Evaluation and Implementation of Augmented Reality for Aerospace Operations and Sustainment

by

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Submitted to the MIT Department of Aeronautics and Astronautics
and the MIT Sloan School of Management
in partial fulfillment of the requirements for the degrees of

Master of Science in Aerospace Engineering

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Abstract

Industry is eager to adopt new technology and realize its predicted benefits, but it is difficult to justify a risky investment in an unproven technology. In the context of the aerospace and defense industry, new technology must meet stringent security standards in addition to being compatible with legacy systems. This thesis defines a collaborative framework for successful augmented reality technology development and implementation, including a process to identify a use case, define requirements, and evaluate existing commercial off-the-shelf solutions. The thesis application case study is motivated to support strategic development at Raytheon Technologies – Raytheon Missiles & Defense. The objectives include proposals for technology down selection and development processes to enable augmented reality capabilities for operations and sustainment of fielded products and to leverage those capabilities for additional applications.

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To my friends outside of my MIT grad experience. Thank you for all the calls, notes, rehearsals, visits, snaps, and fun times over the past two years (and more). I'm looking forward to our reunions soon!

To my family. Thank you for supporting me, hosting us for months, and for the love you pour into us daily. Thank you especially to my husband, who gave up his cushy job to move to *a city* and now has a cooler title than I'll ever have. Thank you for supporting me and for showing me what unconditional love looks like.

All glory to God from whom comes every good thing.

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Chapter 1

Introduction

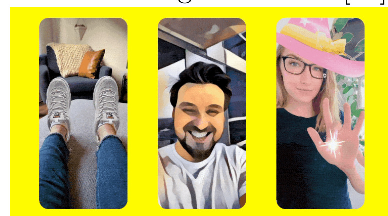
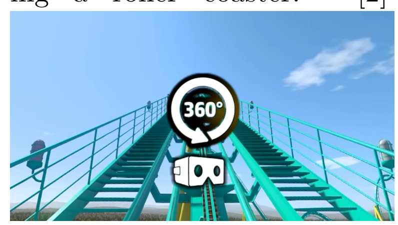
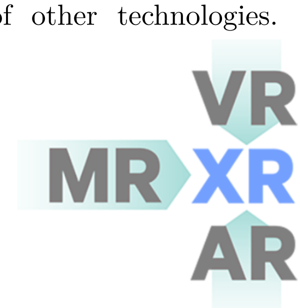
In this work, we assess current and future use cases of Augmented Reality and other Extended Reality technology. The goal is to guide the development of operations and sustainment technology within aerospace and defense companies. This is demonstrated by a case study of an Augmented Reality operations solution within Raytheon Missiles & Defense.[1] The introduction discusses the project motivation, key challenges, and relevant company background and defines the problem to be solved.

1.1 Project Motivation

The focus of this project is a technology that is frequently advertised as being a game-changing capability, particularly for industrial applications: Extended Reality (XR). XR is a term that includes multiple forms of reality-altering technology, such as Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR). [101] As these terms may be easily confused, definitions and examples of each technology are provided in Table 1.1.

[1] This study stems from an internship completed at Raytheon Technologies (RTX) within Raytheon Missiles & Defense (RMD) from June to December 2020.

Table 1.1: Reality-Altering Technology Definitions

Technology	**Definition**	**Example**
Augmented Reality (AR)	AR enhances the physical world while the user remains grounded in reality.	Snapchat enables users to try on articles of clothing or alter their appearance through AR. [83] 
Virtual Reality (VR)	VR immerses the user in a virtual world, and they are almost completely cut off from reality.	VR can make users feel like they are riding a roller coaster. [2] 
Mixed Reality (MR)	MR incorporates virtual objects into the physical world and lets the user interact with them while staying grounded in the physical world.	MR lets users interact with digital objects, such as a product display. [31] 
Extended Reality (XR)	XR is an umbrella term for reality-altering technology and includes AR, VR, and MR.	XR is at the intersection of other technologies. [49] 

XR has been touted as a solution to many business problems and experiences rapid market growth. [41] The lack of stability in XR technology providers due to factors such as mergers and bankruptcies may hinder XR implementation in two ways. First, the churn reduces capability awareness. Second, having few established players in the field makes it difficult to assess the reliability or longevity of any supplier. As a result, prospective adoptive companies are unable to gauge which supplier warrants investment. These factors increase the risk of implementation and reduce confidence in an investment.

Even when an investment is justified, it is difficult to decide how to best leverage the new technology, particularly within the aerospace and defense industry. Relevant questions include which technology to focus on, how to implement it, and whether to focus on internal or external applications. Internal applications for a defense contractor could involve but are not limited to manufacturing, engineering, or quality organizations. External potential applications include warranty support for fielded products or products for collaboration through XR technology. Another key question involves how lessons learned from one internal or external application should be leveraged for alternate applications. These questions inform the technology development strategies of defense contractors.

1.1.1 Company Background: Raytheon Missiles & Defense

Raytheon Technologies (RTX) was formed in 2020 by the merger of The Raytheon Company and United Technologies Corporation. RTX provides aerospace technology solutions in defense and commercial markets. Raytheon Missiles & Defense (RMD), one of four RTX businesses, is comprised of the former Raytheon Missile Systems and Integrated Defense Systems business units and focuses on the detection and deterrence of threats. RMD is supported by 30,000 employees in 28 countries worldwide. [97] Like the other heritage Raytheon businesses, RMD is a technology and technology integration company. Table 1.2 details the merger and location of RMD within the new organizational structure of RTX.

RMD's customer base is largely defense-focused, as indicated by its name and confirmed by its products and services listed in Table 1.3. While this has provided steady business during the downturn spurred by the Covid-19 pandemic, buffering other businesses within RTX whose core customers come from the commercial aerospace industry, the defense focus creates challenges in operations. [113]

1.1.2 Operations Challenges in the Aerospace & Defense Industry

RMD supports technology throughout the entire product life cycle and invests heavily in each stage from research and development of leading edge technologies to support and sustainment later in

Table 1.2: Raytheon Technologies Merger: New Businesses

<table>
<tr><td></td><td></td><td colspan="6">2020: Raytheon Technologies [120]</td></tr>
<tr><td></td><td></td><td>Pratt & Whitney</td><td>Collins Aerospace</td><td colspan="2">Raytheon Missiles & Defense</td><td colspan="2">Raytheon Intelligence Systems</td></tr>
<tr><td colspan="4">2018 - 2020: United Technologies [120]</td><td colspan="4">2014 - 2020: The Raytheon Company [94]</td></tr>
<tr><td>Otis (sold)</td><td>Carrier (sold)</td><td>Pratt & Whitney</td><td>Collins Aerospace</td><td>Integrated Defense Systems</td><td>Missile Systems</td><td>Space and Airborne Systems</td><td>Intelligence, Information and Services</td></tr>
</table>

Table 1.3: Overview of RMD Products & Services

RMD Product & Service Groups [91]
Air Warfare
Counter UAS
Hypersonics
Land Warfare
Missile Defense
Naval Warfare

program life. As in many industries, a great opportunity for cost reduction for customers exists in operations and sustainment. According to the U.S. Department of Defense (DoD), operations and sustainment costs account for 65-80% of the total life cycle cost of a program and are a key target area for cost reduction. [44] Several challenges common to RMD and the rest of the aerospace and defense industry contribute to this high life cycle cost and necessitate unique solutions to maintain and operate RMD products:

1. **Large equipment:** In the aerospace and defense industry, equipment tends to be physically large. The complexity and high cost of shipping such large equipment requires that the maintenance personnel evaluating or servicing the equipment must travel to the equipment rather than the reverse. To illustrate this, a typical radar for RMD is shown in Figure 1-1. Moving the equipment may also negatively impact the defense system's mission capability.

Figure 1-1: Large Scale of Typical RMD Products
Global Patriot™ Solutions [59]

2. **Location:** In addition to being large, defense equipment tends to be placed in remote locations due to its nature of operations, and RMD supports employees in 28 countries across the world. [97] While an international customer base is not atypical in the current business environment, the fact that remote locations are difficult to access, both geographically and sometimes politically, creates a unique operational challenge. The remote locations also typically have reduced network availability, which hinders communication capability.

3. **Response time:** Response time is paramount for mission-critical defense situations. A delay of several hours due to travel or availability could make the difference between mission success and failure.

4. **Security:** Information security standards are exceptionally high in the defense industry. Even

in cases where encryption standards are met, personnel may still have a cultural aversion to using technology due to years of cloud security limitations. Additionally, restrictions around handling export-controlled information and material limits the ways in which information can be disseminated and materials can be transported.

5. **Knowledge retention:** Frequent personnel changes in the defense industry, coupled with complex electro-mechanical systems, create challenges for on-boarding and knowledge retention. Similarly, the long program life in the defense industry requires support and knowledge retention for decades.

1.1.3 XR for Operations & Sustainment

These operations challenges led RMD to assess insertions of custom technology solutions to improve accessibility and reduce risk and cost, including investing in and patenting XR solutions. One key patented and patent pending AR initiative, VirtualWorx™, combines commercial off-the-shelf (COTS) components and internally developed capabilities to connect people in the field with Subject Matter Experts (SMEs) while maintaining information security and enabling connections in low bandwidth scenarios. This process, often called "reach back support," can reduce or eliminate travel and improve response time. Figure 1-2 shows the VirtualWorx system in use.

Figure 1-2: VirtualWorx in Use
A field technician demonstrates the VirtualWorx system being used with a handheld tablet. [95]

Interest in remote collaboration has also spiked due to the Covid-19 pandemic and the advent of social distancing and travel restrictions, and this has expanded the application of AR beyond remote expert support in the field. Additional potential VirtualWorx applications include remote inspections, travel avoidance, and increased communication between engineering and production to reduce problem resolution time and cost. RMD is interested in continuing to develop and leverage the VirtualWorx capability for these and other alternate applications as needs arise.

This thesis investigates a case study conducted within RMD. However, this is only intended to be a typical example of XR development and implementation for operations applications. Additionally, although this study focuses on aerospace and defense, it does not intend to limit its applications in other industries. Areas with similar operations challenges involving large equipment, such as mining and forestry, can leverage similar remote maintenance solutions to accommodate high equipment utilization.

1.2 Problem Statement

RMD seeks to develop and scale their VirtualWorx AR technology for external and internal operations applications. Since the XR field is changing rapidly, RMD continues to reevaluate COTS portions of its solution to determine if they should pursue other providers for the VirtualWorx capability in parallel with their current efforts. Additionally, they desire to determine how they can best leverage this and other XR capabilities for alternate applications within the RMD business unit and across the greater RTX enterprise.

1.2.1 Problem

The maturity and staying power of many COTS XR solutions are incompatible with immediate defense industry needs. Information security requirements and system hardware and software may not be sufficient for demanding industrial applications at scale. Additionally, a new technology may take months or years to gain approval for use in the defense industry, only to be replaced with an updated technology version during the review process. The abundance of new XR offerings makes it difficult for a team to compare new capabilities and determine which are worth implementing within the long defense program life cycle.

1.2.2 Intervention

This thesis develops a framework that teams can use to quickly evaluate how XR can fill unmet customer and user needs. This framework defines use cases, defines requirements for those use cases, and evaluates potential solutions against those requirements through a high-level trade study. Key performance metrics involve capability, scale, security, and implementation. This framework is then used to answer the question of how to continue the development and roll-out of the VirtualWorx capability within RMD and accelerate its implementation.

1.2.3 Intended Result

The result of this study will be twofold. First, it will inform the development of the VirtualWorx capability by determining if any other COTS providers should be investigated for their ongoing work and by identifying how the capability should be utilized in alternate applications. VirtualWorx is used as a case study, as it is representative of many thorough AR solutions on the market. Second, the framework will be generalized to other assessments of XR for use cases beyond operations and sustainment, such as collaboration for training, documentation, or design. Using the framework developed in this thesis, detailed in a strategy playbook controlled by a central and internal Community of Practice (CoP), teams across RTX can rapidly assess high-level requirements to fill identified customer needs, either through COTS or internally-developed tools, in order to facilitate adoption of new technologies, improve and standardize evaluation, and reduce costs.

1.3 Thesis Organization

In Section 2 we analyze existing literature, both internal and external to the defense industry, to inform the research approach. Section 3 describes the chosen methodology. Results are discussed in Section 4, with the strategy playbook defined in Section 4.4.1. A summary and questions for future work are captured in Section 5. Appendix A includes more detail on documented use cases of XR technology, and Appendix B elaborates on the trade study performed.

1.4 Introduction Summary

In summary, this project will develop a framework for rapid XR technology assessment to enable implementation. Use of the framework is demonstrated by its application to a specific need within RMD: guiding the continued development of the VirtualWorx AR solution to reduce the cost of operations and sustainment. To leverage past work, previously completed studies relevant to both XR and technology investment within the defense industry are evaluated in Chapter 2.

Chapter 2

Background

This background assesses prior work with a goal to inform the definition of a framework for rapid XR technology assessment to enable further development and implementation. This is accomplished through a literature review and a broad industry survey. The literature review focuses on other approaches to technology assessment and methods of quantifying value added. The broad industry survey captures industry activity in the XR field beyond the defense industry.

2.1 Methods of Technology Evaluation and Implementation

At the core of this project is a need to assess emerging XR technology to determine if it meets defense customer needs. The defense industry and the XR technology are separately studied. This section investigates how technology is evaluated in the defense industry and how XR capabilities have been developed by commercial companies for implementation.

2.1.1 Evaluating Technology in the Defense Industry

The defense industry often funds early stage research but is wary of adopting early stage technology before it is proven due to the associated financial and national security risk. Keat's 2012 dissertation, "An Enhanced Evaluation Framework for [Defense] R&D Investments Under Uncertainty," highlights the difficulty in evaluating technology for new applications in the defense industry. [70] They propose a framework to encourage innovation that involves a novel scoring method, factoring in both financial metrics and details of the application itself. The resulting recommendation is a set of four different evaluation methods, dependent upon the Technology Readiness Level (TRL, low or high) and the uncertainty of the application (low or high). [70, 76] Similarly, Cogliandro proposes a method of introducing new technology within the defense industry. [36] By highlighting the inverse risk, or the risk of not taking risk, Cogliandro advocates for different levels of acceptable risk by program life cycle stage. [36] This work is important in that it enables innovation in the defense industry, but it is broadly applicable to any technology and does not consider XR specifically. It provides heuristics to guide early investment in new technology but does not directly connect those technologies to specific use cases or their associated requirements. The framework developed in this thesis should address how to assess XR technology not just as a whole but for defined use cases.

Another group of experts at Ball Aerospace, a small defense and civil space contractor, starts to incorporate one defined use case in XR assessment. Bershinsky and Narciso have acknowledged the "struggle to determine the impact MR will have on current workflows and when to invest," sharing their work as "a call for collaboration and a starting point for finding the best method to quantitatively assess MR interfaces used in Aerospace applications." [24] In one study, they define a framework to determine if a given task should be completed via a Human-Computer Interface (HCI), and they subsequently collect data on processes with the intent of using historic data to predict where HCIs will enable higher efficiencies than their manual counterparts. While this work is pertinent to applying XR technology, it is specific to manufacturing processes, and defense contractors have opportunities to apply XR outside of manufacturing. Bershinsky et al. acknowledge gaps in their knowledge, noting that "more information is required to confidently select the scenarios where these tools offer the greatest return... correlations will emerge between functional requirements for each use-case, allowing decision makers to form broader interpretations of the data and make educated decisions on tools to apply in new use-cases," and they hope that "many independent studies will help form a bigger picture and a deeper understanding of HCIs." [24] The call for additional independent studies reiterates the need for a framework to assess XR system requirements for applications beyond the manufacturing scenarios considered in their study.

2.1.2 Accelerating XR Technology Implementation

The large range of product offerings, maturities, and capabilities in the field of XR is acknowledged as a potential hindrance to its implementation. Wright et al. highlight how, in the Internet of Things (IoT) era, hardware and software is increasingly vendor-specific, and they propose a "Mixed Reality Control Panel (MRCP) system" as an "open-source, vendor-neutral" solution. [129] Although this effort is advantageous for the broader community to accelerate the implementation of XR, the aerospace and defense industry cannot benefit from a similar system due to industry-specific security constraints.

