XR-powered Remote Maintenance Support and Training for Naval Shipyards

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ABSTRACT

The US Naval-shipyards are in critical need of cost-saving and time-saving technologies that can improve their vital function of maintaining fleet-readiness. Augmented-Reality/Virtual-Reality/Mixed-Reality (AR/VR/MR) (Extended-Reality (XR)) has the potential to transform the landscape of shipyard operations via accelerated training in simulated environments, improved safety-practices at the dry docks and efficient maintenance procedures on the ships. However, there are several barriers to entry of these technologies: cost of hardware/software; cybersecurity and technological hurdles in secure environments. Current approaches in XR do not consider the fact that training and operations are interrelated activities, and knowledge gained during one should be shared with the other. Furthermore, they do not support direct integration with learning management systems (LMSs). Another challenge is that XR devices become obsolete rapidly. Hence, it is imperative that XR technologies procured for shipyards have good return-on-investment, are scalable and are device-agnostic.

In this paper, the research team presents an immersive ecosystem that enables speedy content generation and integration of maintenance and safety procedures with training. The approach employs modern open-source web-based AR/VR technologies to enable: conversion of contextual procedural content from legacy documents such as standard operating procedures (SOPs) into secure XR format; live remote assistance for performance-support, thereby avoiding travel and saving costs; capture of objective quality evidence (OQE) while performing safety procedures, employing MR to augment live machine readings in the tablet's view of the physical world for inspectors; enabling eLearning profiles such as ***cmi5*** to facilitate distributed learning architecture with the aid of LMSs, Learning Record Stores (LRSs), learner record standards such as eXperience-API (xAPI); and generating ***metrics*** that quantify student performance to identify maintenance gaps. The approach uses a knowledge continuum - single-source-of-knowledge - between training and maintenance/performance-support, where information captured in one is channeled back into the other, resulting in improved quality-of-maintenance.

This paper documents the experiments that convert traditional Navy shipyard training guides into an XR format that can be rendered in various XR-enabled devices. The paper concludes with best practices and lessons learned from these content conversion experiments.

ABOUT THE AUTHORS

Mr. Deepak Haste is a Senior Director of Engineering at Qualtech Systems, Inc. (QSI), with a focus on customer-driven enhancements, productization, and commercialization of QSI's products through several key Small Business Innovations Research (SBIR) projects with NASA and DoD. His recent productization efforts include feature extensibility through plugin frameworks, prognostic capabilities, and embedding and interfacing of diagnostic software within onboard platforms. He is currently leading efforts to add AR/VR and Maintenance Training capabilities into QSI's product suite. Mr. Haste holds a Master of Science (M.S.) degree in Electrical Engineering from Clemson University and a Bachelor of Technology (B. Tech.) in Electrical Engineering from the Indian Institute of Technology (IIT), Bombay, India.

Mr. Michael Renda is a Software Engineer at QSI and is currently involved in enhancing its product suite with modern AR/VR capabilities. This work has manifested in QSI's AR/VR designer, a tool that enables military instructors to author AR/VR scenes for training students in an immersive context. In addition, he has extended photogrammetry tools to develop a 3D-scanning app for iOS, allowing instructors to capture their machinery into 3D models and import them into educational content created via the AR/VR designer. Mr. Renda holds a Bachelor of Science (B.S.) in Computer Science and a B.S. degree in Economics from Wesleyan University.

Dr. Sudipto Ghoshal is a Vice President of Engineering at QSI, with experience in system diagnostics and prognostics, as well as design-time assessment and mitigation of operational risk and improvement of system availability. His research also involves the development of a failure-space modeling methodology leveraging general purpose system design languages such as SysML and adapting it for QSI's products. He has been a committee member of the IEEE SCC20 Diagnostics and Maintenance subcommittee since 1991. Dr. Ghoshal holds an MBA from the Kelley School of Business, Bloomington, Ph.D. and an M.S. degree in Biomedical Engineering from the University of Connecticut, and a B. Tech. in Electrical Engineering from IIT, Kharagpur, India.

Mr. Deniz Ferrin serves as a Technology Focus Team Program Manager within NAVSEA 04XT, specializing in integrating innovative technologies into public shipyards. His role involves uniting stakeholders to transition emerging technologies into daily operations, enhancing safety, efficiency, and quality for maintainers. Deniz's team addresses technical challenges by resolving barriers to technology implementation. Under his leadership, the Technology Focus Teams establish enterprise milestones and roadmaps, creating a centralized repository for specific technologies. Deniz earned his Bachelor of Science in Chemistry from the University of Washington and is passionate about driving progress in shipyard modernization efforts.

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INTRODUCTION

The United States Navy Shipyards face key fleet-readiness challenges and have a need for cost-saving and time-saving Extended Reality (XR) technologies to facilitate safety and maintenance procedures. To address this need, the research team devised an enterprise platform and an immersive ecosystem that enables speedy XR content generation and integration of maintenance procedures with training, and provides continuous knowledge transfers between them to further improve the quality of maintenance. The solution employs modern web-based XR technologies to provide (a) hands-free virtual co-location, contextual procedural content and remote assistance by subject matter experts (SMEs) for performance-support; (b) use of Learning Management Systems (LMSs) and Learning Record Stores (LRSs) to facilitate continuum of learning in shipyards and quantify student performance in safety and maintenance procedures.

BACKGROUND

Current State of Shipyard Maintenance

XR technologies are gradually being introduced in the Naval Shipyards for safety training and operations. However, the current industry-standard approaches in XR do not consider the fact that training and operations are interrelated processes, and knowledge gained during one needs to seamlessly flow into the other. For instance, most augmented reality/virtual reality (AR/VR) solutions lack direct integration with LMSs. Furthermore, the performance-support task procedures have to be hand-coded, as with any XR system. Another challenge is that the XR devices rapidly become obsolete. Hence, it is imperative that the XR technology procured for the shipyards is worth the investment, is scalable, and device-agnostic, and is not playing “catchup” with device compatibility. Thus, a solution is desired that is intuitive, cost-effective to implement, and sustainable in the long run, given the rapid turnover of XR devices.

