



**POLITÉCNICO
DE LEIRIA**

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E GESTÃO

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Escola Superior de Tecnologia e Gestão
Departamento de Engenharia Informática
Mestrado em Engenharia Informática – Computação Móvel

INTEGRATING DIGITAL TWIN AND AUGMENTED
REALITY FOR MONITORING, EDUCATION AND
TRAINING IN THE MINERAL INDUSTRY

Ana Cassia Vasconcelos Cruz

Leiria, Fevereiro de 2025



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Leiria, Fevereiro de 2025

ACKNOWLEDGMENTS

This work would not be possible without the support and guidance of key people throughout this journey. Firstly, I express my deepest gratitude to all the teachers who taught me throughout my academic journey, especially to my supervisors, Nuno Rodrigues, Roberto Aguiar, Alexandrino Gonçalves and Anabela Marto. I thank you for your unconditional support, your inexhaustible patience and the valuable teachings that guided me at each stage of this journey. Even in moments when fear and uncertainty haunted me, you were by my side, offering encouragement and motivation for me to face adversity with courage and determination.

I would also like to thank the Polytechnic University of Leiria and the Computer Science and Communications Research Center (CIIC), not only for the institutional support, but also for the opportunities for academic and professional growth. I want to thank the projects "INOVMINERAL 4.0 - Advanced technologies and software for mineral resources (this work was supported by the European Regional Development Fund (Brussels, BE) POCI-01-0247-FEDER-046083)", "Sustainable Stone by Portugal - Valuing Natural Stone for a digital, sustainable and qualified future (this work was supported by the Sustainable Stone by Portugal agenda funded by European Union/Next Generation EU under Grant 02/C05-i01.02/2022.PC644943391-00000051)" and "SafeAR - Supporting privacy and confidentiality in Augmented Reality contexts (This work was funded by FCT - Fundação para a Ciência e a Tecnologia, I.P., through project with reference 2022.09235.PTDC)."

I cannot fail to mention the support of my colleagues and research friends, who shared ideas, challenges and achievements with me, and who served as volunteers for my "experiments". Your feedback was always worthy and without sparing words for improvements, namely Carla Mendes, Enrico Gomes, José Areia and especially Tiago Ribeiro and Diogo Francisco. The exchange of knowledge and inspiring discussions were essential for the development of this work. You all made this journey much richer and more motivating.

Finally, my most special thanks go to my boyfriend Carlos Gomes, who has been with me since the beginning of my degree in Computer Engineering, to my mother Cristiane Vasconcelos, who always did everything possible and impossible for me, to my brother Wendell Vasconcelos, who always encouraged me to follow

my dreams, and to all my family. You were my emotional foundation, offering love, understanding, and strength at all times. Your support gave me the confidence to move forward and never give up.

To all of you, my sincere and profound gratitude. This work is as much yours as it is mine.

ABSTRACT

This report explores the application of Digital Twin (**DT**) and Augmented Reality (**AR**) technologies in addressing key challenges within the mineral industry, including high operating costs, hazardous working environments, and resource management. To achieve this, a solution leveraging the HoloLens 2 is proposed, integrating real-time monitoring, educational content, and training for industrial tasks. The developed system is structured into three interconnected layers—Factory Environment, **AR** System, and Cloud Platform—which collectively facilitate the extraction, visualization, and dissemination of data to users.

As part of this project, an initial Android **AR** application using Unity was developed for the mining industry and tested in factory environment with real factory worker users. This application served as the basis for the evolution of the new **AR-DT** system, as it had already been validated for its monitoring capabilities and educational content (text, audio, and video).

Based on this knowledge, the system was expanded to integrate **AR** with **DT**, using HoloLens 2 for a more immersive experience. On the factory environment, real-time data from the machines is monitored via **OPC UA**-compatible servers. This data is subsequently made accessible on the **AR** glasses, providing users with contextual information. In parallel, the Cloud Platform stores training content such as videos, audio and text, as well as **3D** objects used in training. The **AR** System bridges the gap between physical and digital environments, enabling interactive training where operators can interact with virtual replicas of machine parts, simulating the real-time process monitoring and the machine's educational training content, such as manuals via text, audio and even tutorial videos, which contribute to improving operational efficiency, safety and the development of workers' skills.

To evaluate the effectiveness of this new approach, a usability evaluation was conducted, focusing on user performance, cognitive load and the interface usability. The results were promising, demonstrated by high task completion rates (between 81.8% and 100%), positive scores in usability tests carried out using the System Usability Scale (**SUS**) (average of 72.4) and low levels of frustration, physical demand and effort, as measured by **NASA-TLX**. The qualitative analysis, using the **VADER** algorithm, confirmed a mostly positive reception of the **AR** technology,

although some challenges in the interface were identified as opportunities for future improvements.

In addition, an [AR](#) prototype was developed with a focus on preserving privacy in industrial environments. The solution employs a client-server architecture, in which the [AR](#) device diffuses images for remote processing, receiving them back with sensitive regions (e.g. faces, screens) obfuscated via techniques such as Gaussian blurring or pixelation. This prototype is the initial step towards the secure integration of wearable systems in industrial contexts, laying the foundations for future advances in harmonizing security and usability.

At the same time, the system includes a training module for assembling computer components, designed as a proof of concept for industrial simulations. The ultimate goal is to integrate real-time obfuscation with interaction during training, guaranteeing data protection without compromising the user experience in [AR](#) glasses.

These findings underscore the potential of the [AR-DT](#) system to enhance operational efficiency, safety, and skills development within the stone industry. The study's outcomes suggest that such integrated [AR-DT](#) solutions could contribute to advancing Industry 4.0 practices within the sector, potentially leading to more efficient and safer industrial processes.

RESUMO

Este relatório investiga como as tecnologias Digital Twin (DT) e Realidade Aumentada (AR) podem ajudar a enfrentar desafios da indústria mineral, como elevados custos operacionais, ambientes de trabalho perigosos e a gestão de recursos. Para isso, propõe-se uma solução baseada no uso do HoloLens 2, combinando monitorização em tempo real, conteúdos de formação e treino para tarefas industriais. O sistema desenvolvido estrutura-se em três camadas interligadas—Factory Floor, Sistema de AR e Cloud Platform—que, em conjunto, permitem a extração, visualização e entrega dos dados aos utilizadores.

Como parte deste projeto, uma aplicação Android AR inicial usando Unity foi desenvolvido para a indústria mineral e testada chão de fábrica com utilizadores operários reais de fábrica. Esta aplicação serviu como base para a evolução para o novo sistema AR-DT, pois já havia sido validado por suas capacidades de monitoramento e conteúdo educacional (texto, áudio e vídeo).

Com base nesses conhecimentos, o sistema foi expandido para integrar AR com DT, utilizando o HoloLens 2 para uma experiência mais imersiva. No ambiente de fábrica, os dados em tempo real das máquinas são monitorados através dos servidores compatíveis com OPC UA. Esses dados são posteriormente disponibilizados nos óculos de AR para fornecer informações contextuais. Paralelamente, a Cloud Platform armazena conteúdos de formação, como vídeos, áudio e texto, bem como objetos 3D utilizados em treinos. O Sistema de AR preenche a lacuna entre ambientes físicos e digitais, permitindo treinamento interativo onde os operadores podem interagir com réplicas virtuais das peças da máquina, simulando o monitoramento de processos em tempo real e o conteúdo de formação educacional da máquina, como manuais por meio de texto, áudio e até vídeos tutoriais, que contribuem para melhorar a eficiência operacional, a segurança e o desenvolvimento de habilidades dos trabalhadores.

Para avaliar a eficácia desta nova abordagem, foi realizada uma avaliação de usabilidade focada no desempenho dos usuários, na carga cognitiva e na usabilidade de uso da interface. Os resultados foram promissores, demonstrados por altas taxas de conclusão de tarefas (entre 81,8% e 100%), pontuações positivas nos testes de usabilidade feitos com recurso à escala System Usability Scale (SUS) (média de

72,4) e baixos níveis de frustração, demanda física e esforço, conforme medidos pela [NASA-TLX](#). A análise qualitativa, utilizando o algoritmo [VADER](#), confirmou uma recepção majoritariamente positiva da tecnologia de [AR](#), embora alguns desafios na interface tenham sido identificados como oportunidades para futuras melhorias.

Adicionalmente, desenvolveu-se um protótipo de [AR](#) com foco na preservação da privacidade em ambientes industriais. A solução emprega uma arquitetura cliente-servidor, na qual o dispositivo de [AR](#) transmite imagens para processamento remoto, recebendo-as de volta com regiões sensíveis (ex: rostos, ecrãs) ofuscadas via técnicas como embaciamento gaussiano ou pixelização. Este protótipo constitui a etapa inicial para a integração segura de sistemas de [AR](#) em contextos industriais, estabelecendo bases para futuros avanços na harmonização entre segurança e usabilidade.

Paralelamente, o sistema inclui um módulo de treino para montagem de componentes informáticos, concebido como prova de conceito para simulações industriais. O objetivo último consiste em integrar a ofuscação em tempo real com a interação durante o treino, garantindo a proteção de dados sem comprometer a experiência do utilizador nos óculos de [AR](#).

Em suma, as descobertas ressaltam o potencial do sistema [AR-DT](#) para otimizar a eficiência operacional, aumentar a segurança e promover o desenvolvimento de habilidades na indústria mineral. Os resultados sugerem que essas soluções integradas podem impulsionar o avanço das práticas da Indústria 4.0, contribuindo para processos industriais mais eficientes e seguros.

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LIST OF ABBREVIATIONS

2D	Two-Dimensional.
3D	Three-Dimensional.
3DoF	3 Degrees of Freedom.
6DoF	6 Degrees of Freedom.
AI	Artificial Intelligence.
AM	Additive Manufacturing.
ANOVA	Analysis of Variance.
API	Application Programming Interface.
AR	Augmented Reality.
CAD	Computer-Aided Design.
CAGR	Compound Annual Growth Rate.
CPS	Cyber-Physical System.
D3D	Direct3D.
DT	Digital Twins.
FoV	Field of View.
GCP	Google Cloud Platform.
HMD	Head-Mounted Display.
HTTP	HyperText Transfer Protocol.
ID	Identifier.

List of Abbreviations

IIoT	Industrial Internet of Things.
IoT	Internet of Things.
JSON	JavaScript Object Notation.
MQTT	Message Queuing Telemetry Transport.
MR	Mixed Reality.
MRTK	Mixed Reality Toolkit.
MTDT	Machine Tool Digital Twins.
NASA-TLX	NASA Task Load Index.
NFC	Near Field Communication.
OPC UA	Open Platform Communications Unified Architecture.
PC	Personal Computer.
QR Code	Quick Response Code.
RAM	Random Access Memory.
SDKs	Software Development Kits.
SoC	System on a Chip.
SUS	System Usability Scale.
ToF	Time-of-Flight.
UWP	Universal Windows Platform.
VADER	Valence Aware Dictionary and sEntiment Reasoner.

VR Virtual Reality.

XR Extended Reality.

INTRODUCTION

The mineral industry, a major player of global economic development, has an important role in providing essential raw materials for various sectors, including construction, manufacturing, and energy (Onifade et al., 2023). The global dimension stone market, valued at approximately USD 8.93 billion in 2024 to USD 9.51 billion in 2025 and with a [Compound Annual Growth Rate \(CAGR\)](#) of 6.6%, demonstrates the sector's substantial economic impact and emphasize the importance of technological advancement in this field (*Dimension Stones Global Market Report 2025*).

Within this broad field, the dimension stone industry represents a significant subsector, specializing in extracting and processing natural stone for architectural and ornamental purposes (Samarakoon et al., 2023). This specific industry faces different challenges that threaten its long-term sustainability and operational efficiency. These challenges include the finite nature of mineral resources, complex and hazardous working environments, high operational costs, and a persistent shortage of skilled labor (Onifade et al., 2023). The complexity of these challenges is further amplified by increasing global competition, stricter environmental regulations, and rising consumer demands for sustainable practices (Careddu et al., 2019; Cosi, 2015).

These multifaceted challenges necessitate innovative technological solutions that can simultaneously address operational efficiency, safety concerns, and workforce development while maintaining economic viability (Horberry et al., 2016; Onifade et al., 2023). Such solutions must be scalable, cost-effective, and capable of delivering measurable improvements across various operational aspects (Keskar and Malaga, 2023). The integration of digital technologies presents an opportunity to transform traditional industrial practices and address these challenges.

In response to these challenges, the concept of Industry 4.0 has emerged as a potential solution that offers a significant change in industrial operations by integrating advanced technologies, such as the Internet of Things and Artificial Intelligence (Lasi et al., 2014). This concept refers to the fourth industrial revolution, characterized by the convergence of digital technologies with physical industrial processes. Among the key technologies driving Industry 4.0, [Digital Twins \(DT\)](#) and [Augmented Reality \(AR\)](#) stand out as emerging solutions for addressing the

specific challenges faced by the dimension of the stone industry (Begout et al., 2022; Francisco et al., 2023).

Regarding the concept of [DT](#), it enables the creation of virtual counterparts to physical systems, processes, and products, facilitating real-time simulation, analysis, and prediction of their behaviors (Pires et al., 2019). This capability allows for superior operational efficiency, predictive maintenance, and data-driven decision-making processes (Redelinghuys et al., 2020).

On its turn, [AR](#) considers the overlay of digital information onto the physical world, and its application has gained significant interest in recent years (Minaee et al., 2022). [AR](#) provides an interactive experience for users by seamlessly blending virtual content with the real environment (Azuma, 1997). Its applications span diverse fields, including education, healthcare, and gaming, among other industries. In the educational sector, [AR](#) applications like Anatomy 4D have demonstrated the technology’s potential to enhance learning experiences (Alenezi, 2019). Similarly, in the retail industry, companies such as IKEA have utilized [AR](#) to improve customer experiences through virtual product placement (Ozturkcan, 2021).

In the context of the mineral industry, [AR](#) technology offers significant potential for enhancing operational efficiency, safety, and training (B. R. Martins et al., 2023). It also enables on-site learning directly on the factory floor, allowing workers to interact with machinery while receiving instruction. The use of [AR](#)-enabled smart glasses facilitates hands-free learning, allowing the workers to complete tasks while simultaneously receiving training (Turan and Karabey, 2023). This approach not only improves the efficiency of training programs but also improves knowledge retention and understanding of complex tasks in the industrial environment (Minaee et al., 2022).

The pervasive adoption of [AR](#) in industrial settings introduces critical privacy concerns that must be addressed to ensure ethical and compliant deployment. [AR](#) devices continuously capture and process visual data from their surroundings, potentially exposing sensitive information such as worker identities, proprietary machinery details, or confidential documents (Cruz et al., 2025). To mitigate these risks, this work integrates privacy-preserving obfuscation techniques—blurring, masking, and pixelation—into the [AR](#) system. As demonstrated in our parallel study (Cruz et al., 2025), user acceptance of these techniques varies significantly with demographic factors (e.g., age, occupation) and operational contexts, necessitating a tailored approach to privacy management.

Furthermore, [AR](#) technology can significantly improve worker safety by providing synchronous and real-time contextual information overlaid on the physical environment (Marques et al., 2019). This capability improves situational awareness, reduces errors, and supports more informed decision-making processes in complex industrial settings. The integration of [AR](#) with real-time machine monitoring data from [DTs](#) can further augment operational efficiency and support data-driven decision-making (Francisco et al., 2023).

This work aims to evaluate the integration of [DT](#) and [AR](#) technologies for monitoring, training, and education in the stone industry. The study focuses on three primary objectives: (i) describe the implementation of an [AR](#) system to support the integration of [DT](#) technology in stone industry; (ii) assessing the system’s usability for monitoring, training, and task completion and analysing how different user profiles impact performance and perception; (iii) measuring the cognitive workload associated with using the [AR](#) system in an industrial setting.

The practical implications of this work extend beyond theoretical contributions, offering benefits for industry stakeholders. The proposed system provides immediate access to critical information in real-time enhanced monitoring capabilities, training and education resources in factory environment for machine operators and workers.

By addressing these objectives, this study seeks to develop innovative solutions to the pressing challenges faced by the sector, particularly in the areas of operational efficiency, worker safety, and skills development.

As such, this study proposes a solution that integrates [AR](#) and [DT](#) technologies to enhance operational efficiency, safety, monitoring, education, and training in the stone industry. The architecture comprises three interconnected layers: Factory Environment, [AR](#) System, and Cloud Platform. The Factory Environment includes machines with sensors connected to [Open Platform Communications Unified Architecture \(OPC UA\)](#) servers, providing real-time data. The [AR](#) System utilizes [AR](#) headsets to offer workers immediate access to contextual information and interactive guidance. The Cloud Platform manages and stores data, including [Three-Dimensional \(3D\)](#) models, multimedia content, and operational information, while hosting a web application for data visualization and analysis. The [DT](#) integration is reflected in the real-time monitoring and visualization of machine states.

While the mineral stone industry encompasses various operational aspects, this study focuses specifically on [DT](#) to monitoring, training, and education purpose, with particular emphasis on machine operation and maintenance procedures. While recognizing that economic and broader organizational effects are outside the cur-

rent purview, the work takes into account both technical and human aspects of implementation.

Considering the goals identified for this study, the following research questions were defined:

- **RQ1:** How does perceived workload ([NASA Task Load Index \(NASA-TLX\)](#)) relate to perceived usability ([System Usability Scale \(SUS\)](#)) in the [AR](#) system?
- **RQ2:** To what extent does the user’s familiarity with [AR](#) technology affect their performance and perception of usability of the [AR](#)-enabled system?
- **RQ3:** What are the main difficulties or barriers users encountered while using the system, and which aspects did they appreciate the most?

This work focuses on the connection of [AR](#) and [DT](#) technologies, and explores their potential to transform traditional practices. The following contributions highlight the key areas of development and evaluation undertaken in this study:

- Development and evaluation of an [AR](#) system to support [DT](#) technology for the mineral industry, combining interactive training, real-time monitoring, and decision support, with a focus on improving operational efficiency, safety, and skills development.
- Integration of a web platform that facilitates the management and updating of monitoring, education content, and training, integrating [AR](#) and real-time monitoring data, with the potential to incorporate predictive maintenance and data analytics functionalities.
- Privacy-Aware Design, implementation of context-sensitive obfuscation techniques (pixelation) to protect sensitive data in [AR](#) environments, informed by empirical user studies (Cruz et al., 2025).
- Comprehensive analysis of the system’s usability and effectiveness, considering different user profiles and their prior experiences with [AR](#) technology, providing insights into the challenges and opportunities for implementing [AR-DT](#) technologies in industrial environments.

This present work is structured as follows. Section 2 provides an overview of key concepts and technologies related to immersive visualization and interaction, focusing on [AR](#), [Virtual Reality \(VR\)](#), and [Mixed Reality \(MR\)](#), privacy in [AR](#) environment, as well the concept of [OPC UA](#) and [DT](#) and their role in enhancing [AR](#) experiences. Additionally, this section provides insights into development tools and deployment platforms. Section 3 identifies and analyses literature related to this

work, covering real-time monitoring systems and instructional systems in the context of manufacturing. Section 4 details the present work's plan, as the development processes and evaluation methods adopted to develop the project, and also presents a proposed solution that was applied in this research, describing the architecture and operation of the proposed AR System, which integrates real-time machine monitoring, interactive training simulations, and educational multimedia content. Section 5 details the implementation, including the technologies used, such as OPC UA servers, AR headsets, and game engines. Section 6 describes the methodologies to evaluate the usability, task cognitive workload, and general user experience while using the system and, presents an analysis of the results, discussing the system's strengths and limitations based on the findings. Section 7 demonstrates the practical implementation of two operational modules: (1) a privacy-preserving image obfuscation pipeline, and (2) an AR-based training simulator for industrial maintenance workflows. Finally, Section 8 summarizes the conclusions drawn from the developed system and outlines future work that requires exploration.

This chapter provides the foundational knowledge necessary to understand the technological context of this research on integrating **DT** and **AR** for the mineral industry. Immersive technologies are revolutionizing how digital content is engaged with and transforming industrial processes, among the most popular immersive technologies are **AR**, **VR**, and **MR**. In the context of industrial manufacturing, the concept of **DT** is gaining traction, where a virtual replica of a physical system or process is created to simulate, analyses, and predict its behaviour (Pires et al., 2019).

Considering **AR** as the focus of this research, this section describes the differences between the previously mentioned immersive technologies, identifies the advantages of **AR** in enhancing the **DT** experience, and finally, focuses on the tools for the development and deployment of **AR** experiences. Additionally, this thesis explores the specific hardware and **Google Cloud Platform (GCP)** used, providing context for the implementation decisions described in later chapters.

2.1 OVERVIEW OF IMMERSIVE TECHNOLOGIES

Starting with **AR**, this concept integrates computer-generated content, such as images, sounds, and **3D** models, into the user's real-time view of the physical world. It is typically experienced through a mobile device, such as a smartphone or tablet, or smart glasses, which are equipped with cameras and other sensors, which are used to detect the user's environment so that digital content can be displayed accordingly (Van Krevelen and Poelman, 2010). The most common types of **AR** are represented in Figure 1 (Aggarwal and Singhal, 2019, Malta et al., 2023) and described next.

- **Marker-based AR:** Uses a physical marker such an image or a 3D object to trigger digital content display.
- **Markerless-based AR:** In contrast to the prior method, it uses computer vision techniques like localization and object identification to project virtual objects into their **Field of View (FoV)**.

