethora of VR headsets such as the Oculus Rift and Quest series,[6] HTC Vive,[7] and Valve Index.[8] While each of these devices consist of a head mounted display which obscures the users view of the physical environment, features and capabilities such as being all-in-one or PC-powered, resolution, field of view, and control options vary between the models. Some products such as the HP Reverb G2[9] and the Vive Business Edition[10] are beginning to be released with a focus on professional applications.

MR hardware

MR headset devices require a more sophisticated transparent display than either VR or AR, which subsequently makes them more expensive. The Microsoft HoloLens 2 and Magic Leap 1

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[3] Reprinted with permission from PTC Inc.: Source: https://www.ptc.com/-/media/Images/new-org/625x525/AR/what-is-industrial-ar-625x525.jpg extracted from https://www.ptc.com/en/technologies/augmented-reality
[4] https://realwear.com/products/hmt-1/
[5] https://www.vuzix.com/products/m4000-smart-glasses
[6] https://www.oculus.com/compare/
[7] https://www.vive.com/us/
[8] https://store.steampowered.com/valveindex
[9] https://www.hp.com/us-en/vr/reverb-g2-vr-headset.html
[10] https://business.vive.com/eu/BE/

are the most prominent MR headsets but others include the HP Windows Mixed Reality Headset[11] and NReal Light.[12]

A brief description of the hardware to support each type of XR with a few examples is provided in Table 1.

Table 1. XR hardware differentiation and examples

	Description	Hardware	Differentiating Factors?
Augmented	Typically, single screen with data overlayed on image of scene.	Smartphones, RealWear HMT-1, or Vuzix M300/M400/M4000	Can be used on existing smartphones or on specialized equipment such RealWear HMT-1
Mixed	Overlaying of digital objects or animations on physical world as seen by user.	Hololens 2, Magic Leap, Nreal Light	Needs specialized headset but allows interaction with overlays in real world
Virtual	Immersive virtual world with a dedicated screen per eye. Uses external cameras or sensors for positioning	Oculus Rift and Quest, HTC Vive, HP Reverb, Valve Index	Needs specialized headset and overlays information on virtualized world.

DEVELOPMENT TOOLS

Interactive remote collaboration requiring no development effort

Several products are available that enable interactive consultations and trainings. For example, Vuforia Chalk and Microsoft Dynamics 365 Remote Assist allows attendees to make annotations that track with the physical environment when a user's field of view changes. The applications were originally designed for AR systems and available on tablets and smartphones, but they are now also available for mixed reality systems like RealWear devices [14] and the HoloLens 2.

Instructions and expert capture requiring minimal development effort

Several products are available that allow users to capture knowledge from subject matter experts to be shared with others within the organization. For example, Vuforia Instruct,[13] Vuforia Expert Capture,[14] and Microsoft Dynamics 365 Guides[15] are intended to simplify creating 3D step-by-step work instructions but can also be used to capture quality inspections.

Solutions leveraging existing CAD and industrial plant data require some development effort

Vuforia Studio is a standalone development suite used to integrate CAD models into XR experiences. This package is developed to overlay information on the physical environment. Graphics and annotations can be added after importing or creating a 3D model. Data can also be overlayed to give real time visualizations of information such as safety lines or performance data [15].

Bespoke solutions require more significant development effort

[11] https://www.hp.com/us-en/shop/cv/mixed-reality-headset
[12] https://www.nreal.ai/light/
https://www.nreal.ai/light/
products/vuforia/vuforia-instruct
[14] www.ptc.com/en/products/vuforia/vuforia-expert-capture
[15] https://dynamics.microsoft.com/en-us/mixed-reality/guides/

Software developers have access to an extensive set of capabilities that enabled the applications listed above. Many bespoke solutions leverage a 3D engine and development environments such as Unity or Unreal, which are responsible for the 3D mapping and display of the environment.

3D Engine—The improved capabilities of VR and AR in professional applications are largely attributed to the maturing of supporting software such as applications programming interfaces (APIs), software development kits (SDK), and 3D modeling engines. These capabilities vary depending on the combination of SDK, modeling engine, and hardware.

Unity—The Unity3D Engine was created in 2005 for videogame development but has since become the most popular 3D engine for both game development and XR applications [16]. The size of Unity's community and content has resulted in a comprehensive asset store, which can greatly accelerate development [17].