Present Needs of the Naval Shipyard

During several touchpoints with NAVSEA stakeholders who are overseeing the shipyard modernization efforts, the research team learnt of the critical objectives necessary to successfully implement XR across the shipyards:

1. *Ingest and display work instructions and data collection forms with augmented, graphical cuing to the maintainer*
2. *Provide remote reach-back capability (live annotated video calls) between the maintainer and offsite SMEs*
3. *Provide virtual simulations of work processes for task training/rehearsal (AR and Immersive VR capabilities)*
4. *Automatically collect the objective quality evidence (OQE) where possible and report it back to the master maintenance records archives*
5. *Provide the maintainer with a real-time interface to ancillary logistics systems such as parts/material ordering.*

Augmented-procedures and Immersive Live-assistance to increase Shipyard Efficiencies

The research team developed an XR distributed maintenance support and training ecosystem for the Navy technicians, with hands-free, just-in-time (JIT) training and maintenance, enabling them to perform like experts, thereby improving ship maintenance activities. The solution will reduce the need for physical training assets, thereby allowing technicians to practice outside of their work environments, rather than traveling to a shipboard training facility. It also will address a major impediment to the broad adoption of XR training, namely requiring advanced XR design and specialized programming skills to generate XR content. The solution will streamline the creation of XR content, minimizing the number of steps required to convert legacy troubleshooting and maintenance documents into usable XR content, thus providing SMEs with full control over the content generation process via an intuitive immersive scene designer interface. The resulting XR scenes can be managed in libraries and be subsequently reused multiple times.

MODELING AND SIMULATION ARCHITECTURE AND CONCEPT OF OPERATION (CONOPS)

The novel solution follows an agile ***TrainOps*** (akin to DevOps (DevOps, 2025) process to do away with stove-piped approaches. The immersive and adaptive e-learning platform (1) provides the ability to easily author immersive XR maintenance content for Naval Shipyards, and (2) provides VR-based training to students with adaptive learning content and hints based on their performance. Figure 1 shows the numbered CONOPS of the immersive ecosystem:

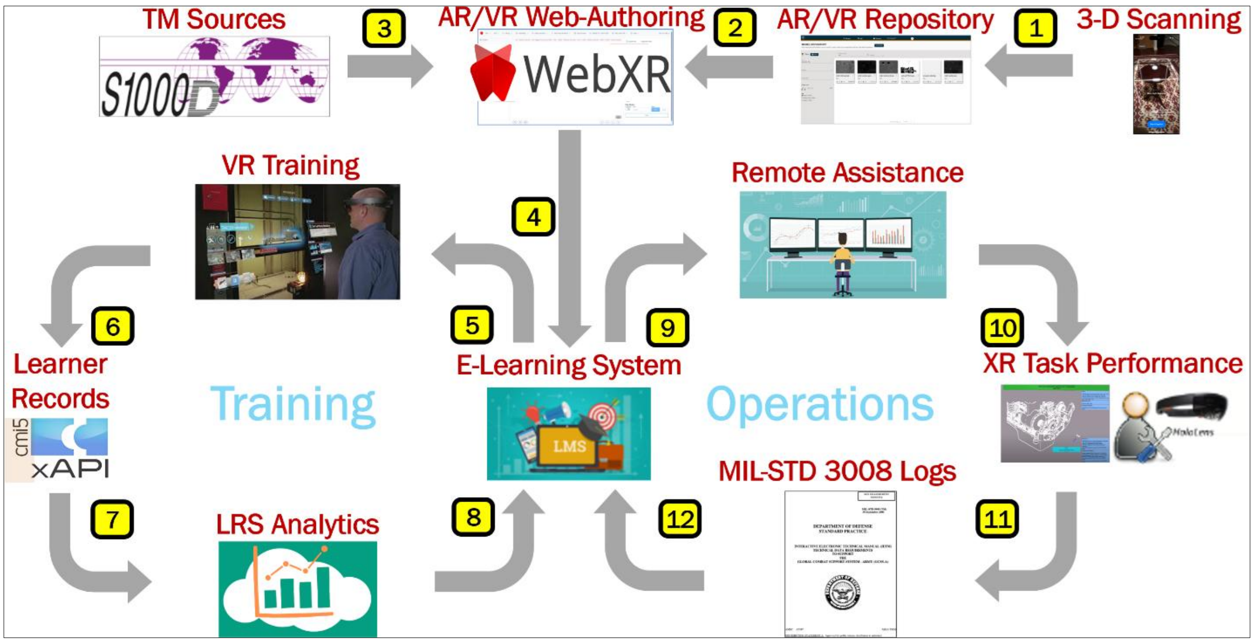

Figure 1: TrainOps (Training + Operations) continuous improvement concept for XR shipyard maintenance

1. The process begins with 3D-models that form the building blocks of immersive content. The research team developed a 3D-scanning App which can be used by content developers to create 1:1-scale virtual 3D models for use in AR/VR training content.
2. The 3D objects are then stored in a reusable and searchable asset repository.
3. Standards-based maintenance procedure documents such as technical manuals (TMs) in S1000D (S1000D, 2025) and MIL-STD 3008 (MIL-STD-3008, 2024) formats are converted to procedural AR/VR maintenance content.
4. Next, the AR/VR content is curated to render procedural maintenance steps by combining AR/VR assets and scenes with imported procedural maintenance narratives. This step will utilize the AR/VR designer to generate zero-code immersive content using proven web-based AR/VR technologies such as WebXR (WebXR, 2022). The immersive content, combined with maintenance procedures, will be deployed to an LMS that is accessed by the schoolhouses for VR training, and by technicians for XR-based procedural support during operations. Instructors will use a cmi5-compliant content hosting platform to store training content. Based on the trends from the maintenance logs, instructors will tailor the training to address problem areas and assign appropriate VR learning activities, familiarity exercises, and exams to the students.
5. **Training CONOPS**: The students take immersive exams and receive their performance-driven hints.
6. Performance metrics and ratings from student activities in the eLearning system are formatted as xAPI statements.
7. These xAPI statements are logged into the LRS.
8. Analytics from the LRS are mined to identify learning deficiencies in students and to tailor individualized training.
9. **Operations CONOPS**: The XR content is then used by technicians for maintenance activities at the shipyard.
10. The technician can also be connected, if needed, to the in-house SME for remote assistance.
11. The technician performs hands-free at-platform troubleshooting and maintenance using the immersive interface. The immersive view is augmented with instructions and contextual information via AR anchoring. Condition indicators and machinery status are also streamed into the device via MR for greater situational awareness.