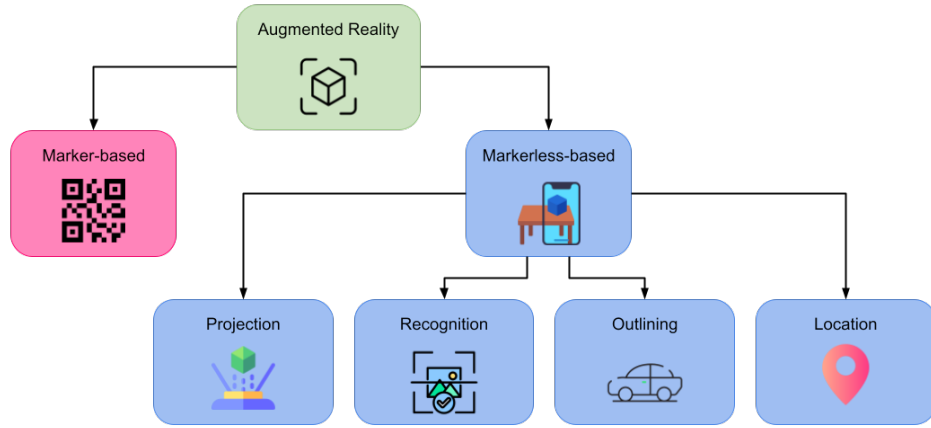


Figure 1: Types of Augmented Reality (AR), adapted from Malta et al., 2023.

- **Projection AR:** Projects digital content onto a physical surface.
- **Recognition AR:** Identifies components of the real world and initiates AR experiences.
- **Outlining AR:** Uses image recognition to obtain a better understanding of the current environment. With the use of specialized cameras, users may generate shapes and contours of the real world.
- **Location AR:** Uses GPS or other device location systems to gather real-time data in order to overlay AR content according to the user’s location.

In contrast to AR, VR is a technology that immerses the user in a completely digital environment. VR is typically experienced through a headset that blocks out the user’s view of the real world and replaces it with a computer-generated environment, interactive or not (Hamad and Jia, 2022).

On its turn, MR is a technology, that the own term is often subject to discussion, as its definition can vary depending on the context and technological perspective (Fidalgo et al., 2023). Some interpretations consider MR as a spectrum that encompasses both AR and VR, while others define it more strictly as an environment where digital and physical elements coexist and interact seamlessly in real-time (Evangelidis et al., 2021). MR is typically experienced through a headset or smart glasses that use advanced sensors and cameras to track the user’s environment and overlay digital content accordingly (Papadopoulos et al., 2021). The extent of how virtual data is overlaid on the physical world, as illustrated by the reality-virtuality continuum in Figure 2, might change throughout AR implementations (Marto and Gonçalves, 2024).

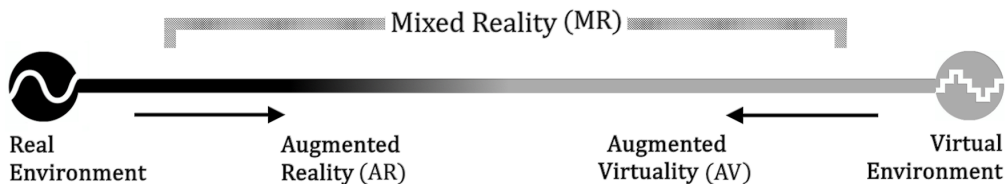


Figure 2: **Reality-Virtuality (RV) Continuum.** A spectrum of Mixed Reality environments, including AR, overlays virtual information on the physical world, and virtual reality, denotes a completely virtual environment. Adapted from Milgram et al., 1995.

All three technologies have the potential to transform interactions with digital content, offering new and innovative ways to learn, work, and play (Al-Ansi et al., 2023). AR, VR, and MR have been around for several decades, and recent advancements in hardware and software have made them more accessible and affordable than ever before.

MR has shown great promise in a variety of industries, from healthcare and education to manufacturing and entertainment (Costanza et al., 2009, Sumit Patel et al., 2020). As these technologies continue to evolve and mature, they are likely to have a profound impact on daily life, transforming communication, collaboration, and the way the world is experienced.

With their potential to revolutionize the interaction with digital information, has been identified four key principles that demonstrate the advantages of using AR in the factory context. These principles were selected based on their relevance to the factory setting, impact on operational efficiency, and worker support. They are the following.

- **Enhanced learning and training:** Provide interactive 3D visualizations that make complex concepts easier to understand and retain (Sahin and Yilmaz, 2020).
- **Cost savings:** Reduce costs by minimizing the need for physical prototypes or real machines, reducing training time, and improving operational efficiency (Osborne and Mavers, 2019).
- **Data visualization:** Visualize complex data in a more intuitive and interactive way, making it easier to understand and analyse (Natephra and Motamedi, 2019).

- **Remote collaboration:** Facilitate more effective collaboration among geographically dispersed teams, bridging physical distances and enabling real-time, context-aware interactions (P. Wang et al., 2021).

2.2 DIGITAL TWIN

A **DT** is a virtual representation that serves as the real-time digital counterpart of a physical object or system. This technology is an essential component in the context of Industry 4.0, where it plays a critical role in enhancing the performance, maintenance, and efficiency of physical systems by enabling predictive analytics and real-time monitoring. **DTs** integrate data from various sources, including sensors, **Internet of Things (IoT)** devices, and historical data, to create a dynamic model that mirrors the current state and predicts the future state of the physical asset (Jiang et al., 2021). Figure 3 demonstrates a mirrored space from a real space.

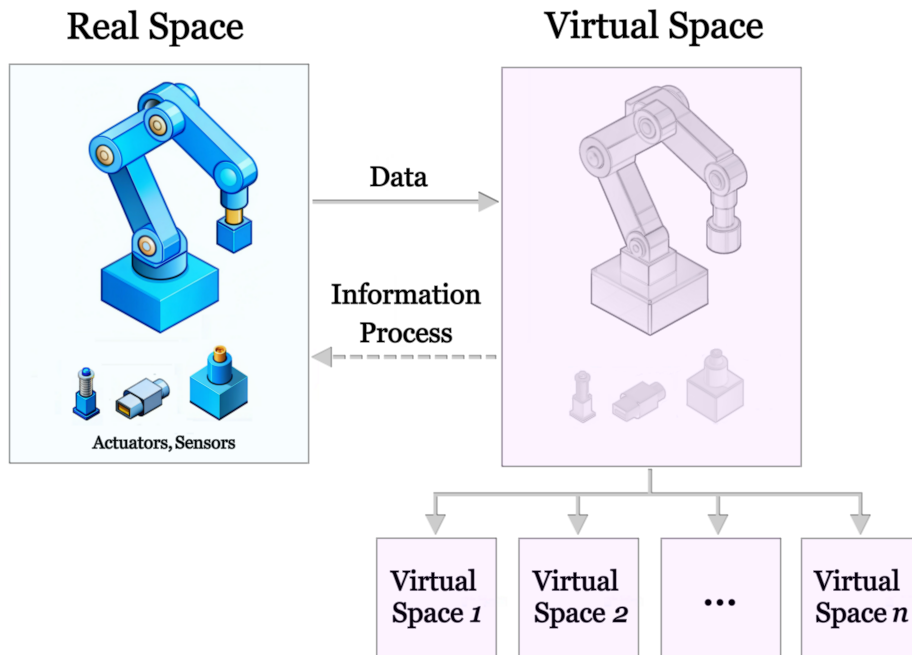


Figure 3: **Mirror Spaces Model (MSM)**. The Real Space (RS) represents the physical system, while multiple Virtual Spaces (VS1 -VSn) depict diverse digital representations of RS. Each VS can focus on different aspects or levels of detail, facilitating various analyses of the physical system. Adapted from Grieves Jiang et al., 2021.

The concept of **DT** technology was first introduced by NASA to improve the performance and reliability of its spacecraft through advanced simulation and modeling (Grieves, 2014). Today, it has expanded into a wide range of industries, including manufacturing, healthcare, smart cities, and transportation, where it is used for

purposes such as optimizing production processes, enabling proactive maintenance, and improving the design and operational efficiency of complex systems (Attaran and Celik, 2023).

One of the key benefits of DTs is their ability to provide a detailed and accurate visualization of the physical entity, which helps workers make informed decisions. For instance, in manufacturing, a DT can simulate production line processes, predict potential failures before they occur, and suggest optimized maintenance schedules. This predictive capability not only reduces downtime but also extends the lifespan of the equipment (Tao et al., 2018).

By merging AR into the visualization features of DT, the potential of these technologies can be improved. For example, AR can be used to represent the virtual part of a DT or to facilitate the visualization of complex DT data in more intuitive and interactive approaches.

2.3 OPEN PLATFORM COMMUNICATIONS UNIFIED ARCHITECTURE (OPC UA)

OPC UA is an advanced industrial communication framework designed to support secure, reliable, and platform-independent data exchange between diverse devices and systems. By including a service-oriented architecture and strong security features like encryption and signed, OPC UA, created by the OPC Foundation¹, marks a substantial advancement over earlier OPC standards and resolves many of the issues with earlier implementations (Busboom, 2024; Mahnke et al., 2009).

One of OPC UA's main advantages is its layered architecture, which separates application-specific logic from fundamental communication protocols. This abstraction enables interoperability across various hardware and software platforms, making it an ideal candidate for Industry 4.0 applications where integration of heterogeneous systems is paramount. Its comprehensive information modeling capabilities allow for the representation of complex industrial processes, which facilitates seamless integration and real-time data exchange in environments ranging from manufacturing and technologies (R et al., 2024).

Within the context of this report, OPC UA serves as the core communication protocol that enables interaction between remote system components. The successful integration of DT concepts depend on their ability to provide real-time data

¹ <https://opcfoundation.org>

transfer and preserve system integrity by ensuring that modifications to the physical environment are adequately and securely mirrored in the virtual environment, if one exists.

2.4 TOOLS FOR AR DEVELOPMENT

When it comes to [AR](#), contemporaneous game engines offer a complete set of tools and compatibility solutions for the development and deployment of [AR](#) experiences. Examples are Unity, Unreal Engine, and Godot (Vakaliuk and Pochtoviuk, 2021). Several authors consider Unity as the most convenient and most used development environment for the implementation of immersive experiences (Turan and Karabey, 2023). One of the key features that make Unity an attractive choice for [AR](#) development is its ability to integrate native [Software Development Kits \(SDKs\)](#) for various [AR](#) platforms, like Apple’s [ARKit](#)² or Google’s [ARCore](#)³. This integration simplifies the process of developing [AR](#) experiences. It provides access to a wide range of features such as plane detection, spatial mapping, motion tracking, and light estimation, among others.

The growing technological development and the democratization of access to mobile devices have driven the popularization of [AR](#) in people’s everyday life, expanding its application beyond smartphones and tablets, to also in [Head-Mounted Display \(HMD\)](#) also known as smart glasses such as [HoloLens](#)⁴, [Meta Quest](#)⁵, among others (Vidal-Balea et al., 2020). Microsoft’s [HoloLens 2](#) represents a significant advancement in [MR](#) and [AR](#) technology, offering versatile functionalities applicable across diverse industries. This untethered headset leverages a suite of sensors, including high-definition cameras, accelerometers, microphones, and infrared [Time-of-Flight \(ToF\)](#) depth measurement, to achieve a true heads-up display experience. Significantly, [HoloLens 2](#) facilitates tasks in the industry by enabling the visualization of interactive [Two-Dimensional \(2D\)](#) and [3D](#) objects within the user’s [FoV](#) (Ungureanu et al., 2020).

To provide a comprehensive overview of the current state of [AR/VR](#) headsets, present a comparison of four prominent devices in [Table 1](#). This table highlights the key features and specifications of the [Microsoft HoloLens 2](#), [Magic Leap 2](#), [Meta Quest 3](#), and [Apple Vision Pro](#), including their release year, resolution, [AR/VR](#)

² <https://developer.apple.com/augmented-reality/>

³ <https://developers.google.com/ar>

⁴ <https://www.microsoft.com/pt-br/hololens>

⁵ <https://www.meta.com/quest/>

capabilities, visualization technology, [FoV](#), and controller types. By examining these characteristics, it is possible to better understand the strengths and limitations of each headset and make informed decisions about their adoption and application.

Table 1: Comparison of leading Augmented Reality (AR) and Virtual Reality (VR) headsets.

Headset	Release	Resolution per-eye	Type & Display	Interface & Field of View (FoV)
Microsoft HoloLens 2	2019	1440x936	AR only See-through (holographic lenses)	Controls: Hands gesture, Eye, Voice FoV: $\sim 52^\circ$
Magic Leap 2	2022	1440x1760	AR only See-through display (LCOS)	Controls: Ad-hoc controller FoV: $\sim 44^\circ$ horizontal / $\sim 53^\circ$ vertical / $\sim 70^\circ$ diagonal
Meta Quest 3	2023	2064x2208	AR & VR Pass-through camera	Controls: Ad-hoc controller FoV: $\sim 110^\circ$ horizontal / $\sim 96^\circ$ vertical
Apple Vision Pro	2024	3660x3200	AR & VR Pass-through camera (micro-OLED)	Controls: Hands gesture, Eye, Voice FoV: $\sim 90^\circ$

A critical issue of the immersive experience provided by these devices is their capability to support [6 Degrees of Freedom \(6DoF\)](#). Initially, many AR experiences on mobile devices relied on [3 Degrees of Freedom \(3DoF\)](#) tracking, which captured only the user’s rotational movements—pitch, yaw, and roll—allowing users to look around and interact with virtual objects to a certain extent. However, [3DoF](#) lacked the spatial awareness and freedom of movement offered by [6DoF](#), which tracks the full range of a user’s movements, including three translational movements (forward/backward, up/down, left/right) in addition to the rotational ones. [Figure 4](#) illustrates the difference in movements across each axis. This precise tracking enables [HMDs](#) like the HoloLens 2 to allow interactions with virtual objects as if they were physically present in the surrounding environment (Trivedi, 2019, Goh et al., 2019).

To further enhance the capabilities of the HoloLens 2 and facilitate the development of [AR/MR](#) applications, Microsoft has released the [Mixed Reality Toolkit \(MRTK\)](#)⁶. [MRTK](#) is an open-source development platform that provides a set of tools and components to create interactive experiences that combine virtual and real-world objects. [MRTK](#) supports multiple platforms, including HoloLens,

⁶ <https://learn.microsoft.com/en-us/windows/mixed-reality/mrtk-unity/mrtk3-overview/>

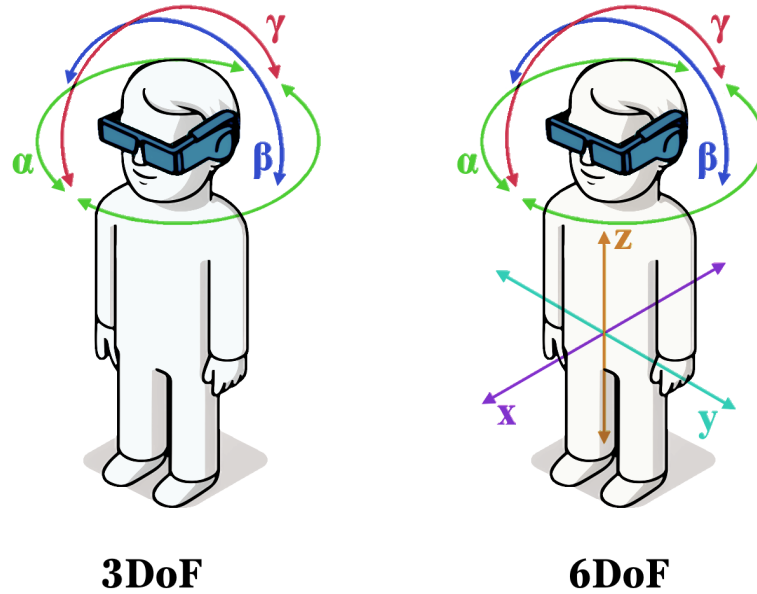


Figure 4: **Comparison of 3DoF and 6DoF.** The 3DoF AR system (left) allows only rotational movements: yaw (α), pitch (β), and roll (γ), limiting the AR device to orientation-based interactions. The 6DoF AR system (right) incorporates both rotational and translational movements along the X, Y, and Z axes, enabling full spatial tracking and interaction within the AR environment. This representation considers a left-handed coordinate system with a Z-up axis. Adapted from Assumpção and Cuperschmid, 2021

Windows MR headsets, and mobile devices and is compatible with the game engines Unity and Unreal Engine (*Mixed Reality Toolkit 2023*).

2.4.1 Microsoft HoloLens 2: Technical Specifications

The Microsoft HoloLens 2, which is central to the implementation of this report’s implementation, represents a significant advancement in AR headset technology with specifications particularly suited to industrial environments. Figure 5 shows the Microsoft HoloLens 2 device.

Beyond the basic specifications presented in Table 1, the following sections provide detailed technical specifications and capabilities of the HoloLens 2 (*About HoloLens2 2024*):

- **Processing Power:** The Snapdragon 850 is a **System on a Chip (SoC)** that includes a Qualcomm Kryo 385 CPU, an Adreno 630 GPU, and a Snapdragon X20 LTE modem. It also includes a second-generation holographic processing unit and 4GB of LPDDR4x system DRAM. It supports Wi-Fi 802.11ac,



Figure 5: Microsoft HoloLens 2 mixed reality headset. Photo by Ana Cassia.

Bluetooth 5.0 and a storage of 64GB, and provides approximately 2-3 hours of active use, with hot-swappable batteries available for extended operations.

- **Display:** Utilizes see-through holographic waveguides for its optical system, producing a 2K resolution (2000 pixels per eye) with a 3:2 aspect ratio. The holographic display boasts a density of over 2.5 million radiants. The system's design is eye-based, meaning the screen is optimized for the 3D position of the user's eyes.
- **Sensor Array:** For head tracking, it utilizes 4 light cameras and 2 infrared cameras for eye tracking. Depth information is captured by a 1MP ToF depth sensor. An inertial measurement unit provides data from an accelerometer, gyroscope, and magnetometer. For imaging, the device features an 8MP camera capable of capturing still photos and recording video at 1080p resolution at 30 frames per second. Also, the device features a five-channel microphone for capturing audio input, and for audio output, it includes integrated speakers that support spatial sound.
- **Interaction Capabilities:** Supports direct manipulation of holograms with hand tracking, eye-tracking, and voice commands, as well as natural language with internet connectivity. Also offers 6DoF tracking, enabling positional control within a global-scale environment. It performs real-time spatial mapping,

generating a dynamic environment mesh, and seamlessly blending virtual holograms and videos with the user’s physical surroundings.

These specifications make the HoloLens 2 particularly suitable for industrial applications in the mineral industry, where workers require hands-free access to digital information in potentially challenging physical environments. The device’s untethered nature allows for freedom of movement throughout the factory floor, while sensor capabilities enable the alignment of [DT](#) with physical machinery.

2.5 CLOUD INFRASTRUCTURE

Cloud Platform provides services that support the technical requirements of the proposed [AR-DT](#) integration.

In this case, the [GCP](#) using Cloud Storage provides high-performance, scalable object storage for multimedia assets including [3D](#) models, instructional videos, and audio guides. The service’s global edge caching capabilities content to [AR](#) devices regardless of geographic location (Praveen Borra, 2024).

Cloud infrastructure empowers the proposed system with key capabilities, including centralized content management for training materials, [3D](#) models, and multimedia, enabling remote updates without altering the [AR](#) application. Furthermore, it facilitates real-time monitoring by processing and delivering sensor data from factory machinery to [DT](#) representations and [AR](#) visualizations.

2.6 PRIVACY IN AR ENVIRONMENTS

[AR](#) devices are constantly capturing information from the environment, which can include sensitive data such as faces, documents and other identifiable elements. This continuous collection exposes users to risks if such data is not managed properly. In contexts where multiple users interact, such as in training or industrial environments, there is an increased risk of exposure of private information. The overlap of digital data with the real environment can lead to the accidental visualization of confidential information (Abraham et al., 2024; Langfinger et al., 2017).

To reduce the risk of exposure, obfuscation techniques as Blurring, Masking and Pixelation can be used to protect sensitive data without completely compromising the user’s visual experience. As illustrated in Figure 6, these techniques include:

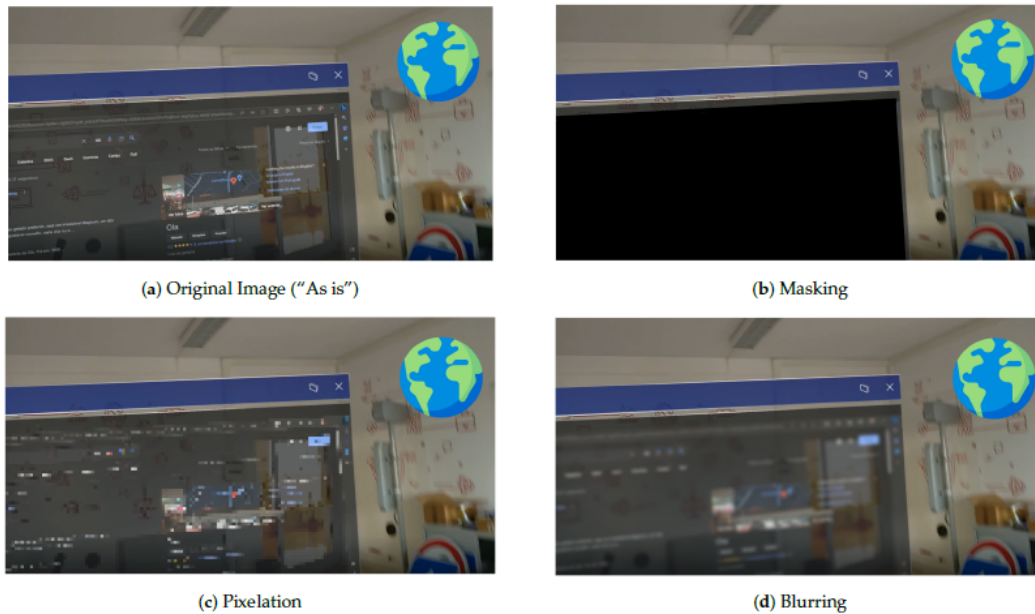


Figure 6: Privacy protection techniques (Cruz et al., 2025)

- **Masking:** This involves applying a solid colour mask to completely hide sensitive data (Enireddy et al., 2021).
- **Pixelation:** Replaces sensitive areas with aggregates blocks as pixels (Fan, 2018).
- **Blurring:** This consists of smoothing specific areas containing sensitive data (Neustaedter et al., 2006).