Some efforts to streamline the software development of XR applications have been made outside of the defense industry. Rokhsaritalemi et al. propose a five layer framework for the development of MR applications. [98] Linder, of the MIT Media Lab, discusses “Rapid Development, Real-World Deployment, and Evaluation of Projected [AR] Applications” in a 2017 dissertation with a goal “to advance the practical use of projected AR interface in the real world.” [72] However, both these studies focus on developing new software applications for platforms, such as specific programs that run on preexisting hardware and software operating systems. They do not focus on developing the XR platforms themselves, which include the COTS software operating system and hardware platform. This thesis evaluates the platforms because they are the prerequisite to building novel applications.

One effort has been made to standardize requirements for XR platforms, but it is not specific to the defense industry. Quandt et al. propose high-level requirements for generic industrial AR systems, organized by process step: development and integration, set-up, and operation. [93] However, these requirements are broadly defined, only including two to three requirement categories for each process step for a total of eight requirements. They point out that “the presented requirements have been collected with a cross-application approach and show a rather low level of detail.” [93] Additionally, although Quandt et al. define a set of use cases within industrial applications, including product/plant design, training, production assistance/logistics, quality assurance, and remote maintenance, the requirements do not differentiate between use cases of AR within industrial applications. [93] While this framework is helpful to categorize industrial XR applications and related requirements, the level of detail would not be enough to meaningfully differentiate between COTS platforms for XR technology assessment. The authors note that “industrial AR applications are expected to perform well” according to the broad requirements but do not define what “well” entails. [93] The aerospace and defense industry would welcome participation in a standard requirements and applications development.

Further work is needed to define use cases for XR within the aerospace and defense industry and to subsequently define requirements linked to those use cases. Specific COTS applications could then be assessed against the defined requirements. The probability of success in XR technology development can be improved by using a framework that takes a customer need and translates it into a specific use case and associated requirements. If requirements match the customer need and are predefined, implementation time can be reduced while still meeting the customer need.

2.2 Quantifying Value Added

Another core question to this study and a major complicating factor that prevents emerging XR technology from being implemented is a poor definition of customer value added. Generalized motives for identifying the value added through VR and AR have been proposed by Steffen et al. but intentionally cover many fields and are not specific to aerospace and defense or even one use case. [112] Steffen et al. quantify the perceived value XR adds on a scale of 1 to 10 but do not discuss the associated monetary gains, as they would be difficult to assess across different fields. [112]

In a thesis excerpt adapted for The Lean Aerospace Initiative Report Series, author Slack defines value according to lean principles, or as interpreted by the customer, within the military aerospace context. [105] Slack provides a customer value definition that incorporates the need for the product, the ability and availability of the product to meet that need, and the cost to the customer. However, Slack breaks from traditional lean principles and acknowledges that value streams of employees and shareholders should also be included, as they create a more complete and global system of value. [105] This thesis work adapts the shared value approach to accommodate the benefits of XR experienced both internally and externally as discussed in Section 1.1. We propose three major types of value that can be added which are shared between both the customer and the supplier:

1. **Closure:** Meeting an unmet need. This could include improvements to a product or service, providing a new product or service, providing more of that product or service, trading, or generally solving a problem, which leads to market capture. This incorporates Slack's definition of customer need for the product and ability of the product. [105]

2. **Cost avoidance:** Meeting the same need with fewer resources. This could be a reduction in cost through a faster process cycle time, faster development time, lower personnel requirements, higher quality and less rework, or lower material costs. This value can be shared by both the customer and the providing organization. This accounts for Slack's customer value components of direct cost to the customer and product availability, as customer cost is reduced if the product is available when they need it. [105]

3. **Assurance:** Convincing the customer to agree to the exchange. This could be something like insurance, capabilities that are only relevant in rare instances, or supplier expertise. While

in most cases the customer will not receive a quantifiable benefit as a result of the increased assurance, it will make them more likely to agree to the trade, enabling subsequent closure or cost avoidance. This value is not specifically detailed by Slack but is captured by the supplier and could be shared with the customer.

While each of these sources of value are beneficial, the focus of this project is on "Closure" value added, which includes the customer need for the product and the capability of that product. Still, each type of value is important to understand although it is not quantified in this report.

2.2.1 Closure

Value that comes from closure is due to demand from customers and subsequent market capture. Prior to the Covid-19 pandemic, demand was increasing within the U.S. aerospace and defense market. [77] Even when the market cannot be robustly quantified, if there is an expressed customer need, a solution that creates value will find use. Some value added through closure may also add value in other ways. For example, using XR for training adds value through closure by improving user safety, but it also adds value through cost avoidance by reducing the reliance on expensive equipment.

2.2.2 Cost Avoidance

Consider this example of cost avoidance: a manufacturing AR application helped operators set up die cutters, resulting in cost savings when the same setup process was completed in a shorter time. [8] Cost savings were not only limited to labor associated with the equipment setup time but also led to lower storage cost, lower material waste, and improved quality. [8] Cost avoidance can sometimes be difficult to assess in detail in industrial defense applications. For example, the die cutting operation chose not to include cost savings numbers in their study, as labor rates are comprised of many complex interacting data streams, and publicly stating cost savings can impact customer expectations. Customers may expect that a portion of the cost savings would be passed on to them. However, the reduction in total cycle time is beneficial to all.

Depending on the industry, it may not be possible to assess cost avoidance from outside a company, as doing so requires a thorough understanding of the process steps involved. While process steps are certainly well understood internally, they are typically not published for information security and competitive interests, and many companies are hesitant to publicly comment on the details of such cost-cutting measures. When they are published, they are generalized. For example, when discussing savings that resulted from AR-based instruction for manufacturing on a space program, Peterson of Northrop Grumman indicated only a wide range of labor reduction: 30-50%. [118] While this thesis project considers cost avoidance, it is not quantified in this report.

2.2.3 Assurance

Assurance value is the most difficult of the three types to quantify. While value added in this sense could enable the capture of a program worth billions, a component of the proposal cannot claim that entire value by itself. Assurance may also be difficult to measure because the impacts are not directly measurable. For example, an AR technology could enable an event, such as an inspection, to take place sooner than would be possible with traditional in-person methods. The in-person event could still happen, but the delay could lead to widespread supply chain and schedule issues. For this reason, assurance is subject to managerial discretion and is not repeatable.

As seen in the case of the Covid-19 pandemic, it is much easier to quantify the value added from assurance items after an adverse event than it is to make an estimate in advance. A study by Belhadi et al. compared the expected impact of the pandemic on the global automotive and airline industries: the automotive industry leaned into digital connectivity, beginning with material requirements planning systems and leveraging local supply sources as solutions. [23] While the worldwide automotive industry impact is projected to be between $520 billion with a V-shaped recovery and $804 billion with a U-shaped recovery, early predictions from increased manufacturing in China indicate that the recovery profile will likely match the V-shaped, lower loss profile. [23] The automotive industry's decision to focus on digital connectivity enabled them to work through unforeseen circumstances and reduced the financial impact of the pandemic by almost $300 billion, or a 35% reduction compared to the alternative realistic scenario. [23] However, savings determined retroactively cannot solidify a future business case for investing in any one technology.

2.3 Benchmarking

Benchmarking studies capture prior work but cannot fully represent the current state of the XR industry. In 2018, Cipresso et al. completed a thorough study of over 30,000 VR and AR scientific papers to identify the key areas of significant work of the past few decades. Their findings indicate the depth and breadth of the XR field by highlighting the networks of industries, countries, institutions, and applications of XR and how they have changed over time. [35] Similarly, Palmarini et al. surveyed AR applications in maintenance to determine the "current state of the art" and prospects for the future based on which industries are most involved in AR at the time of the study in 2018. [87] While previously completed industry surveys and analyses point out current capabilities, applications, and industry leaders, recent changes in the XR industry are not captured.

This thesis includes a broad industry survey here in Chapter 2 to identify XR applications of interest outside of the aerospace and defense industry. A similar study focused on the aerospace and defense industry is discussed in Chapters 3 and 4; however, it is important to also understand how other industries are using a given technology to leverage prior work. These two surveys are combined to inform the use case repository in Section 4.4.1, which is regularly updated and is an attempt at an accurate snapshot of the state of the XR industry.

2.3.1 Broad Industry Survey

Although the focus of this project is on XR for aerospace and defense, understanding other XR applications helps craft recommendations and identifies potential solutions. A tool that can be updated continually would be advantageous compared to episodic reviews. Additionally, it is helpful to identify the activities of individual XR hardware providers, software providers, and integrators to understand the active XR industry. For example, Caterpillar's LIVESHARE remote support system is similar in intent to RMD's VirtualWorx solution, and Caterpillar and RMD share similar industrial challenges, so it is a helpful point of comparison. [126]

To enable this validation and assessment of capabilities, a broad industry survey was completed through a search of publicly available news releases, articles, and journals. While this list is not meant to be exhaustive, it is a starting point to identify potential COTS software providers, hardware providers, and integrators. See Table A.1 for a list of documented industry use cases. The use case categorization system applied is defined in Section 3.2.1. This survey is an input to the framework to assess XR technology for applications within RMD, where a use case repository is established to be regularly updated as part of the strategy playbook discussed in Section 4.4.1. As a key takeaway, the quantity and diversity of recent applications uncovered in the broad industry survey validate the need for a tool to be continually updated to capture the knowledge of the organization in the broad field of XR and to stay informed about the current state of the industry.

2.4 Background Summary

The literature review and industry survey highlight the need for additional, ongoing research to identify the success and challenge factors when adopting XR in complex industrial settings. This research informs the approach for developing XR capabilities for operations and sustainment at RMD, which is discussed in Chapter 3. This thesis attempts to answer the call for defined use cases relevant to the aerospace and defense industry beyond only manufacturing, detailed in Section 3.2.1. The need for a set of requirements to easily and quickly assess potential solutions to fill the customer needs, defined in Section 2.2, is investigated in Section 3.2.3. The method to quantify value added through "Closure" is described in Section 3.4.1. Finally, a way to make sense of and utilize these framework components as a whole is provided through the strategy playbook in Section 4.4.1, including a continually updated use case repository to maintain awareness of the current state of the art. In Chapter 3, we continue by describing the research approach and the specific plan for developing a framework for XR technology assessment at RMD.

Chapter 3

Research Approach

This section explains the research approach and how a standardized framework enables RTX to rapidly identify and meet previously unmet customer needs or improve upon currently met needs. Although this example focuses on RTX and their interests in operations and sustainment, the framework is broadly relevant to the aerospace industry and the DoD. It is also relevant to other industries who face similar challenges.

3.1 Overview of Methodology

This research generates a recommended strategy playbook (Section 4.4.1) that utilizes a new framework of standardized use cases and requirements for XR technology. The framework allows teams to easily identify unmet customer needs and to assess available solutions that can then be rapidly and effectively evaluated for implementation.

The inputs to the strategy recommendation playbook can be broken into three categories:

1. **Demand:** Identify common internal or external customer needs to drive investment in new capabilities. Define requirements based on customer needs.

2. **Supply:** Leverage existing COTS products and assess their capabilities against the defined requirements.

3. **Value Added:** Invest in areas where there is an opportunity to meet an unmet need ("Closure" as discussed in Chapter 2). Confidence in quantified value added is necessary to minimize the inherent risk in investing in unproven technology. Performance metrics relate to capability, scale, security, and implementation.

Figure 3-1 lays out the inputs for each category. Each component is explained in greater detail throughout Chapter 3, and the analysis and results are documented in Chapter 4.

Figure 3-1: Research Methodology

3.1.1 Unique Organizational Considerations

Any recommendations must align with the norms of RMD, namely that processes are valued and that RMD is a technology company at its core. These takeaways are based on informal observations gained over the period of several months of full-time work within RMD, although as noted in Chapter 1, the organization was in flux due to restructuring. The year of 2020 brought unmatched change for RTX, but the defense culture trusts processes. While seen by outsiders as a hindrance, the organization is accepting of structure and embraces it as a way to ensure success the first time. The selected methodology takes this into account by generating a framework that can be followed as a formalized process.

3.2 Customer Need

The first input to the strategy playbook formulation is the demand relevant to RTX's interest in utilizing AR for operations and sustainment. This section identifies areas of RTX customer need relevant to XR technology. Customers include both external groups, such as the U.S. Armed Forces, and internal functions, such as manufacturing. Identified RTX customer needs are grouped into six high level use cases defined in Section 3.2.1: Attract, Design, Document, Train, Operate, and Enhance. Then, a set of common requirements for each use case can be defined for a repeatable and rapid yet meaningful initial assessment. The accuracy of the requirements for the initial assessment increases the likelihood that any investment efforts will contribute towards a successful solution.

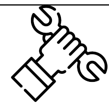
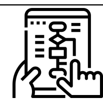
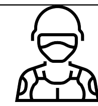
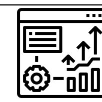
3.2.1 Standardized Use Cases

A set of six XR use cases captures the range of XR customer needs in the aerospace industry, making meaningful and repeatable assessments of the market space possible: Attract, Design, Document, Train, Operate, and Enhance. They are described in Table 3.1 along with examples of internal and external customer applications. These use cases are intended to be broad enough to capture all potential XR applications uncovered in the market analysis discussed later in Section 3.2.2 and 3.3.1. They could also be applicable in other situations or industries with slight modifications, but the focus remains on the aerospace and defense industry for the purpose of this case study. From the perspective of an aerospace contractor such as RTX, a single XR solution could serve internal customers, external customers, or hybrid needs across a single use case.

In addition to enabling documentation of the research approach, standardized use cases also enable rapid assessment of customer needs not previously possible. Due to concerns regarding competitive advantage and intellectual property (IP), aerospace contractors may not be willing to share details of their applications with external parties. Information sharing is further hindered by interests of national security, meaning that only generalizations about the end application can be shared even within a company. This leads to a host of custom solutions where it may have been more effective to leverage one platform. A framework for standardization may enable more customers, both internal and external, to benefit from the initial investment, which can both reduce cost and development time.

Acknowledging that standardization could lead to XR capabilities being treated as commodities, it is important to maintain some product differentiation while still benefiting from the economies of scale. Consider a personal computer: although each company has access to only a handful of operating system choices, it is the specific application of that operating system that is used to benefit their customer, and the computer enables further value creation. Similarly, although the same XR platforms could be used by multiple companies within the aerospace and defense industry, customer value and differentiation come from the specific application of the technology and how well it meets the needs of the customer. The framework developed in this thesis does not seek to standardize to the point where any solution is a commodity, but it attempts to allow teams to leverage existing COTS platforms as the starting point for further solution development.

Table 3.1: Use Case Definitions

XR Use Cases. Icons made by Freepik. [54]					
 Attract	 Design	 Document	 Train	 Operate	 Enhance
Highlight advanced capabilities to recruit and retain top talent or customer interest	Lower cost of manufacturing by enabling collaboration for supply chain, engineering	Reduce cost and improve quality via step-by-step guides, instructions, and on-the-spot training	Reduce cost, improve preparedness and safety through realistic field training	Reduce downtime and cost through data analytics and remote expert help, inspection, and warranty support	Increase probability of field success through decision aids
External Customer Examples (DoD)					
Simulate job experience to recruit	Customer buy-in prior to costly hardware	Step-by-step guides for operations or troubleshooting	Realistic field training	Call in remote support or attend inspections virtually	Field decision aids
Internal Use Examples (Contractor)					
Talent retention through technology leadership	Engineering, process, or supply chain planning	Guides as on-the-spot training for manufacturing	Realistic manufacturing or on-the-job training	Remote expert help for manufacturing issues, inspections	Process decision aids
Hybrid Examples (Support)					
Demos to attract customers	Collaborate and plan for emergent field solutions	Step-by-step guides for servicing	Realistic warranty support training	Enable low cost warranty support	System status decision aids

In order to standardize use case definitions, it is important to first understand where industry players are interested in using XR as well as where they have needs that XR can support. The use case definitions are defined in conjunction with the market analysis discussed later in Chapter 3 Sections 3.2.2 and 3.3.1, as well as the broad industry survey discussed in Chapter 2 Section 2.3.1.