Unreal—Unreal Engine, developed by Epic Games, historically was used by big budget game developers because it offers very high-quality graphics. Unreal Engine uses a slightly different licensing model than Unity [18] and as a result has fewer but higher quality assets available for purchase. In early 2016 Unreal began expanding its XR features. The most recent version 4.27, released Aug 19, 2021, includes many groundbreaking new XR features including support for Open XR. These new features may allow Unreal to increase in popularity for new XR developments relative to Unity.

Development infrastructure

The end user experience relies on SDK packages to bridge the gap between hardware and the 3D engine. PTC's Vuforia Engine, OpenXR, and WikiTude are some of the most widely used cross-platform SDKs. While others such as ARKit were developed by Apple and are only available on iOS devices. Capabilities and usability can vary greatly between these packages, and developers should carefully select an SDK according to the end goal of their application.

Vuforia Engine—The Vuforia Engine is a popular SDK used in many current AR applications. It offers developers extensive access to XR capabilities, enabling complex and customized applications. Vuforia Engine is targeted at custom AR and MR applications with support for HoloLens 1 and 2, Magic Leap, RealWear, and Vuzix [19].

The Spatial Toolbox is an extension primarily used in combination with the Vuforia Engine but provides premade data visualizations and other graphics. The extension uses a computer vision software to tag components and link data streams or information to objects in real space [20].

OpenXR—OpenXR is an open API developed by Khronos to aid in cross-platform app development. The API itself is used with Unity or Unreal to access native XR features [21].

Wikitude—Wikitude is a recent addition to the SDK field; its focus is AR environments and incorporates features similar to Vuforia Engine. Wikitude includes features such as geolocation, cloud recognition, and distance-based scaling, which may not be available in Vuforia Engine [22].

ARKit—ARKit is developed by Apple for use on iOS devices. The ARKit platform shares several features with ARCore by Google but focuses on the end-user experience. For example, ARKit provides better planar tracking for 3D object placement as well as object detection. These benefits often come at the cost of mapping speed, taking longer to map the environment than other mobile AR solutions [23]. The SDK also provides the ability to track multiple faces and leverage the use of both cameras on a standard flagship phone.

ARCore—ARCore was developed to bring open source XR experiences to Android devices. Unlike some of the other packages, ARCore can work with Vuforia to enable an extensive range of XR capabilities on Android devices.

Potential opportunities for international safeguards

We believe XR technologies can be leveraged in a variety of ways to substantially benefit the IAEA safeguards regime. Some of the potential opportunities are described below.

Remote assistance—AR and MR are becoming powerful tools in industrial markets and could dramatically impact the way safeguards inspectors in the field receive remote assistance from experts at IAEA headquarters. Most notably, an inspector in the field and experts at headquarters may be able to simultaneously view a piece of equipment while the expert annotates the image in real-time to provide instructions to the inspector. Vuforia Chalk and Microsoft's Dynamics 365 Remote Assist offer no–development cost approaches that generate a 3D representation of a scene using photogrammetry from live video taken using a smartphone or structured light. Once the 3D representation has been generated, the IAEA experts could remotely make annotations that track with the environment as the local user changes the smartphone's field of view. This type of capability might be useful during the inspection of a piece of IAEA unattended equipment. If the equipment appears to be broken, MR technologies can be employed to help the inspector troubleshoot the issue, avoiding the need to send a technician on a follow-up trip. Remote assistance capabilities may also help an inspector during the collection of environmental swipe samples in a facility. For example, the inspector may show an expert at headquarters a particular area that they are considering for sample collection, and the expert can circle the recommended locations to collect samples as well as circle areas where previous samples have been taken.

Figure 4. Remote expert has added annotations to a field technicians screen using Vuforia Chalk.[16]

[16] Reprinted with permission from PTC Inc. Source: https://www.ptc.com/-/media/Images/new-org/1366x500/toyota-1366x500.jpg extracted from https://www.ptc.com/en/products/vuforia/vuforia-chalk

Step-by-Step guidance—Some nondestructive assay techniques or procedures such as taking environmental swipe samples are complex, requiring steps to be performed in sequential order. It may not be challenging for experts to perform those steps, but some inspectors may only need to perform those steps infrequently. MR step-by-step guides enabled using authoring tools such as Vuforia Instruct or Microsoft Dynamics 365 Guides might allow the relevant subject matter experts to record the proper sequence for inspectors to consult in the field. Leveraging an MR head mounted display would also free the hands of workers in the field to attend to the task.