12. The solution will log all technician activity, maintenance status, into a standards-based maintenance log format such as MIL-STD-3008. These recorded actions are also logged as xAPI learner records in LRSs to discover maintenance trends, and the cycle continues (back to Step 9) to achieve learning-in-a-continuum.

Thus, updates from maintenance during operations in the shipyard are continuously being used to improve the schoolhouse training. A deeper dive into the individual technologies and features follows in the sections below.

S1000D ingestion

The research team sourced various procedural content standards such as S1000D for XR content ingestion. The team has developed an AR/VR content creation pipeline (Haste, 2022) that enables users to generate immersive content. The underlying storage format of the immersive content is JavaScript Object Notation (JSON), which is a machine-readable portable file format. The research team leveraged open-source S1000D parsers (S1000D SCORM, 2021) to transform these Interactive Electronic Technical Manual (IETM) procedures into a similar JSON format that can be injected into the immersive scenes as instructions and can be visualized in a tablet or an XR headset (Figure 2) for procedural support. The resultant content is automatically optimized for XR format to allow pagination and annotation. The team also investigated training standards such as S6000T (S6000T, 2023) to enhance the training methodology.

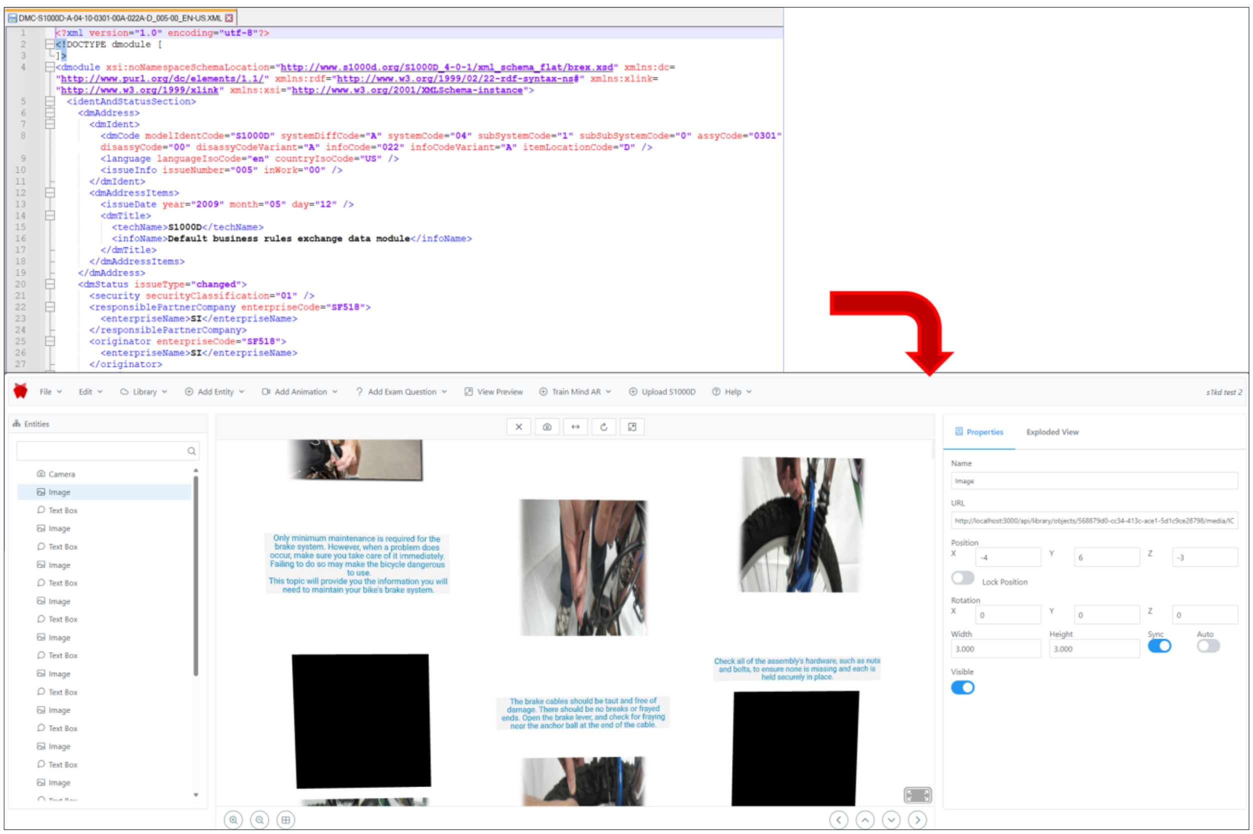

Figure 2: Conversion of IETM file formats such as S1000D to XR content

Remote Live Assistance

The research team built a prototype of the remote assistance capability to enable remote/shore SMEs to connect and guide/assess technicians in performance-support via web-based, on-demand video/audio/text chat and remote screen-replication capability (Figure 3). The team leveraged "networked A-frame" (Networked Aframe, 2025), a web framework that allows multi-user interactions, to enable the expert to visualize the maintenance and provide audio/video instructions to technicians. The team also plans to integrate Microsoft Teams chat with the aid of a plugin (MS Teams App Template, 2025) that embeds the chat capability within the XR application. This aligns with the

Navy's plan of adopting Microsoft Office -based enterprise platforms.

Annotations and Markup

The research team added a remote annotations and markup capability to enable a hands-free, AR-enabled contextual visual aid for maintenance and troubleshooting. The feature uses object recognition and A-frame's AR-anchoring feature (MindAR, 2024) to juxtapose relevant step-by-step instructions, videos, images and animations on physical-world objects.

The "Networked A-frame" library allows multi-user interaction, enabling an expert to connect and chat with technicians, visualize the maintenance, and provide audio instructions. The research team also implemented annotations that allow the instructor to remotely mark technician's tablet screen during a remote live assistance session in order to highlight and bring to attention certain areas in technician's field of view (Figure 4).

The SMEs can also remotely tap and drop markers or transfer 3D objects or animations to the technician's tablet view of the physical world via remote markup (Figure 5). The performance-support user activities are logged in standard maintenance log formats such as MIL-STD-3008.

