Project Booklet

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Human-Centric AI-Enabled Extended Reality Applications for the Industry 5.0 Era

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PART ONE · 19 ARTICLES

Architectural Concepts and Methodologies

Foundations of the XR5.0 platform: reference architectures, standards, data management, digital twins, integration strategies, and ethical and legal frameworks governing human-centric XR for Industry 5.0.

Extended Reality-Based Training in the Industry 5.0 Era

Industry 5.0 sets a paradigm shift in the sector, focusing on a person-centric approach that emphasizes human-machine cooperation to improve productivity and worker well-being [1].

One area that is rapidly evolving is industrial training, thanks to recent advancements in XR technology combined with advanced AI paradigms promoting human-AI interaction. This evolution is driving more natural user experiences blending real and virtual elements, while enabling training to be personalized a priori based on individual preferences or characteristics and adapted in real time to user's metrics or performance [2].

With XR-based AI training seamlessly adjusting to users, this trend is leading to more organic interaction and enhancing the learning experience of trainees. The transition from virtual reality (VR) to Extended Reality (XR), as illustrated by Milgram's Reality-Virtuality Continuum [3], also allows more flexible training that can be conducted in various formats and settings. This improves learning outcomes by facilitating training activities in both off-the-job and on-the-job contexts.

Off-the-Job Training

Off-the-job training refers to training activities that take place away from the actual work environment, typically conducted in person at a training center or through online courses. This form of training focuses on developing skills, knowledge, and competencies outside the stressors of the workplace, allowing learning to occur in a more structured and focused manner. VR may be one of the best options for off-the-job training, providing highly immersive and interactive learning environments that allow users to engage deeply with the training materials. This capability is particularly beneficial for training on new equipment or procedures, as users can focus on the task without the risk of real-world consequences. By combining various feedback sources, users quickly understand and respond to different scenarios, thereby improving their decision-making skills. The natural and intuitive interaction methods, which mimic real-world motor coordination and physical movements, contribute to faster and more effective learning. Users can engage with interactive 3D models and spatially aware interfaces that enhance their understanding and retention of complex operational processes.

On-the-Job Training

On-the-job training refers to training activities that take place directly within the workplace environment, typically involving guidance from a senior element or supervisor. XR training opens new possibilities to the training activity by blending real and virtual elements, overlaying real-time data directly onto physical elements. This feature is critical for monitoring multiple pieces of equipment and making simultaneous decisions based on diverse information sources. On the shop floor, XR promotes spatial awareness by allowing operators to view objects in their actual spatial environment, aiding them in making informed decisions and enhancing their contextual understanding of the operational environment. This form of augmented feedback with real-world elements is essential for continuous

improvement and skill refinement. By practicing in a mixed reality environment that combines virtual and real-world elements, operators can prepare for real-world challenges and enhance their procedural knowledge without interrupting actual production processes.

New opportunities with XR-based AI training

The integration of AI with XR features in both off-the-job and on-the-job training opens new opportunities for personalization and adaptation of training scenarios in Industry 5.0. In the context of XR5.0, we are now exploring how AI-based training can contribute to customizing training programs to meet individual requirements while allowing real-time adaptation to the user. AI-driven training will make the learning process more intuitive and effective by bringing it closer to the user's needs, reducing the gap between theoretical knowledge and real-world application. Therefore, the integration of XR and AI will not only enhance the training experience but also contribute to the overall goal of Industry 5.0 that focuses on creating a harmonious and productive synergy between humans and technology.

References

[1] Moser T, Wolfartsberger J, Sorko S, Abu Naim B(2024)Extended Reality Based Education and Training for Human-Centric Industry 5.0 Skill Enhancement NOMS 2024-2024 IEEE Network Operations and Management Symposium10.1109/NOMS59830.2024.10575896(1-4).

[2] Moser TSchlager A(2024)Training and Assistance in Industrial Environments Using Extended Reality2024 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)10.1109/VRW62533.2024.00023(97-103)Online publication date: 16-Mar-2024

[3] Singh J, Singh G, Verma R, Prabha C. (2023). Exploring the Evolving Landscape of Extended Reality (XR) Technology. 3rd International Conference on Smart Generation Computing, Communication and Networking (SMART GENCON) Karnataka, India. Dec 29-31, 2023

Shaping the Future: Designing XR5.0 Architecture for Industry 5.0 Applications

AI and XR Solutions Integration: Architectural Foundations for Industry 5.0

The convergence of Artificial Intelligence (AI) and Extended Reality (XR) technologies is revolutionizing industries, paving the way for the realization of Industry 5.0's vision, which emphasizes human-centric, sustainable, and intelligent manufacturing. At the heart of this revolution lies the need for robust, scalable, and interoperable architectures that integrate these advanced technologies seamlessly. The XR5.0 Reference Architecture stands as a blueprint for achieving this integration, driving innovation and collaboration in human-machine ecosystems.