2.7 TECHNOLOGICAL VALIDATION

The technological context described in this chapter provides the foundation for understanding why this research project was initiated and its potential significance for the stone industry. The convergence of several technological trends has created a unique opportunity to address long-standing challenges in this sector:

- **Maturity of AR Hardware:** The evolution of AR headsets like the HoloLens 2 has reached a level of capability, reliability, and ergonomics suitable for industrial applications.
- **Standardization of Industrial IoT:** The widespread adoption of standards like OPC UA has simplified integrating digital systems with industrial machinery, reducing the technical barriers to implementing DT.

- **Cloud Infrastructure Economics:** The decreasing cost and increasing cloud computing capabilities have made data processing and storage accessible to industrial applications without prohibitive capital investment.
- **Development Tool Accessibility:** The maturation of tools like Unity and [MRTK](#) has reduced the specialized knowledge required to develop industrial [AR](#) applications, making implementation more feasible.

RELATED WORK

The manufacturing industry has shown great interest in [AR](#) and its possible uses. This section identifies and describes literature related to this research, covering several projects that focus on solutions for real-time process monitoring or instructional systems. This analysis aims to understand how to harness [AR](#)'s potential to improve manufacturing procedures regarding monitoring and personnel education.

In Vidal-Balea et al. (2020), the authors present the development and validation of an [AR](#) teaching system for use in education. The proposed system is based on the Microsoft HoloLens 2 headset and edge computing technology. The authors describe the design of the [AR](#) teaching system, which includes the development of [3D](#) models, the creation of [AR](#) content for educational content, and the integration of edge computing to enable real-time data processing and analysis. Also, the authors present a case study to validate the effectiveness of the [AR](#) teaching system. The results showed that a large number of students using [AR](#) devices at once would have an impact on how well the suggested system and application works. The proposals based on mmWave and 5G communication systems have been made in response to the prospective and challenging needs of capacity and latency of wireless communication. However, the lack of access to 5G networks to adopt these kinds of [AR](#)-based solutions, radio planning studies and modifications to the existing infrastructure (typically Wi-Fi) are the standard method. Figure 7 illustrates part of the proposed architecture.

Although this study demonstrates the use of [AR](#) in an educational context, which is directly applicable to student training, and was tested in a classroom environment with the target audience, it does not clearly specify how the testing was conducted, or whether any systems were used to measure usability or the effort required to use the system.

In Cai et al. (2020), authors present an approach for creating a [DT](#) of a reconfigurable [Additive Manufacturing \(AM\)](#) system using [AR](#). This research involves the use of [AR](#) markers to track the position and orientation of the various components of the [AM](#) system. This information is then used to create a [3D](#) model of the system, which can be displayed on an [AR](#) headset or mobile device. The paper also describes two case studies to demonstrate the capability of using [AR](#) technique to read an

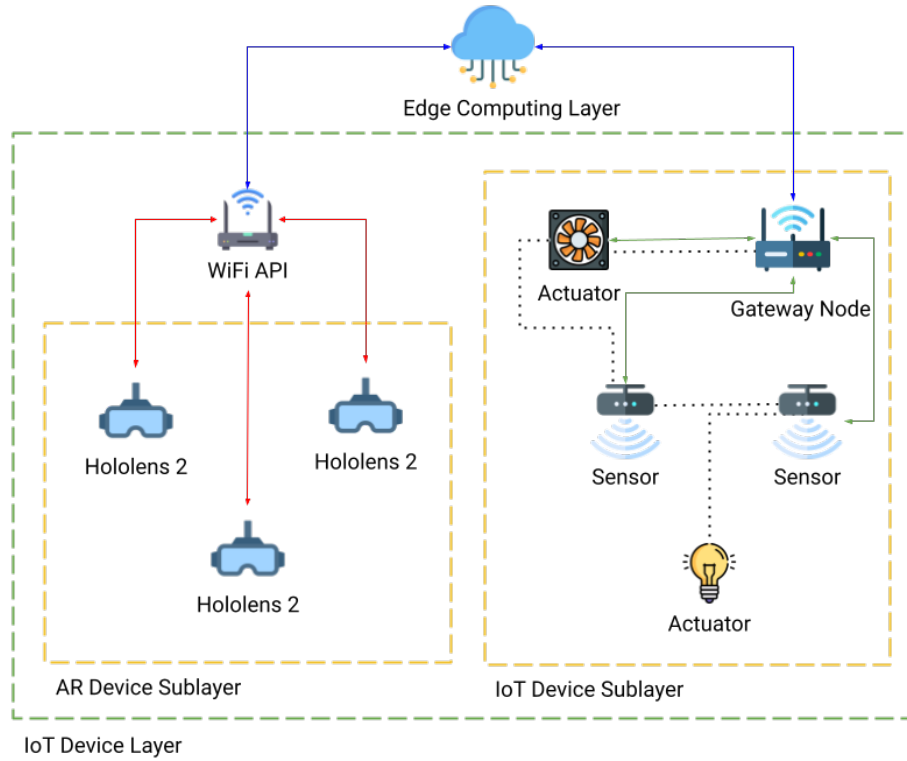


Figure 7: Proposed architecture for IoT device layer, adapted from Vidal-Balea et al., 2020.

existing physical layout for reconstruction in the **DT** and another to demonstrate the capability of using **AR** technique to guide as training the user to deploy a layout of the robotic arms generated in the **DT** based on simulation results. The results of the case study demonstrated that the developed methodology enables rapid retrieval of position information from the physical system layout into the **DT** and facilitates convenient deployment of a layout determined in the **DT** based on simulation and optimization into the physical system. However, there is inherent inaccuracy of the **AR** marker tracing due to various reasons like camera image distortion, marker misdetection, and unfavourable lighting condition. Nonetheless in practice, there will be more accurate methods for calibration of the actuators.

Limitations in **AR** marker tracking accuracy were noted, suggesting the need for more precise calibration methods in practical applications and potentially more comprehensive user-centred evaluations in future research. Moreover, while the authors demonstrated the system’s capability to synchronize physical and virtual domains through case studies, they did not conduct specific tests to evaluate user cognitive load or system usability.

In Zhu et al. (2019), the authors present a system for visualizing **DT** data in manufacturing using **AR**. The system is designed to provide real-time monitoring

and visualization of production data, allowing operators to quickly identify issues and optimize production processes, as can be seen in Figure 8. The authors used the HoloLens headset and the Unity game engine to develop the AR application. The paper describes the system architecture, which consists of three main components: the data acquisition and processing module, the DT module, and the AR visualization module. The data acquisition and processing module collects information from various sensors and machines on the factory floor, while the DT module creates a virtual representation of the production process. The AR visualization module then overlays the DT data onto the real-world environment, providing operators with a clear and intuitive view of the production process.

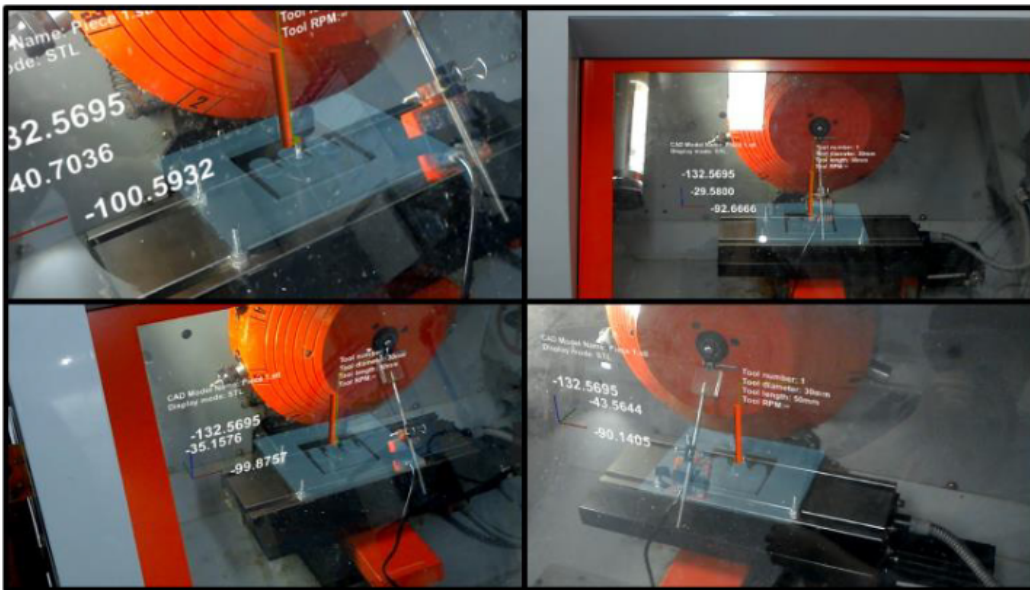


Figure 8: Example of a system for real-time monitoring, using HoloLens 2, obtained from Zhu et al., 2019.

Although the paper argues for the system's effectiveness in improving production and monitoring, it suggests the approach's viability and benefits reasons to validate the system's usability or operational benefits.

In S. Liu et al. (2021), the authors present a framework for integrating DT and AR technologies in manufacturing, highlighting the potential benefits of such integration, including improved efficiency, reduced downtime, and enhanced quality control. The authors also discuss the challenges and limitations of implementing these technologies in manufacturing, including issues related to data security, interoperability, and user acceptance. The method aims to improve the efficiency and accuracy of machining process monitoring by providing real-time visualization of the machining process

and enabling operators to interact with the [DT](#) through [AR](#) using gestures and voice commands.

While the authors present a thorough case study demonstrating the technical implementation and potential benefits of an [AR](#)-based [DT](#) monitoring system in manufacturing, they do not focus on the system's usability, cognitive load on operators or user experience.

In C. Liu et al. (2018), using open, unified, and platform-independent communication standards such as MTConnect and [OPC UA](#), the authors provide an approach for modelling [Machine Tool Digital Twins \(MTDT\)](#). Through two applications, the authors show the viability and benefits of the suggested approach, as can be seen in [Figure 9](#). The first application makes use of an MTConnect-capable [MTDT](#) and is a web-based machine tool status monitoring system. A web page is populated with real-time machining data, such as axis positions, power status, feed rate, and cutting forces. This enables users to remotely check on the machine tool's performance and learn more about the machine's health. The second application uses an [OPC UA](#)-enabled [MTDT](#) to see and simulate [AR](#)-assisted machining. Virtual [3D](#) models are imposed over actual machine tool and its surroundings using a wearable [HMD](#), such as Microsoft HoloLens. Users are given an intuitive grasp of the machining process through the visualization of real-time data from the [MTDT](#) in the [HMD](#), which also enables high-fidelity simulation. This data includes axis positions and machine tool status. Overall, by introducing a modelling technique for [MTDT](#) and showcasing its practical applications for machine tool status monitoring as well as [AR](#)-assisted visualization and simulation.

While the study effectively showcases the modelling technique for [MTDT](#) and its practical applications, it does not include usability testing, task load assessment, or user training and education as part of its scope.

In Rabah et al. (2018), the authors discuss how [AR](#) and [DT](#) technologies can be combined to advance manufacturing in the future, with a focus on predictive maintenance. The authors introduce the eRolling2 project, a study that intends to create a new technique for monitoring and detecting forces and failures in rolling bearings for higher-speed motors, is introduced by the authors. This case study was carried out as part of the project. The project focuses on creating a [DT](#) for a bench test that replicates the behaviour of the actual product and provides a proof-of-concept for preventative maintenance. The authors highlight the significance of [DT](#) and [AR](#) technology integration in the context of Industry 4.0, notably for predictive maintenance. They suggest a paradigm in which the

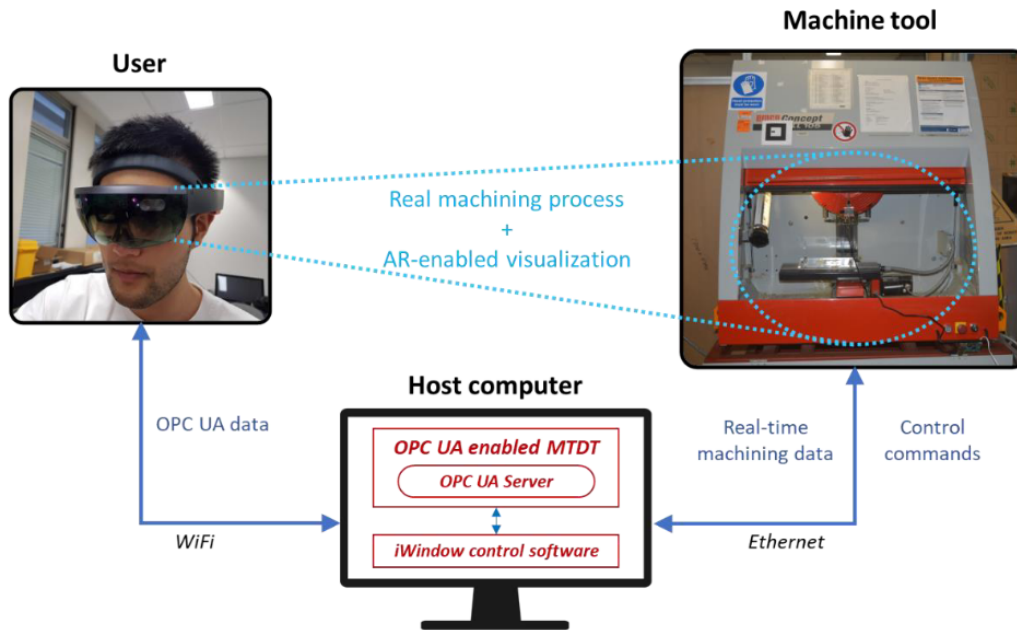


Figure 9: Integration between user, machine tool, and host computer, obtained from C. Liu et al., 2018.

supervisor utilizes the [DT](#) to monitor and assess the system's status, evaluate data, create maintenance intervention scenarios, and initiate the ensuing maintenance procedure. The operators are then given access to this information via [AR](#), enabling them to interact with the process's components and carry out maintenance chores. Finally, after the maintenance procedure is finished, a report is generated for the supervisor.

Although the study offers a promising framework, the authors point out that the [AR](#) application's robustness, autonomy, and usability still need to be assessed, a task they leave to tackle in future research.

In Rahman et al. (2022), the authors provide a comprehensive review of [AR](#) technology and its applications in digital manufacturing. The authors discuss the various types of [AR](#) Systems, including [HMD](#), smart glasses, mobile devices, and their features and limitations. The paper also presents a detailed overview of the different applications of [AR](#) in digital manufacturing, including product design, assembly, quality inspection, maintenance, and training. The authors highlight the benefits of using [AR](#) in these areas, such as improved accuracy and efficiency, reduced errors and costs, and enhanced worker safety and productivity. The authors also discuss the challenges and limitations of using [AR](#) in digital manufacturing, such that before this technology can genuinely benefit industrial applications, the most challenging issues need to be tackled in tracking accuracy, usability, latency, and human aspects.

However, they also identify several challenges and limitations. Usability remains a significant concern, particularly in designing user interfaces that are easy to navigate and interact with. Cognitive load is another challenge, as users often struggle to manage interactions between the virtual and real environments simultaneously, which can hinder performance. Social acceptance is impacted by privacy concerns, security issues, and the bulky, obtrusive nature of some AR devices. Human factors, such as ergonomics and environmental conditions, also play a crucial role in user comfort and effectiveness.

In Lhachemi et al. (2019), the authors provide a comprehensive review of the state-of-the-art research on the integration of AR, Cyber-Physical System (CPS), and feedback control in AM as can be seen in Figure 10. The authors discuss the potential benefits of using AR, CPS, and feedback control in AM, including improved process monitoring and control, enhanced quality, and productivity. The authors also review the current challenges and limitations in the integration of AR, CPS, and feedback control in AM and identify future research directions and opportunities in this area. The authors highlight the need for further research on real-time data processing and analysis and human-machine interaction in AR-based AM systems. Overall, the paper provides a valuable resource for researchers and practitioners interested in the application of AR, CPS, and feedback control in AM, and offers insights into the current state-of-the-art and future trends in this area.

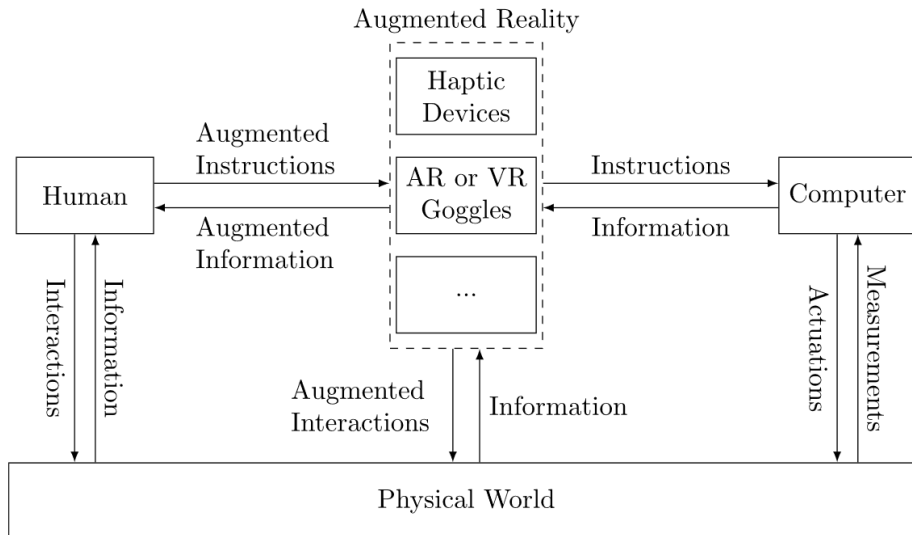


Figure 10: Augmented Reality (AR) system, obtained from Lhachemi et al., 2019.

However, the authors also review current challenges and limitations in the integration of AR, CPS, and feedback control in AM. Notably, while AR interfaces are more intuitive for manipulating 3D models, they face significant limitations

in industrial applications. They point out that existing [HMD](#)'s lack precision in mid-air gesture-based inputs, posing challenges for generating accurate [3D](#) models, especially for non-expert users. This imprecision is particularly problematic in industrial settings where accuracy is crucial. To address these issues, some researchers propose hybrid approaches, such as switching between classic [Computer-Aided Design \(CAD\)](#) interfaces (precise but less intuitive) and [AR](#) modes (intuitive but less precise) for [3D](#) model design.

In Schein and Rauschnabel (2023), the authors investigate the barriers to the adoption of [AR](#) technology in the manufacturing industry from the perspective of workers and managers. The study suggests that perceived usefulness and ease of use are significant predictors of workers' intention to use [AR](#) in manufacturing. The authors propose using established tools such as [NASA-TLX](#) for assessing cognitive load and the [SUS](#) for evaluating usability, alongside their own measures, as diagnostic instruments for companies considering [AR](#) implementation. These tools can help benchmark and assess workers' views on [AR](#), which is crucial in the early stages of adoption. The study also identifies several barriers to [AR](#) adoption, including data privacy concerns, technical difficulties, and the need for training. Interestingly, the research finds that workers with [AR](#) experience generally perceive lower barriers, suggesting that hands-on experience and proper training could facilitate adoption.

In Lotsaris et al. (2021), the authors present an [AR](#)-based framework designed to support human workers in flexible manufacturing environments. The framework uses [AR](#) technology to provide workers with real-time information and guidance, enabling them to perform complex tasks more efficiently and accurately. The developed application offers users handy tools to interact with the mobile platform, give direct instructions to the robot, and receive information about the robot's and the broader system's state, all through an [AR](#) headset. Communication between the headset and the robot is achieved through a Robotic Operating System based that interconnects the resources.

The proposed framework consists of three main components: an [AR](#) interface, a task management system, and a knowledge base. The [AR](#) interface provides workers with visual instructions and feedback, while the task management system assigns tasks to workers and monitors their progress. The knowledge base contains information about the manufacturing process and the various tasks involved.

The authors evaluated the proposed framework through a case study in a real-world manufacturing environment. The results from testing this [AR](#) tool with students from the University of Patras showed several benefits: a reduction in

programming time, fewer programming errors due to improved visualization, decreased idle time during errors, and increased operator confidence. Users rated their experience positively, though one user preferred the [Personal Computer \(PC\)](#) interface for robot programming. The main drawback identified was the ergonomics of the HoloLens headset, which caused discomfort during extended use. While the study highlights improvements in performance and usability, the methods used for evaluating these aspects are not explicitly detailed.

In Elbazi et al. (2022), the authors highlight the application of [DT](#) technology as an option for problems with production, maintenance, and energy usage. The four layers of the proposed architecture are cloud data, edge computing, physical, and data pre-processing. Together, these layers improve the mining equipment's performance. The case study of a stacker machine in an experimental open pit mine is the writers' main topic.

By simulating the stacker machine's automation and mechanism, the developed [DT](#) makes it possible to model crucial situations and optimize the machine's availability, dependability, and utilization. The stacker machine case study illustrates the practical outcomes and advantages of applying [DT](#) technology to maximize machine performance, particularly in the mining sector.

The article offers a thorough examination of the application of [DT](#) technology in the mining industry. Still, its scope does not extend to investigating the potential benefits of [AR](#) technology, examining cognitive load, or assessing user experience.