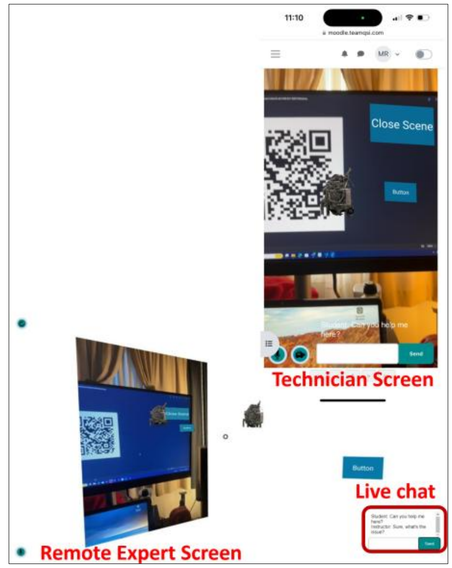

Figure 3: Remote screen replication

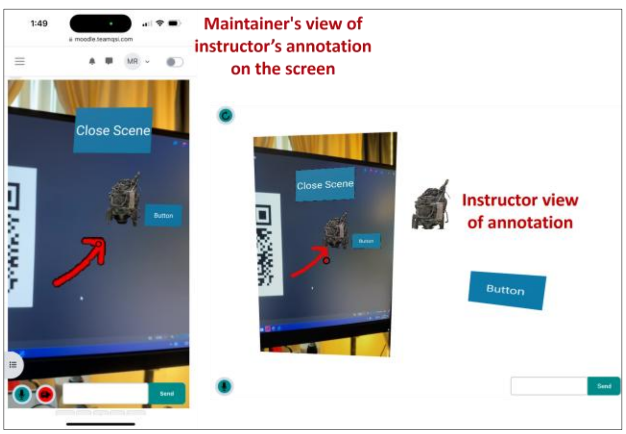

Figure 4: Remote annotations on SME's screen

Figure 5: Remote markup on SME's screen

Live overlays of IoT sensor readouts

The research team implemented mixed reality (MR) hotspots for displaying live performance indicators such as pressure, temperature, etc. on machinery components in the AR performance-support mode, and on virtual 3D models in the VR training environments. In the AR performance-support mode, the live machinery status can be anchored onto a physical world object viewed from a tablet or AR/VR headset, and in VR training mode it can be overlaid on the virtual 3D objects. The research team is leveraging networked A-Frame's ability to "push" a feed from a central server to the remote AR/VR device. The capability builds upon common IoT protocols such as Message Queue Telemetry Transport (MQTT, 2025) and A-frame MQTT integration library (A-frame MQTT, 2025). Figure 6

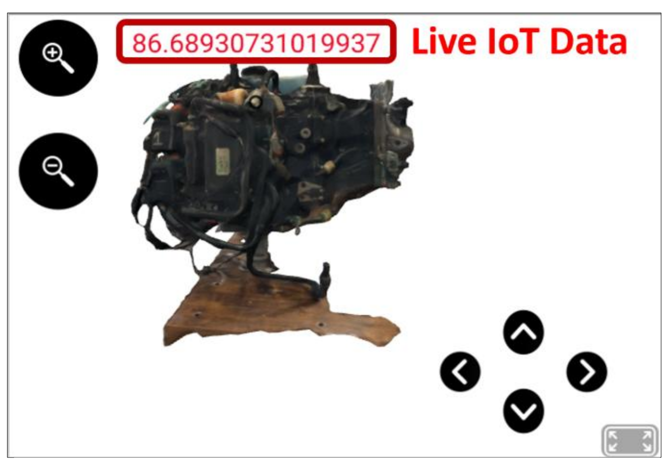

Figure 6: Live IoT data streaming in the XP application

shows the prototype XR screen with simulated data streamed on the message bus.

Corrosion Detection

The NAVSEA stakeholders recommended using “computer vision” techniques to automatically determine ship surface integrity in order to speed up inspection. To this end, the research team developed a Corrosion Detection prototype to automatically determine ship surface integrity to speed up ship surface inspections for damage to paint-coating or corrosion. To achieve this, the team applied “deep learning vision” techniques such as a pretrained DeepLabV3+ model (Corrosion Classifier, 2021) which processes images and performs semantic segmentation of corrosion condition states which are color-coded and overlaid on the original picture. The process computes quantitative measures of detected corrosion. With the click of a button, the captured image within a bounding box of the Tablet view is sent to the deep learning model, which overlays the image with color codes for corrosion states (Figure 7). Then the Corrosion App does a pixel-wise computation of the percentages of colors for minimal, fair and severe corrosion compared to the total pixel area in the captured image. The dashboard lists the percentages of each level of corrosion in relation to the entire image. This is helpful for inspectors for flagging certain areas for “spot fixing”. For instance, if the affected area is damaged more than 30% of the total area, the inspector will mark that area for surface-stripping and schedule appropriate maintenance procedures.

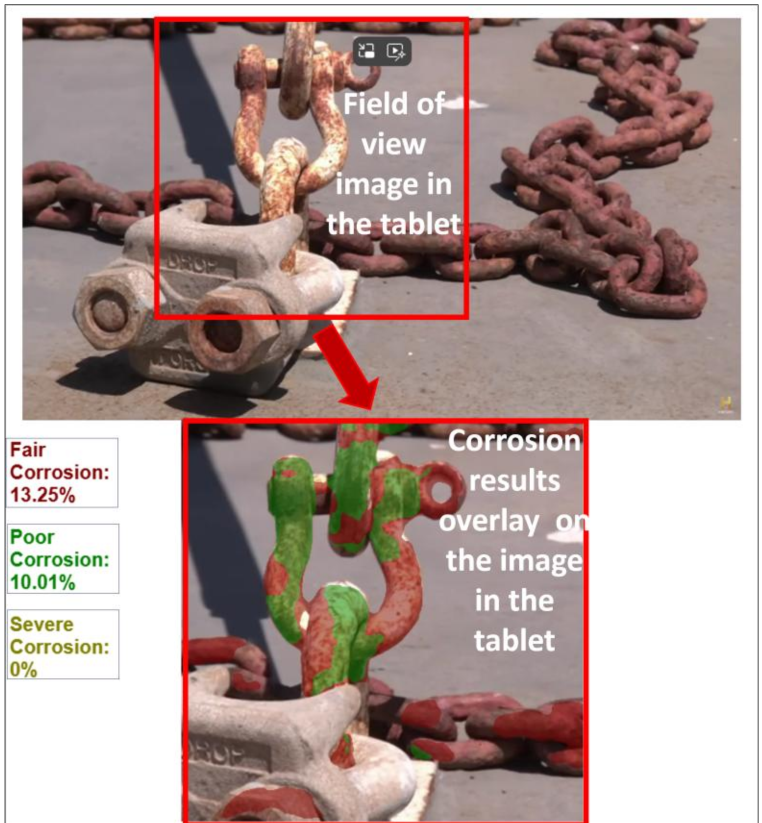

Figure 7: Live corrosion percentages in the technician’s tablet

Objective Quality Evidence (OQE)