3.2.2 Market Analysis: DoD Customers

After standardized XR use cases have been defined, the core work of identifying the location and amount of customer interest in XR capabilities can be completed through a thorough market analysis. The first component of the market analysis focuses on external DoD customers. Acknowledging that a traditional market analysis is not possible given heightened information security for any defense applications, it is still important to be able to assess the needs of each DoD player.

The customer portion of the market analysis focuses on DoD customers, or each branch of the U.S. Armed Forces, shown in Table 3.2. The documented needs of each player were assessed through a search of publicly available news releases, articles, stated capabilities or investment areas, requests for funding or proposals, budget requests, or other similar publicly available material. Examples of typical sources are shown in Figure 3-2. For this thesis, we assume most foriegn military allies have similar requirements. Then each customer's XR application interests are categorized according to the standardized use cases defined in Table 3.1. While this search is not meant to be exhaustive, it is intended to be representative of DoD interests in XR. Note that while AR was the focus of this study, VR and MR were also included in this study but were not prioritized in the search, as AR lends itself to hands-free implementations, which are the predominance of sustainment repair and maintenance tasks. This may lead to a lower level of perceived interest in VR and MR compared to AR. The results of this approach are discussed in Chapter 4.

Table 3.2: Market Analysis: DoD Focus Organizations

Branches of the U.S. Armed Forces
Army
Navy
Air Force
Marines
Space Force
Coast Guard

3.2.3 Standardized Requirements: Operate

Once a customer use case is identified, the next step is to define the requirements for that use case. A set of requirements can then be reused for subsequent applications involving that use case. Here, the focus is on the Operate use case, as it is most relevant to RMD's interest in utilizing XR for operations and sustainment and is further justified by the analysis in Section 4.3.1. The Operate use case requirements are intended to be detailed enough to aid in technology down-selection for development decisions. They are not meant to be a thorough or final requirement set for an implemented system. The requirements span four categories:

1. **Capability:** Requirements pertaining to the hardware and software requirements most rele-

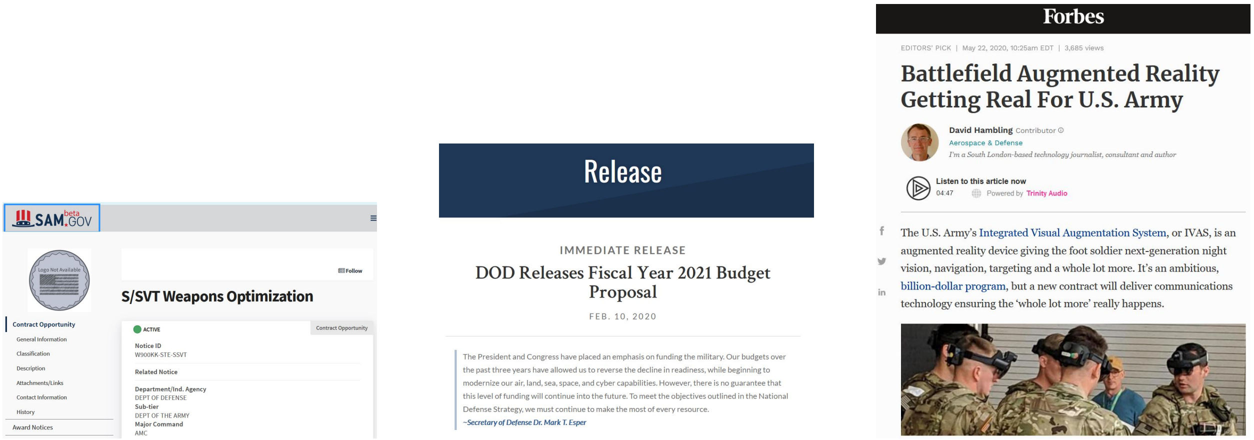


Figure 3-2: Market Analysis Examples: DoD. Examples of the type of applications that were identified in the market analysis (news articles, stated priorities in budget requests, proposals, or similar). [27, 46, 60]

vant to end users, such as hands-free operation, the ability to share live video or screen share, or the number of platforms supported.

2. **Scale:** Requirements pertaining to supporting multiple users across an enterprise, such as the number of callers who could be involved in a call.

3. **Security:** Requirements pertaining to information security, such as encryption standards, export or import requirements, and user qualifications.

4. **Implementation:** Requirements pertaining to getting the system operational across an enterprise, such as user training.

By developing a requirement set, the needs of a particular customer can be documented. Then, potential solutions can be assessed, and their evaluations can be reused for additional instances of a use case. For example, if one team completes a trade study evaluating COTS providers for the Operate use case, another team seeking a solution for another Operate use case can leverage their work and build upon it by evaluating COTS providers that were not previously evaluated or by updating existing COTS capabilities. In this way, an organization could collaborate without sharing key technical data, and efforts to complete trade studies to assess paths forward could be more efficient.

Tables 3.3, 3.4, 3.5, and 3.6 detail the defined requirements. Each requirement comes with "low," "medium," and "high" level definitions so that an application's requirements can be quickly identified by an expert or even someone less familiar with the technology by simply selecting one of three levels. For example, if the requirement pertains to the ability to export the technology, the "low" requirement would restrict the technology to only U.S. use, "medium" would apply some restrictions on which countries the technology can be exported to, and "high" would make the technology available for use in any country. Some proprietary technical details have been eliminated, particularly in Table 3.4, but some detail is provided with the hope that readers can understand the intent of the requirement set.

These requirements are not designed to be all-inclusive for the development of a solution. They merely point teams towards the most promising candidates. Alternate contributing factors that could be included in a high level assessment include other implementation requirements such as company culture fit or cost. Cost is not included in this first pass, high level requirement set, as assessing cost would require additional detail about the end system in order to request quotes from COTS providers. Cost can be more effectively added in a second round of trade study when a handful of potential solutions are assessed. Availability of existing solutions can be determined through the completion of the trade study process, detailed in Section 3.3.2.

Table 3.3: Capability Requirements for Use Case: Operate

	Feature	**Low**	**Medium**	**High**
1	Real time sharing capability	Live voice, static photo sharing	Live voice and video, static photo sharing	Live voice, video, and screen sharing
2	Augmentation capability	Minimal augmentation capability	Static telestration, recording, zoom	Hand gestures, smart devices, telestration with true tracking/overlay
3	Hands-free	No hands-free capability	Hands required for some functions, partial hands-free capability	Complete hands-free
4	Device agnostic	Works with only one specific device	Works with 2 - 3 devices (i.e. one headset and mobile or tablet)	Works with multiple devices and classes of devices (multiple headsets, Android/iOS mobile, tablet, etc.)

	Feature	Low	Medium	High
5	Usage statistics and integration	Available to server owner, shareable to users upon request	Personal user statistics available to users	Custom dashboard showing personal user statistics available to users
6	Bandwidth tailoring	Bandwidth requirements fixed	Bandwidth automatically optimized	Bandwidth configurable
7	Annotate photos	No annotation capability	Some annotation capability	Intuitive, multi-design annotation capability
8	Photo saving	Photos taken cannot be saved	Photos saved to individual devices	Photos saved to shared repository

Table 3.4: Scale Requirements for Use Case: Operate

	Feature	Low	Medium	High
9	Concurrent sessions	1 - 10 concurrent sessions	11 - 99 concurrent sessions	100+ concurrent sessions
10	Maximum callers per session	2 callers	3 - 9 callers	10+ callers
11	Minimum acceptable bandwidth	High	Medium	Low
12	Minimum acceptable latency	High	Medium	Low
13	Server requirements	High	Medium	Low
14	Client application platform requirements	High	Medium	Low

Table 3.5: Security Requirements for Use Case: Operate

	Feature	Low	Medium	High
15	Identity management	None	Shared login credentials	Individual users
16	Multifactor/two step authentication	No multifactor/two step authentication	Two step authentication	Multifactor/two step authentication
17	Remote control client access	No remote control client access	Remote camera zoom/lock	Remote camera zoom/lock, remote log out
18	Encrypted data	Approved for unclassified use only	Approved for classified use on a subset of devices	Approved for classified use in all cases
19	Encrypted device	Approved for unclassified use only	Approved for classified use on a subset of devices	Approved for classified use in all cases

	Feature	Low	Medium	High
20	Operating system patch management	No patch management	Patch management, can be declined	Automatically pushed patch management
21	Security features	Low	Medium	High

Table 3.6: Implementation Requirements for Use Case: Operate

	Feature	Low	Medium	High
22	User citizenship/status	U.S. persons only	Limitations on which persons can use	Largely open to U.S. and non-U.S. persons
23	Exportable	U.S. use only	Limitations on where can use	Largely open to all locations of use
24	Cloud/FedRamp status	Not FedRamp approved	Approved with restrictions	FedRamp approved
25	Software distribution	Case-by-case distribution, no patches/updates without request	Available on managed app store	Available on internally managed app store, patches/updates pushed automatically
26	Documentation and training	Documentation only	Documentation and help line	Complete documentation and training included
27	Accessibility	No additional accessibility	Closed caption enabled	Closed caption enabled, multiple language translation supported

3.3 Supplier Offerings

The second input for the recommended strategy playbook presented in Section 4.4.1 is a thorough understanding of supplier offerings. Knowing what is currently available is important to ensure that the chosen customer need is not already met by a competitor as well as to best leverage COTS capabilities when providing a technology solution. Section 3.3.1 discusses the approach to assess the XR activities of competitors in the defense industry. Section 3.3.2 details the methods to evaluate specific COTS XR solutions.

3.3.1 Market Analysis: Contractor Competitors

The second component of the market analysis focuses on the supply by identifying the level of interest in each XR use case by key aerospace government contractors. Five large government contractors, detailed in Table 3.7, were identified using public media and typical financial identifiers.

Table 3.7: Market Analysis Focus Organizations: Government Contractors

Government Contractors
BAE Systems
The Boeing Company
Lockheed Martin
Northrop Grumman
Raytheon Technologies

The publicly released XR applications of the five key aerospace government contractors are assessed through a search of publicly available news releases, articles, stated capabilities or investment areas, conference proceedings, presentations, or other similar publicly available material. Examples of the types of applications identified are detailed in Figure 3-3. Then each contractor's XR capabilities are categorized according to the standardized use cases defined in 3.1.

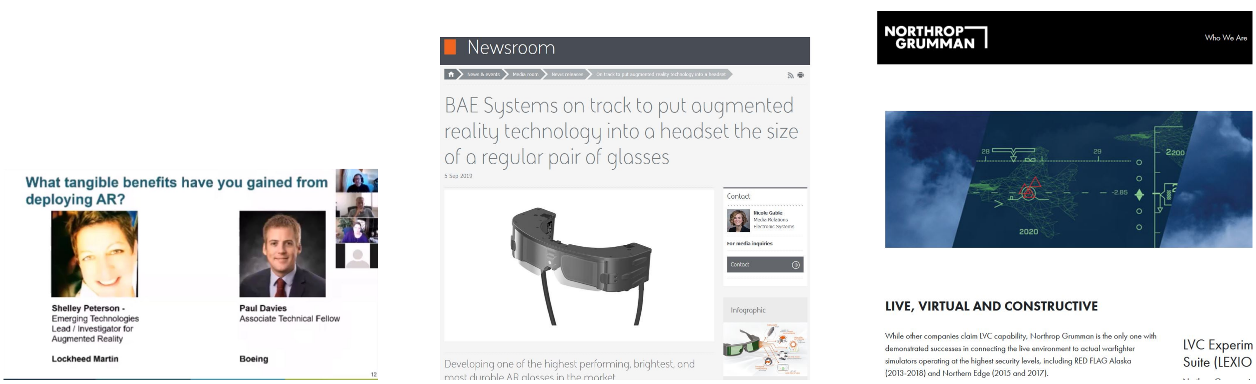


Figure 3-3: Market Analysis Examples: Contractors. Examples of applications that were identified in the market analysis (news articles, conference proceedings, stated interests). [118, 86, 73]

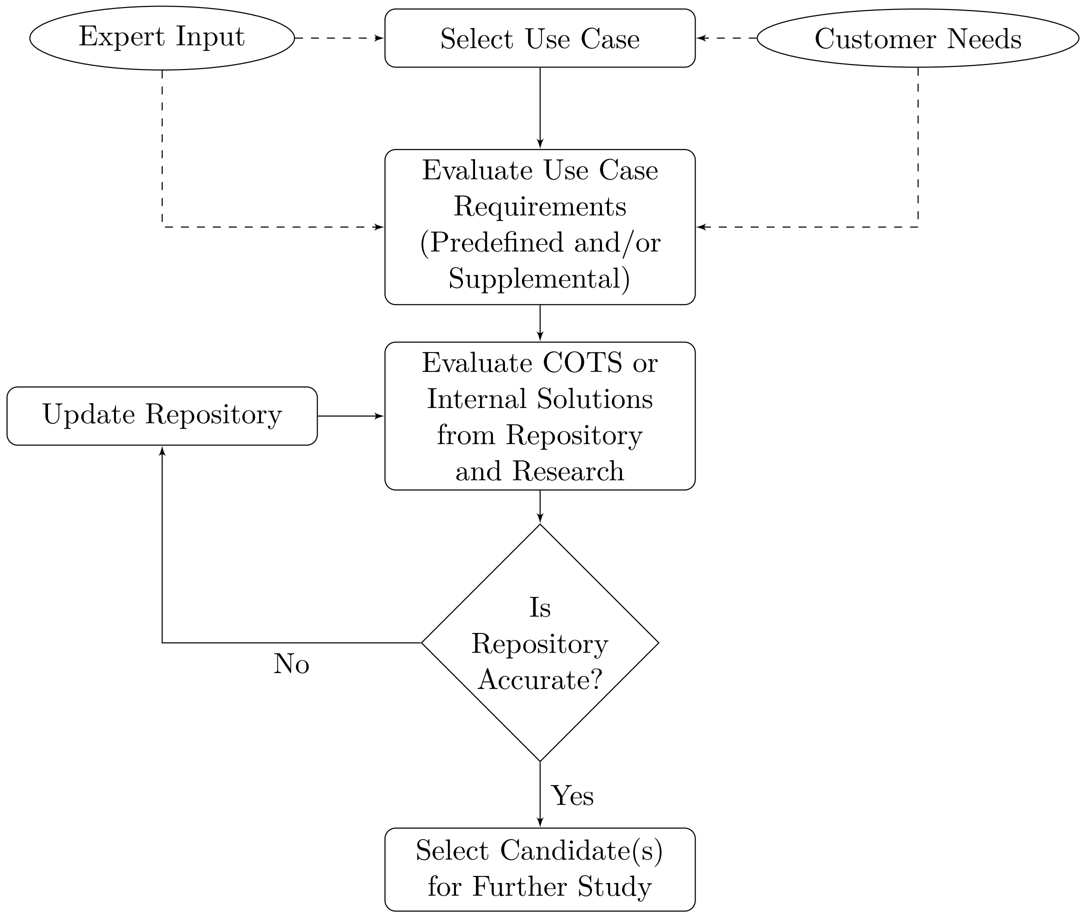
As the government contractors may be less willing to share information that may hinder their competitive advantage, the true range of competitor activity is likely not captured. However, by evaluating efforts or investments that have been publicly released, it is possible to infer areas of current or future activity. Similar to the assessment of DoD needs, this study's focus on AR may lead to a lower level of perceived interest in VR and MR compared to AR. The results of this approach are also discussed in Chapter 4.

3.3.2 Trade Study

A trade study evaluates potential solutions against the requirements. In this case, it is used to point towards promising COTS capabilities for the Operate use case. While RMD has already invested in an AR solution for operations and sustainment, the trade study enables RMD to consider other use cases and easily reassess potential suppliers to reduce program risk. This involves evaluating new providers, identified through the defense market analysis and through the Broad Industry Survey in Section 2.3.1, updating the shared use case repository (Section 4.4.1), and down-selecting to one or more solutions.