Figure 5. Step-by-step guides could give less experienced inspectors more confidence as they complete complex tasks at remote facilities.[17]

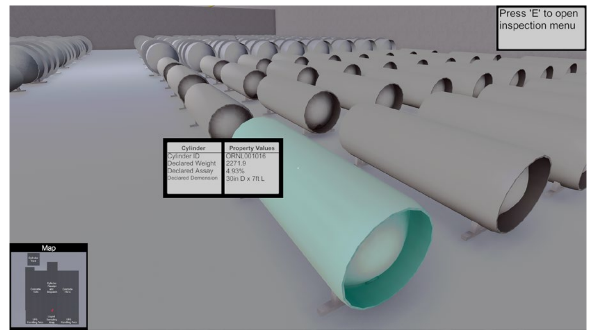

Figure 6. Inspectors in the field could use supplemental information displayed on their tablet or MR headset similar to what is shown in this VR example of data about UF_6 stored in a cylinder.[18]

Highlight and display supplemental information about safeguards systems or plant parameters—XR could be used to highlight and display relevant information about the location and operating parameters for equipment, measurement data or supplemental information about safeguards-relevant systems throughout a facility. For example, as an inspector walks around a bulk handling facility, AR technologies could highlight the location of known material holdup deposits throughout the facility to the inspector's attention, as well as display relevant nondestructive assay measurement data for these deposits. XR technology could also alert if the most recent nondestructive assay measurements are inconsistent with historical values, potentially indicating that the inspector should examine inconsistencies in the measurement data. Additionally, XR technologies could highlight or label complex systems of interest, such as product piping in a bulk handling facility, and display flow rate, temperature, pressure, declared valve positioning (e.g., open/closed), and directional flow information. Other use cases include displaying the boundaries of material balance areas, identifying the location of key measurement points, and displaying accountancy data. Furthermore, XR can be used to display the field of view of surveillance cameras, indicating to the inspector that the cameras have not been repositioned to create blind spots in the facility. Finally, XR technology can be used to display relevant information about specific storage containers such as UF_6 cylinders and spent nuclear fuel casks, which can assist inspectors during physical inventory verification exercises (Figure 2).

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[17] Reprinted with permission from Microsoft. Source: https://1gew6o3qn6vx9kp3s42ge0y1-wpengine.netdna-ssl.com/wp-content/uploads/prod/2019/02/HoloLens2_Guides-1024x683.jpg extracted from https://blogs.microsoft.com/blog/2019/02/24/microsoft-at-mwc-barcelona-introducing-microsoft-hololens-2/

[18] Original work of ORNL.

Design information verification—During the design information verification process, XR tools could be used to highlight new equipment or systems that have been installed since the most recent inspection. Additionally, this technology could identify equipment that has been moved or modified using the original design information provided to the IAEA or information from the previous inspection.

Complementary access—Inspectors could wear an MR headset during complementary access visits. The video from the headset could be fed back to IAEA headquarters for senior experts to review or the video could be fed to an artificial intelligence (AI) system which would identify specific items of safeguards relevance. The inspector could then use the MR headset to display comments made by senior inspectors or supplemental information about the object enabled by artificial intelligence identification.

Dual use equipment—Additionally, AR or MR tools coupled with artificial intelligence could be used to identify and provide information about dual use equipment in a facility. Dual use equipment could be highlighted, and relevant information about the equipment's potential nuclear use cases could be displayed, along with comments from senior inspectors.

Training—XR tools could provide a means for inspectors to conduct pre-job training with a 3D representation of the real systems with step-by-step prerecorded guidance from the relevant subject matter experts. This could enable on-demand training using a digital twin of the actual systems for inspectors working from home, at the facility, or even at headquarters for systems that do not have a physical twin at the IAEA headquarters.

CONCLUSION

XR is rapidly being adopted by industrial firms for its competitive advantages. Adoption by many of the firms was hastened as a result of COVID-19 travel restrictions, but the benefits have demonstrated XR's longer term and broader potential. This paper described several example of how industrial firms are leveraging XR technologies, some of the hardware and software that can be leveraged to provide cost-effective XR experiences, and several potential use cases for international safeguards.

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