One of the desirable features sought by NAVSEA is to be able to provide live feedback to operators when performing a maintenance task. For instance, during procedures that require the use of a torque wrench to turn a valve, the XR application can use vision-based AI to verify that the valve is turned correctly. The research team investigated image recognition techniques to verify the maintenance steps, e.g., recognize the position of the valve.

The process begins with capturing images from live video feed (ImageCapture, 2025) and sending them to an image processing library. A reference image of the correct setup is compared to the images of the

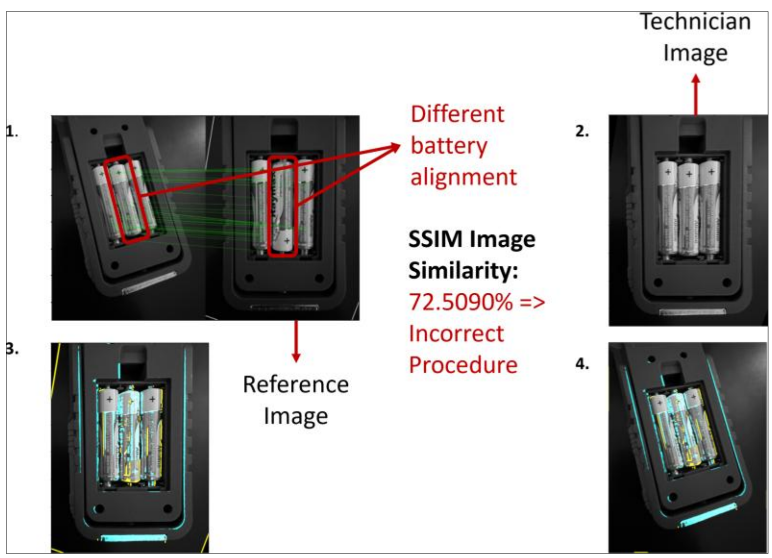

Figure 8: XR recognizing incorrect repair in the technician’s tablet

setup that the technician is working on in the same environment. Euclidean distance is calculated to reflect similarity between the two images, and is qualified as a success if similarity score is above a certain threshold. The research team used Scale-Invariant Feature Transform (SIFT, 2025) image processing library, a versatile and robust similarity detection method that detects salient points/areas in images even when the image is modified (i.e., cropped, rotated, etc.). The OQE capability is achieved using a 4-step process: (a) Match features from technician's image to reference image via SIFT; (b) Create matrix transformation from the SIFT results and warp the perspective of the technician's image to match the reference image; (c) Apply Gaussian blur to the warped image and reference image to eliminate miniscule discrepancies and subtract pixel values to obtain differences; (d) Calculate inverse of matrix transformation from step 'b'; and (e) apply this to the difference mask (step 'c') to obtain highlighted overlay on technician's image.

The technique can detect when the difference in the images fall below a certain threshold (Figure 8). This will be flagged as a non-conformance, and it will prevent the technician from proceeding further until the step is rectified. Once the technician rectifies the step, the new image will satisfy the threshold for matching the reference image, and the step will be marked as compliant (Figure 9). The research team will scale the method to minimize the overhead that could impact real-time performance. Additionally, the approach will be enhanced to account for variations in brightness of the OQE background using image normalization.

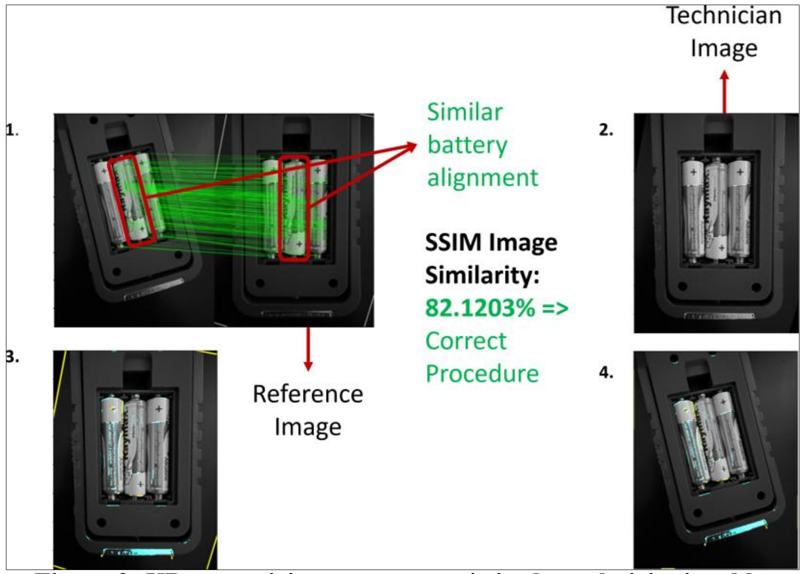

Figure 9: XR recognizing correct repair in the technician's tablet

EXPERIMENTAL VALIDATION AND TESTING OF XR CONTENT GENERATION PROCESS

Naval Shipyard Maintenance Use cases

The research team reviewed some shipyard maintenance use cases sent by NAVSEA for XR content creation:

Use Case I: Testing of water-activated alarm in the dry dock drainage tunnel:

- The team authored an immersive scene where the user can click a button to trigger a simulation of flooding on the dry dock drainage tunnel. When water in the drainage tunnels rises to the level of the alarm sensor present in the dry dock pumpwell, it triggers the "water-activated flooding alarm" in the operator panel.
- Additionally, when the back pressure increases to a certain level, it activates the alarm pressure switch located on the drainage pump automatic-control air-manifold in the drydock pumpwell, triggering the "pressure-activated flooding alarm" in the operator panel.
- The technician tests the flooding alarm by opening/turning the ball valve located at the "Forward" section. Water is sprayed on the "flooding sensor", triggering the "flooding alarm" on the operator panel.
- The technician calls up a subject matter expert (SME) via "remote assistance" feature in the XR application. The SME reviews the technician's screen and confirms that the "Flood Alarm Test Valve" is correctly set.
- The SME is in constant communication with the technician for guidance through the task (remote assistance).