The trade study process is illustrated in Figure 3-4. First, the needs of the customer and expert input determine the relevant use case defined in Table 3.1. Then, the requirements described in Tables 3.3, 3.4, 3.5, and 3.6 are assessed by a team of experts, both to determine the requirement and to weight the importance of that requirement. Ideally, this team of experts would include several members who are familiar with the problem being solved, but they may be less familiar with existing COTS solutions. For example, in this case, a team of experts determined the minimum requirement for the problem at hand individually. Then, they weighted those requirements on a scale of 1 - 5 to give more weight to more important requirements. This provided a set of weighted requirement values for each requirement. Then, a set of candidate COTS solutions, documented in a shared use case repository compiled through the market analysis (Sections 3.3.2 and 3.3.1) and broad industry survey (Section 2.3.1), are similarly assessed based on publicly available information and compared against the weighted requirements. The capabilities of existing suppliers in the use case repository should also be updated as each subsequent trade study is performed and the assessments are shared. The output of this process is the selection of one or more promising candidates for further development. The results of the trade study are detailed in Chapter 4.

Figure 3-4: Trade Study Process Diagram



3.4 Business Justification

Historically, aerospace companies were more focused on designing high performance products that perform in adverse environments than on costs. Still, since investment in unproven technology involves inherent risk, the value must be quantified based on literature and best estimates, even if that value is to provide a service not otherwise offered. Alternatively, some offerings may become a mandatory cost of doing business as the greater defense industry becomes more cognizant of cost and adopts XR technology. A robust strategy recommendation could yield a key competitive advantage in implementing XR. This holds true both for broader industry as well as within an aerospace company such as RTX.

3.4.1 Identify Opportunities

A gap analysis reveals areas of unmet need in the market, or places where value can be created. By comparing the relative levels of interest in each XR use case by the DoD and contractors, opportunities for development can be identified where there is less contractor activity than DoD need. While intended to be largely qualitative, as the market analysis is only a snapshot of activity by DoD and government contractors, simple weightings as shown in Table 3.8 indicate the relative level of interest of each party for each use case. Then the average value for each use case can be compared between the DoD and contractors to reveal areas where value can be added so that they can be prioritized for development.

Table 3.8: Gap Analysis Weightings

Gap Analysis Weighting	
2	Confirmed interest: Specifically mentioned in publicly available articles, conference proceedings, funding requests, or similar
1	Suspected interest: Alluded to or indirectly mentioned
0	No indication of interest

3.5 Research Approach Summary

In summary, the research approach is to create a reusable, flexible framework that groups within RTX can follow as a strategy playbook defined in Section 4.4.1. While this thesis focuses on XR solutions for operations and sustainment within RMD, this approach can be generalized for evaluation of XR technology within the defense industry or elsewhere. The approach discussed here is applied to the RMD case study within Chapter 4.

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Chapter 4

Analysis and Results

This section applies the approach discussed in Chapter 3 to analyze the customer need, supplier offerings, and value added in order to formulate a recommended strategy playbook for AR operations and sustainment technology applications at RTX.

4.1 Customer Need

First, areas of DoD customer need relevant to XR technology must be identified. Using the six standardized use cases defined in Table 3.1, a market analysis reveals key areas of DoD interest in XR technology. The analysis justifies RMD's investment in using AR for the Operate use case. In Section 4.3.2 we discuss why the Operate use case is a focus. Then, the relevant generalized requirements are assessed and weighted for a meaningful initial assessment.

4.1.1 Market Analysis

A summary of the DoD market analysis is shown in Table 4.1. Activities or interest in each use case are uncovered according to the method defined in Section 3.2.2. Then, each branch of the DoD was assessed as having a low, medium, or high level of interest in using XR for each of the six defined use cases according to the weightings defined in Section 3.4.1. The market analysis reveals heavy DoD customer interest in using XR for the "Train," "Attract," "Operate," and "Enhance" use cases, although there is consistent interest across each use case and branch of the DoD. Detailed summaries of DoD interest or activity for each of the six generalized use cases follow the summary table, providing justifications for the assessment. The complete list of DoD applications identified can be found in Appendix A, Table A.2.

Table 4.1: Market Analysis: DoD Summary

Branch	**Attract**	**Design**	**Document**	**Train**	**Operate**	**Enhance**
Army	Dark gray	Light gray	Light gray	Dark gray	Dark gray	Dark gray
Navy	Light gray	Dark gray	Dark gray	Dark gray	Dark gray	Dark gray
Air Force	Light gray	Light gray	Dark gray	Dark gray	Dark gray	Light gray
Marines	Dark gray	Light gray	Light gray	Dark gray	Light gray	Dark gray
Space Force	Light gray	Light gray	Light gray	Light gray	Light gray	Light gray
Coast Guard	Light gray	Light gray	Light gray	Light gray	Light gray	Light gray

Dark gray, or high interest, indicates confirmed interest: specifically mentioned in publicly available articles, conference proceedings, funding requests, or similar. Light gray, or medium interest, indicates suspected interest: alluded to or indirectly mentioned.

Attract

While recruiting and retaining talent may not seem like a primary use case for XR technology, it is a core capability of a strong defense force. For example, to alleviate a pilot shortage, the Marine Corps are utilizing six VR flight simulators for recruitment events through the Marine Corps Flight Orientation Program, and they requested proposals to cover maintenance over the program life. [40]

The Air Force Recruiting service and NASCAR teamed up in the spring of 2020 to utilize a virtual flyover due to restrictions of the Covid-19 pandemic. [7] Additionally, the Air Force Air Education and Training Command sought XR capabilities to support their Undergraduate Pilot Training initiative when a lack of T-38 aircraft threatened pilot production. [32]

It is likely that each branch of the armed forces could benefit from XR recruiting and retention aids. XR could also help attract talent for less well-recognized roles, such as maintenance or equipment technicians, by showing candidates what their experience might really be like if they were to join.

Design

Although design tasks fall primarily on contract manufacturers, DoD branches could also benefit from having on-site capability to review designs and assess performance before beginning the long and costly process to procure hardware. Model based engineering and visualization to enable iteration for design processes are at the forefront of DoD applications for XR. For example, the Naval Surface Warfare Center sought to purchase "an augmented reality and stereoscopic display wall system" for "visualization needs in research and development of digital engineering." [17] Similarly, other branches of the Armed Forces could benefit from such design aids, and interest in visualized digital twins for design aids exists, as well as other low cost design evaluation methods such as 3D printing. [45]

Train

The most DoD excitement in XR applications exists around VR field training opportunities, as VR offers a safety and cost advantage while still immersing trainees in the field exercise. The Air Force is currently using VR to train pilots on the T-1 Jayhawk, reducing reliance on the aircraft fleet while adding the benefit of a modular approach to accommodate the skill level of each student individually. [88] The Air Force is also utilizing VR to train pilots on a simulated HH-60G. [96] The documented needs of the Air Force extend beyond their current XR applications, including a need for four trainer systems with "capability for closed network linking for mission rehearsal... capacity for cockpit training" to include "checklist rehearsal, emergency procedure training, and CRM development practice" for the Sikorsky HH-60G Pave Hawk helicopter. [25]

DoD interest in training capability extends beyond combat applications. The Army is interested in using VR for paint spray training, complete with hardware, software, training, and technical support. [122] The Air Force is investigating a VR medical simulator with a panoramic view for military medical simulations. [109] They are also looking into VR training for commercial driver's licenses. [6] The Air Mobility Command is already using VR to train aircraft maintainers on the C-130J Super Hercules at Dyess Air Force Base, reducing the number of aircraft that need to be taken out of service to train new recruits. [4]

While VR training applications are a DoD focus, AR is also important for training. The Air Force and Marine Corps are using the Airborne Tactical Augmented Reality System (A-TARS) for pilot training. [16] In 2019, Cubic Defense Applications and Meggit Training Systems were awarded $3.1M for a prototype to "provide Soldiers with an affordable instrumented and/or surrogate squad weapon compatible with [COTS AR] Head Mounted Displays." [99, 27] More broadly, the Air Force wants to reduce acquisition planning time for "faster mission capable mixed-reality training device deployment times without compromising quality," showing opportunity for a contractor to provide a complete solution. [26] The U.S. Army Research Lab is collaborating with the University of Southern California and the Combined Arms Center to develop a Synthetic Training Environment. [19] The Integrated Visual Augmentation System (IVAS) will improve training as well as enhance operational capability. [60].

Although the interests of the Space Force and Coast Guard are not confirmed, they likely have similar training needs and interests that could be addressed through XR technology. Given the early stages of the Space Force, it was difficult to uncover stated priorities beyond those that applied to all branches of the Armed Forces. Similarly, mentions of XR applications specific to only the Coast Guard were infrequent.

Document

Documentation, while related to training, focuses more on the content for procedures than simply the capability to train. This means that training could be reduced or eliminated through the utilization of XR for the Document use case. The DoD is invested in content creation and instructional improvement, as indicated by the Navy's Aviation Courseware Competition for courseware "development, international courseware formatting, and training technologies." [20]

The Air Force has also expressed interest in the Document use case, shown by a recent call for Air Force Medical and Technical Training Programs for capabilities such as physical therapy. [102] The Air Force Agency for Modeling and Simulation is part of Team Orlando, a collaboration between DoD and industry experts working towards modeling and simulation capability for XR training. [121] The Air Force's 100th Maintenance Group seeks to utilize VR documentation to instruct students in a classroom setting. [111] Other VR documentation applications are already in use at the Precision Measurement Equipment Laboratory at Keesler Air Force Base. [90] The Air Education and Training Command is also developing virtual aircraft hangars for training. [5]

Operate

The DoD is interested in smarter, lower cost methods of operation. The Army is seeking Intelligent Automation, Augmentation, and Analytics (IA3) to leverage data to improve operational efficiency, with an initial $30M in funding to create "fast-paced development methodologies... using open systems architecture, open-source software, and/or [COTS] software/hardware." [10] The Air Force is interested in being able to call in a remote expert for maintenance help. [51, 68]

One focus of the DoD operational strategy is to leverage industry best practices. The Army is using AR for weapon maintenance, inspired by BMW. [43] The Navy's "Request for Prototype Proposals for 5G-enabled [XR] and Naval Smart Warehouses" points towards a need for interoperability with existing communications standards. [47] The effort to reduce maintenance costs exists across the DoD. This is summarized in a program called Condition Based Maintenance Plus (CBM^{+}), which aims to incorporate digital twins so that maintenance can be performed only when it is necessary based on the state of the system. This reduces cost compared to performing traditional maintenance at routine intervals by instead matching maintenance to system needs. [44] This is a possible application of XR technology that would incorporate additional data analytics as needs evolve to educate the system operator.

Enhance

XR is widely expected to improve field capabilities. The Naval Research Laboratory is actively looking to use AR for enhancement in areas such as X-ray vision, depth and other perception, information filtering, and eye-tracking for object selection. [14] One application that is closer to implementation is the Integrated Visual Augmentation System (IVAS) project, which will fit 40,000 members of the Army and Marines with Hololens 2 MR goggles for enhanced warfighter capabilities as well as realistic training scenarios. [107]

The Army released a request for a Future Vertical Lift Head Mounted Display System for aviation systems. [116] They also seek AR capability for the Assault Breacher Vehicle Remote Control System to include "auditory, visual, and haptic feedback." [11] The Army Mission and Installation Contracting Command at Joint Base Lewis-McChord is using Glenair Inc. to provide equipment for an AR heads up interface. [39] The broader DoD is researching VR to bring "innovative capabilities to the warfighter," so there is general excitement surrounding the ability to enhance warfighter capabilities through XR. [110]

4.1.2 Note on Alternate Internal Applications

Additional alternate use cases are also identified from across heritage Raytheon to define internal customer needs. The majority of the identified applications (11 of 12) fell into the Operate use case. They are not detailed in this report but validate the importance of the Operate use case for a range of applications within RTX. A newly expanded RTX Community of Practice is exploring the ever-increasing uses and applications of collaboration across the enterprise.

4.2 Supplier Offering

4.2.1 Competitor Activity

The other portion of the market analysis, focusing on government contractor capabilities, reveals most aerospace contractor activity in using XR for the "Document," "Design," and "Train" use cases. There was a mix of interest in serving external and internal customers.

Table 4.2 summarizes DoD contractor activity in the context of the standardized use cases. Broad assessments of each contractor's publicly available activity and strategy follow in the rest of Section 4.2.1. In this case, unlike the DoD summaries of activity, the summaries are organized by company instead of by use case to provide a clear picture of each company's XR strategy. The complete list of use cases identified can be found in Table A.3 in Appendix A.

Table 4.2: Market Analysis: Contractor Summary

Contractor	**Attract**	**Design**	**Document**	**Train**	**Operate**	**Enhance**
BAE	Light gray	Dark gray	Dark gray	Dark gray	Light gray	Dark gray
Boeing	Light gray	Dark gray	Dark gray	Light gray	Light gray	Light gray
Lockheed	Light gray	Light gray	Dark gray	Dark gray	Light gray	Light gray
Northrop	Dark gray	Dark gray	Dark gray	Dark gray	Light gray	Light gray
RTX	Dark gray	Dark gray	Dark gray	Light gray	Dark gray	Light gray

Dark gray, or high interest, indicates confirmed interest: specifically mentioned in publicly available articles, conference proceedings, funding requests, or similar. Light gray, or medium interest, indicates suspected interest: alluded to or indirectly mentioned.

BAE Systems

BAE Systems is investing in XR as a "Future [Technology]". [55] BAE focuses on applying XR to enhance physical capabilities, and they are developing hardware internally. [86] As of 2019, the company was developing their own hardware for both military and commercial use, with one application of AR allowing "the officer responsible for the ship's safety to work outside of the operations room and still be able to see tactical situation data and other vital information from anywhere on the ship." [1]

BAE is also developing AR for virtual guide instructions, like most other DoD contractors. They were able to improve efficiency by 30-40% when training new employees. [22] VR is being used for warship design and to familiarize soldiers with their ship environment through immersive training. [42, 74]

The Boeing Company

Paul Davies, a Boeing Technical Fellow and leader of AR initiatives, highlighted Boeing's goals within XR to be focused primarily on three manufacturing applications: wiring, feature location, and installing firm parts, with one more area of non-manufacturing focus on 3D viewers for design. [21] Manufacturing training applications could be leveraged for maintenance as well. [29] According to a panel at the LiveWorx 2020 Conference, Boeing's AR Kit (BARK) has an accuracy of less than 0.5 inches on large assemblies, which is sufficient for overlays or for checking if a part is present. They have realized large benefits in assembly time and error reduction, with the most mature application being wiring installation where they reduced installation time by 25% and quality problems by 80%. [118]

Davies also mentioned customer viewing options for interior design and exterior decorative livery as another potential application. [118] Boeing does mention interest in using AR for remote assistance but does not elaborate on any specific applications, and expert assistance has been mentioned but has not been a focus of external releases. [28, 64]

Lockheed Martin

Lockheed Martin is investigating using AR for on demand training for the Marine Corps and VR for immersive training. [117] They have an Innovation Demonstration Center for training, familiarization, and demonstration. [67] Lockheed's barriers are similar to those of the other contractors: largely security and IT infrastructure as well as interacting with customers, so they have adopted workarounds to avoid using WiFi or Bluetooth in restricted areas. [118]

Lockheed Martin's primary internal use case, as released, seems to be manufacturing savings through AR documentation. According to Shelley Peterson, Emerging Technologies Lead & PI for AR at Lockheed Martin, AR-based instruction for manufacturing on a space program resulted in a 30-50% reduction in labor. [118] Lockheed Martin is able to use AR for position alignment if items can be placed within 0.5 inches. [65]

Northrop Grumman

Northrop Grumman applies AR through their AR sandbox technology, which uses Kinect sensors to provide feedback for real-time processes. [56, 37] They are also invested in VR technology. They provide Live, Virtual, and Constructive training solutions for the Air Force, simulating warfare conditions for training. [74]

Internal applications of XR are also a focus for Northrop Grumman. Manufacturing lines currently benefit from XR technology combined with AI and ML, though they do not provide much detail. [85] They have learned from other industry players, including Caterpillar and Idaho National Labs, to develop their own Immersive Visualization Lab for many business applications, including product design, facilities and tooling verification, human factors, operations training, recruiting, product simulation, and manufacturing process and workflow simulation. [79]

Raytheon Technologies

RTX has multiple initiatives related to XR capabilities. Two of these efforts are VirtualWorx and the Immersive Design Center. VirtualWorx is an internally developed, patented capability that leverages COTS software and hardware to enable certain operations and sustainment. [95] Early stage collaboration for design is made possible through the Immersive Design Center, a multidimensional, highly connected collaboration space, both to reduce cost and increase customer satisfaction. [38]

4.2.2 Trade Study

The requirements defined for the Operate use case are assessed for the VirtualWorx application within RMD. First, a team of five VirtualWorx product experts assessed, or graded, the requirements for the application out of the three options for each feature (low, medium, or high). They also weighted each feature's importance on a scale of one to five, which was translated into a percentage weighting factor. Similarly, a set of 22 software integrators or suppliers, identified through the market analysis and industry survey, are assessed against a subsection of the weighted requirements that were deemed most pertinent to RMD's intended application. The weighted requirements can then be compared to the weighted capabilities of each integrator, showing which integrators are most promising for continued investment. A summary of the assessed requirements compared to the performance of the top five integrator contenders is detailed in Table 4.3. Note that the values themselves are not inherently meaningful, but the relative size of the gaps between the application requirements and the supplier capabilities is meaningful to indicate how much additional investment might be required. The complete sets of requirement grading and weighting can be found in Appendix B.