In Tkachuk et al. (2023), the authors present a range of methods for creating [AR](#)-based training materials and demonstrate their effectiveness in improving student engagement and understanding of complex mining processes. The authors show some approaches for developing [AR](#)-based training materials, including using videos and [AR](#) applications to visualize training materials and creating [Quick Response Code \(QR Code\)](#) or [AR](#) objects to link to instructional videos. The potential of [AR/VR](#) technologies to modernize mining education and provide a more immersive and interactive learning experience for students is also discussed. The authors also examine the development of [AR](#)-based training materials, the evaluation of their effectiveness in enhancing student learning outcomes, and the exploration of the potential of [AR/VR](#) technologies to transform the field of mining education.

Despite that, this study does not provide a precise [AR/VR](#) implementation, nor does it conduct a systematic evaluation of cognitive load, user experience, and usability of operators in real-world scenarios.

Table 2 presents a summary of selected projects related to AR in the context of manufacturing. These studies demonstrate the potential benefits of these technologies while also highlighting the need for further research and development to overcome the challenges and limitations associated with their implementation in real-world manufacturing environments. Moreover, the literature review indicates that no existing solution integrates all of the features intended for implementation in the mineral industry, thereby underscoring the significance of the proposed approach. This gap in the literature highlights the need for a comprehensive and integrated solution that addresses the complex challenges faced by the mineral industry. The proposed solution, which combines AR and DT to enable real-time monitoring, deliver educational content, and facilitate operational training, has the potential to transform the mineral industry.

These significant limitations will be addressed in this thesis, focusing on improving usability, reducing cognitive load, and enhancing the user experience of AR technologies in digital manufacturing.

Table 2: Summary of Related Work Projects.

Paper	Mineral Industry	Factory Floor	Monitoring	Educational	Training	Augmented Reality	Digital Twin
Vidal-Balea et al. (2020)			✓	✓		✓	
Cai et al. (2020)		✓			✓	✓	✓
Zhu et al. (2019)		✓	✓			✓	✓
S. Liu et al. (2021)		✓	✓			✓	✓
C. Liu et al. (2018)		✓	✓			✓	✓
Rabah et al. (2018)		✓	✓			✓	✓
Rahman et al. (2022)		✓	✓	✓	✓	✓	
Lhachemi et al. (2019)		✓	✓			✓	
Schein and Rauschnabel (2023)		✓	✓			✓	
Lotsaris et al. (2021)		✓	✓		✓	✓	
Elbazi et al. (2022)	✓		✓			✓	✓
Tkachuk et al. (2023)	✓		✓	✓	✓	✓	
This Project	✓	✓	✓	✓	✓	✓	✓

3.1 PRIVACY AND SECURITY CHALLENGES IN INDUSTRIAL AR APPLICATIONS

While the primary focus of this report lies in leveraging AR for real-time monitoring, educational content delivery, and operational training in the mineral industry, it is crucial to acknowledge the privacy and security challenges associated with AR systems, particularly in industrial settings. The immersive and interactive nature of AR, which often involves continuous environmental scanning and data sharing, introduces unique risks related to the protection of sensitive information, such as proprietary industrial processes and workers' privacy. This subsection reviews key studies that address these challenges and explores how their findings can inform the development of privacy-aware AR solutions for industrial applications, aligning with the objectives of this research.

Roesner et al. (2014) examine security and privacy challenges in AR systems, highlighting how sensitive information can inadvertently be displayed or recorded by AR devices. Their work is particularly relevant to industrial contexts, where equipment configurations, proprietary processes, and workers' activities may be captured and potentially exposed. The authors propose mechanisms such as access controls for data streams, obfuscation of sensitive elements, and user-consent protocols to mitigate these risks without compromising the AR experience. These techniques could be adapted for industrial AR applications, such as those proposed in this report, by ensuring that only authorized personnel can access specific data overlays or that sensitive areas of the factory floor are visually obscured in real-time.

Complementing this approach, Li et al. (2017) investigate the effectiveness of visual obfuscation techniques, such as blurring and pixelation, in protecting the privacy of individuals in images. Their findings indicate that while these techniques can obscure facial features, their effectiveness varies depending on the context and the observer's familiarity with the subjects. In an industrial setting, such as the mineral industry, similar methods could be employed to protect workers' identities or conceal proprietary equipment details in shared visual data. However, the study suggests that these techniques may not be entirely fail-safe, requiring a careful balance between privacy and the need for clear, interpretable visual information in operational contexts.

Oh et al. (2016) explore the limitations of facial obfuscation, demonstrating that person identification can still occur through body shapes, clothing, and postures, even when faces are obscured. This raises important considerations for industrial

AR applications, where workers may be identifiable through other visual cues, potentially compromising their privacy. The study underscores the need for more comprehensive privacy protection strategies that extend beyond facial concealment, particularly in environments where workers frequently interact with AR systems in close proximity.

Finally, Demiris et al. (2009) address privacy concerns in vision-based monitoring systems, which are analogous to AR systems due to their continuous capture of visual data. Their research highlights the tension between safety monitoring and privacy, proposing obfuscation techniques such as low-resolution imagery and selective masking of sensitive areas. These methods could be particularly useful in industrial AR applications, such as those developed in this report. For instance, in the mineral industry, areas containing proprietary processing techniques or sensitive machinery could be automatically obscured in the AR view, ensuring that only authorized personnel have access to detailed visual information.

While the aforementioned studies provide valuable insights into privacy and security in AR, it is notable that few have empirically evaluated the effectiveness of obfuscation techniques in AR-specific contexts, particularly through user surveys or field tests. This gap in the literature suggests an opportunity for future research to assess the performance of these techniques in real-world industrial environments, where factors such as lighting conditions, worker movement, and the complexity of visual data may influence their efficacy.

In the context of this report, although privacy and security are not the primary focus, acknowledging these challenges is essential for developing a holistic AR solution that is both effective and acceptable to stakeholders in the mineral industry. By incorporating privacy-aware design principles, such as selective data visualization and user-controlled access to sensitive information, the proposed AR system can better serve the needs of the mineral industry while safeguarding proprietary and personal data. Thus, this discussion enriches the present chapter by addressing a critical yet often overlooked aspect of industrial AR applications, demonstrating a comprehensive understanding of the challenges associated with their implementation.

3.2 PRELIMINARY WORK

Before the developing and integration of this AR System and DT to HoloLens 2, an initial prototype was developed as a mobile application for Android, using Unity as a library, and the Moverio BT-40s (see Figure 11) AR glasses to enhance the

AR experience. This preliminary work laid the foundation for the current system, focusing on real-time machine monitoring and educational content support for factory workers.



Figure 11: Moverio BT-40S AR glasses. Photo by Ana Cassia.

A key outcome of this phase was a published conference paper, “Augmented Reality and Digital Twin for Mineral Industry” (Francisco et al., 2023), which detailed the initial implementation of a mobile-based AR solution for the mineral industry. This solution enabled machine operators to scan a QR Code using an Android device, which then triggered a Unity scene displaying machine parameters. The system provided real-time sensor data, accessed via the OPC UA protocol, and also included an educational module with text, video, and audio content designed to support worker training.

The application, designed for mining industry workers, underwent factory floor testing with a limited initial sample, providing valuable, targeted feedback due to the direct interaction with the intended users in their operational environment.

The development process faced several challenges, including the integration of Unity into the Android application, ensuring communication between the mobile application and the backend infrastructure, and optimizing the AR interface for industrial use. Despite these obstacles, this prototype already demonstrated the feasibility of applying AR and DT in an industrial setting, paving the way for further enhancements in the HoloLens 2 implementation.

The transition from a mobile-based solution to an AR headset provided significant improvements, such as hands-free interaction, better spatial awareness, and new

module to immersive training experiences. The lessons learned from the Android development phase directly influenced the design decisions in the HoloLens 2 implementation, particularly in UI/UX refinement, data visualization techniques, and the expansion of interactive training capabilities.

METHODOLOGY

The strategy used to create and assess the integrated system between **AR** and **DT** technologies is described in this chapter. The methodology consists of eight stages: participation in the state of the art, requirements definition, system design, application architecture definition, system development, module integration, testing, and this thesis.

The first phase began with an in-depth study of the needs of the mineral industry sector, focusing on identifying functional and non-functional requirements that would guide the system's development. This involved a comprehensive review of scientific literature related to **AR** technologies, **DTs**, and their applications within the minerals industry. The Android application developed and the previous study also directly influenced the requirements for the development of this new system. Additionally, the study included an exploration of the technical capabilities of the HoloLens 2, evaluating its potential for delivering immersive **AR** experiences.

Following this, the requirements definition stage aimed to transform the findings from the previous study of related work into clear and specific objectives for the system. These objectives were organized into three main functional areas:

- **Monitoring:** Using **OPC UA** for seamless integration with existing industrial systems, ensuring real-time data acquisition and visualization;
- **Educational content:** Through multimedia content, including videos, audio guides, and text instructions to provide contextual learning experiences;
- **Training:** Leveraging interactive **3D** objects to simulate technical operations, enabling users to practice procedures in a safe and controlled **AR** environment.

The third stage, system design, involved translating the requirements into a conceptual model that would form the blueprint for the system. The design process focused on an intuitive system, and oriented for industrial environments. Use-case scenarios were created to map out the interactions between operators and the system, highlighting the flow of information and user actions. Mockups and conceptual diagrams were developed to visualize the user interface and the system's overall functionality.

In the fourth stage, application architecture is defined to support the integration of [AR](#) and [DT](#) components. The architecture was divided into three layers: Factory Floor, [AR](#) System, and Cloud Platform. The Factory Floor layer is responsible for collecting real-time data from industrial machines using [OPC UA](#) servers. This data is then processed and transmitted to the [AR](#) System layer, which utilizes the HoloLens 2 to present contextual information, interactive training simulations, and immersive educational content to the operators. The Cloud Platform layer serves as the central repository for multimedia content, [3D](#) models, and training resources, ensuring continuous updates and accessibility anywhere.

The fifth stage, system development, was carried out using the Unity platform with the integration of the [MRTK 3](#), which optimized the [AR](#) experience for the HoloLens 2. The development process focuses on implementing monitoring, training, and educational content functionalities. The Monitoring module was designed to capture real-time data from [OPC UA](#) servers and present it contextually in the [AR](#) interface. The Educational module integrated multimedia content, including videos, audio, and text, to provide comprehensive learning experiences. The Training module allowed users to interact with [3D](#) objects, simulating technical operations to enhance practical skills.

Once the modules were developed, the integration of the modules phase began. This stage aimed to combine the Monitoring, Educational content, and Training modules into a unified system. [Application Programming Interface \(API\)](#) were created to facilitate communication between the [AR](#) System and the Cloud Platform, ensuring real-time content delivery and data synchronization. Integration testing was conducted to validate the modules' interoperability and ensure consistent data representation within the [AR](#) environment.

The seventh stage, testing, focused on evaluating the system's usability, performance, and user effort rate. Tests were conducted in a controlled environment to assess the solution's efficiency and intuitiveness for industrial operators. Usability testing measured task completion rates, cognitive workload, and user satisfaction using metrics such as the [SUS](#) and [NASA-TLX](#). Feedback from participants was gathered and analysed to identify usability issues and opportunities for improvement.

The final stage, production of this thesis, involved documenting the research and development process, from initial conception to final implementation and evaluation. Each section was written to provide a comprehensive understanding of the project's context, objectives, and outcomes.

4.1 PROPOSED SOLUTION

This study proposes a solution supported by a system that enables the extraction and visualization of sensory data from stone industry machines, making it accessible to factory employees on the factory floor in real-time. Our goal is to create a user-friendly platform that not only facilitates the visualization of sensory data but also provides instructional content to enhance the learning curve of factory employees. This includes multimedia content such as videos, text, and audio, as well as interactive, hands-on instructional operations using 3D models to teach employees how to operate the machines. By providing quick and convenient access to relevant information, the aim is to empower factory employees to make informed decisions and improve overall factory efficiency.

The architecture of the developed system is presented in Figure 12. This architecture offers a comprehensive understanding of the system as a whole by illustrating the primary components. As said before, the architecture enables the extraction of sensory data from the monitored machines and makes it accessible to users on the factory floor. The architecture can be divided into three parts: Factory Floor, AR System, and the Cloud Platform. The router enables communication between the factory floor and the AR System, as well as between the AR System and the Cloud Platform via the internet, which acts as a communication bridge.

Factory floor encompasses the physical components that reside on the factory floor. These include machines, employees, and various sensors. Each machine communicates with an OPC UA server that is responsible for providing real-time data on the machine's operational state. The OPC UA server functions as an address space with nodes representing the machine's various sensors and controls. This is also where the AR System is placed, using a AR headset that enables them to interact with the system.

The employees interact with the AR system and access relevant real-time information about the machines and production processes. The AR headsets are equipped with cameras, microphones, and sensors that allow employees to identify the goal machine. The AR System provides employees with step-by-step guidance, enabling them to perform tasks more efficiently and accurately. The AR allows workers to access information quickly and conveniently with hands-free. This information can be data from machine sensors, such as training or educational content, that allows an increase in the learning curve of factory employees (Chiang et al., 2022).

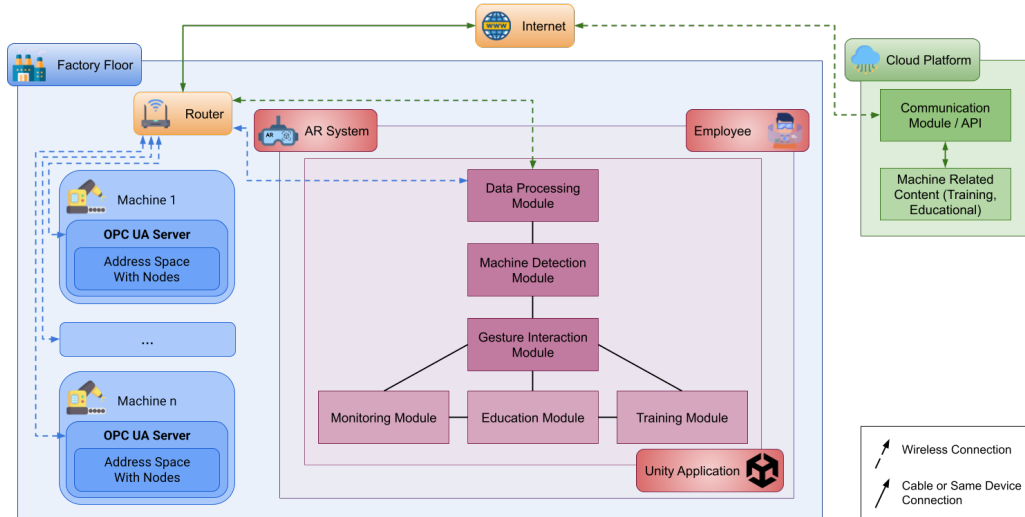


Figure 12: General architecture of the proposed system. Consist in a Cloud Platform, a Factory Floor, and an AR System.

The architecture incorporates a Cloud Platform, which is designed to store and manage information from various sources, including 3D models, videos, texts, and audio. It provides a centralized location for data access and management. It also hosts a web application with a user-friendly interface to oversee and coordinate the module responsible for displaying AR data.

The following sections will describe in detail the three main parts of the modular system architecture.

4.2 CLOUD PLATFORM

The cloud platform serves as the central repository and management system for machine-related content and handles the communication with the AR System. It ensures that the data is up-to-date and accessible to users through the following modules.

Communication Module/API: This module is responsible for managing the communication between the AR System and the Cloud Platform. It ensures that the information related to the machines available in Machine Related Content is reliably transmitted through the router, keeping the data up-to-date and accessible to users.

Machine Related Content: This module stores various types of content related to the machines, such as training materials and educational resources. This content

is configured via a web application, making it easy to update and manage. Once configured, this content is delivered to the AR System through the previous module: Communication Module/API, ensuring that employees have access to the most current and relevant information for training and educational purposes.

4.3 FACTORY FLOOR

The Factory Floor is the physical environment where machines and users operate. Each machine is equipped with an OPC UA server that facilitates standardized communication and data exchange:

The Factory Floor is equipped with multiple machines, each integrated with an OPC UA server. These OPC UA servers provide a standardized communication interface for the machines, allowing efficient data exchange and monitoring. Each machine's OPC UA server contains an address space with nodes representing various data points and parameters of the machine. This setup facilitates seamless integration with the AR System, enabling real-time monitoring and interaction with the machines on the factory floor.

The router acts as a central hub, managing the communication between the machines and AR System, and the Cloud Platform and the AR System, ensuring secure and reliable data transmission.

4.4 AR SYSTEM

The AR System provides an interactive interface for employees to monitor, interact with, and learn about the machines on the factory floor. It integrates key modules to enhance the user experience:

Data Processing Module: This module is responsible for collecting and analysing data from the factory machines via the OPC UA servers (indicated by the blue arrow) and from the cloud platform (indicated by the green arrow). It performs data cleaning, filtering, and transformation operations to convert the raw data into a usable format for further analysis and visualization by other modules within the AR System.

Machine Detection Module: This module is responsible for detecting and identifying the machines in the factory that are being monitored by the system.

Gesture Interaction Module: This module enables users to interact with the AR System using hand gestures, allowing users to control the system and access information without needing physical input devices.

Monitoring Visualization Module: This module is responsible for visualizing the real-time monitoring data collected from the machines in the factory. It provides a text representation of the data to help users quickly understand the status of the machines and identify any potential issues.

Education Visualization Module: This module provides visual content, such as videos, images, and text-based manuals, to support employee learning and development. It offers a library of multimedia content that can be accessed, allowing employees to self-pace their learning and refer back to materials or manuals as needed.

Training Module: This module provides factory employees immersive and interactive training experiences. It leverages AR technology to overlay training content, 3D models, and animations onto real-world machines and equipment. This allows employees to learn in a more engaging and hands-on way, aiming to improve knowledge retention and reduce training time.

The AR can be divided into three main scenes: Monitoring, Education, and Training. When data is sent to the AR scene, it is processed by the Data Processing module within the application. This module handles the data, applies business logic, and prepares it for future use. The AR project receives input or instructions from the web app through the integration and responds accordingly. This includes updating object states, triggering events, monitoring machines, and providing machine-related information.

The AR System incorporates functionality such as the Machines Identifier (ID) scanning Module, responsible for identifying QR Code associated with specific machines on the factory floor. This enables differentiation between multiple machines present in the factory environment.

Monitoring, Education, and Training modules will be further explained in Section 5. In summary, the objective is to allow workers to access real-time machine data in the AR monitoring module. In the education visualization module, workers can access video, text, and audio content while being able to view the machine and even operate it simultaneously. The training module allows direct interaction with the machines using 3D models; this way, daily operations can be done by viewing these contents without having to have a more experienced employee always around to teach new employees.

Overall, this architecture enables seamless interaction between the [AR System](#), leveraging the strengths of both platforms to provide a cohesive and immersive user experience.

Several alternatives were considered in evaluating various SDKs, applications, or frameworks capable of delivering functionalities similar to this project's requirements. For instance, Dynamic 365 Guide offers a robust, albeit paid, training system. Other platforms, such as Vuforia, Azure Custom Vision, and ARFoundation, were also examined, mainly because they provide capabilities for configuring parameters and come with a broad range of features. Although preliminary tests indicated that these solutions could be effectively applied within the mineral industry, the cost associated with licensing and integration presented a significant limitation.

In contrast, the solution developed in this project avoids these recurring expenses by implementing a custom, internal approach. This not only reduces financial overhead but also enhances flexibility in adapting the system to specific project needs.

The system developed for this project plays a crucial role in providing real-time data from the machines on the factory floor. It goes beyond offering training resources by allowing workers to access information specific to each machine quickly. To achieve this, the application comprises three modules: Monitoring, Education, and Training, each with detailed functionalities described below.

To identify the machines, the solution proposes the use of [QR Code](#). Although alternative technologies like [Near Field Communication \(NFC\)](#) may be taken into consideration (*Best alternatives to QR Code 2017*), [QR Code](#) were selected because of their ease of use and device compatibility. By utilizing [QR Code](#), the application only requires the camera on the user's phone, and in this case, the camera from HoloLens 2, avoiding the limitation of relying on devices with [NFC](#) technology.

Employees can use [AR](#) glasses to access virtual data related to each machine while operating the machines normally and keeping a clear view of the surrounding actual world. This implementation ensures there are no obstacles in the operator's [FoV](#).

Figure 13 illustrates the workflow of the [QR Code](#) reading functionality, as implemented in the HoloLens.

When the application is launched, the user must grant permission to access the device's camera. Without this permission, the application will be unable to function.

Once permission is granted, the next step is to scan a [QR Code](#). This [QR Code](#) is crucial as it identifies the specific machine or environment where the [AR](#) services will be provided. It serves as a unique identifier, ensuring the application interacts with the correct machine or setup. If a valid [QR Code](#) is not read, the process will not proceed.

After the [QR Code](#) is validated, the application provides the core [AR](#) services, which include Monitoring, Education, and Training. The user can switch between these available services as needed. Once the user has completed their tasks or wishes to switch to a different machine, the system will either adjust to the new machine or conclude the session.