Use Case II: Testing of air-activated alarm in the dry dock drainage tunnel:

- The SME guides the technician for testing the air activated flooding alarm.
- SME remotely marks up the "Auto" selector switch (remote markup).
- The technician tests the air-activated flooding alarm by turning the drainage pumps' "Auto" selector switch to the "OFF" position.

- Next, the technician closes the "pressure valve" until an audible alarm sounds. Then the technician opens "pressure valve" and verifies that the pressure alarm light is lit on the operator panel.
- The technician opens the "pressure reset" valve to reset the pressure switches, and then slowly closes the valve to reset the air manifold to the "NORMAL" valve position.
- After the test is done, SME will remotely perform quality control (image recognition for OQE) to verify position/orientation of "pressure reset" valve.

Use Case III: Remote assistance and annotation during inspection of a leak in a pressure valve:

- Inspector discovers a fault e.g., a hissing sound from pressure valve.
- Inspector pulls up a tablet and points it at pressure valve.
- The XR application shows animation of how to maintain pressure valve.
- The XR application also overlays a pressure reading "in red" since it is lower than normal pressure reading, namely, a "low pressure" error.
- Inspector calls up the SME via "remote assistance" capability in the XR application. The SME can see the inspector's screen, and confirms that the pressure valve is indeed faulty.
- The SME marks up the pressure value (remote markup) and schedules the repair with a technician.
- The technician reviews a VR scene with a 3D scan of the pressure value that shows how to remove and replace the valve.
- The technician then visits the ship repair site, pulls up the tablet and points to the pressure value. The XR application pops up an AR scene and instructs how to remove and replace the valve.
- The SME is in communication with technician to assist (remote assistance).
- After the repair is done, SME will remotely perform quality control (image recognition, video for OQE) to verify position/orientation of the pressure valve.
- All maintenance and repair action will be logged in a Maintenance Report.

Implementation of Naval Shipyard maintenance use cases in XR environment

The research team developed XR content in the AR/VR designer for various shipyard use cases (Figure 10). The AR/VR designer allows instructors to author XR simulations over the web using the WebXR framework, providing a realistic and immersive XR experience for the students. This approach does not require 3D programming and graphical design skills, or any specialized commercial software, or hardware. The immersive editor has an interface to pull pictures, 3D objects and other reusable content from libraries to sequence 3D animations. The editor supports authoring of complex immersive scenes, component identification tests and practical applications (e.g., proper removal of a part from an engine) that can be hosted in an LMS platform. The embedded AR/VR scenes serve as immersive VR training content in a schoolhouse setting.

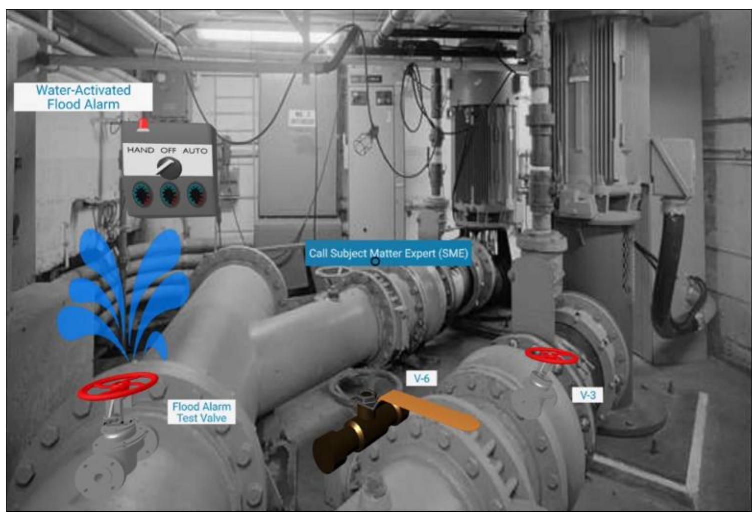

Figure 10: Remote web-based XR training content creation

cmi5 for Distributed Content and Learner Tracking

An important requirement for maintenance support is documenting who did the inspection and when. The xAPI standard enables online course-tracking via automatic information collection. It replaces Sharable Content Object Reference Model (SCORM, 2025) and tracks learner records via xAPI statements in LRS, and can be hosted in LMSs. cmi5 is an e-learning specification built upon xAPI, and builds on the flexibility of SCORM with the ability to support distributed course content as opposed a single central location. The cmi5 profile supports virtual content-hosting in distributed servers as course units, linking those activities to LMSs via the cmi5 xAPI profile. cmi5 will facilitate integration with vendor-neutral technologies that can host their immersive content in their native environments, and are not required to upload their content to an LMS as compliant SCORM packages. Furthermore, the solution will leverage the xAPI standard to send student progress and performance indicators to LMSs over the network, and thus it will be able to standardize the remediation approach.

Metrics to Assess Maintenance Gaps

The research team identified various performance metrics that could be captured from the maintenance logs during operations and student records during training in order to identify maintenance and safety gaps and provide task recommendations. The maintenance logs include various measures such as Mean-Time-To-Repair (MTTR), Mean-Time-To-Failure (MTTF), time-between-maintenance, operational availability (Ao), etc. LRS analytics and dashboards display maintenance trends and flag problem areas that impact the performance, e.g., if maintenance issues are taking longer to troubleshoot, or if maintainers often seek remote assistance, those could be addressed via training.

COST BENEFIT ANALYSIS OF VARIOUS 3D MODEL CREATION PIPELINES

Development Risk Reduction

The solution mitigates any risks associated with the development time, cost and complexity of the solution:

- AR/VR designer, with a high maturity level and low deployment risk, can be used for content generation
- The Government has unlimited use-rights, thus making it a zero-cost solution.
- Since the immersive content generation does not require programming skills, the time to create AR/VR content using this solution will be less than that of commercial 3D applications which have a steep learning curve.