The trade study results show that the largest opportunity for improvement in COTS capabilities to meet aerospace and defense needs exists in the area of security. This is not surprising and validates the current VirtualWorx strategy of focusing on security. [95] The VirtualWorx initial investment led to patents that are closely correlated with security. No major technological hurdles in capability, scale, or implementation prohibit a successful adaptation of COTS capabilities, though implementation also has challenges as indicated by the negative weighted gap between the performance of the top five integrators and the application average weighted requirements. Given RMD's previous investment in security for the VirtualWorx AR capability, it is recommended that they continue to leverage the base platform with customized security features for additional applications, validating the current strategy.

Table 4.3: Performance of Top Integrator Contenders Against Requirements

Average Requirement		A	B	C	K	P	**Weighted Gap**
Capability	2.2	2.5	2.8	2.8	2.7	2.8	0.22
Scale	2.1	2.7	3	2.7	2.7	2.3	0.47
Security	2.5	2.4	1.5	1.8	2	1.3	(0.58)
Implementation	2.6	2.7	2.3	2.3	2.3	2.3	(0.23)

Integrator contenders are anonymized with letters. A negative weighted gap indicates that, on average, the top five contenders do not meet the requirement in that requirement group. A positive weighted gap indicates that they exceed the requirements in that requirement group on average.

4.3 Business Justification

The business case for applying AR to the Operate use case involves two key and atypical definitions of value. One is to solve customer needs that cannot be addressed in another way within reasonable cost or time. The other is to maintain competitive advantage by keeping up with current technology, which is beneficial to increase the probability of winning contracts as mentioned in Section 3.4.

4.3.1 Identify Opportunities

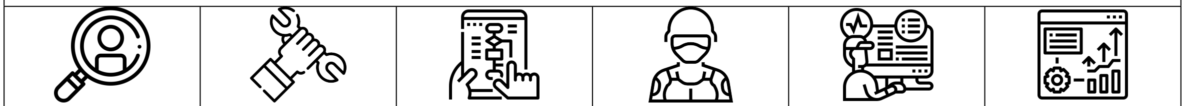
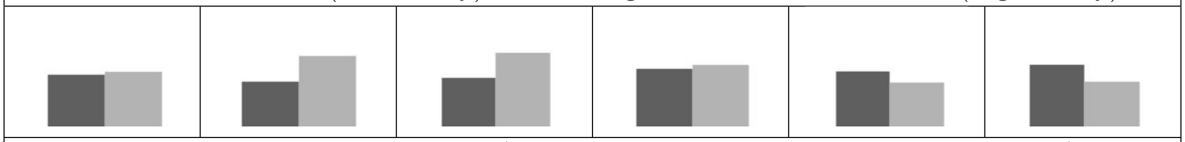
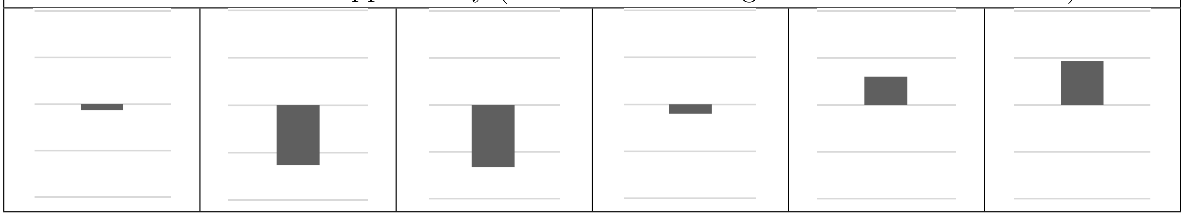
The end result of the market analysis is to identify opportunities to fulfill customer needs where competitor activity is insufficient. By comparing the relative activity of contractors detailed in Appendix A Table A.3 to expressed DoD needs detailed in Appendix A Table A.2, potential gaps or opportunities for investment are revealed according to the weightings defined in Table 3.8. Results are summarized in Table 4.4. Quantities are not labeled, as the intent is to provide a general depiction of the market and potential areas of opportunity.

The Operate and Enhance use cases are key candidates for investment, as they exhibit higher customer need than contractor capability. This justifies RMD's investment in the Operate use case through VirtualWorx. The focus should remain on operations and sustainment applications of XR technology, as it exhibits the greatest area of unmet internal and external customer need and aligns with previous investment strategy. This does not mean that other more active use cases should be ignored; it is still important to continue to develop solutions in other areas to be able to compete.

4.3.2 Business Value

Since investment in unproven technology involves inherent risk, the value must be quantified to justify the investment. The standard best practice is to use a Net Present Value (NPV) analysis,

Table 4.4: Market Opportunity by Use Case

XR Use Cases					
					
Attract	Design	Document	Train	Operate	Enhance
Levels of DoD Need (Dark Gray) and Average Contractor Investment (Light Gray)					
					
Relative Level of Opportunity (DoD Need - Average Contractor Investment)					
					

Icons made by Freepik [54]. Relative activity by DoD contractors compared to DoD needs in context of use case definitions. Row 1 shows each use case. Row 2 shows DoD relative interest in dark gray and contractor relative interest in light gray. Row 3 shows the subsequent opportunity in each use case.

which takes the time value of money into account to determine in an investment is worthwhile. [3] One key challenge that prohibits a customary NPV analysis of using AR for operations and sustainment is that, increasingly, collaboration technology such as AR is an expected cost of doing business, and metrics on improvement over the baseline are not available. Increasing industry adoption of remote work policies and other externalities, such as travel restrictions, indicate that industry is on a path for XR to become a required capability. [30]

4.4 Recommendations

This technology assessment framework can continue to be used within the context of RTX and their four new businesses while adhering to the following tenets:

1. **Accessibility:** Process clarity through documentation will enable efficient reuse of platforms for a given XR use case.

2. **Awareness:** Internal frameworks for sharing XR platforms, such as documentation within a centrally located Community of Practice, can leverage prior development while respecting IP boundaries.

3. **Adaptability:** A base platform with customization for each program implementation will enable only new technology to be developed for customer customization and will capitalize on the RMD pride of inventing.

These guiding principles inform the recommended strategy playbook.

4.4.1 Strategy Playbook

In order to retain knowledge and prevent the need for individual trade studies to be completed every time a team wishes to evaluate XR solutions, a sharing platform is proposed and is being implemented at RTX. This platform is accessible through a centralized "Community of Practice" (CoP) to share a process for XR technology assessments and a repository of high level information about COTS and internal solutions: most importantly, their classification by use case. A use case repository is accessible by anyone internally and can be updated by anyone to share knowledge of COTS options. A snapshot of a sample use case repository, compiled through the broad industry survey and market analysis, is shown in Figure 4-1 and can be tailored to the needs of an organization.

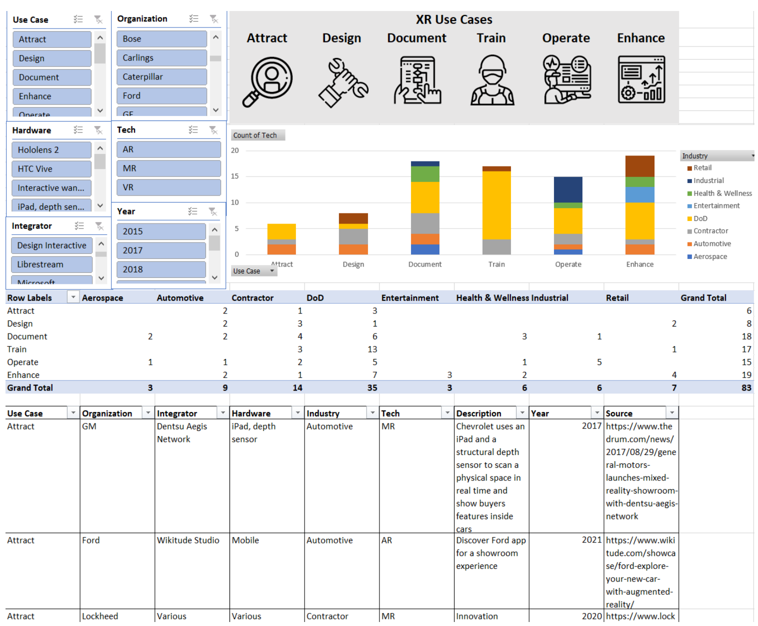


Figure 4-1: Use Case Repository

In addition to preventing parallel development projects that could have leveraged each other's work, this will increase awareness of available solutions. A key set of documentation, owned by the CoP leader but edited by anyone, will guide employees through the process to complete initial, quick, and cost effective XR technology assessments:

1. **Identify use case and associated requirements.**
   (a) Select use case: Choose the relevant use case from the six defined use cases. The market analysis strategy can be more quickly performed by leveraging information in the shared repository of COTS and internal solutions.
   (b) Identify requirements: Select which existing requirements are relevant to that use case. Add any additional requirements that may be relevant to that specific instance. Assess and weight the requirements for that use case. Although only the Operate use case requirements are defined now, requirements can be created and leveraged for each of the six use cases.
2. **Assess COTS or internal solutions against requirements.**
   (a) Evaluate solutions: Using the requirement levels defined in step 1, evaluate COTS or internal capabilities that meet the requirements for the given instance. Previously assessed capabilities may exist in a shared use case repository that could be leveraged, and additional solutions that are evaluated can be added to the shared repository.
3. **Select a solution.**
   (a) Leverage existing solutions where possible.
   (b) Also leverage customization to add IP and pride in technology development to create a solution that is tailored to the customer.

XR solutions should leverage previous technologies developed that fit a given XR use case. However, each solution should be customized and can be developed on a case-by-case basis to meet the precise customer needs as well as to develop custom IP.

4.5 Analysis and Results Summary

The analysis and results have generated a recommended strategy playbook defined in Section 4.4.1 that utilizes a new framework of standardized use cases and requirements for XR technology. The recommendations, which are currently being implemented within greater RTX, will allow teams to easily identify unmet customer needs and to assess available solutions that can then be rapidly and effectively evaluated for mission-centric implementation. Chapter 5 reviews takeaways from the thesis and looks ahead to future work.

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Chapter 5

Conclusion

This section summarizes the proposed framework for XR technology assessment and highlights how it is beneficial to RMD and broader RTX. It also discusses ways in which the proposed framework is relevant outside of the defense industry as well as for technologies other than XR. Finally, this section includes a call to action to individual companies and to the broader research community to continue to develop frameworks for the standardization of XR technology applications so that industry as a whole can realize the expected benefits of XR.

5.1 Problem and Solution Statement

Revisiting the problem defined in the introduction, we assess how the proposed framework for XR technology assessment is relevant to the specific needs of RMD and the VirtualWorx team.

5.1.1 Problem

As defined in Chapter 1, RMD seeks to develop and scale their VirtualWorx AR capability for operations applications. They would like to reevaluate COTS capabilities to determine if they should pursue any additional COTS providers, and they would also like to better leverage VirtualWorx and other XR capabilities across RTX, but program silos and instability in the XR market make evaluation difficult.

5.1.2 Solution

This research satisfies the problem statement with a solution that is both relevant to the VirtualWorx AR capability and to other XR applications within RTX. The following generalized framework, first defined and used in Chapters 3 and 4, is restated here with additional detail to summarize how it was used for the VirtualWorx case study:

1. **Identify use case and associated requirements.**
    (a) Select use case: For VirtualWorx, this was the "Operate" use case, chosen from the six defined use cases. In this first application of the framework, the use cases were defined according to expressed XR needs of DoD and government contractors. The market analysis can be revisited as customer needs change, but due to the solid baseline documented understanding of the market space, it can be more quickly updated to include new COTS or internal solutions in subsequent iterations.
    (b) Identify requirements: Again, in this first application of the framework, the requirements for the "Operate" use case needed to be defined, and those relevant to the VirtualWorx capability were identified, assessed, and weighted. Requirements were defined within the categories of capability, scale, security, and implementation. The requirements can be updated as customer needs change, and sets of requirements can be defined for each of the other five use cases or as additional use cases emerge.
2. **Assess COTS or internal solutions against requirements.**
    (a) Evaluate solutions: Using the requirements defined in step 1, COTS capabilities were evaluated. The use case repositories, generated from the industry survey in Chapter 2 and the market analysis in Chapter 4, informed the selection of COTS capabilities for investigation. As the market changes, additional internal and external solutions can be added to the shared repository.
3. **Select a solution.**
    (a) Leverage existing solutions where possible: This study identified the five most promising integrator candidates for further study by the VirtualWorx team. Their current integrator was one of the highest performers, particularly in the area of security, indicating that the team is set up for success. However, to reduce risk, it is beneficial to know that other integrators who perform similarly are available.
    (b) Leverage customization to add IP and pride in technology development: Since the team has a solid baseline capability, they should invest their time and efforts in customization for their customer, focusing on RTX's strength as a technology company.

Now that this framework has been set up and demonstrated through the VirtualWorx case study, it can be leveraged internally for future development efforts through RTX's XR CoP without sharing key technical or customer data. Additionally, all future users of the framework can benefit from and contribute to the use case repositories.

5.2 Industry Implications

This framework can be leveraged in greater industry, both internal and external to the aerospace and defense industry.

5.2.1 Within Aerospace & Defense

Other government contractors, such as those previously defined in Table 3.7, can leverage a similar framework for XR technology assessment for implementation. Contractors who are focused on defense work can particularly benefit, as the market analysis for this work focused on defense applications. Even if they do not have centralized research departments, they can utilize a CoP or similar central information resource to coordinate information transfer and avoid redundant development work.

It is difficult to justify increasing development spending when contracts incentivize raising costs to raise revenues. However, with the defense industry increasingly focused on cutting operational cost, this will not be an option in future years. RTX has the opportunity to be a leader in reducing waste and lowering customer cost, which will improve their competitive advantage.

Commercial aerospace players can similarly apply such a framework to identify areas where XR development has or should occur. While their customers may require different end products, such as air transportation, they can alter the use case definitions of the framework to better match their audience. Still, whether commercial or defense-focused, aerospace companies have similar information security and equipment size constraints that point to similar requirements and ultimate solutions for XR systems. Particularly in the airline industry, which is not expected to reach pre-pandemic levels again until 2024, there is an opportunity to focus on identifying new sources of customer value. [69] The application of a similar framework to the airline industry may be beneficial in directing recovery efforts.

5.2.2 Beyond Aerospace & Defense

Outside of the aerospace and defense industry, other players with industrial applications could take a similar approach to evaluating XR technology. Such a framework will be most helpful and relevant if they have a range of products or if they have similar information security concerns that restrict the replication of XR applications. Still, even if information security is not a concern, a similar framework can be applied, and more detail can be shared about specific applications to make the knowledge transfer even more meaningful. However, care should be taken to ensure that use cases remain broad enough to leverage the pooling of capabilities.

Ultimately, this methodology is not limited to only XR technology evaluation. At the heart of this study is the question of how to implement new technology amid uncertainty. While some risks will pay off and others will not, more knowledge sharing through a framework such as the one proposed in this study will enable new technologies to be quickly implemented so that their benefits can be more immediately realized.