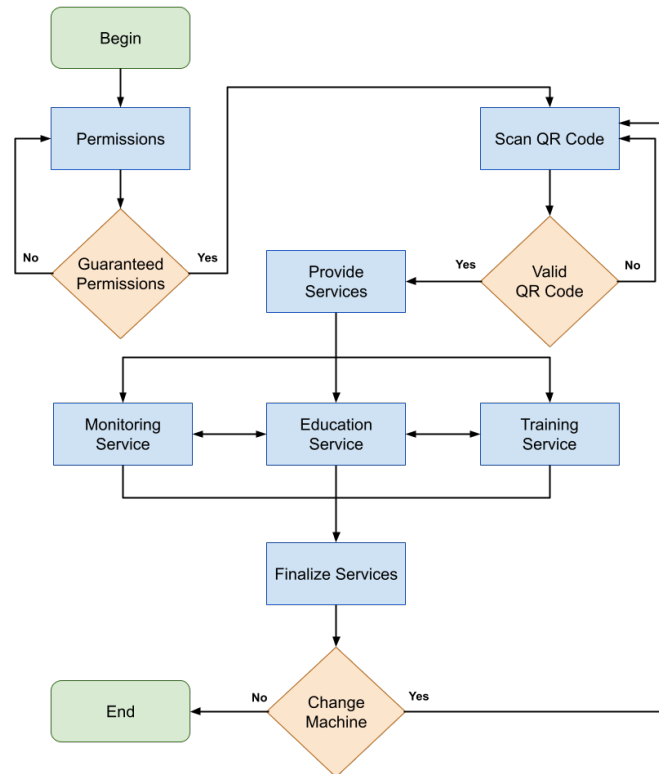


Figure 13: Workflow diagram to the HoloLens implementation for the QR Code reading functionality of the AR system.

To interact with the virtual components, it can be the distance pointing to the object with the hand ray, then air tap to select the object; if it is necessary to move the object, you can perform the air tap and hold, then move to the specified location and release.

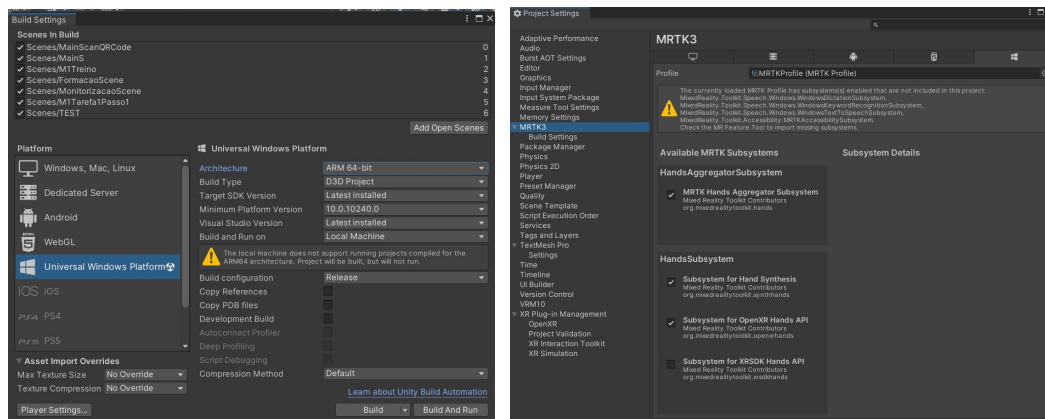
5.1 SYSTEM SETUP

To ensure that objects within the application are graspable, each must include both a collider component native from Unity and the Object Manipulator(Script) provided by [MRTK](#). Specifically, existing [MRTK](#) prefabs, which were incorporated into the application, inherently possessed these components, thereby obviating the need for manual configuration of their manipulability.

This project was developed within the Unity game engine, explicitly targeting the [Universal Windows Platform \(UWP\)](#) on the ARM 64-bit architecture to ensure native compatibility with the Microsoft HoloLens 2 hardware. A [Direct3D \(D3D\)](#) project build type was employed, leveraging the most current [SDKs](#) available at the

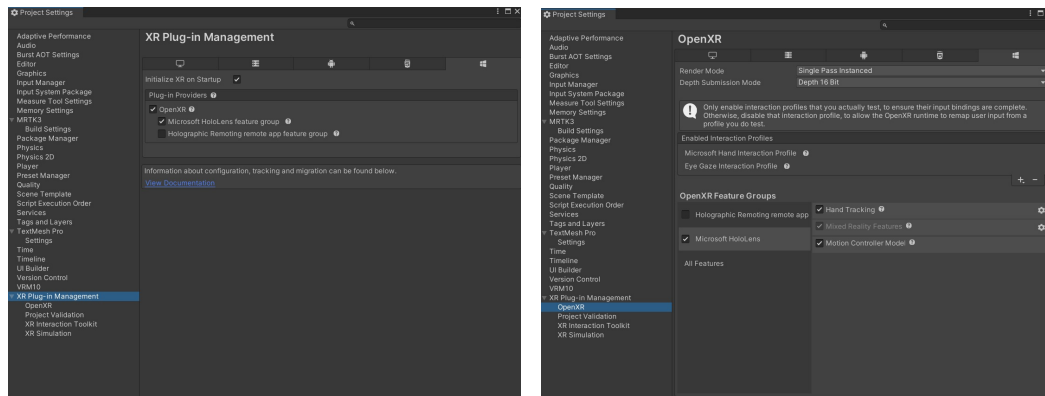
time of development. The minimum platform version required was set to 10.0.10240.0, and development was conducted using Visual Studio 2022.

To facilitate seamless integration of **Extended Reality (XR)** functionalities, the **XR Plugin Management** system was initialized at project startup with the **OpenXR** plugin and the **Microsoft HoloLens Feature Group** enabled. Within the **OpenXR** settings, the **Microsoft Hand Interaction Profile** and the **Eye Gaze Interaction Profile** were activated, enabling robust and intuitive user interaction within the **HoloLens 2** environment. The configuration of these Unity project settings is illustrated in **Figure 14**.



(a) Build Setting

(b) Project Settings MRTK



(c) Project Settings XR Plug-in

(d) Project Settings OpenXR

Figure 14: Unity Project Configuration Settings.

5.2 AR MONITORIZATION

One of the core functionalities of our **AR System** is real-time machine monitoring, empowering operators to swiftly identify performance anomalies and take corrective

actions (Tatić and Tešić, 2017). This section provides an examination of the implementation specifics of this feature, outlining the integration with sensor data and the AR interface design for data visualization. The AR interface design for data visualization is illustrated in Figure 15, which shows a scene of our AR monitoring.

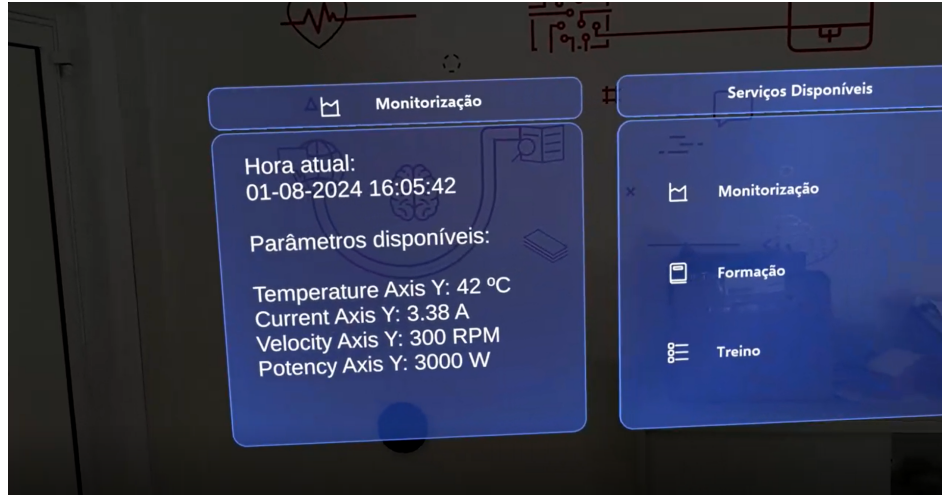


Figure 15: Scene AR Monitoring: Using HoloLens 2 to monitor machine workers can access important parameters of each machine, such as temperature, potency, and more relevant parameters.

The real-time aspect hinges on the system's ability to seamlessly connect with the sensor network of the machines under observation. This typically involves leveraging [Industrial Internet of Things \(IIoT\)](#) protocols for data acquisition. Standard options include [Message Queuing Telemetry Transport \(MQTT\)](#) for lightweight messaging and [OPC UA](#) for secure and reliable data exchange (Rocha et al., 2019).

[OPC UA](#) is particularly well-suited for industrial applications due to its platform independence, security, and extensibility. It provides a standardized framework for data exchange between different industrial devices and systems, making it an ideal choice for AR Systems that need to communicate with a diverse range of machinery (Kim and Sung, 2017). The AR interface serves as the bridge between the raw sensor data and the operator's perception. One of the key features of our AR System is the ability to monitor machines in real-time. This allows operators to quickly identify any issues or anomalies in the machine's performance and take appropriate action (He et al., 2021).

The data visualized through the AR interface could encompass various parameters critical for machine health. These may include temperature, pressure, vibration levels, and others. The AR System can help operators maintain optimal machine performance and prevent potential breakdowns by presenting these parameters in a real-time, interactive format. Not all sensor data is equally crucial for monitoring

purposes. The [AR](#) interface is focused on presenting the most critical parameters for each machine; this ensures operators are not overloaded with information and can focus on the most relevant data points.

The system correctly identifies the specific machines being monitored to ensure accurate and reliable monitoring. This involves configuring the system to recognize the machine's unique identifiers, such as [QR Code](#).

In the Android application, developed using Unity as a library, a custom [OPC UA](#) connectivity solution was implemented. To mitigate the financial burden associated with the 250€ commercial package, [OPCUA4Unity](#)¹, available on the Unity Asset Store, this custom solution uses an open-source library, [UA-.NETStandard](#)², to integrate [OPC UA](#) functionality directly within the application.

The process begins by processing the [JavaScript Object Notation \(JSON\)](#) response obtained from the server. Initially, the raw [JSON](#) string is reformatted into a valid [JSON](#) object and then deserialized into a structured C# object. During this stage, we create a dictionary that maps each unique nodeID to its corresponding content details, such as the updated value, unit of measure, content type, and description. This dictionary forms the basis for our subsequent data monitoring.

The following code excerpt [Listing 1](#) demonstrates the method that handles the [JSON](#) response. It converts the received string into a valid [JSON](#) object, deserializes it, and populates the dictionary. Additionally, it starts a new thread to initiate the [OPC UA](#) connectivity process.

¹ <https://assetstore.unity.com/packages/tools/utilities/opcua4unity-143980>

² <https://github.com/OPCFoundation/UA-.NETStandard>

Listing 1: Function 'ShowRecebido' processing JSON from a request and initiating OPC UA data handling.

```

1 void ShowRecebido(string stringRecebidaRequest)
2 {
3     // Format the received JSON string into a valid JSON object
4     string stringRecebida = string.Concat("{\"machines\":",
5     ↪ stringRecebidaRequest, "}");
6     machines = JsonUtility.FromJson<RootObject>(stringRecebida);
7
8     // Populate the dictionary with content details keyed by nodeId
9     if (machines != null && machines.machines != null &&
10    ↪ machines.machines.conteudoTextoDtos != null)
11     {
12         foreach (var conteudoTextoDto in machines.machines.conteudoTextoDtos)
13         {
14             nodeIdDictionary[conteudoTextoDto.nodeId] = conteudoTextoDto;
15         }
16     }
17
18     // Start a new thread to handle OPC UA connectivity and subscriptions
19     Thread thread = new Thread(new ThreadStart(mythread1));
20     thread.Start();
21 }

```

Following the data acquisition, the system sets up an **OPC UA** subscription. For each nodeID in the dictionary, a monitored item is created so that any change in data triggers a notification event. When such an event occurs, the corresponding entry in the dictionary is updated with the new value. The update method continuously prints the dictionary's contents to the console, enabling ongoing debugging and monitoring of the system state. The following code segment Listing 2 illustrates how the **OPC UA** subscription is configured and how the notification callback updates the data:

Listing 2: OPC UA client thread establishing connection, subscribing to node changes, and processing notifications.

```

1 void mythread1()
2 {
3     // Create OPC UA client application configuration
4     var config = new ApplicationConfiguration()
5     {
6         ApplicationName = "OPCClient",
7         ApplicationUri = Utils.Format(@"urn:{0}:ClientOPCUA", "localhost"),
8         ApplicationType = ApplicationType.Client,
9         TransportConfigurations = new TransportConfigurationCollection(),
10        TransportQuotas = new TransportQuotas { OperationTimeout = 15000 },
11        ClientConfiguration = new ClientConfiguration { DefaultSessionTimeout =
12        ↪ 60000 },
13        TraceConfiguration = new TraceConfiguration()
14    };
15
16    var application = new ApplicationInstance

```

```

16     {
17         ApplicationName = "OPCClient",
18         ApplicationType = ApplicationType.Client,
19         ApplicationConfiguration = config
20     };
21
22     var selectedEndpoint =
23     ↪ CoreClientUtils.SelectEndpoint("opc.tcp://127.0.0.1:4840", useSecurity:
24     ↪ false);
25
26     using (var session = Session.Create(config,
27         new ConfiguredEndpoint(null, selectedEndpoint,
28         ↪ EndpointConfiguration.Create(config)),
29         false, "", 60000, null, null).GetAwaiter().GetResult())
30     {
31         // Create a subscription to monitor node changes
32         var subscription = new Subscription(session.DefaultSubscription) { };
33
34         var list = new List<MonitoredItem>();
35
36         // Create monitored items for each nodeID in the dictionary
37         foreach (var kvp in nodeIdDictionary)
38         {
39             list.Add(new MonitoredItem(subscription.DefaultItem)
40             {
41                 DisplayName = kvp.Key,
42                 StartNodeId = kvp.Key
43             });
44         }
45         // Assign the OnNotification callback to each monitored item
46         list.ForEach(item => item.Notification += (monitoredItem, e) =>
47         ↪ OnNotification(monitoredItem, e, nodeIdDictionary));
48         subscription.AddItem(list);
49
50         session.AddSubscription(subscription);
51         subscription.Create();
52
53         // Keep the subscription active
54         while (true)
55         {
56
57         }
58     }
59
60     static void OnNotification(MonitoredItem item,
61     ↪ MonitoredItemNotificationEventArgs e, Dictionary<string, ConteudoTextoSdtos>
62     ↪ nodeIdDictionary)
63     {
64         foreach (var value in item.DequeueValues())
65         {
66             if (float.TryParse(value.Value.ToString(), out float parsedValue))
67             {
68                 float roundedValue = Mathf.Round(parsedValue * 100) / 100;

```

```

64         string valueString = roundedValue.ToString("F2");
65
66         if (nodeIdDictionary.ContainsKey(item.DisplayName))
67         {
68             nodeIdDictionary[item.DisplayName].valor = valueString;
69         }
70     }
71     else
72     {
73         if (nodeIdDictionary.ContainsKey(item.DisplayName))
74         {
75             nodeIdDictionary[item.DisplayName].valor =
76                 ↪ value.Value.ToString();
77         }
78     }
79 }

```

The custom [OPC UA](#) connectivity solution was implemented in the Android application using Unity as a Library to address specific integration requirements with a collaborative project. For the HoloLens 2 development, a more streamlined, independent approach was adopted. The project's primary objective drove this decision: to serve as a proof-of-concept, validating the application's core functionality within the [AR](#) environment. The focus was on demonstrating the feasibility of the application's core mechanisms, allowing for more direct validation when using HoloLens 2.

5.3 AR EDUCATION

In addition to its monitoring capabilities, the [AR](#) System empowers operators with access to a rich repository of multimedia training materials directly linked to the machines they interact with. This content, encompassing text, videos, audio resources, and a range of multimedia, empowers operators to deepen their understanding of the machines, troubleshoot issues efficiently, and confidently perform maintenance tasks (Simón et al., 2014).

In Figure 16, we illustrate an example of audio content in our [AR](#) System, showing how operators can access audio clip content. Detailed audio controls, such as pause, play, and rewind functions, enable audio management. In Figure 17, we demonstrate how text content can be utilized in our [AR](#) System, enabling operators to access critical machine information, such as maintenance procedures and troubleshooting guides, through clear and easily readable manuals. In Figure 18, we present an

example of video content in our AR System, illustrating how operators can access video feeds of the machine in operation. Similar to the audio content, the video content includes controls for pause, play, and rewind, enabling operators to manage the video.

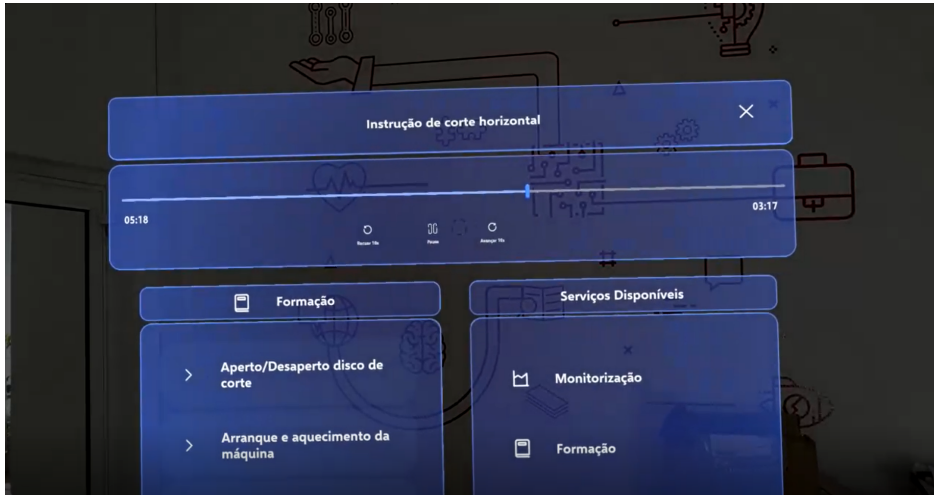


Figure 16: Scene AR Education Audio Content: Using HoloLens 2 works can play, pause, forward, or rewind audio content for educational purposes.

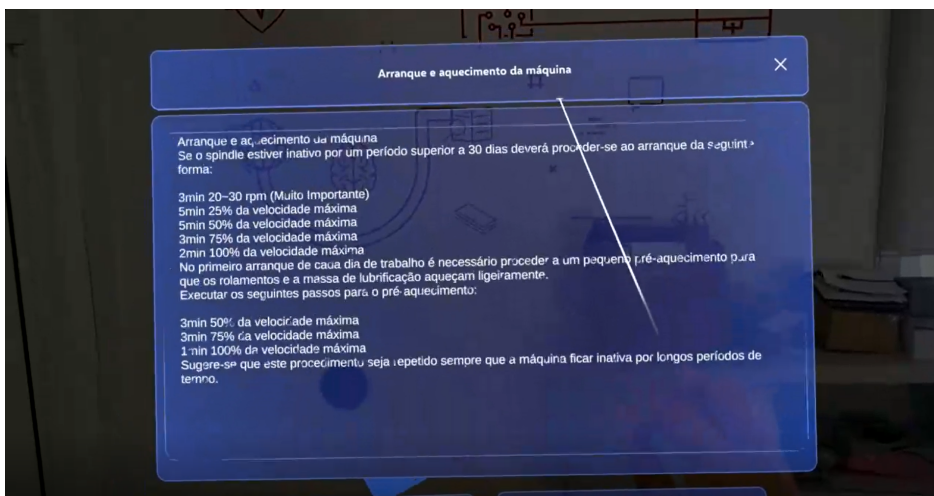


Figure 17: Scene AR Education Text Content: Displaying Textual Information with HoloLens 2. This feature enables users to access and interact with text-based content and access manuals and information about the machine.

To implement the AR education functionality, the system was integrated with a database of multimedia content related to the machines being monitored. This content is organized by machine type and model, making it easy for operators to find the needed resources. The content can be accessed directly from the AR interface, allowing operators to view videos, listen to audio recordings, and read text resources without having to leave the AR environment.

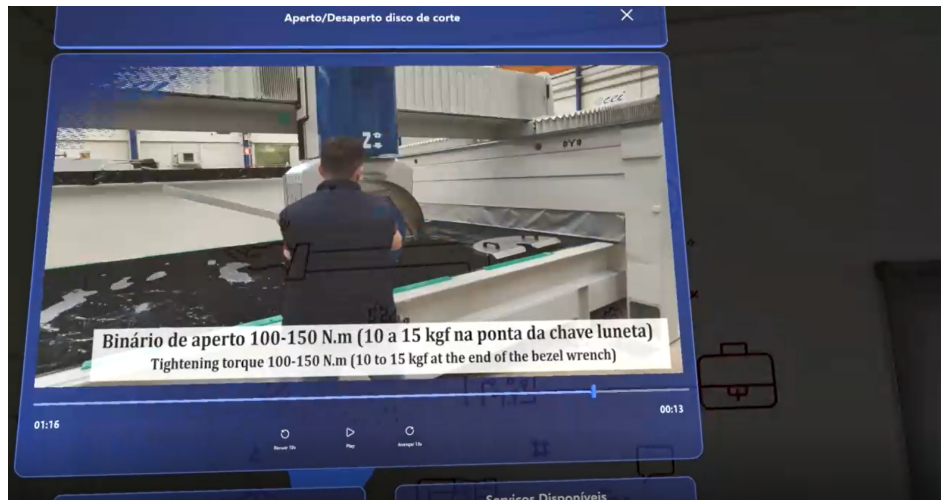


Figure 18: Scene AR Education Video Content: Enhancing Learning with HoloLens 2. Users can engage with video content in a more immersive and interactive way, enhancing their educational experience. Works can play, pause, forward, or rewind video content for educational purposes.

Video content could encompass machine operation demonstrations, maintenance procedures, and safety instructions. Text content could provide detailed descriptions, such as the manual and troubleshooting tips. Audio content could offer voice instructions, warnings, and explanations. By presenting this information in a multimodal, interactive format, the AR System can cater to different learning styles and enhance the overall user experience.

The AR educational functionality of the app provides operators with a powerful tool for learning about the machines, troubleshooting issues, and performing maintenance tasks. By providing easy access to multimedia education content directly from the AR interface, the app helps operators work more efficiently and effectively.

5.4 AR TRAINING

The AR Training feature of our AR System is a tool that leverages the capabilities of AR Monitorization and AR Education to provide operators with immersive, hands-on training experiences. Using AR in training can reduce the risks and expenses related to using conventional training techniques. For example, it dispenses with the necessity for actual training tools and facilities and enables operators to practice techniques and procedures in a controlled environment. The AR interface design for training is illustrated in Figure 19, which shows a scene of our AR training.