The foundational technology for the solution is WebXR that provides hardware drivers for AR/VR devices and is device-independent. Built on top of that is Three.js, a JavaScript library that uses WebXR API to create web-based 3D scenes using WebGL. A-frame (A-frame, 2025) is an entity component framework built on top of Three.js and enables developers to author immersive scenes with only basic knowledge of HTML programming (DOM-oriented approach). The research team created an intuitive GUI that enables drag-and-drop and forms-based stitching of immersive scenes, and built a JSON wrapper on top of A-frame to serialize those scenes in JSON format.

Open-systems Architecture Considerations

The XR content, generated as HTML using WebXR API /A-Frame framework, is in an open-standard non-proprietary format that supports multiple device modalities (AR/VR headsets, smart phones, tablets, PCs, Laptops, etc.). Since the underlying XR tools/software to author/convert the XR content are open-source, the content can be reloaded/accessed/modified without restrictions, and is not vendor-locked. Additionally, since the XR content can be packaged in a standardized SCORM format, the learning activities can be easily adapted to any LMS that is part of NAVSEA's technology-stack for the Shipyard learning enterprise.

Return-On-Investment (ROI) Considerations

The research team assessed various metrics related to the cost associated with the XR-based immersive content and benefits of improved training outcomes and performance-support as compared to the current shipboard maintenance methods. By analyzing the XR-based performance-support and training, and comparing it to the traditional paper-based performance-support and training, and accounting for physical and personnel resources required for training, the team generated a cost-benefit-analysis to justify the XR investment. Some of the metrics under consideration are:

- Potential improvement in task completion rate, thus reducing the labor hours.
- Improvement in operational availability of the ship, thus reducing downtime.
- Reduction in the physical training equipment costs and time for setup with the help of VR-based training. Additionally, owing to the distributed and individualized XR student training content, instructors do not have to spend time providing personalized training, hence the training time is reduced.

- Improvement in performance-support tasks owing to "remote maintenance assistance", thus avoiding expenses incurred by SMEs while travelling to the maintenance site.

The main investments in transitioning traditional shipyard maintenance activities into modern XR-assisted ones are:

- **XR devices:** The XR technology supports tablets and smartphones, and does not require advanced AR/VR headsets. If the maintainers have government-approved smartphones, then no investment is necessary.
- **XR development hardware:** The XR technology does not require any specialized hardware to create the XR content. The XR App is completely web-based and can be accessed from any networked laptop or PC.
- **XR software:** The research team is democratizing the content generation by having the XR app built from open-source software and libraries. Hence there is no licensing cost to own the software.
- **3D modeling and graphical design experience:** Authoring the XR content does not require knowledge of 3D modeling and graphical design. The authoring interface is web-based and supports drag-and-drop and simple user controls. Thus, the amount of training required is minimal.
- **Outside contractors for authoring content:** Since the XR content can be authored by anyone, no outside contractors are necessary.

Some of the upfront investment in terms of hardware, software and personnel time includes:

- **Hardware**
  - **Tablets:** cost about **$1000** each.
  - **Hardware infrastructure and networking:** The research team envisions deploying one server and associated IT equipment such as switches and routers. The team anticipates the cost to be around **$5000 - $6000** per installation of high-end server + networking equipment.
- **Software**
  - **XR software licensing cost: $0**.
- **Personnel Cost/Time**
  - **Training:** Since the shipyards will have full ownership of XR content generation capability, the trained maintenance personnel themselves can train future maintainers. The team anticipates that training the content developers on the software will take about 2 days.
  - **Content Development:** Each XR content will take about 1 day = 8 hrs. to develop.

Following is our cost-benefit-analysis of the XR investment:

- According to a recent GAO report on Navy Ship Maintenance (GAO Report, 2022), ship maintenance occurs anytime from an intermediate-level maintenance, lasting at least 3-weeks to depot-level maintenance lasting at least 6 months. Furthermore, as per the report, the ship crew size ranges around 13 junior enlisted crew members for each division, while there are about 18 shore-based maintenance experts. The crew members work minimum of 12 hrs. on port. Assuming that the enlisted crew makes about $30/hr. (Marine Mechanic Salary, 2025), the approximate **cost of performing intermediate maintenance** on a ship = $30/hr. x 12 hrs. x 21 days x 13 crew members = **$98,280** just for the crew labor cost.
- Also, let us assume that the rate for shore-side experts is $45/hr. Assuming, the crew needs help from shore-side SMEs about 25% of their time, the approximate **cost of providing expertise guidance** = $45/hr. x (25% x 12 =) 3 hrs. x 21 days x 13 SMEs = **$36,855**
- According to various studies, XR has potential to bring **50% reduction** in troubleshooting and maintenance steps over traditional paper and fixed computer procedural displays (Schlueter, 2018). Hence, **total cost of intermediate-level maintenance aided by XR** = ($98,280 + $36,855)/2 = **$67,568**.
- The report also states that a maintenance task takes any time from 3 hrs. to 9 hrs. Hence, on an average each crew member finishes one task per day, and 21 tasks during the 21 days. Let us assume that one XR content is needed for each of the 21 tasks, and that the content is developed by shore-side experts. Hence the **cost to generate XR content** for each of 21 tasks performed by one crew member, assuming each expert is assigned to a crew = $45/hr.

x 8 hrs./XR-content x 21 XR- content x 13 SMEs (1 SME assigned to each of the 13 crew members) = **$98,280**

- **Initial hardware investment** = (13 tablets x $1000) + (1 server/IT/Network equipment x $6000) = **$19,000**
- **Initial crew training cost** = $30/hr. * 8 hrs. * 2 days * 13 crew members = **$6,240**
- **Initial shore-based expert training cost =** $45/hr. * 8 hrs. * 2 days * 13 experts = **$9,360**
- Hence, the **total initial XR investment** = $98,280 + $19,000 + $6,240 + $9,360 = **$132,880**
- **Cost-saving of each intermediate-level maintenance** = ($98,280 **+** $36,855)/2 = **$67,568**
- Therefore, it will take only about $132,880/$67,568 = **2** intermediate-level maintenance visits to begin receiving **positive returns on the total XR investment**.