5.3 Future Work

Within RMD, work can continue within the VirtualWorx team to apply the recommendations of this project, focusing on their key value propositions and technology or IP that is unique to them and their customers. For greater RTX, the XR CoP can implement the framework at a broader scale, maintaining the use case repositories of both internally and externally available solutions to prevent redundant development and accelerate the implementation of XR solutions. As the framework is used, additional requirements and applications can be documented, which will continue to improve the effectiveness of the framework and enable its use in new areas.

This research also raises additional questions for future work external to RTX. One key area of future work involves quantitative models to predict benefits and justify spending on XR capability development. Acknowledging that the quantified cost reduction value could not be detailed in this report, it is important to note that other industry players have similar concerns that prohibit knowledge sharing in this area. Due to these restrictions, some separate entity in academia or even a company could lead in developing frameworks that can be applied internally. The standardization of XR use cases and capabilities that are defined in this study are a prerequisite to such work so that any frameworks developed are relevant to a wide variety of industry players.

One important warning to companies such as RTX that was not investigated in detail in this study is the risk of not investing in technology, as Cogliandro pointed out by defining inverse risk. [36] Just as it is beneficial to provide new value for customers, eventually what is a differentiator becomes a requirement. As more of an industry acquires XR capabilities, those capabilities may become essential to compete. This was seen in the onset of the Covid-19 pandemic when travel ceased to be an option and working from home became a requirement to continue progress as opposed to an employee perk. Still, it is best to be a leader in the space and take advantage of the customer value added while it is still a differentiator. RMD's early investment in AR paid off many years later during the pandemic, a return that could not be anticipated or easily quantified.

Finally, this report serves as a call for additional studies to continue to define frameworks for assessing XR technology. Similarly to how Bershinsky et al. shared "a call for collaboration and a starting point for finding the best method to quantitatively assess MR interfaces used in Aerospace applications," there is an opportunity to iterate upon and improve this framework to make it more robust and useful for aerospace companies seeking to implement XR. [24]

5.4 Conclusion Summary

This study attempts to provide a comprehensive view of XR within the aerospace and defense industry that leads to a useful framework for XR technology assessment for implementation. Just as it was applied to the VirtualWorx team, it can continue to be utilized within RMD and greater RTX, as well as by other defense industry players. We encourage continued iterations and improvements to these or other frameworks to aid all of industry in realizing the expected benefits of XR technology.

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Appendix A

Use Case Repository

A.1 Industry XR Use Cases

Table A.1: Use Case Repository: Industry

Use Case	**Industry**	**Tech**	**Organization**	**Description**
Document	Aerospace	AR	Jamco America	Commercial aircraft interior training and maintenance [82]
Document	Aerospace	AR	Safran	Maintenance procedures for Safran Landing Systems [18]
Operate	Aerospace	AR	Safran	Remote expert support for Safran Helicopter Engines [100]
Attract	Automotive	MR	GM	MR dealership, V-Showroom, enables virtual showroom experience [58]
Attract	Automotive	MR	Ford	Discover Ford app for a showroom experience [53]
Attract	Automotive	AR	Ford	Discover Ford app to provide customers information about Ford products [53]
Design	Automotive	AR	Lykan	Lykan HyperSport supercar customer design [15]

Use Case	Industry	Tech	Organization	Description
Design	Automotive	MR	Ford	Ford engineers using Microsoft Hololens to design, interfacing virtually with clay models [124]
Document, Enhance	Automotive	AR	Mercedes	AskMercedes improves the user experience [78]
Document	Automotive	AR	Volvo	Improved documentation enables customization in manufacturing without reducing rate [123]
Operate	Automotive	AR	Toyota	Remote subject matter experts can be involved to resolve manufacturing equipment or safety issues [63]
Enhance	Automotive	AR	Usens	Overlays of additional information for enhanced safety when driving [50]
Enhance	Automotive	AR	General Motors	Potential hazards and other important visible features are highlighted for the driver through overlays to improve driving safety [48]
Enhance	Entertainment	AR	Illumix	Enhancing the physical environment through MR improves the user experience for Five Nights at Freddy's AR: Special Delivery [108]
Enhance	Entertainment	AR	Snap	Lenses for object recognition and subsequent adaptation [106]
Enhance	Entertainment	AR	Lego	Extension of Lego models through AR to improve engagement [62]
Train, Document	Health & Wellness	MR	GE	GE Healthcare training with AR and VR [57]
Train, Document	Health & Wellness	AR	Atlas Copco Ct	AR to improve technician training [125]

Use Case	Industry	Tech	Organization	Description
Document	Health & Wellness	AR	Pfizer	Automated expert guidance as an addition to Standard Operating Procedures [75]
Operate	Health & Wellness	AR	Various, IBM Remote Assist	24/7 support through mobile Augmented Remote Assist [114]
Enhance	Health & Wellness	AR	Augmedics	AR enables x-ray vision for a surgery guidance system [12]
Enhance	Health & Wellness	AR	uSens	Healthcare solutions for chronic pain management and therapy for occupational injury, amputee, or stroke patients [61]
Operate	Industrial	AR	Lee Company	Remote expert for HVAC maintenance [92]
Operate	Industrial	AR	SGS	Remote inspection in industrial settings [103]
Operate	Industrial	AR	Caterpillar	LIVESHARE remote support to keep equipment operational [126]
Operate	Industrial	AR	National Oilwell	TrackerVision remote expert with end-to-end encryption [80]
Operate	Industrial	AR	Various, Tech-See	Remote support plus computer vision to identify and resolve issues [13]
Train, Document	Industrial	AR	General Electric	Skylight enables improved training and real time instructions [104]
Design	Retail	AR	Warby Parker	Potential customers can try on glasses using AR [119]
Design	Retail	AR	Bike Store: Cannondale	Cannondale was able to improve sales and improve their ability to sell bikes using Vuforia [33]
Design	Retail	MR	Various	VisionX enables consumers to visualize an item in their home [115]

Use Case	Industry	Tech	Organization	Description
Train	Retail	VR	Walmart	Walmart uses VR for realistic training modules for employees to experience and prepare for times such as the holiday rush [66]
Document, Enhance	Retail	AR	Within	Interactive storytelling [128]
Enhance	Retail	AR	Carlings	AR designs on t-shirts to reduce material waste and improve customer Instagram or similar experiences [9]
Enhance	Retail	AR	Bose	Sunglasses with sound to physically augment reality were discontinued [34]
Enhance	Retail	AR	Google	Google Lens enables users to interact with both the digital and real world through real time scanning, translations, and information association [89]

A.2 DoD XR Use Cases

Table A.2: Use Case Repository: DoD

Use Case	Industry	Tech	Organization	Description
Attract	DoD	VR	Marines	VR flight simulators to attract talent and avoid a pilot shortage [40]
Attract	DoD	VR	Air Force	Recruiting through virtual displays such as a virtual flyover at NASCAR iRacing [7]
Attract	DoD	VR	Air Force	Air Force Air Education and Training Command's Undergraduate Pilot Training initiative (UPT 2.5) [32]
Design	DoD	AR	Navy	Naval Surface Warfare Center ship design [17]

Use Case	Industry	Tech	Organization	Description
Train	DoD	VR	Air Force	Reducing reliance on the T-1 Jayhawk Trainer in favor of simulators utilizing virtual reality [88]
Train	DoD	VR	Air Force	Virtual reality for training missions on a simulated HH-60G [96]
Train	DoD	VR	Air Force	The Air Force seeks to purchase four VR trainer systems [25]
Train	DoD	VR	Army	Virtual reality for paint spray training [122]
Train	DoD	VR	Air Force	Virtual reality for military medical simulations [109]
Train	DoD	VR	Air Force	Virtual reality for training for commercial driver's license training [6]
Train	DoD	VR	Air Force	Virtual reality for C-130 training through the Air Mobility Command [4]
Train	DoD	AR	Army	Cubic Defense Applications and Meggit Training Systems awarded $3.1M for AR training equipment [99]
Train	DoD	AR	Air Force	Airborne Tactical Augmented Reality System (A-TARS) for pilot training [16]
Train	DoD	AR	Air Force	Training to reduce acquisition planning time [26]
Train	DoD	AR	Army	USC, Army Research Laboratory, and Combined Arms Center developed the Synthetic Training Environment [19]
Train	DoD	AR	Navy	Naval Research Laboratory using augmented reality for embedded training [84]
Train	DoD	AR	Army	Integrated Visual Augmentation Systems (IVAS) for training [60]

Use Case	Industry	Tech	Organization	Description
Document	DoD	MR	Navy	Aviation Courseware Competition [20]
Document	DoD	AR	Air Force	AR for air force medical and physical therapy technician training [102]
Document	DoD	MR	Air Force	Air Force Agency for Modeling and Simulation [121]
Document	DoD	VR	Air Force	Virtual Reality training for the 100th Maintenance Group [111]
Document	DoD	VR	Air Force	Precision measurement equipment [90]
Document	DoD	VR	Air Force	Virtual aircraft maintenance hangars [5]
Operate	DoD	MR	Army	Army seeks Intelligent Automation, Augmentation, and Analytics (IA3) to leverage data to improve operational efficiency [10]
Operate	DoD	AR	Army	Augmented reality for weapon maintenance [43]
Operate	DoD	MR	Navy	Request for prototype proposals for 5G-enabled AR and VR in Naval Smart Warehouses [47]
Operate	DoD	MR	Navy	Digital twins for rapid innovation [81]
Operate	DoD	AR	Air Force	AR for remote expert maintenance support [52]
Enhance	DoD	AR	Navy	Naval Research Laboratory researching X-Ray vision [14]
Enhance	DoD	AR	Army, Marines	40,000 MR goggles will be distributed through the Integrated Visual Augmentation System (IVAS) project [107]
Enhance	DoD	AR	Army	Future vertical lift head mounted display system [116]

Use Case	Industry	Tech	Organization	Description
Enhance	DoD	AR	Army	Assault Breacher Vehicle remote control system [11]
Enhance	DoD	AR	Army	Glenair Inc. communication hub. [39]
Enhance	DoD	VR	All DoD	VR tools to bring innovative capabilities to enhance warfighter decision-making [110]
Enhance	DoD	AR	Air Force	Librestream Onsight used for joint engineering disposition infrastructure [68]

A.3 DoD Contractor XR Use Cases

Table A.3: Use Case Repository: Contractors

Use Case	Industry	Tech	Organization	Description
Attract, Design, Train	Contractor	MR	Lockheed	Innovation Demonstration Center for training, familiarizing, and demonstration [67]
Design	Contractor	VR	BAE	Advanced visualization for warship design and servicing [42]
Design	Contractor	MR	Boeing	Boeing Augmented Reality Kit for aircraft manufacturing [21]
Design	Contractor	MR	RTX	RTX virtual environment for design and manufacturing planning [38]
Train	Contractor	VR	BAE	Familiarization training for ships [74]
Train	Contractor	MR	Lockheed	On demand training for the Marines, both AR and VR [117]
Train	Contractor	MR	Northrop	Live, Virtual and Constructive training [74]
Document, Enhance	Contractor	AR	Boeing	Reduced airline ground delays through maintenance [71]
Document	Contractor	AR	BAE	XR for documentation and training [22]

Use Case	**Industry**	**Tech**	**Organization**	**Description**
Document	Contractor	AR	Boeing	Enterprise augmented reality deployment for large assembly manufacturing [118]
Document	Contractor	AR	Lockheed	Step-based instruction for manufacturing on a space program [118]
Operate	Contractor	AR	RTX	Repair and training from a distance [95]
Operate	Contractor	AR	RTX	Android Tactical Assault Kit for soldier collaboration [127]
Enhance	Contractor	AR	BAE	In-house development of AR glasses for information additions to the user [86]

Appendix B

Trade Study

B.1 Trade Study Requirements Grading and Weighting

Table B.1: Requirements for Use Case: Operate

	Feature	**Low (1)**	**Medium (2)**	**High (3)**	**Weight Factor**	**Avg. Grade**
1	Real time sharing capability	Live voice, static photo sharing	Live voice and video, static photo sharing	Live voice, video, and screen sharing	0.92	2.6
2	Augmentation capability	Minimal augmentation capability	Static telestration, recording, zoom	Hand gestures, smart devices, telestration with true tracking/overlay	0.6	1.8
3	Hands-free	No hands-free capability	Hands required for some functions, partial hands-free capability	Complete hands-free	0.56	2.2
4	Device agnostic	Works with only one specific device	Works with 2 - 3 devices (i.e. one headset and mobile or tablet)	Works with multiple devices and classes of devices (multiple headsets, Android/iOS mobile, tablet, etc.)	0.84	2.6

	Feature	Low (1)	Medium (2)	High (3)	Weight Factor	Avg. Grade
5	Usage statistics and integration	Available to server owner, shareable to users upon request	Personal user statistics available to users	Custom dashboard showing personal user statistics available to users	0.32	1
6	Bandwidth tailoring	Bandwidth requirements fixed	Bandwidth automatically optimized	Bandwidth configurable	0.76	2.8
7	Annotate photos	No annotation capability	Some annotation capability	Intuitive, multi-design annotation capability	0.54	2.2
8	Photo saving	Photos taken cannot be saved	Photos saved to individual devices	Photos saved to shared repository	0.60	2.6
9	Concurrent sessions	1 - 10 concurrent sessions	11 - 99 concurrent sessions	100+ concurrent sessions	0.56	2.3
10	Maximum callers per session	2 callers	3 - 9 callers	10+ callers	0.60	2.0
11	Minimum acceptable bandwidth	High	Medium	Low	0.64	1.8
12	Minimum acceptable latency	High	Medium	Low	0.56	2.8
13	Server requirements	High	Medium	Low	0.32	2.2
14	Client application platform requirements	High	Medium	Low	0.44	1.6
15	Identity management	None	Shared login credentials	Individual users	0.84	2.8
16	Multifactor/two step authentication	No multifactor/two step authentication	Two step authentication	Multifactor/two step authentication	0.68	2.6
17	Remote control client access	No remote control client access	Remote camera zoom/lock	Remote camera zoom/lock, remote log out	0.62	2.2
18	Encrypted data	Approved for unclassified use only	Approved for classified use on a subset of devices	Approved for classified use in all cases	1.0	2.0

	Feature	Low (1)	Medium (2)	High (3)	Weight Factor	Avg. Grade
19	Encrypted device	Approved for unclassified use only	Approved for classified use on a subset of devices	Approved for classified use in all cases	0.84	2.0
20	Operating system patch management	No patch management	Patch management, can be declined	Automatically pushed patch management	0.68	2.8
21	Security features	Low	Medium	High	0.80	2.8
22	User citizenship/status	U.S. persons only	Limitations on which persons can use	Largely open to U.S. and non-U.S. persons	0.67	2.5
23	Exportable	U.S. use only	Limitations on where can use	Largely open to all locations of use	0.92	2.6
24	Cloud/FedRamp status	Not FedRamp approved	Approved with restrictions	FedRamp approved	0.28	3
25	Software distribution	Case-by-case distribution, no patches/updates without request	Available on managed app store	Available on internally managed app store, patches/updates pushed automatically	0.48	2.8
26	Documentation and training	Documentation only	Documentation and help line	Complete documentation and training included	0.68	3
27	Accessibility	No additional accessibility	Closed caption enabled	Closed caption enabled, multiple language translation supported	0.40	1.4

Gray rows were not included in the candidate software integrator assessment.

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Bibliography

[1] *£20m investment in naval combat systems | BAE Systems | International*. URL: https://www.baesystems.com/en/article/future-naval-combat-systems (visited on 01/31/2021).

[2] 3D VR 360 VIDEOS. *VR 360 Video of Top 5 Roller Coaster Rides 4K Virtual Reality*. Dec. 25, 2019. URL: https://www.youtube.com/watch?v=hNAbQYU0wpg (visited on 02/09/2021).

[3] "A Refresher on Net Present Value". In: *Harvard Business Review* (Nov. 19, 2014). Section: Finance & Accounting. ISSN: 0017-8012. URL: https://hbr.org/2014/11/a-refresher-on-net-present-value (visited on 03/01/2021).