Figure 19: Scene AR Training: Hands-on using HoloLens 2, where operators can practice and develop their skills in an immersive environment.

Training simulations could encompass various scenarios, from routine machine operation to complex troubleshooting and maintenance tasks. By presenting these scenarios in an immersive, interactive format, the AR System can provide operators with hands-on training experiences that closely mirror real-world situations. This can significantly enhance their skills and confidence in operating and maintaining the machines.

In terms of implementation, the first step is to create 3D models of the machines, tools, and components that will be used in the training simulations. These models can be downloaded from the web or created using 3D modeling software or by scanning physical objects with a 3D scanner.

Once the 3D models have been created, they can be imported into the AR System in runtime and used to create the training simulations. The models can be easily updated, or new ones can be inserted from the cloud, ensuring that the data is accessible from anywhere and always up to date. This allows training to be configured directly within the web application, enhancing flexibility and efficiency.

The system was designed to load objects in multiple formats, such as OBJ, FBX, and GLTF. Although the Trilib³ package could seamlessly handle various formats, its cost necessitated a more flexible and cost-effective approach. In our proof-of-concept, we opted for a local storage solution where, for instance, only GLTF files are currently imported at runtime.

³ <https://assetstore.unity.com/packages/tools/modeling/trilib-2-model-loading-package-157548>

An initial strategy using `System.IO.File.WriteAllBytes` to save files in the `Assets/Resources` folder on the headset resulted in no visible output—subsequent attempts to save files to a path generated via `Path.Combine(Application.persistentDataPath)` also failed, likely due to limitations in file path support and possible permission restrictions on the HoloLens 2. A final approach was then explored using direct URL requests to retrieve a byte array, but it also failed. The solution was to use a package from GitHub that allows the importation at runtime using `GLTFUtility`⁴.

Regarding OBJ format support, the `OBJLoader` package by `Dummiesman`⁵ was considered. However, its functionality was limited to the Unity Editor environment, precluding its use for runtime importation on the HoloLens 2. The FBX format can be imported locally in the Resource path.

Figure 20 illustrates a step in the task of cleaning the rotating motor connection, which is part of the engine cleaning and maintenance training module. This figure presents a sequence of images capturing the animated movement of a spray bottle during our training session using HoloLens 2. The objective is to guide the worker to put the bottle in a specified location to simulate the cleaning process. The animation using `DOTween`⁶ package shows the movement trajectory the object should follow to reach its final destination. Once the spray bottle is correctly positioned at the specified location, matching the animated guide, the step is completed, allowing the user to proceed to the next step.

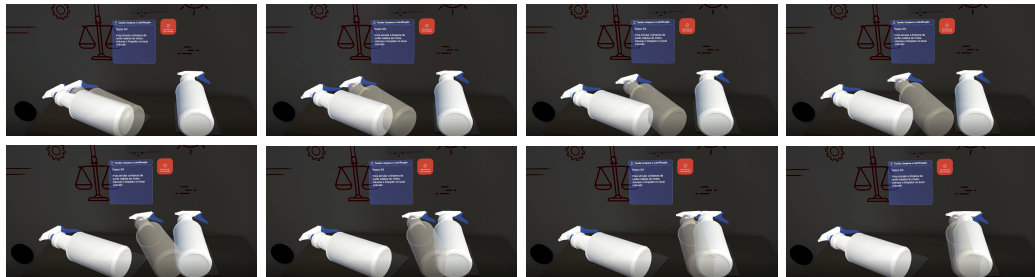


Figure 20: A collection of images demonstrating the animation movement of an object in the AR Training session using HoloLens 2.

Operators can interact with virtual representations of machines, tools, and components, allowing them to practice procedures and techniques. The AR System provides real-time feedback and guidance, helping operators learn. Additionally, the training simulations can be customized to address specific training needs and objectives, ensuring that operators receive targeted and relevant instruction.

⁴ <https://github.com/siccity/gltfutility>

⁵ <https://assetstore.unity.com/packages/tools/modeling/runtime-obj-importer-49547>

⁶ <https://assetstore.unity.com/packages/tools/animation/dotween-hotween-v2-27676>

In the early stages of the project, an [Artificial Intelligence \(AI\)](#) based approach was initially considered to identify objects in the real world; the idea was to leverage [AI](#) to automate object detection.

Further investigations were directed towards object recognition methods using external services and pre-trained models. One potential solution involved the use of Azure Custom Vision⁷, which is capable of identifying objects accurately. However, the implementation of this solution would necessitate the continuous capture and transmission of images (like screenshots) from the HoloLens 2 camera to the server for classification. This approach presents a limitation in terms of real-time responsiveness and dynamic interaction, rendering it less suitable for the proposed application, in addition, it only classified the images sent and they could only be accessed in the azure dashboard, the result was not “sent” back to the application.

An alternative approach was the integration of a pre-trained YOLOv7 model (C.-Y. Wang et al., 2022). This model was exported to the ONNX format and integrated into Unity via the Barracuda⁸ package and then by Sentis⁹ package. Although initial implementation encountered issues—particularly with the “split” operation—using an alternative ONNX model eventually allowed for progress. Still, there were problems with the dataset not being related to factory objects, for example, and having the output but not knowing how to use it due to a lack of experience with [AI](#).

⁷ <https://azure.microsoft.com/en-us/products/ai-services/ai-custom-vision>

⁸ <https://docs.unity3d.com/Packages/com.unity.barracuda%401.0/manual/index.html>

⁹ <https://docs.unity3d.com/Packages/com.unity.sentis@1.0/manual/upgrade-guide.html>

This study evaluated the usability and cognitive workload of the developed AR System in a controlled environment, simulating a factory floor. To assess usability, the SUS (Bangor et al., 2008) was employed, which required participants to respond to 10 questions using a 5-point Likert Scale, ranging from "strongly disagree" to "strongly agree" (Joshi et al., 2015). Additionally, the NASA-TLX (Werrlich et al., 2018) was utilized to evaluate the cognitive workload after completing the tasks. The NASA-TLX was chosen due to its comprehensive cognitive workload assessment, encompassing factors such as mental demand, physical demand, and overall performance.

A custom questionnaire was designed so that participants could test at least all the functionalities (monitoring, education, and training) of the developed system. Quantitative data from Likert-scale questions within this questionnaire were analysed using one-way Analysis of Variance (ANOVA) to identify statistically significant differences in user responses across different system functionalities. Furthermore, open-ended questions were included to gather qualitative insights into user experiences. The sentiment expressed in these open-ended responses was analysed using the Valence Aware Dictionary and sEntiment Reasoner (VADER) algorithm, providing a quantitative measure of positive, negative, and neutral sentiment.

Participants who had or had not interacted with AR or VR technologies started by using the HoloLens Tips App¹ as can be seen in Figure 21 which is an application developed for HoloLens that is usually already installed from factory. Using this application, the participants have the opportunity to have first contact with the glasses and can interact with the virtual content in a guided way. Once started, the application for hand gestures is given instructions to quickly teach the most basic gestures for the interaction of HoloLens 2, from air tap, move, grab, rotate, resize, and start gestures.

¹ <https://www.microsoft.com/en-us/p/hololens-tips/9pd4cxkk47>

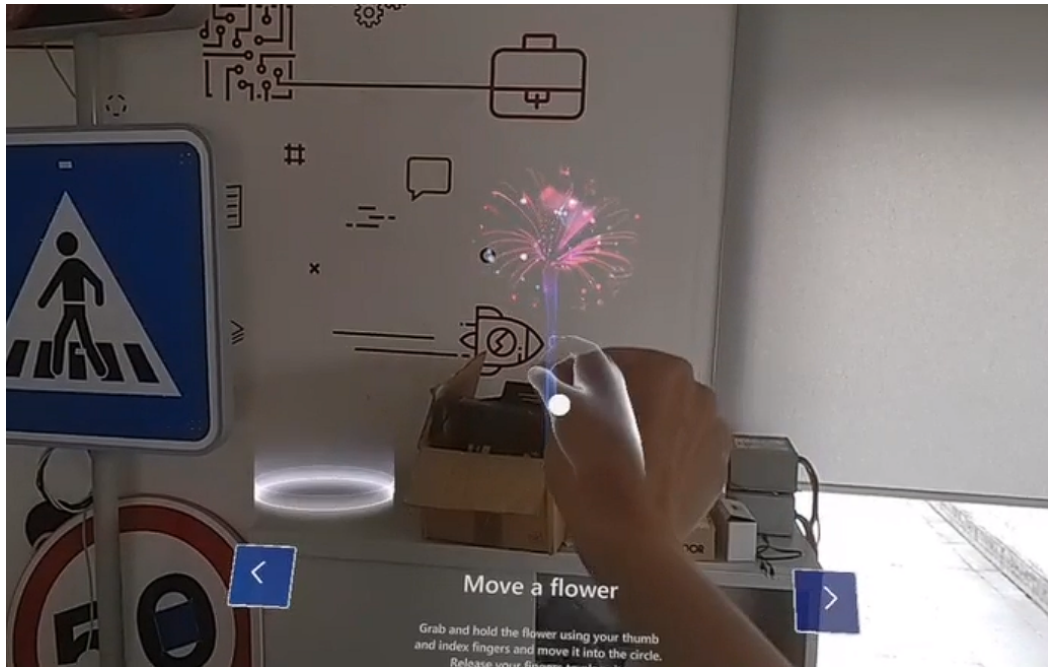


Figure 21: Participant using "HoloLens Tip App" as a first interaction with HoloLens 2 before the tests begin.

6.1 CUSTOM QUESTIONNAIRE

The tests are carried out individually through the questionnaire that can be divided into six sections: the 'Stone' section, which comprises the first four parts and includes collection of demographic information and familiarity with AR Systems, performance of tasks, an open question for criticism and praise, and questions for participants with industry experience; followed by the SUS assessment and NASA-TLX evaluation. All sections can be visualized in the Appendix Section.

Users are prepared to begin the test after their initial interaction with the HoloLens Tips App. Starting with the first section of the questionnaire that can be visualized in Table 5.

In the second part of the questionnaire, the participants read the task and try to execute them, using the AR System. The tasks in question can be seen in Table 6 in the Appendix. At the end of each task, participants rated the difficulty on a 7-point Likert Scale, where 1 is "very difficult" and 7 is "very easy". The goal was for the volunteers to perform the tests in a way that only follows the questionnaire, without our interference; eventually, some requested help to perform a particular task, and we can observe some issues raised at the moment.

The third section of the questionnaire is an open-ended question available in Table 7.

The fourth part of the questionnaire only needs to be answered by those who have already worked with the use of non-industrial machines. These questions are available in Table 8.

After the fifth part of the questionnaire, the participants filled out a [SUS](#) questionnaire and provided qualitative feedback on their experience. The [SUS](#) is a reliable scale that can be used for global assessments of systems usability (Brooke, 1996). As said before, it consists of a 10-item questionnaire available in Table 9 to respond with a 5-point Likert Scale. As the test was done with Portuguese people, the whole questionnaire, including the [SUS](#) was done in Portuguese language (A. I. Martins et al., 2015).

For the last part, the [NASA-TLX](#) method was used, available in Table 10 is a widely used assessment tool that rates perceived workload (Hart, 2006) on six subscales: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration.

After collecting the data from the questionnaire, the [SUS](#) and [NASA-TLX](#), the data analysis phase was carried out. This analysis included descriptive statistics to summarize the data distribution, correlation analysis to identify significant relationships between variables, [ANOVA](#) tests to examine the influence of categorical variables on outcomes, scatter plot analysis to explore relationships between variables, and frequency analysis to investigate the distribution of categorical variables, and sentiment analysis using [VADER](#) to analyse the emotional tone and sentiment of the text data.

6.2 BETA TESTING

Before starting the official tests, the application was tested by two volunteers who did not participate in the official tests and who have some familiarity with [AR](#). They were introduced to the context of the application's use and its objectives. Then, they were set free to explore the application and report some improvements before going to the official tests and some improvements for future work.

The first volunteer noted that the [QR Code](#) reading area could be enhanced by incorporating a visual indicator to better guide users, and they recommended that scrolling be limited to the vertical axis to facilitate navigation. Additionally,

suggestions were made to enlarge interface elements such as sliders and buttons. Other recommendations included adding a loading indicator during video playback, implementing markdown support for text content, ensuring that titles remain fixed at the top of the slider, and making audio controls more prominent with a clearly defined 10-second sprite in the rewind and forward buttons.

In the monitoring and training modules, the tester observed that the training card should be movable and that it would be beneficial to clearly indicate the current module (education, training, or monitoring). It also recommended displaying task progress with clear, visible cues, such as colour indicators and advised against making the step list clickable to reduce potential confusion. Moreover, they suggested that the system should not automatically return to the main menu upon completion of all steps.

The second volunteer suggests the need for clarity in [QR Code](#) identification by including a full-text description of the [QR Code](#)'s meaning. The user also pointed out the importance of maintaining consistency across the monitoring interface, such as using uniform fonts and the same language, improving the formatting of dates, and bolding parameter names. Regarding training, exploring alternative audio examples, incorporating chevrons to facilitate navigation through content, and improving the clarity of initial instructions are recommended.

Most of these suggestions were still implemented before going to the official tests, and others were considered for future work due to the limited time. In general, all the suggestions were taken into account, except for one that suggested that the buttons should be on the side of the sliders, which was not considered since it was not considered intuitive.

6.3 TEST CONDITIONS

The tests were conducted in a controlled laboratory environment, where participants were instructed to imagine a factory floor setting to simulate realistic working conditions. Before starting, they underwent a brief familiarization session with the HoloLens 2 using the HoloLens Tips App.

Each session lasted an average of 17 minutes and 41 seconds, during which participants used the HoloLens 2 to complete tasks independently, receiving assistance only when strictly necessary. Participants used a laptop to answer and follow

the questionnaire, making them more independent as they follow the information provided. Only for the [NASA-TLX](#) evaluation was it on printed paper.

6.4 EVALUATION RESULTS AND DISCUSSION

This section presents our study's findings. We analyse task performance, system usability, cognitive workload, and the influence of user characteristics on these factors.

6.4.1 *Participants Demographic*

Our study involved 22 volunteers (13 male, 9 female) aged 18 to 40 years. The sample mean (μ) age was 25.9 years with a standard deviation (σ) of 5.9 years. Participants primarily consisted of students and professionals from education and information technology, exhibiting varying levels of familiarity with [AR](#) technology, from not comfortable to very comfortable. [Figure 22](#) visually represents this demographic data.

The fourth part of the questionnaire for industry professionals will not be analysed, as only one of the participants has worked in the industry, and there is not enough sample to reach any conclusion.

6.4.2 *Task Performance and Difficulty*

Participants completed a series of seven tasks using the [AR](#) System, as outlined in the Custom Questionnaire section. The specific task prompts are presented in [Table 3](#), while the response alternatives for each task are documented in [Table 6](#) within the appendix.

[Table 4](#) presents a summary of the results, with the task success rates of the answer tasks listed on the left and the average difficulty rating and standard deviation of each question on the right.

Task success rates were generally high, with perfect completion for Tasks 2 and 5. Task 1 and 7 had the lowest completion rate (81.8 %) and the highest variability in difficulty ratings ($\sigma = 1.9$ and $\sigma = 1.1$) respectively. This suggests that Tasks 1 and 7 may have been more complex or open to interpretation, leading to a broader range

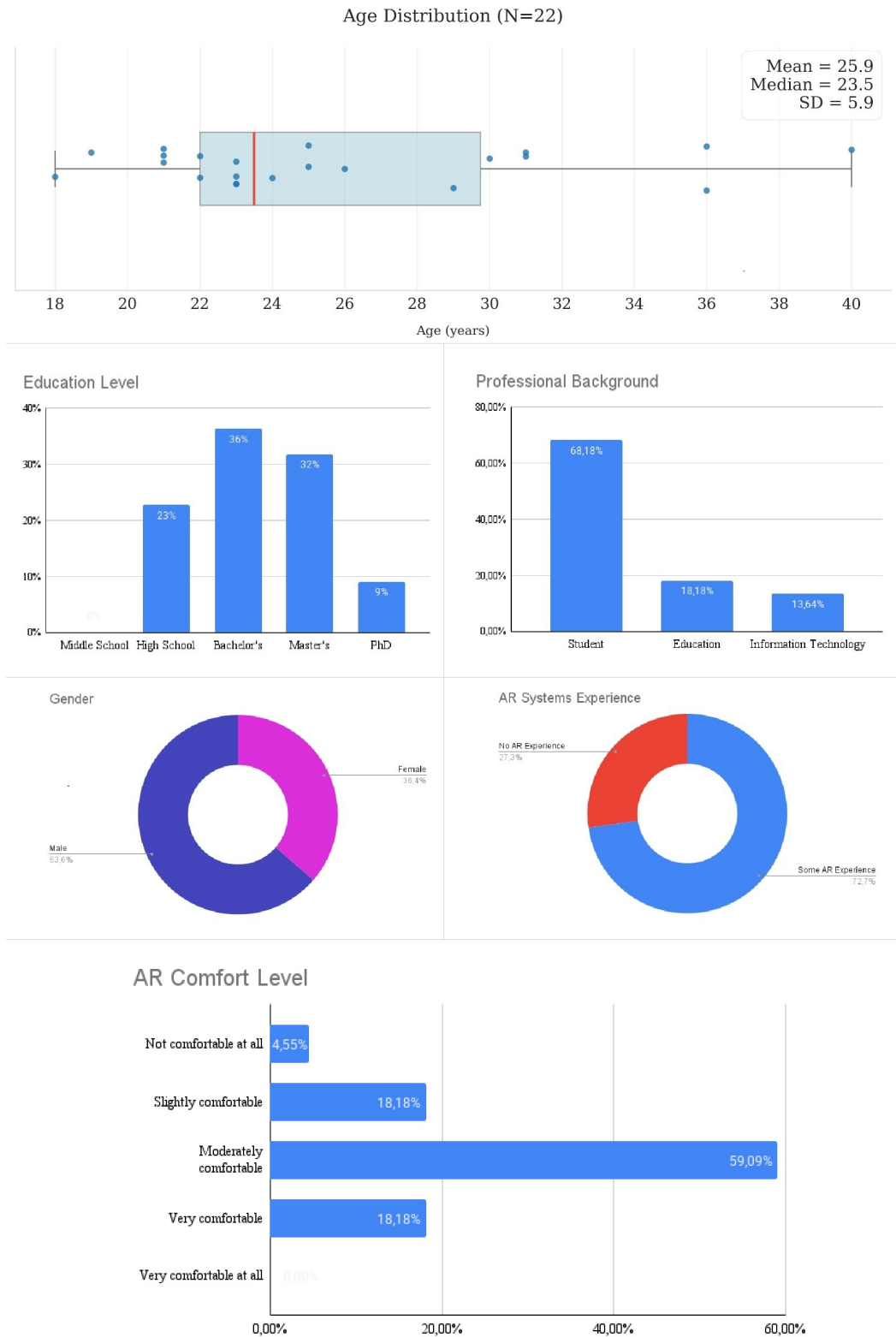


Figure 22: **Demographic** data from 22 participants: Information as **Age Distribution** (18-40); **Educational Level** (Middle School, High School, Bachelor´s, Master´s and PhD); **Professional Background** (Student, Education, Information Technology); **Gender** (female or male); **AR System Experience** (none or some); **AR Comfort Level** (Not comfortable at all, Slightly comfortable, Moderately comfortable, Very comfortable, Very comfortable at all).

Table 3: Task scenarios designed to evaluate user interaction with core functionalities (monitoring, education, and training) of the AR System

Task #	Question
1	Identify the machine in question. What is the name of the machine identified?
2	How many services are available for the identified machine?
3	Access the monitoring service. How many parameters are available?
4	Access the education service. Explore the available content. What type of content is available?
5	Select the 3 ^o content available in the training. What type of content?
6	Select the 1 ^o content available in the training. Select the alternative that most closely resembles what you understood from the content presented.
7	Access the training service. Select the 1 ^o training available. Select the alternative that most closely matches the training objective in question. NOTE: To follow the instructions given during the training to move the object, move the QRCode.

of difficulty ratings from participants. Conversely, the perfect completion rates for Tasks 2 and 5 suggest that these tasks were well-designed and easily achievable.

In addition to task performance and difficulty, we analysed the total time participants took to complete all seven tasks. The recorded time reflects the entire duration from the start to the end of the Stone questionnaire's second part (see Table 6 in the appendix).

On average, participants completed all tasks in 17 minutes and 41 seconds, with a standard deviation of 4 minutes and 35 seconds (see Figure 23). The time spent by participants ranged from as short as 7 minutes to as long as 26 minutes.

This analysis reveals that most participants completed the tasks within a relatively consistent time frame, although there was some variability. The relatively low standard deviation indicates that the time taken to complete the tasks was fairly uniform across participants, suggesting that the tasks were of comparable difficulty and that the participants had a similar level of familiarity with the system.

Table 4: In the left Task Performance, and at right the respective difficulty ratings (1-7) of each task and standard deviation.