CHALLENGES, LESSONS LEARNED AND MITIGATION STRATEGIES

Limitations of the Research

Owing to the limited funding, the team was not able to realize the full potential of this research. For instance, we were unable to deploy the implemented XR use cases in a naval shipyard for use by technicians to gather usage data and assess ROIs. We will perform these field tests in a future funded effort from the Navy or another Government branch.

Real-time performance of Corrosion Detection and OQE models

A key research challenge was limited availability of training data for corrosion detection. The deep learning model was trained on images from bridge inspections. The research team plans to retrain the model using "transfer learning" (Transfer Learning, 2025) on image datasets from ship inspections. There are several challenges on training on a large dataset, which results in large model size that may introduce lag in a web application. Thus, the team will optimize the model-training dataset for the ship use case. The performance of Corrosion Detection and OQE capabilities is constrained by the processing speed of their underlying ML models. Coupled with network latency, a continuous real-time rendering of results may not be feasible. However, a slower frequency of update, e.g., with a 1-second interval, is feasible. This interval will provide sufficient time to capture snapshots from the tablet/smartphone's camera feed, send it to the ML model for processing, receive the results and overlay them on the active image in the camera.

Configuration Management

While the XR repository enables the users to generate, upload and modify 3D content, configuration control of the content is necessary. The content repository will be equipped with appropriate revision control and access permissions to ensure that only the users with proper privileges are able to create, modify or delete repository content.

Technological Considerations and Constraints

During conversations with NAVSEA shipyard stakeholder, the research team identified requirements and constraints that will be addressed prior to the ultimate deployment of the solution in a shipyard:

- *Containerization*: Due to the IT restrictions associated with a Navy installation, all the software components of the solution would need to be containerized so that it can be managed and hosted.
- *Ability to use inhouse or outside contractors*: Need for a democratized immersive content generation pipeline that enables future modifications to the XR content without needing any programming or graphical skills.
- *Device Support*: NAVSEA recommended having support for rugged devices without peripherals such as mouse, keyboard. Typically, tablets and headsets could be used on the deck plates, with hands-free viewing. Workers in the bilge will operate in a network-constrained environment, requiring support for offline tablet and smartphones, allowing the immersive content to be synced locally on the user device. Due to the high humidity environments, and the potential for falls while holding devices, optical see-through head-mounted displays (OST-HMDs) such as Microsoft HoloLens will fare better due to their ability to maximize natural light in dark environments.
- *File formats for immersive content*: GLTF 3D file formats, MP3 sound file format and MP4 video formats are all supported by the solution.
- *Network Bandwidth and Reliability*: In the offline case where all content is pre-downloaded, users will be able to

quickly move from step to step. For connected cases, access will be via web without the need to download content.

Cybersecurity Compliance and Enterprise Accessibility Considerations

Cybersecurity is identified as an important consideration for deployment of this technology. The research team identified the following the cybersecurity constraints related to the solution deployment:

- *IT cybersecurity*: Wi-Fi enabled AR/VR devices pose a risk of being hacked. The solution will allow the devices to sync content when they are inside a secure enclave using secure https connections, and operate and log data in a standalone mode. When devices reconnect to the secure network, maintenance logs are synced with the server. Most LMSs have mobile Apps that support content download to local devices for offline viewing.
- *Ability to perform work in Controlled Industrial Area (CIA)*: Ability to work with classified data by implementing security controls to the AR/VR content server for downloading content to the AR/VR devices and viewing training exercises, and user access via Common Access Card (CAC). Once synced, the devices can be used outside the CIA boundary. Track and manage classification level of generated XR content for access restriction, reuse, etc.
- *Transferring data outside the firewall*: In connected environments, use SIPRNet to connect to enterprise server.
- *Network encryption*: The solution incorporates encryption out-of-the-box for XR since the Networked A-Frame (NAF) server sits behind Apache HTTPD which encrypts incoming and outgoing traffic. AES256 encryption is used in communications between the maintainer's device and the central enterprise server, e.g., during live feeds from the shipboard secure environment, remote assistance, IoT sensor overlays, OQE, etc.
- *Camera Security*: AR/VR headsets, smartphones, etc. are a significant concern for cybersecurity when transmitting video through camera sensors in sensitive areas, e.g., for processing OQE and corrosion. Porting the image processing server-side library to JavaScript libraries enables it to be embedded in the technician devices, transmitting only the processed outputs from the libraries to the remote server in an encrypted manner.

Future Work

Future potential research will involve conducting studies of typical shipyard operations and training practices, conducting usability assessment of the solution and capturing user impressions/feedback from SMEs and crew. The team will assess the ROI benefits of the implemented XR use cases and incorporate these usability enhancements:

- *Reduce HUD-induced Nausea* – Reducing headaches and nausea due to rapid change in the field of view; Designing the virtual interfaces with proper placement of controls and fields to minimize the need for rapid head movement, by grouping information fields that update simultaneously at a similar rate.
- *Improve the posture and safety* – Capturing ergonomic user experiences for the right posture in restrictive environments such as the bilge; Designing UI/UX based on MIL-STD-4005 recommendations (MIL-STD-4005 2012) to minimize ergonomic stress; Adapting to the devices that meet the safety glass requirements.
- *Sound/voice activated*: To minimize distractions, adding voice activation for menus and commands.
- *Gesture/voice activated*: Using gesture and voice command to confirm all the cautions and advisories.

Another potential research area is investigating techniques to parse MIL-STD 3008 documents to extract maintenance data such as removed and repaired parts, their mean-times-between-repair (MTTRs) and mean-times-between-failure (MTTFs). This contextual information can be displayed to the ship personnel, overlaid in the field of view of the maintainer or the SME using AR anchoring. For instance, while performing task support, or during inspections, the XR application could display past repair history, average failure rates (MTTFs), last repair/replace incident, etc. to identify maintenance that is overdue for a recognized part, and thus facilitate rapid case resolution.

CONCLUSIONS

In this paper, the research team demonstrated the concept of an XR content-generation pipeline that provides time and cost savings by utilizing open source methods. Moreover, this process does not require any 3D modeling or graphical design skills. The resulting content supports remote/distributed learning via web-based content, multi-device modality, reduced training footprint, and an ability to gather training-related metrics through cmi5 and xAPI. The resulting training and operations can help the Navy achieve the strategic goal of optimizing the shipyard maintenance activities.

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