[4] *AETC partners with multiple MAJCOMs to create virtual aircraft maintenance hangars*. U.S. Air Force. URL: https://www.af.mil/News/Article-Display/Article/2093066/aetc-partners-with-multiple-majcoms-to-create-virtual-aircraft-maintenance-hang/ (visited on 01/08/2021).

[5] *AETC, AMC team up on VR solutions for modern C-130 training*. Air Mobility Command. URL: https://www.amc.af.mil/News/Article-Display/Article/2066720/aetc-amc-team-up-on-vr-solutions-for-modern-c-130-training/ (visited on 01/08/2021).

[6] *AF helps Airmen obtain CDL*. U.S. Air Force. URL: https://www.af.mil/News/Article-Display/Article/1075577/af-helps-airmen-obtain-cdl/ (visited on 01/08/2021).

[7] *Air Force Recruiting, 4th Fighter Wing fill void at NASCAR iRacing with innovation*. U.S. Air Force. URL: https://www.af.mil/News/Article-Display/Article/2166835/air-force-recruiting-4th-fighter-wing-fill-void-at-nascar-iracing-with-innovati/ (visited on 01/08/2021).

[8] Hugo Álvarez et al. “Augmented reality system to guide operators in the setup of die cutters”. In: *International Journal of Advanced Manufacturing Technology* 103.1 (July 2019). Publisher: Springer Nature, pp. 1543–1553. ISSN: 02683768. DOI: 10.1007/s00170-019-03634-0. URL: https://search.ebscohost.com/login.aspx?direct=true&db=a9h&AN=137363210&site=eds-live&scope=site (visited on 02/11/2021).

[9] *AR filters for clothing come to Instagram | Vogue Business*. URL: https://www.voguebusiness.com/technology/carlings-ar-t-shirt-instagram-digital-clothing (visited on 01/22/2021).

[10] *Army launches Assault Breacher Vehicle Remote Control System Market Survey*. Defense Systems Journal. June 3, 2020. URL: https://www.dsjournal.com/2020/06/03/assault-breacher-vehicle-remote-control-system-market-survey/ (visited on 01/22/2021).

[11] *Army posts IA3 sources sought*. Intelligence Community News. May 28, 2020. URL: https://intelligencecommunitynews.com/army-posts-ia3-sources-sought/ (visited on 01/08/2021).

[12] *Augmedics Lands $15M for FDA-Cleared Augmented Reality Guidance System for Surgery -*. June 15, 2020. URL: https://hitconsultant.net/2020/06/15/augmedics-augmented-reality-guidance-system-for-surgery-funding/ (visited on 01/22/2021).

[13] *Augmented Reality (AR) Remote Assistance [Complete Guide - TechSee]*. TechSee. Nov. 6, 2018. URL: https://techsee.me/blog/augmented-reality-remote-assistance/ (visited on 01/22/2021).

[14] *Augmented Reality | Information Management and Decision Architectures*. Jan. 6, 2017. URL: https://web.archive.org/web/20170106100127/https://www.nrl.navy.mil/itd/imda/research/5581/augmented-reality (visited on 01/31/2021).

[15] *Augmented Reality and Marketing Innovates Lykan Automotive Sales | PTC*. URL: https://www.ptc.com/en/case-studies/lykan (visited on 01/08/2021).

[16] *Augmented Reality Goes Airborne*. SIGNAL Magazine. Mar. 24, 2020. URL: https://www.afcea.org/content/augmented-reality-goes-airborne (visited on 01/08/2021).

[17] *Augmented Reality May Revolutionize Army Training*. URL: https://ict.usc.edu/news/press-releases/augmented-reality-may-revolutionize-army-training-3/ (visited on 01/08/2021).

[18] *Augmented Reality: Welcome to maintenance 4.0!* Safran. Jan. 17, 2019. URL: https://www.safran-group.com/media/augmented-reality-welcome-maintenance-40-20190117 (visited on 01/08/2021).

[19] *AUGMENTED REALITY/STEREOSCOPIC DISPLAY WALL N0016420Q0184 - GovTribe.* URL: https://govtribe.com/opportunity/federal-contract-opportunity/augmented-realitystereoscopic-display-wall-n0016420q0184 (visited on 01/22/2021).

[20] *Aviation Courseware Competition N6134020R0109 - GovTribe.* URL: https://govtribe.com/opportunity/federal-contract-opportunity/aviation-courseware-competition-n6134020r0109 (visited on 01/22/2021).

[21] *AWE USA 2019 - Evolution of the Boeing Augmented Reality Kit, and its application to Airplane Manufacturing.* URL: https://www.awexr.com/130-evolution-of-the-boeing-augmented-reality-kit-and-/agenda/130-evolution-of-the-boeing-augmented-reality-kit-and- (visited on 01/31/2021).

[22] *BAE Systems leverages the power of Mixed Reality with Microsoft and PTC | PTC.* URL: https://www.ptc.com/en/resources/augmented-reality/video/bae-systems-mixed-reality-with-ptc (visited on 01/31/2021).

[23] Amine Belhadi et al. "Manufacturing and service supply chain resilience to the COVID-19 outbreak: Lessons learned from the automobile and airline industries". In: *Technological Forecasting and Social Change* 163 (Feb. 1, 2021), p. 120447. ISSN: 0040-1625. DOI: 10.1016/j.techfore.2020.120447. URL: https://www.sciencedirect.com/science/article/pii/S0040162520312737 (visited on 02/11/2021).

[24] Kellin Bershinsky and Rachel Narciso. "An Experimental Framework for Determining the Usability of Mixed Reality Interfaces for Aerospace Applications". In: *AIAA Scitech 2019 Forum.* AIAA Scitech 2019 Forum. San Diego, California: American Institute of Aeronautics and Astronautics, Jan. 7, 2019. ISBN: 978-1-62410-578-4. DOI: 10.2514/6.2019-0064. URL: https://arc.aiaa.org/doi/10.2514/6.2019-0064 (visited on 02/10/2021).

[25] *beta.SAM.gov.* URL: https://beta.sam.gov/opp/3b692f0ff1e1e3a3ccc96ef36230b181/view (visited on 01/31/2021).

[26] *beta.SAM.gov.* URL: https://beta.sam.gov/opp/0274923dc4af4d1f8fefd6cbc72704a3/view#general (visited on 01/22/2021).

[27] *beta.SAM.gov | Search.* URL: https://beta.sam.gov/opp/e694cb6c95fa4d9b4b43e5ed0b31-741d/view?keywords=%22augmented%20reality%22&sort=-relevance&index=&is_active=true&page=2 (visited on 01/26/2021).

[28] *Boeing.* AREA. URL: https://thearea.org/area-members/boeing/ (visited on 01/31/2021).

[29] *Boeing's AR Service Strategy For Maintenance Training.* Field Service 2021 | The Service & Support Virtual Summit. URL: https://fieldserviceusa.wbresearch.com/boeing-ar-technology-strategy-maintenance-training-transform-ty-u (visited on 01/31/2021).

[30] Taylor Borden et al. *21 major companies that have announced employees can work remotely long-term.* Business Insider. URL: https://www.businessinsider.com/companies-asking-employees-to-work-from-home-due-to-coronavirus-2020 (visited on 03/01/2021).

[31] BrandonBray. *What is Mixed Reality? - Mixed Reality.* URL: https://docs.microsoft.com/en-us/windows/mixed-reality/discover/mixed-reality (visited on 02/09/2021).

[32] *CAE.* URL: https://www.cae.com/news-events/press-releases/cae-usa-awarded-contract-to-support-us-air-force-pilot-training-transformation-initiative/ (visited on 01/08/2021).

[33] *Cannondale Leverages Augmented Reality Customer Experience | PTC.* URL: https://www.ptc.com/en/case-studies/cannondale (visited on 01/22/2021).

[34] Ashley Carman. *Bose gives up on its augmented reality sound project.* The Verge. June 16, 2020. URL: https://www.theverge.com/2020/6/16/21293372/bose-augmented-reality-frames-glasses-over (visited on 01/22/2021).

[35] Pietro Cipresso et al. "The Past, Present, and Future of Virtual and Augmented Reality Research: A Network and Cluster Analysis of the Literature". In: *Frontiers in Psychology* 9 (2018). Publisher: Frontiers. ISSN: 1664-1078. DOI: 10.3389/fpsyg.2018.02086. URL: https://www.frontiersin.org/articles/10.3389/fpsyg.2018.02086/full (visited on 02/10/2021).

[36] John Cogliandro. "System and method for risk adjusted strategic planning and phased decision management". U.S. pat. 8527316B2. John Cogliandro. Sept. 3, 2013. URL: https://patents.google.com/patent/US8527316/en (visited on 03/30/2021).

[37] *Come Play in an Augmented Reality Sandbox Like No Other*. Northrop Grumman. Jan. 6, 2020. URL: https://www.northropgrumman.com/life-at-northrop-grumman/come-play-in-an-augmented-reality-sandbox-like-no-other (visited on 01/31/2021).

[38] Raytheon Corporate Communications and Raytheon Corporate Communications. *Raytheon: Raytheon Immersive Design Center wins Aviation Week 2017 Program Excellence award - Nov 6, 2017*. Raytheon News Release Archive. URL: https://raytheon.mediaroom.com/2017-11-06-Raytheon-Immersive-Design-Center-wins-Aviation-Week-2017-Program-Excellence-award (visited on 01/22/2021).

[39] *Communications HUB and cables PANMCC20P0000017615 - GovTribe*. URL: https://govtribe.com/opportunity/federal-contract-opportunity/communications-hub-and-cables-panmcc20p0000017615 (visited on 01/22/2021).

[40] Diana Stancy Correll. *Why the Marine Corps is eyeing new virtual reality flight simulators for recruiting events*. Marine Corps Times. Section: Your Marine Corps. June 4, 2020. URL: https://www.marinecorpstimes.com/news/your-marine-corps/2020/06/04/why-the-marine-corps-is-eyeing-new-virtual-reality-flight-simulators-for-recruiting-events/ (visited on 01/08/2021).

[41] Young Entrepreneur Council. *Council Post: Extended Reality (XR) Is The Hot Topic Of 2020 And Beyond: Here's Why*. Forbes. Section: Entrepreneurs. URL: https://www.forbes.com/sites/theyec/2019/07/08/extended-reality-xr-is-the-hot-topic-of-2020-and-beyond-heres-why/ (visited on 02/09/2021).

[42] *CSC celebrates first Visualization Suite opening in Ottawa*. BAE Systems | en - Canada. URL: https://www.baesystems.com/en-ca/article/csc-celebrates-first-visualization-suite-opening-in-ottawa (visited on 01/22/2021).

[43] *DAU News - Powerful Example: Army starts using augmented reality to help maintain weapons*. URL: https://www.dau.edu:443/powerful-examples/blog?TermStoreId=dce24bd1-67d5-449a-a845-034b26f02d5e&TermSetId=39ac198e-e3d9-446c-8d38-b59df6ce18ef&TermId=02795a12-60d5-480e-a237-420465faf899&UrlSuffix=Powerful-Example--Army-starts-using-augmented-reality-to-help-maintain-weapons (visited on 01/08/2021).

[44] Deputy Under Secretary of Defense for Logistics {and} Materiel Readiness. *Condition Based Maintenance Plus (CBM+) Guidebook.pdf*. May 2008. (Visited on 02/11/2021).

[45] *Department of Defense unveils additive manufacturing strategy*. 3D Printing Industry. Feb. 4, 2021. URL: https://3dprintingindustry.com/news/department-of-defense-unveils-additive-manufacturing-strategy-183832/ (visited on 03/01/2021).

[46] *DOD Releases Fiscal Year 2021 Budget Proposal*. U.S. DEPARTMENT OF DEFENSE. URL: https://www.defense.gov/Newsroom/Releases/Release/Article/2079489/dod-releases-fiscal-year-2021-budget-proposal/ (visited on 01/08/2021).

[47] *DOD Releases Fiscal Year 2021 Budget Proposal*. U.S. DEPARTMENT OF DEFENSE. URL: https://www.defense.gov/Newsroom/Releases/Release/Article/2079489/dod-releases-fiscal-year-2021-budget-proposal/ (visited on 01/22/2021).

[48] Addy Dugdale and Addy Dugdale. *GM to Use Augmented Reality Tech for Safer Driving*. Fast Company. Mar. 17, 2010. URL: https://www.fastcompany.com/1586608/gm-use-augmented-reality-tech-safer-driving (visited on 01/22/2021).

[49] *Extended reality: A convergence is coming | Qualcomm*. URL: https://www.qualcomm.com/news/onq/2017/05/31/extended-reality-convergence (visited on 02/09/2021).

[50] *Falcon Suite*. Usens Inc. URL: https://en.usens.com/industry-solutions/falcon-suite/ (visited on 01/22/2021).

[51] Phil Goldstein Twitter Phil Goldstein is a web editor for FedTech et al. *Air Force Turns to VR, AR for Training and Maintenance*. Technology Solutions That Drive Government. URL: https://fedtechmagazine.com/article/2020/04/air-force-turns-vr-ar-training-and-maintenance (visited on 01/31/2021).

[52] Phil Goldstein Twitter Phil Goldstein is a web editor for FedTech et al. *Air Force Turns to VR, AR for Training and Maintenance*. Technology Solutions That Drive Government. URL: https://fedtechmagazine.com/article/2020/04/air-force-turns-vr-ar-training-and-maintenance (visited on 01/27/2021).

[53] *Ford - explore your new car with Augmented Reality*. URL: https://www.wikitude.com/showcase/ford-explore-your-new-car-with-augmented-reality/ (visited on 01/08/2021).

[54] *Free vector icons designed by Freepik*. Flaticon. URL: https://www.flaticon.com/authors/freepik (visited on 01/31/2021).

[55] *Future technologies*. BAE Systems | International. URL: https://www.baesystems.com/en/what-we-do/future-technologies (visited on 01/31/2021).

[56] *Future Vertical Lift Head Mounted Display System W909MY20RC024 - GovTribe*. URL: https://govtribe.com/opportunity/federal-contract-opportunity/future-vertical-lift-head-mounted-display-system-w909my20rc024 (visited on 01/22/2021).

[57] *GE Healthcare Introduces Virtual Reality Training for Healthcare Technology Management Professionals | GE News*. URL: http://www.ge.com/news/press-releases/ge-healthcare-introduces-virtual-reality-training-healthcare-technology-management (visited on 01/22/2021).

[58] *General Motors launches mixed reality showroom with Dentsu Aegis Network*. The Drum. URL: https://www.thedrum.com/news/2017/08/29/general-motors-launches-mixed-reality-showroom-with-dentsu-aegis-network (visited on 01/08/2021).

[59] *Global Patriot Solutions | Raytheon Missiles & Defense*. URL: https://www.raytheonmissilesanddefense.com/capabilities/products/global-patriot-solutions (visited on 02/09/2021).

[60] David Hambling. *Battlefield Augmented Reality Getting Real For U.S. Army*. Forbes. Section: Aerospace & Defense. URL: https://www.forbes.com/sites/davidhambling/2020/05/22/battlefield-augmented-reality-gets-real/ (visited on 01/08/2021).

[61] *Healthcare*. Usens Inc. URL: https://en.usens.com/healthcare/ (visited on 01/22/2021).

[62] *How Boeing Uses Upskill Skylight AR To Boost Productivity*. URL: https://www.forbes.com/sites/charliefink/2019/02/26/how-boeing-uses-upskill-skylight-ar-to-boost-productivity/?sh=10ba6b156093 (visited on 01/31/2021).

[63] *How Lockheed Martin is Using Augmented Reality in Aerospace Manufacturing by IsaacMaw*. Engineering.com. URL: https://www.engineering.com/story/how-lockheed-martin-is-using-augmented-reality-in-aerospace-manufacturing (visited on 01/31/2021).

[64] *How to use the LEGO® Hidden Side™ Augmented Reality app | LEGO.com*. URL: https://www.lego.com/en-us/themes/hidden-side/ar-games (visited on 01/22/2021).

[65] *How Toyota Deploys Augmented Reality Remote Expert Assistance Tools | PTC*. URL: https://www.ptc.com/en/case-studies/toyota-selects-vuforia-chalk (visited on 01/22/2021).