Task #	Success Rate (%)	Average (μ)	SD (σ)
1	81.8	5.3	1.9
2	100.0	6.5	0.8
3	86.3	6.5	0.7
4	86.3	5.9	0.9
5	100.0	6.5	0.7
6	95.5	6.5	0.9
7	81.8	5.5	1.1

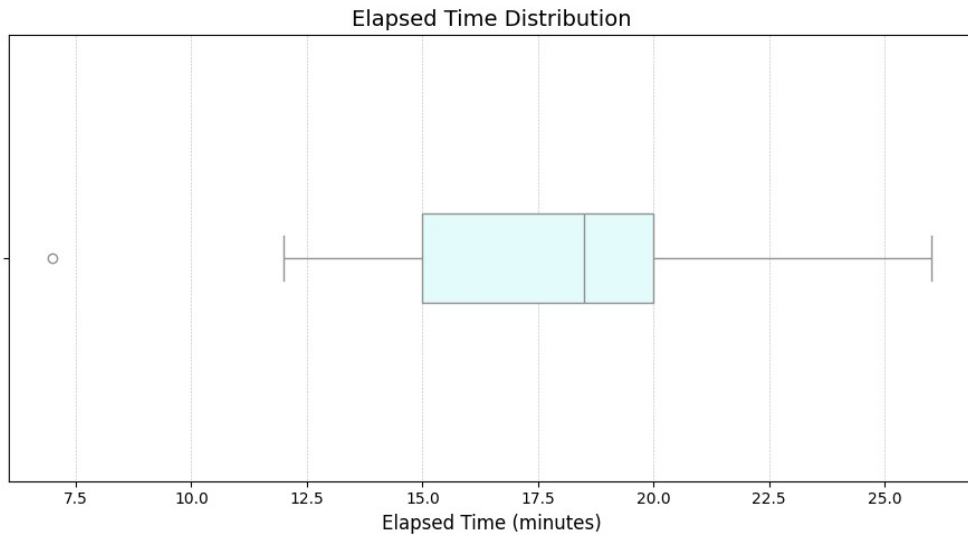


Figure 23: **Elapsed Time:** spent by participants to do the fourth part of the questionnaire relating to tasks. ($\mu = 17:41$ minutes, $\sigma = 4:35$ minutes).

6.4.3 System Usability

The **SUS** analysis revealed that the **AR** System's usability was rated positively, with an average score of 72.4 ($\sigma = 11.2$), according to Bangor (2009) indicating a OK usability but significantly closer from Good. Figure 24 shows the distribution of **SUS** scores, which range from 1 (strongly disagree) to 5 (strongly agree), providing a visual representation of how participants rated the system's usability. Figure 25 shows the distribution of **SUS** score from all 22 volunteers.

The relatively high **SUS** score suggests that participants found the **AR** System intuitive and easy to use, which is crucial for its practical application in industrial settings.

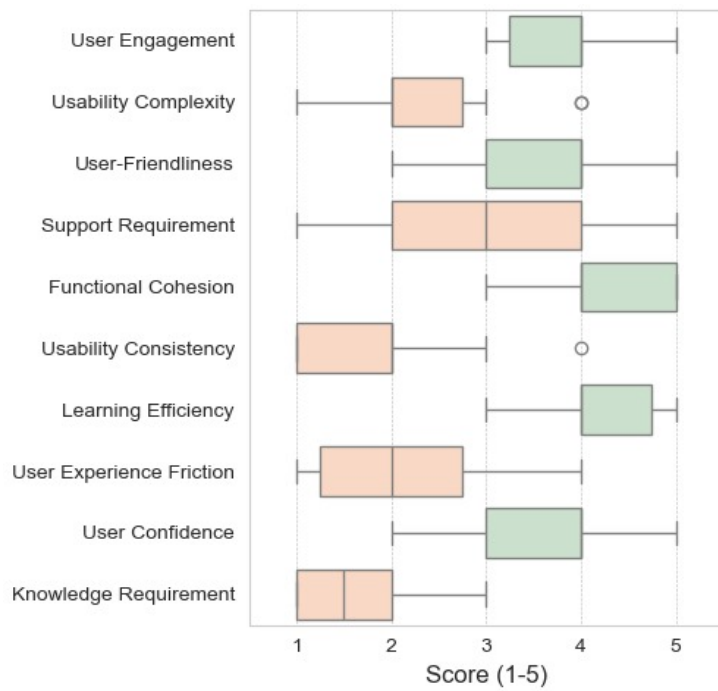


Figure 24: System Usability Scale distribution for each question.

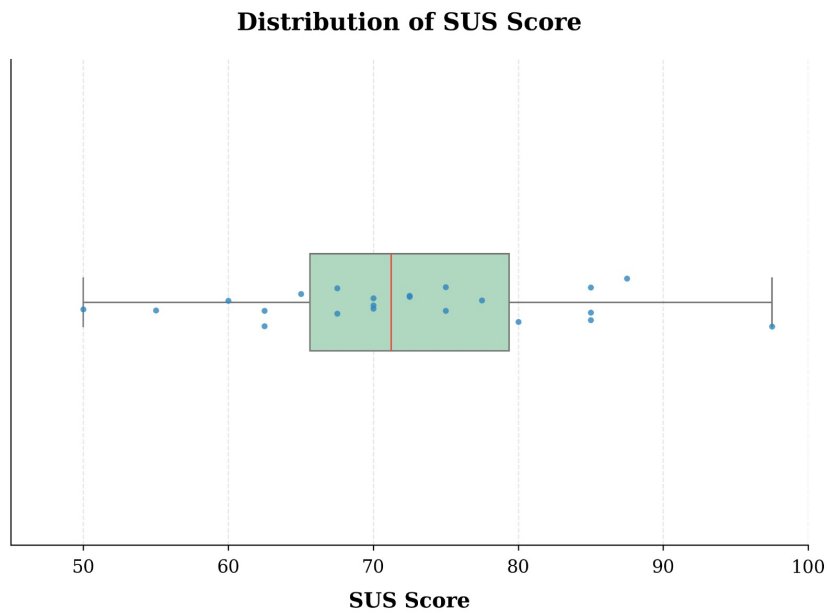


Figure 25: System Usability Scale Scores: ($\mu = 72.4, \sigma = 11.2$).

6.4.4 Cognitive Workload

We assessed the perceived workload using the [NASA-TLX](#) questionnaire. Figure 26 summarizes the results across the six subscales.

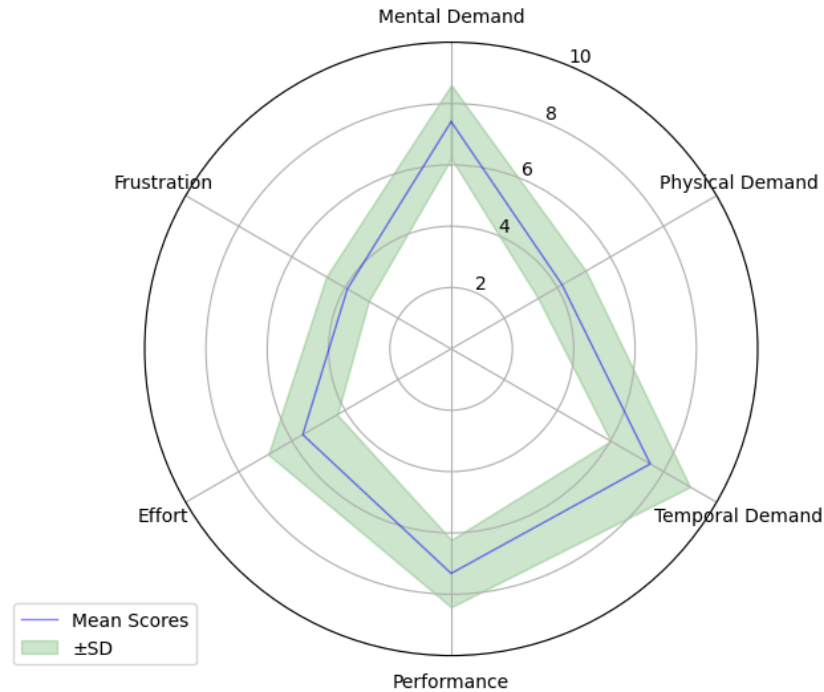


Figure 26: **NASA Task Load Index (TLX) Scores:** Higher scores indicate greater workload. Note that, for the Performance subscale, lower scores indicate better-perceived performance. For better visibility, only data up to 10 is shown (rather than to 21).

The average scores across the six subscales indicate that users perceived the system to have a low to moderate level of mental demand (7.4), temporal demand (7.5), and performance (7.3). This suggests that users did not find the system overly demanding regarding mental effort, time pressure, or performance expectations. On the other hand, the effort score (5.6), physical demand (4.2), and frustration (3.9) scores were relatively low, indicating that users did not find that they had to make much effort to use the system to complete tasks, was not physically demanding and did not experience significant frustration when using the System.

6.4.5 Relationship Between Cognitive Workload and System Usability

The relationship between perceived cognitive workload, as measured by the [NASA-TLX](#), and system usability ([SUS](#) scores) was analysed using Pearson correlations

and coefficient of determination (R^2) metrics. Figure 27 illustrates the scatterplot of overall NASA-TLX scores against SUS ratings, revealing a moderate positive correlation ($r = 0.373$, $p = 0.087$), with ($R^2 = 0.139$). While this relationship did not achieve statistical significance ($\alpha = 0.05$), the effect size suggests that 13.9% of the variance in usability perceptions can be attributed to differences in overall cognitive workload.

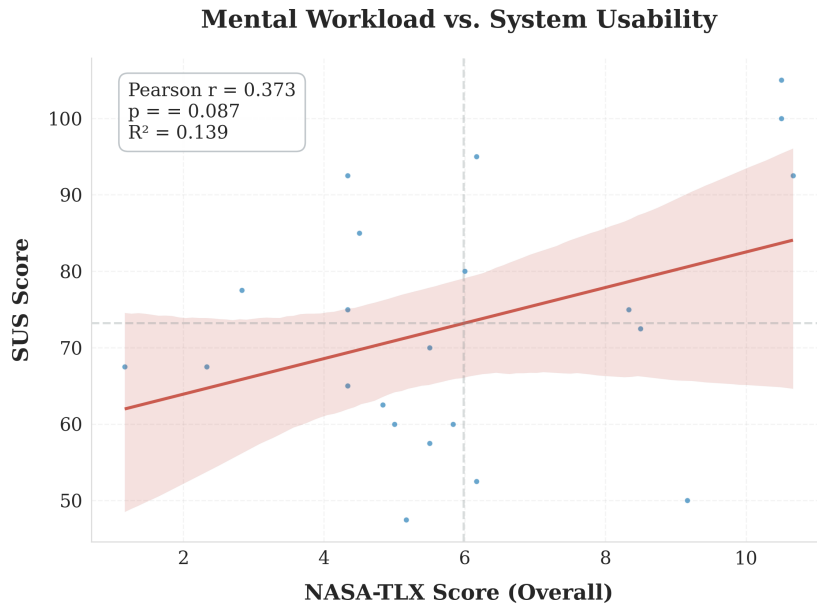


Figure 27: Scatterplot of overall NASA-TLX scores versus SUS ratings.

A granular analysis of NASA-TLX subcomponents (Figure 28) revealed distinct patterns:

Mental Demand: Exhibited a statistically significant positive correlation with SUS ($r = 0.467$, $p = 0.029$, $R^2 = 0.218$), indicating that participants who perceived higher cognitive engagement rated the system as more usable.

Physical Demand: Showed a weak inverse relationship ($r = -0.189$, $p = 0.400$, $R^2 = 0.036$), aligning with qualitative feedback highlighting the system’s low physical strain.

Temporal Demand: Demonstrated an exceptionally strong positive correlation ($r = 0.765$, $p < 0.001$, $R^2 = 0.585$), suggesting that time pressure perceptions were paradoxically linked to higher usability scores.

Performance, Effort, and Frustration: Displayed negligible correlations ($|r| < 0.2$, $p > 0.1$, $R^2 < 0.1$), implying these factors were secondary to usability evaluations.

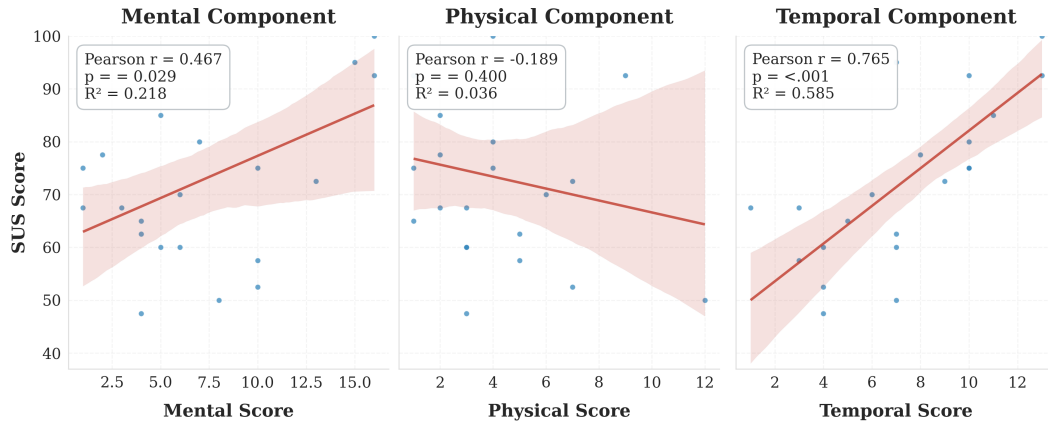


Figure 28: Scatterplots of NASA-TLX Mental, Temporal, and Physical Demand subcomponents against SUS ratings.

6.4.6 Influence of User Characteristics on Performance and Perception

Our analysis revealed a significant relationship between education level and task performance measured by the Stone questionnaire. Participants with higher education levels, particularly those with tertiary education, demonstrated superior performance, with six individuals completing all seven tasks. This finding suggests that educational background may influence the ability to adapt to our system quickly.

Frequent smartphone users exhibited enhanced performance, with six participants accomplishing all tasks. This observation indicates a potential skill transfer between smartphone usage and AR System interaction, i.e., familiarity with mobile technologies may facilitate adaptation to AR interfaces for this particular instance.

The analysis of variance (one-way ANOVA) revealed a statistically significant difference in perceived difficulty for the initial task across educational levels ($F = 8.1645$, $p = 0.0012$). Here, F represents the ratio of between-group variance to within-group variance, and p represents the probability of observing the test results (or more extreme results) assuming no real difference between groups. The low p -value (usually 0.05) indicates that the observed difference in perceived difficulty between educational levels is statistically significant, and the F -value suggests the magnitude of this difference.

A trend was observed wherein the perception of difficulty decreased, on average, as the educational level increased. This finding suggests that educational background may influence the initial perception of AR system complexity. However, the absence

of significant differences in subsequent tasks indicates a potential learning effect, where users quickly adapt to the system regardless of their educational background.

Our results suggest a positive correlation between **AR** comfort levels and perceived workload, as measured by the **NASA-TLX**. This finding may be explained by the hypothesis that users more comfortable with **AR** technology may invest greater cognitive resources in task completion, resulting in higher perceived workload. This may be partially explained by the notion that individuals with higher technology self-efficacy tend to engage more deeply with new systems, potentially leading to higher perceived cognitive load (Pan, 2020).

Overall, the absence of substantial differences in many of the test results suggests that the tested **AR** System demonstrates a relatively consistent level of usability and effectiveness across various demographic groups and experience levels.

6.4.7 *Open-ended User Responses Analysis*

The qualitative analysis of all user responses to the open question regarding impressions about and experience using our system (see the question of Table 7 in the appendix) revealed that a majority of users reported an overall positive experience, indicating a generally favourable reception of the **AR** technology in this industrial context. A significant proportion of the respondents deemed the application's interface intuitive and user-friendly. Key functionalities that garnered positive feedback included **QR Code** integration and virtual object manipulation. The users particularly noted the application's ability to demonstrate machine operations and maintenance procedures.

Nevertheless, the analysis also uncovered several areas requiring refinement. A substantial number of users reported difficulty with interface interactions. Confusion regarding certain functionalities and issues with element positioning within the interface were also notable concerns.

The learning curve was generally perceived as manageable, with many users explicitly mentioning a good adaptation curve. However, some users expressed concerns about potential challenges for older or less technologically adept users, indicating a need for adaptive learning features or simplified interaction modes to ensure accessibility across different user demographics. Specific suggestions for improvement included the addition of an omnipresent help button and enhancements to the simulator navigation.

In an effort to quantify the overall sentiment of the responses, a simple analysis was performed by employing the [VADER](#) algorithm (Hutto and Gilbert, 2014) to evaluate the emotional polarity of the text. The process involves preprocessing the text by removing stopwords and then analysing the sentiment of each entry using the [VADER](#) algorithm, which returns a dictionary with sentiment scores (positive, negative, and neutral).

The results are visualized in Figure 29, where the first column represents the average sentiment of all responses. The subsequent columns display the sentiment scores for each individual participant. Green indicates a positive sentiment, red indicates a negative sentiment and neutral sentiment is not shown for simplicity. For instance, participant 18's response is not represented in the figure as it had a neutral sentiment, and some only have positive sentiments.

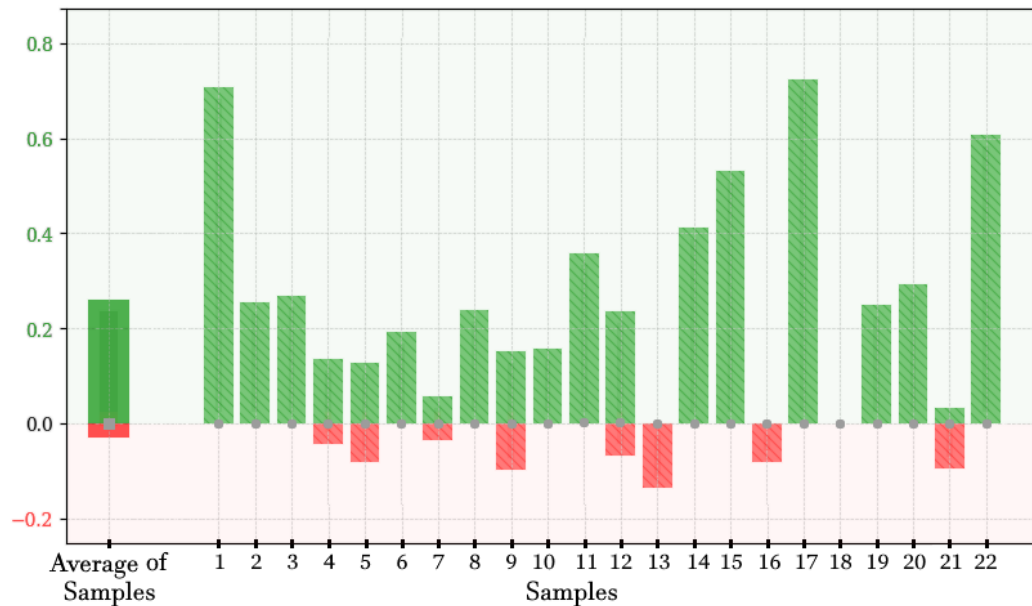


Figure 29: **Sentiment analysis** of open-ended question, in green represents a positive feeling, and in red a negative feeling. To simplify, the neutral feeling was not represented.

6.5 ADDRESSING RESEARCH QUESTIONS

RQ1: How does perceived cognitive workload ([NASA-TLX](#)) influence perceived usability ([SUS](#)) in an [AR](#) system?

Our findings, detailed in Section 6.4.5, indicate that overall cognitive workload does not uniformly dictate usability perceptions. Instead, specific components of the [NASA-TLX](#) emerge as key drivers. Although the aggregate [NASA-TLX](#) score shows

only a non-significant positive correlation with [SUS](#), Temporal Demand exhibits a strong positive relationship with usability—suggesting that the system’s capacity for rapid task execution under time pressure is crucial. Similarly, Mental Demand is significantly associated with higher usability ratings. This finding aligns with research by Longo, [2018](#), who noted that higher mental workload does not necessarily imply lower usability, suggesting a complex relationship between cognitive demands and user experience in interactive systems. In contrast, Physical Demand and Frustration appear to have little impact on usability. Consequently, for [AR](#) systems, design strategies should prioritize optimizing temporal efficiency and harnessing cognitive engagement rather than simply reducing the overall workload.

RQ2: To what extent does the user’s familiarity with [AR](#) technology affect their performance and perception of usability of the [AR](#)-enabled system?

The study reveals that familiarity with [AR](#) technology has a noticeable impact on both user performance and their perception of the system’s usability. Participants who were more accustomed to using [AR](#) systems tended to perform better across tasks, particularly in achieving higher success rates and navigating the system with greater ease. The [SUS](#) scores corroborate this, as participants with more [AR](#) experience rated the system more favourably, finding it intuitive and easy to use. The statistical analysis also highlighted that frequent smartphone users, who likely have higher digital literacy, showed better task performance, suggesting a skill transfer from general mobile technology use to [AR](#)-specific interactions. This demonstrates that prior exposure to similar technologies can enhance both the usability perception and functional performance in an [AR](#) environment.

RQ3: What are the main difficulties or barriers users encountered while using the system, and which aspects did they appreciate the most?

Users encountered some difficulties while interacting with the [AR](#) system, with the most common issues relating to interface interactions and the positioning of elements within the interface. Despite these challenges, most participants reported a generally positive experience, appreciating specific functionalities such as [QR Code](#) integration and the manipulation of virtual objects. The system’s capability to demonstrate machine operations and maintenance procedures was particularly well-received. However, the feedback also highlighted the need for improvements in user support features, such as an omnipresent help button and simplified navigation to better accommodate users who are less familiar with [AR](#) or less technologically

adept. These insights suggest that while the AR system is effective in many aspects, some areas require refinement to enhance user experience and accessibility.

6.6 LIMITATIONS

Our study, while informative, has several limitations. Although sufficient for exploratory purposes, the sample size of 22 participants may limit the generalizability of the results, suggesting a need for larger, more diverse samples, including more people working in the mineral industry for future research. Additionally, the study's focus on short-term AR System use calls for longitudinal research to better understand long-term effects. The limited variety of tasks may not fully capture the breadth of industrial maintenance activities, indicating that future studies should examine a broader range of tasks with varying complexity. Lastly, the potential for self-selection bias, given that voluntary participation, suggests that our sample may be more inclined toward technology adoption.