[66] *How VR is Transforming the Way We Train Associates*. Corporate - US. Section: Innovation. Sept. 20, 2018. URL: https://corporate.walmart.com/newsroom/innovation/20180920/how-vr-is-transforming-the-way-we-train-associates (visited on 01/22/2021).

[67] *Innovation Demonstration Center (IDC) | Lockheed Martin*. URL: https://www.lockheed-martin.com/en-us/products/innovation-demonstration-center-idc.html (visited on 01/22/2021).

[68] *Jedi Comes to Our Galaxy*. Librestream. Dec. 18, 2014. URL: https://librestream.com/articles/jedi-comes-to-our-galaxy/ (visited on 01/22/2021).

[69] Leslie Josephs. *Boeing slashes forecast for new aircraft demand, expects coronavirus pandemic to hurt sales for more than a decade*. CNBC. Section: Aerospace & Defense. Oct. 6, 2020. URL: https://www.cnbc.com/2020/10/06/boeing-covid-pandemic-to-hurt-aircraft-sales-for-more-than-a-decade.html (visited on 02/11/2021).

[70] Ang Choon Keat. "AN ENHANCED EVALUATION FRAMEWORK FOR DEFENCE R&D INVESTMENTS UNDER UNCERTAINTY". PhD thesis. National University of Singapore, 2012. 238 pp. URL: https://scholarbank.nus.edu.sg/handle/10635/31653.

[71] Brian Laughlin. *XR Drives Aerospace Excellence at Boeing*. URL: https://www.sme.org/technologies/articles/2018/july/xr-drives-aerospace-excellence-at-boeing/ (visited on 01/22/2021).

[72] Natan Linder. "Rapid development, real-world deployment, and evaluation of projected augmented reality applications". Accepted: 2018-03-12T19:28:47Z. Thesis. Massachusetts Institute of Technology, 2017. URL: https://dspace.mit.edu/handle/1721.1/114074 (visited on 02/10/2021).

[73] *Live, Virtual and Constructive*. Northrop Grumman. URL: https://www.northropgrumman.com/cyber/live-virtual-and-constructive (visited on 01/22/2021).

[74] *Live, Virtual and Constructive*. Northrop Grumman. URL: https://www.northropgrumman.com/cyber/live-virtual-and-constructive (visited on 01/31/2021).

[75] *LiveWorx 2020 Recap: Augmented Reality Captures Attention*. URL: https://www.ptc.com/en/blogs/corporate/liveworx20-recap-augmented-reality (visited on 01/22/2021).

[76] Thuy Mai. *Technology Readiness Level*. NASA. Publisher: Brian Dunbar. May 6, 2015. URL: http://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html (visited on 02/24/2021).

[77] "MarketLine Industry Profile: Aerospace & Defense in the United States". In: *Aerospace & Defense Industry Profile: United States* (Nov. 2017). Publisher: MarketLine, a Progressive Digital Media business, pp. 1–39. URL: https://search.ebscohost.com/login.aspx?direct=true&db=bth&AN=127466226&site=eds-live&scope=site (visited on 02/11/2021).

[78] *Mercedes Excels With Augmented Reality Customer Support | PTC*. URL: https://www.ptc.com/en/case-studies/mercedes-augmented-reality-customer-support (visited on 01/22/2021).

[79] Nathan Christensen, Jim Maul, Nathan Holyoak, Northrop Grumman Innovation Systems. "Affordable Virtual Reality on Next Generation Launch Systems and Products". Global Product Data Interoperability Summit. 2018. (Visited on 01/31/2021).

[80] *National Oilwell Varco - Increase Effectiveness of Service Technicians -*. Librestream. URL: https://librestream.com/use-cases/nov/ (visited on 01/22/2021).

[81] *Navy using 'digital twins' to speed innovation to the fleet*. Federal News Network. May 14, 2020. URL: https://federalnewsnetwork.com/federal-insights/2020/05/navy-using-digital-twins-to-speed-innovation-to-the-fleet/ (visited on 01/08/2021).

[82] *New Jamco Augmented Reality Technology Creates Efficient Maintenance Service*. Aviation Pros. Feb. 27, 2020. URL: https://www.aviationpros.com/tools-equipment/maintenance-it/press-release/21127477/jamco-new-jamco-augmented-reality-technology-creates-efficient-maintenance-service (visited on 01/08/2021).

[83] *News - Snap Partner Summit: Snap's Augmented Reality Platform - Snap Inc.* URL: https://snap.com/en-US/news/post/snap-augmented-reality-platform (visited on 02/08/2021).

[84] *News: BEMR: A New Reality for the Future Force - Office of Naval Research*. URL: https://www.onr.navy.mil/en/Media-Center/Press-Releases/2015/BEMR-New-Reality-for-Future-Force (visited on 01/31/2021).

[85] *Northrop Grumman Recognized with Manufacturing Leadership Awards*. Northrop Grumman Newsroom. URL: https://news.northropgrumman.com/news/releases/northrop-grumman-recognized-with-manufacturing-leadership-awards (visited on 01/31/2021).

[86] *On track to put augmented reality technology into a headset the size of a regular pair of glasses*. BAE Systems | International. URL: https://www.baesystems.com/en/article/bae-systems-on-track-to-put-augmented-reality-technology-into-a-headset-the-size-of-a-regular-pair-of-glasses (visited on 01/22/2021).

[87] Riccardo Palmarini et al. "A systematic review of augmented reality applications in maintenance". In: *Robotics and Computer-Integrated Manufacturing* 49 (Feb. 1, 2018), pp. 215–228. ISSN: 0736-5845. DOI: 10.1016/j.rcim.2017.06.002. URL: https://www.sciencedirect.com/science/article/pii/S0736584517300686 (visited on 02/11/2021).

[88] Oriana Pawlyk. *Air Force to Cut Use of Jayhawk Trainer, Rely More on Simulators*. Military.com. Section: Daily News. Aug. 18, 2020. URL: https://www.military.com/daily-news/2020/08/18/air-force-cut-use-of-jayhawk-trainer-rely-more-simulators.html (visited on 01/08/2021).

[89] Rob Pegoraro and Rob Pegoraro. *AR is finally infiltrating everyday tasks such as Google search*. Fast Company. Oct. 26, 2020. URL: https://www.fastcompany.com/90567886/ar-is-finally-infiltrating-everyday-tasks-such-as-google-search (visited on 01/22/2021).

[90] *PMEL introduces a safer, efficient way of teaching*. U.S. Air Force. URL: https://www.af.mil/News/Article-Display/Article/2068944/pmel-introduces-a-safer-efficient-way-of-teaching/ (visited on 01/22/2021).

[91] *Products & Services | Raytheon Missiles & Defense*. URL: https://www.raytheonmissilesanddefense.com/capabilities/products (visited on 02/09/2021).

[92] *Profile of a Daily Augmented Reality User at Lee Company*. AREA. Section: AR News. URL: https://thearea.org/ar-news/profile-of-a-daily-augmented-reality-user/ (visited on 01/22/2021).

[93] Moritz Quandt et al. "General Requirements for Industrial Augmented Reality Applications". In: *Procedia CIRP*. 51st CIRP Conference on Manufacturing Systems 72 (Jan. 1, 2018), pp. 1130–1135. ISSN: 2212-8271. DOI: 10.1016/j.procir.2018.03.061. URL:

https://www.sciencedirect.com/science/article/pii/S221282711830163X (visited on 02/10/2021).

[94] *Raytheon Company: Businesses*. URL: https://web.archive.org/web/20140411151518/http://www.raytheon.com/ourcompany/businesses/ (visited on 02/24/2021).

[95] Raytheon Missiles & Defense. *Working remotely in the military - Tech social distances repairs and training from afar*. July 29, 2020. URL: https://www.raytheonmissilesanddefense.com/news/feature/working-remotely-military (visited on 12/28/2020).

[96] *Rescue helicopter pilots showcase VR capability to ACC leadership*. U.S. Air Force. URL: https://www.af.mil/News/Article-Display/Article/1903044/rescue-helicopter-pilots-showcase-vr-capability-to-acc-leadership/ (visited on 01/08/2021).

[97] *RMD*. URL: https://www.rtx.com/our-company/our-businesses/rmd (visited on 02/09/2021).

[98] Somaiieh Rokhsaritalemi, Abolghasem Sadeghi-Niaraki, and Soo-Mi Choi. "A Review on Mixed Reality: Current Trends, Challenges and Prospects". In: *Applied Sciences* 10.2 (Jan. 16, 2020), p. 636. ISSN: 2076-3417. DOI: 10.3390/app10020636. URL: https://www.mdpi.com/2076-3417/10/2/636 (visited on 02/10/2021).

[99] *S/SVT Weapons Optimization - NSTXL*. URL: https://nstxl.org/opportunity/s-svt-weapons-optimization/ (visited on 01/22/2021).

[100] *Safran - Delivers Real-Time Visual Support*. Librestream. URL: https://librestream.com/use-cases/safran/ (visited on 01/08/2021).

[101] Jenny Scribani. *What is Extended Reality (XR)?* Visual Capitalist. Jan. 16, 2019. URL: https://www.visualcapitalist.com/extended-reality-xr/ (visited on 02/09/2021).

[102] *Second Air Force: Building Airmen for tomorrow's Air Force*. Air Reserve Personnel Center. URL: https://www.af.mil/News/Article-Display/Article/2319371/second-air-force-building-airmen-for-tomorrows-air-force/ (visited on 01/22/2021).

[103] *SGS - Remote Visual Inspections*. Librestream. URL: https://librestream.com/use-cases/sgs/ (visited on 01/22/2021).

[104] *Skylight Smart Glasses Software + Vuzix M300 = Solutions*. Upskill. URL: https://upskill.io/company/partners/upskill-and-vuzix/ (visited on 01/22/2021).

[105] Robert Slack. *The Lean Value Principle in Military Aerospace Product Development*. The Lean Aerospace Initiative RP99-01-16. July 1999, p. 17. URL: https://dspace.mit.edu/bitstream/handle/1721.1/83547/REP_99-01-16.pdf?sequence=1 (visited on 02/28/2021).

[106] *Snap: Most Innovative Company*. Fast Company. URL: https://www.fastcompany.com/company/snapchat (visited on 01/22/2021).

[107] Todd South. *Army's do-it-all goggles to reach soldiers' hands in 2021*. Defense News. Section: AUSA. Oct. 8, 2020. URL: https://www.defensenews.com/news/your-army/2020/10/11/armys-do-it-all-goggles-to-reach-soldiers-hands-in-2021/ (visited on 01/08/2021).

[108] Sam Sprigg. *Illumix announces updates to its Five Nights at Freddy's AR game, including new Mixed Reality modes*. Auganix.org. Oct. 30, 2020. URL: https://www.auganix.org/illumix-announces-updates-to-its-five-nights-at-freddys-ar-game-including-new-mixed-reality-modes/ (visited on 01/22/2021).

[109] Sam Sprigg. *SimX awarded US Air Force contract to expand its Virtual Reality training platform for military medical simulations*. Auganix.org. Oct. 29, 2020. URL: https://www.auganix.org/simx-awarded-us-air-force-contract-to-expand-its-virtual-reality-training-platform-for-military-medical-simulations/ (visited on 01/08/2021).

[110] Sam Sprigg. *U.S. Air Force looking to procure Virtual Reality production equipment to create its own aircraft maintenance training program*. Auganix.org. June 11, 2020. URL: https://www.auganix.org/u-s-air-force-looking-to-procure-virtual-reality-production-equipment-to-create-its-own-aircraft-maintenance-training-program/ (visited on 01/08/2021).

[111] Sam Sprigg. *US Department of Defense looking into using Virtual Reality to help "enhance small unity lethality"*. Auganix.org. May 20, 2020. URL: https://www.auganix.org/us-department-of-defense-looking-into-using-virtual-reality-to-help-enhance-small-unity-lethality/ (visited on 01/31/2021).

[112] Jacob H. Steffen et al. "Framework of Affordances for Virtual Reality and Augmented Reality". In: *Journal of Management Information Systems* 36.3 (July 3, 2019), pp. 683–729.

ISSN: 0742-1222, 1557-928X. DOI: 10.1080/07421222.2019.1628877. URL: https://www.tandfonline.com/doi/full/10.1080/07421222.2019.1628877 (visited on 09/24/2020).

[113] Raytheon Technologies. *Raytheon Technologies Reports Fourth Quarter 2020 Results, Announces 2021 Outlook*. URL: https://www.prnewswire.com/news-releases/raytheon-technologies-reports-fourth-quarter-2020-results-announces-2021-outlook-301214606.html (visited on 02/09/2021).

[114] David A. Teich. *IBM Augmented Reality Working To Support And Accelerate How Support Services Are Changing*. Forbes. Section: AI. URL: https://www.forbes.com/sites/davidteich/2020/04/28/ibm-augmented-reality-working-to-support-and-accelerate-how-support-services-are-changing/ (visited on 01/22/2021).

[115] *The 10 most innovative virtual and augmented reality companies of 2020*. URL: https://www.fastcompany.com/90457929/virtual-augmented-reality-most-innovative-companies-2020 (visited on 01/22/2021).

[116] *The Future of Augmented Reality Blends Virtual With Real-life Perspectives*. Now. Powered by Northrop Grumman. URL: https://now.northropgrumman.com/the-future-of-augmented-reality-blends-virtual-with-real-life-perspectives/ (visited on 01/31/2021).

[117] *Three Technologies Transforming Military Training in 2020*. Lockheed Martin. URL: https://www.lockheedmartin.com/en-us/news/features/2019-features/three-technologies-transforming-military-training-in-2020.html (visited on 01/31/2021).

[118] *Tips & Tricks to Successfully Deploy Enterprise Augmented Reality*. Liveworx Archive. URL: https://archive.liveworx.com/sessions/tips-tricks-to-successfully-deploy-enterprise-augmented-reality (visited on 01/22/2021).

[119] "Try on Your Next Pair of Glasses Using Just Your iPhone". In: *Wired* (). ISSN: 1059-1028. URL: https://www.wired.com/story/warby-parker-augmented-reality-app/ (visited on 01/22/2021).

[120] *United Technologies and Raytheon Complete Merger of Equals Transaction*. URL: https://www.rtx.com/news/2020/04/03/united-technologies-and-raytheon-complete-merger-of-equals-transaction (visited on 02/24/2021).

[121] *Virtual reality enhances depot training system for painters | Article | The United States Army*. URL: https://www.army.mil/article/226663/virtual_reality_enhances_depot_training_system_for_painters (visited on 01/08/2021).

[122] *Virtual, Augmented Reality Are Moving Warfighting Forward*. U.S. DEPARTMENT OF DEFENSE. URL: https://www.defense.gov/Explore/Inside-DOD/Blog/Article/2079205/virtual-augmented-reality-are-moving-warfighting-forward/ (visited on 01/22/2021).

[123] *Volvo Group Implements Augmented Reality in Manufacturing Training | PTC*. URL: https://www.ptc.com/en/case-studies/volvo-group-digital-thread (visited on 01/22/2021).

[124] Tom Warren. *Ford is using Microsoft's HoloLens to design cars in augmented reality*. The Verge. Sept. 21, 2017. URL: https://www.theverge.com/2017/9/21/16343354/microsoft-hololens-ford-augmented-reality (visited on 01/08/2021).

[125] *Webcast Replay: Modernizing Technician Training with Augmented Reality | PTC*. URL: https://www.ptc.com/en/resources/augmented-reality/webcast/modernizing-technician-training-with-ar (visited on 01/22/2021).

[126] *Welcoming Augmented Reality to the Industrial World | Cat | Caterpillar*. URL: https://www.cat.com/en_US/articles/customer-stories/built-for-it/augmented-reality.html (visited on 01/22/2021).

[127] *Where We Pokemon GO From Here - Augmented reality technology helps soldiers navigate through danger | Raytheon*. URL: https://www.raytheon.com/news/feature/augmented_reality_app (visited on 01/22/2021).

[128] *Within: About*. Within. URL: https://www.with.in/about (visited on 01/22/2021).

[129] D. Wright, R. Skaggs-Schellenberg, and S. Tayeb. "Networked Mixed Reality Framework for the Internet of Things". In: *2020 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS)*. 2020 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS). Sept. 2020, pp. 1–7. DOI: 10.1109/IEMTRONICS51293.2020.9216397.