Despite these limitations, the study offers a strong foundation for understanding AR Systems in industrial maintenance and provides valuable insights for future research and development.

This chapter presents a prototype that integrates privacy techniques with AR to meet the demands of sensitive industrial environments such as those found in the mining industry. The prototype consists of two modules: an image obfuscation system, which focuses on the protection of visual data, and an interactive training module, that uses AR to simulate assembly processes. By combining these functionalities, the system not only preserves privacy information but also offers a practical and immersive educational tool.

7.1 AR IMAGE OBFUSCATION SYSTEM: AN OVERVIEW

The prototype establishes a privacy-preserving pipeline for AR applications through a decentralized client-server architecture. As illustrated in Figure 30, the Unity-based client captures visual data and transmits it to a remote server, where configurable obfuscation techniques—such as blurring, pixelation, and masking—are applied to predefined sensitive object classes (e.g., faces, license plates, screens).

The server returns the anonymized image to the client, ensuring raw visual data never persists on end-user devices. This separation of concerns minimizes exposure of sensitive information while maintaining real-time usability.

7.1.1 *Operational Workflow*

Image Acquisition and Preparation. The client operates in two modes: static image testing and real-time camera capture. In static mode, the system cycles through six predefined textures every five frames to simulate dynamic input. Camera mode uses Unity’s `PhotoCapture` API to acquire frames, converting raw camera buffers into `Texture2D` objects for downstream processing.

All images undergo mandatory pre-processing to normalize the inputs so that the images are adapted to the format expected by the SafeAR server. Firstly, the `ConvertToRGB24` method removes the alpha channels and converts the textures to a 24-bit RGB format through GPU-accelerated rendering to a temporary

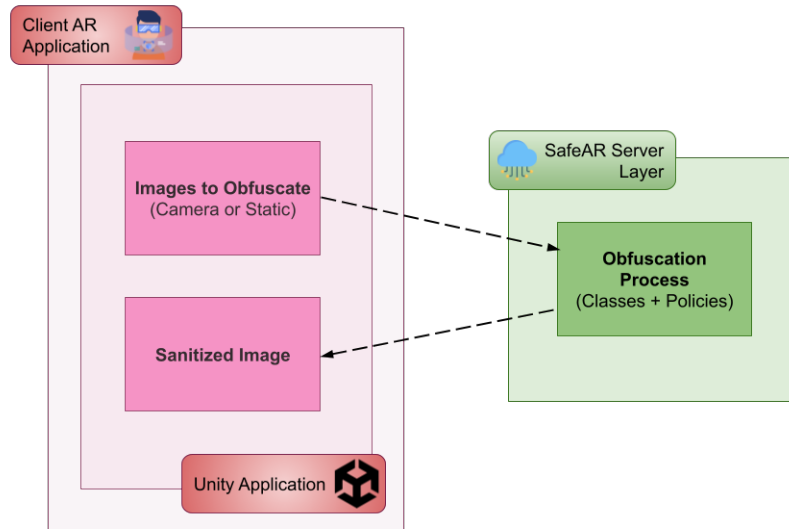


Figure 30: Simplified AR Obfuscation System Architecture: The client transmits raw images to the server, which delegates obfuscation to a dedicated module before returning privacy-compliant results.

`RenderTarget`. Subsequently, the `ResizeTexture` function will resample the images to a fixed resolution of 640×640 , reducing bandwidth requirements and ensuring consistent server-side processing.

Secure Data Transmission. Preprocessed images are serialized as PNG byte arrays, Base64-encoded, and transmitted via [HyperText Transfer Protocol \(HTTP\)](#) POST requests using Unity’s `UnityWebRequest` framework. While the prototype employs unencrypted [HTTP](#) for testing.

Server-Side Anonymization. Upon receiving an image, the server executes a multi-stage pipeline: (1) detecting privacy-sensitive regions using machine learning models (e.g., YOLOv8 (Reis et al., 2024) for object detection and segmentation), (2) applying policy-driven obfuscation techniques to identified classes, and (3) re-encoding the modified image. Policies—configurable via server-side rules—define mappings between object classes (e.g., faces, vehicle plates) and transformation methods (Gaussian blur, pixelation kernels, or binary masking).

Client-Side Reconstruction. The client decodes the server’s Base64 response into a `Texture2D` object, handling both standard PNG/JPG payloads and raw RGB byte streams. Processed images are rendered to the `displayImageRecebid` UI component, with latency metrics logged every ten frames to monitor the quality of service.

Figure 31 presents the obfuscation system developed. To each image, on the right, the original image—sent by the client—exhibits all the raw details, including

potentially sensitive information. On the left, the sanitized image, returned by the server after processing, demonstrates how targeted obfuscation techniques (such as blurring, pixelation, or masking) have been applied to sensitive regions.

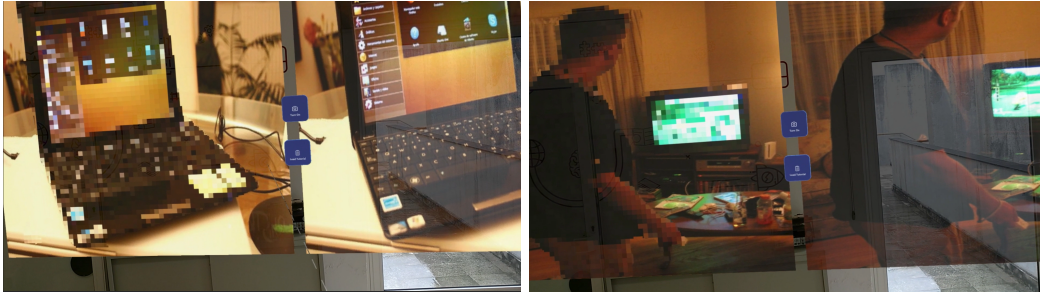


Figure 31: Examples of a visual comparison of the SafeAR privacy-preserving pipeline: (right) the original image submitted for obfuscation and (left) the sanitized image returned by the server.

7.2 PROCEDURAL TRAINING MODULE

An interactive [AR](#) training environment was developed to simulate computer maintenance procedures, serving as a proof-of-concept for industrial applications, particularly in the mineral industry. This module uses [AR](#) to guide the user through a sequence of steps, similar to what was developed in the [AR-DT](#) system. Each training step - from locating and removing the screws to replacing the [Random Access Memory \(RAM\)](#) and replacing the components - is presented interactively using visual cues and contextual instruction.

At the start of the simulation, a prefab representing a [PC](#) is loaded and as the steps are completed the components in question are identified, such as the screws, the side cover, and the memory module. The application uses visual enhancement techniques, changing the material of the components to colors that indicate prominence (in this case, red), and a directional indicator that guides the user to the required action (an animation). As the user carries out the simulated movements - removing or repositioning the components - the system monitors the movement using coroutines that check the proximity of the objects to their target positions. Thus, when positioning is successful, the system moves on to the next step.

In [Figure 32](#) it is possible to visualize in a sequence of images the animations that help in training, visually demonstrating the movements expected for the execution of each task.

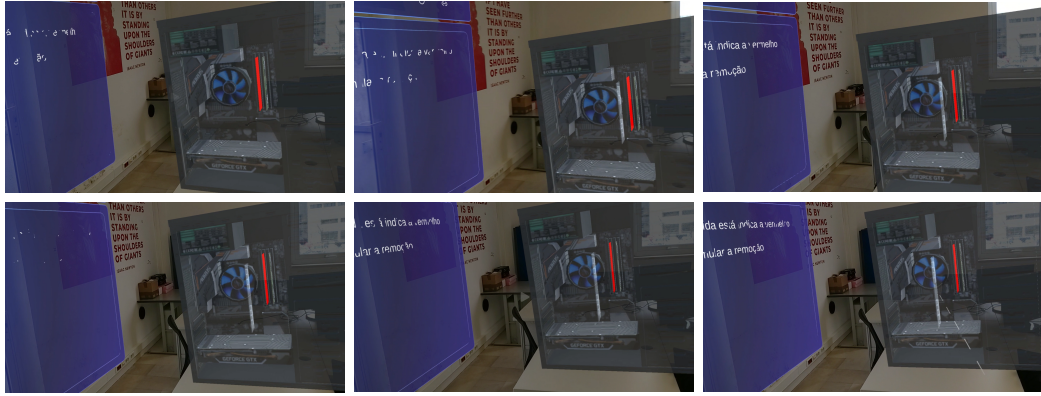


Figure 32: Example of the training sequence progression for component identification, guided removal, part replacement and completion check.

7.3 FINAL CONSIDERATIONS AND FUTURE WORK

Both modules have been developed with the intention of offering an integrated solution that can be adapted to different industrial contexts. The ability to protect sensitive data combined with interactive, guided training demonstrates an advance in the use of AR for practical applications, particularly in the mineral sector. The approach adopted makes it possible for the two systems to be integrated in the near future to create an environment where, for example, interactive training benefits from the security provided by the dynamic obfuscation of images in real-time.

Although the training logic has been consolidated, it should be noted that, as with the obfuscation module, the camera capture functionality is not yet fully operational, and it is planned to implement and improve it in future phases, as well as adapting the training scenario to specific contexts in the mineral industry. The continuation of this work promises to expand the system's capabilities, bringing it into line with the demands of industries that need innovative solutions for privacy management and employee training.

CONCLUSIONS AND FUTURE WORK

The primary objective of this project was to develop an integrated **AR-DT** system tailored for the mineral industry, focusing on improving operational monitoring, worker training, and safety protocols. The proposed system combines real-time **OPC UA** machine data, interactive **3D** training, and cloud-based educational content to address industrial challenges such as high operational costs and hazardous work environments. Additionally, the project explored privacy-preserving techniques for **AR** applications.

This project demonstrates the viability of the proposed system in achieving these objectives. The system successfully integrates real-time data monitoring with interactive training and educational resources (audio, text and video), enhancing both efficiency and safety in industrial operations. Furthermore, Chapter 7 presents a privacy-preserving prototype that applies real-time obfuscation techniques to sensitive visual data, laying the groundwork for secure **AR** deployments in industrial environments.

8.1 KEY CONTRIBUTIONS

The system architecture, comprising Factory Floor, an **AR** System, and a Cloud Platform, demonstrated effective integration of data management, real-time communication, and immersive user experiences. Using standardized protocols such as **OPC UA** facilitated efficient data exchange between industrial machines and the **AR** System, aligning with Industry 4.0 principles.

User testing with 22 participants yielded promising results, with an average **SUS** score of 72.4%, indicating above-average usability. The **NASA-TLX** results revealed significant insights into the user experience with the **AR-DT** system. Users with varying levels of familiarity with **AR** technology displayed differing cognitive loads across the six dimensions (RQ1). Notably, users who did not have prior experience with **AR** reported lower overall workload scores, particularly in the areas of Mental Demand, Effort, and Frustration. This suggests that a lack of familiarity with **AR** can actually lower the cognitive burden associated with using such systems, as

these users tend to have lower expectations and are less aware of the potential complexities, making the technology more accessible and easier to use (RQ2).

During interactions, participants appreciated key features such as [QR Code](#) integration and virtual object manipulation, which enhanced usability. However, some challenges were identified, particularly related to interface design and navigation. While the system demonstrated machine operations and maintenance procedures, participants expressed the need for more user-friendly guidance and support features to who are less familiar with [AR](#) (RQ3). Also, the overall sentiment of the open question is positive.

As a result of this work, two scientific articles were published: [Augmented Reality and Digital Twin for Mineral Industry](#)(doi: 10.1109/ICGI60907.2023.10452719) and [Assessing User Perceptions and Preferences on Applying Obfuscation Techniques for Privacy Protection in Augmented Reality](#)(doi: 10.3390/fi17020055), these publications reflect the impact of the research within the scientific community. Additionally, a third article is being prepared for submission, further contributing to the ongoing discourse on [AR-DT](#) integration into the mineral industry.

The development of the prototype presented in Chapter 7 demonstrated practical viability, processing 640×640 resolution while applying obfuscation policies (blurring, pixelation, masking). Though preliminary, these results confirm the feasibility of balancing data protection with [AR](#)'s visual demands.

8.2 LIMITATIONS AND FUTURE WORK

While this study provides valuable insights into the application of [AR](#) in industrial settings, some limitations and areas for future research have been identified. The sample size of 22 participants is relatively small, potentially limiting the generalizability of the findings. Future studies should involve a more extensive and more diverse group of participants across different industrial roles and settings. This will provide a broader understanding of how the [AR-DT](#) system performs in various contexts and among different types of users.

Additionally, it would be beneficial to conduct long-term studies to track the effects of prolonged use of [AR-DT](#) systems on users, particularly in terms of skill development and cognitive workload. Such research could help determine whether the initial challenges faced by novice users diminish with experience. Future work

should also focus on adapting the system for other industries, testing it in more complex and diverse environments to ensure its broader applicability.

Furthermore, this study did not fully explore the system's scalability for larger industrial environments or different sectors. While the system showed promise in the mineral industry, its adaptability to other industrial contexts remains to be investigated. Also, future work should study the synergies between [AR](#) and other emerging technologies such as artificial intelligence-enhanced decision-making and predictive maintenance.

In terms of implementation when transitioning between scenes, the interface consistently resets to its initial position, resulting in the loss of any previously set position, this affects usability a little, although none of the tests noticed it, and it's not critical, it could be solved in the future. Another challenge pertains to the behaviour of training objects. The red/green prefab that indicates task status follows and rotates with the scene. However, its movement is not sufficiently constrained, leading to potential inconsistencies during training sessions. Additionally, the current implementation of [QR Code](#) reading lacks a better validation to ensure that [QR Code](#) are scanned in the correct order from source to destination, which can lead to procedural errors. Also, the possibilities of more types of objects [3D](#) be imported at runtime.

Another approach that should be explored is the integration of text-to-speech functionalities. This approach required that the host [PC](#) be configured in English and that specific settings be enabled to support text-to-speech. The implementation of [MRTK](#) Speech Commands allowed the mapping of specific keywords to improve a hand-free interaction and should be considered in future work.

Further work could expand the system's capabilities, exploring the application of real-time dynamic image obfuscation integrated with interactive training, and other modules such as monitoring and educational content.

In conclusion, this research demonstrates the potential of [AR](#) technology to significantly enhance the mineral industry's monitoring, training, and education processes. While challenges remain, the positive user feedback and system performance suggest that further development and implementation of such [AR](#) Systems could substantially improve industrial operations and worker capabilities. Future research addressing the identified limitations and exploring new applications will be crucial in realizing the full potential of [AR](#) in industrial settings.

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APPENDIX

A

APPENDIX A

This appendix presents the questionnaires used in our study to evaluate the [AR System](#) applied in the industrial setting. It includes a custom-designed questionnaire to assess user-profiles and performance, as well as two standardized questionnaires: the [SUS](#) and the [NASA-TLX](#).

A.1 CUSTOM AR SYSTEM EVALUATION QUESTIONNAIRE

The following set of tables comprises our custom-designed questionnaire to gather information about user profiles in [5](#), task performance in [6](#), impressions of the [AR](#) prototype [7](#), and questions to who already work in industry in [8](#).

A.2 SYSTEM USABILITY SCALE (SUS)

The [SUS](#) is a reliable tool for measuring the usability of a system represented in [Table 9](#). It consists of a 10-item questionnaire with five response options for respondents, from Strongly Disagree to Strongly.

A.3 NASA TASK LOAD INDEX (NASA-TLX)

[NASA-TLX](#) is a widely used, multidimensional assessment tool developed by Hart and Staveland, represented in [Table 10](#). It rates perceived workload on six subscales to assess mental, physical, and temporal demands, as well as performance, effort, and frustration.

Table 5: **Stone Questionnaire 1st section:** User Profile Questionnaire.

QUESTION	OPTIONS
Gender	<input type="checkbox"/> Female <input type="checkbox"/> Male <input type="checkbox"/> Prefer not to answer
Age	_____
Education level	<input type="checkbox"/> Primary <input type="checkbox"/> Secondary <input type="checkbox"/> Bachelor's <input type="checkbox"/> Master's <input type="checkbox"/> Doctorate
Professional field	<input type="checkbox"/> Student <input type="checkbox"/> Healthcare <input type="checkbox"/> Education <input type="checkbox"/> IT <input type="checkbox"/> Legal <input type="checkbox"/> Finance <input type="checkbox"/> Services
Smartphone usage at work	<input type="checkbox"/> Never <input type="checkbox"/> Rarely <input type="checkbox"/> Sometimes <input type="checkbox"/> Often <input type="checkbox"/> Very often
Previous AR experience	<input type="checkbox"/> Glasses/Headset <input type="checkbox"/> Smartphone/Tablet <input type="checkbox"/> Spatial projection
Comfort level with AR	<input type="checkbox"/> Not at all <input type="checkbox"/> Slightly <input type="checkbox"/> Moderately <input type="checkbox"/> Very <input type="checkbox"/> Extremely
Industrial machine experience	<input type="checkbox"/> Yes <input type="checkbox"/> No
Mineral industry experience	<input type="checkbox"/> Yes <input type="checkbox"/> No
Years in mineral industry	_____

Table 6: Stone Questionnaire 2nd section: User Performance.

TASK	RESPONSE
Initial Hour	____:____
Machine Identification	<input type="checkbox"/> Machine 1 <input type="checkbox"/> Machine 2 <input type="checkbox"/> Machine 3 <input type="checkbox"/> Machine 4 <input type="checkbox"/> StoneCut 5x Mill Classic <input type="checkbox"/> Don't know
Ease of Task 1 (1-7)	_____
Number of Services	<input type="checkbox"/> None <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5+ <input type="checkbox"/> Don't know
Ease of Task 2 (1-7)	_____
Number of Parameters	<input type="checkbox"/> None <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5+ <input type="checkbox"/> Don't know
Ease of Task 3 (1-7)	_____

Continued on next page...

(Continuation of Table 6)

TASK	RESPONSE
Training Content Types	<input type="checkbox"/> Audio <input type="checkbox"/> Text <input type="checkbox"/> Graphics <input type="checkbox"/> Animation <input type="checkbox"/> Video <input type="checkbox"/> Photos
Ease of Task 4 (1-7)	_____
Third Training Content Type	<input type="checkbox"/> Audio <input type="checkbox"/> Text <input type="checkbox"/> Graphics <input type="checkbox"/> Animation <input type="checkbox"/> Video <input type="checkbox"/> Photos <input type="checkbox"/> Don't know
Ease of Task 5 (1-7)	_____
First Training Content Description	<input type="checkbox"/> Tools for cutting disc <input type="checkbox"/> Machine operation <input type="checkbox"/> Water heating <input type="checkbox"/> Motor cleaning <input type="checkbox"/> Don't know
Ease of Task 6 (1-7)	_____
Training Simulation Objective	<input type="checkbox"/> Move & paint <input type="checkbox"/> Disassemble & clean <input type="checkbox"/> Remove screws <input type="checkbox"/> Identify parts <input type="checkbox"/> Don't know
Ease of Task 7 (1-7)	_____
Final Hour	____:____

Table 7: **Stone Questionnaire 3rd section:** Opened question.

TASK	RESPONSE
Describe your impressions of the app and your experience using it	_____

Table 8: **Stone Questionnaire 4th section:** Just to participant that worker on the industry, AR prototype Benefits and Barriers.

QUESTION	OPTIONS
Benefits	<input type="checkbox"/> Improves productivity <input type="checkbox"/> Enhances safety <input type="checkbox"/> Improves training <input type="checkbox"/> Facilitates maintenance <input type="checkbox"/> Increases efficiency <input type="checkbox"/> More engaging processes
Barriers	<input type="checkbox"/> Technical limitations <input type="checkbox"/> Data security and privacy <input type="checkbox"/> Lack of training and support <input type="checkbox"/> Colleague resistance <input type="checkbox"/> Discomfort using equipment <input type="checkbox"/> Equipment durability issues
Interest in AR at work	<input type="checkbox"/> Not at all <input type="checkbox"/> Slightly <input type="checkbox"/> Moderately <input type="checkbox"/> Very <input type="checkbox"/> Extremely
Interest in this prototype	<input type="checkbox"/> Not at all <input type="checkbox"/> Slightly <input type="checkbox"/> Moderately <input type="checkbox"/> Very <input type="checkbox"/> Extremely

Table 9: **System Usability Scale questionnaire 5th section.**

STATEMENT	RATING
I would like to use this system frequently	_____
The system is unnecessarily complex	_____
The system was easy to use	_____
I need technical support to use this system	_____
The functions in this system were well integrated	_____
There was too much inconsistency in this system	_____
Most people would learn this system quickly	_____
The system was very cumbersome to use	_____
I felt very confident using the system	_____
I needed to learn a lot before using this system	_____

Table 10: **NASA Task Load Index questionnaire 6th section.**

DIMENSION	DESCRIPTION
Mental Demand	How mentally demanding was the task?
Physical Demand	How physically demanding was the task?
Temporal Demand	How hurried or rushed was the pace of the task?
Performance	How successful were you in accomplishing what you were asked to do?
Effort	How hard did you have to work to accomplish your level of performance?
Frustration	How insecure, discouraged, irritated, stressed, and annoyed were you?

DECLARATION

I declare on my honour that the work presented in this dissertation, entitled “*Integrating Digital Twin and Augmented Reality for Monitoring, Education and Training in the Mineral Industry*”, is original and was conducted by Ana Cassia Vasconcelos Cruz (2222929) under the guidance of Professor Nuno Carlos Sousa Rodrigues (nunorod@ipleiria.pt), Professor Alexandrino José Marques Gonçalves (alex@ipleiria.pt), Professor Roberto Aguiar Ribeiro (roberto.ribeiro@ipleiria.pt) and Professor Anabela Gonçalves Rodrigues Marto (anabela.marto@ipleiria.pt).

Leiria, Fevereiro de 2025

Ana Cassia Vasconcelos Cruz