The Need for a Unified Architecture

Industry 5.0 envisions smarter, more adaptive systems where humans and machines work side by side to enhance efficiency, sustainability, and user experience. AI and XR technologies play a pivotal role in achieving this vision. AI brings intelligent decision-making, processing capabilities, and automation to the table, while XR enhances human interaction with immersive, real-time data visualization and contextualized assistance.

However, integrating these technologies into complex industrial environments requires a holistic approach. A unified reference architecture must address challenges such as data interoperability, modular design, scalability, and alignment with global standards. XR5.0's architecture delivers on these needs by bridging the gap between cutting-edge tools and practical industry applications.

To set the stage for the XR5.0 Reference Architecture, a Value Stream was first explored, which outlines the flow of value from business needs to technological solutions. This foundational perspective provides critical context for understanding how XR5.0 enables seamless integration between AI and XR solutions.

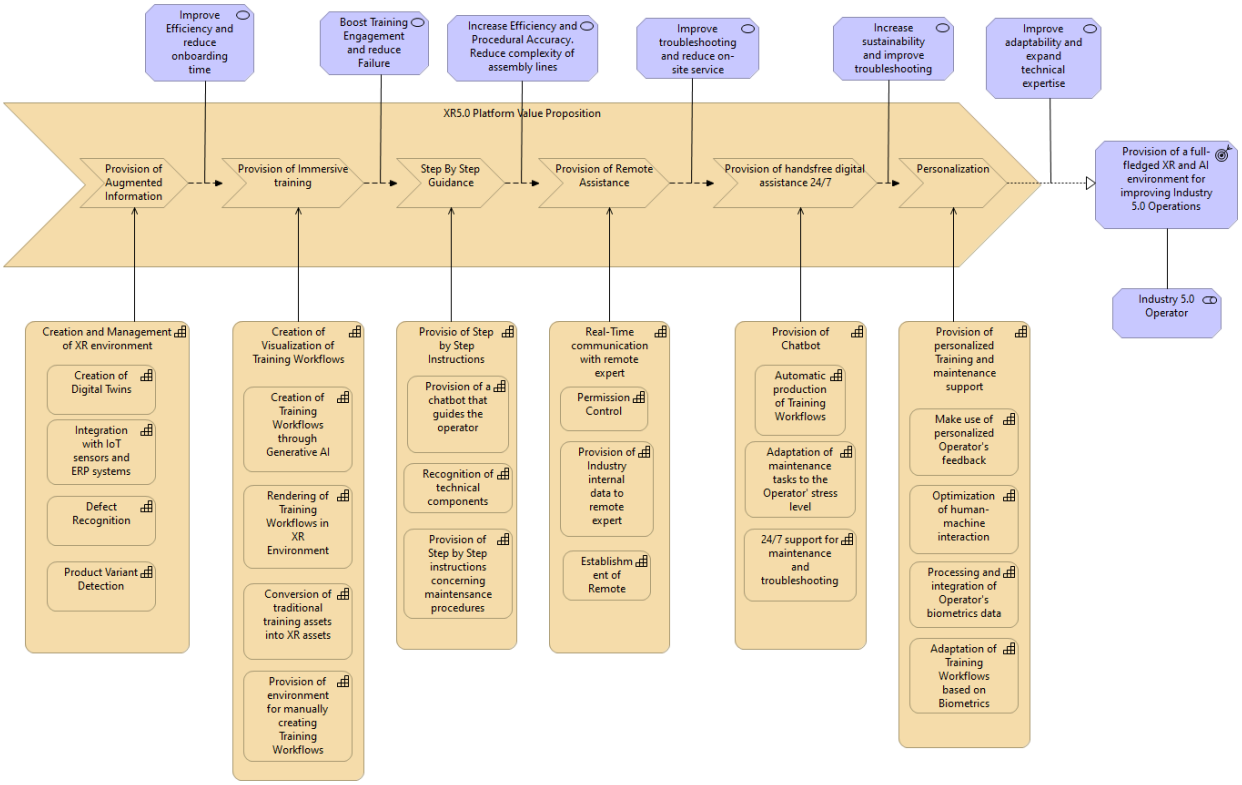


Figure 1: Vision of the XR5.0 Architecture (Value Stream- Strategy layer)

Blueprint for Integration: The XR5.0 Architecture

The XR5.0 Reference Architecture lays the foundation for integrating AI and XR technologies into Industry 5.0 environments. Based on TOGAF [1] principles and modeled using ArchiMate [2] and C4 methodologies [3], this architecture is both strategic and actionable, addressing business, application, and technology layers.

Business Layer: Human-Centric Processes

The XR5.0 business layer focuses on creating value through human-centric processes. For example, it introduces services like **Maintenance** and **Personalized Training Assistance**, tailored to enhance operators' capabilities. These services are mapped to business functions that leverage AI-driven insights and XR-enhanced visualizations. By aligning these processes with Industry 5.0's goals, the architecture ensures improved decision-making, safety, and productivity.

Application Layer: Modular and Scalable Tools

At the application level, the architecture integrates tools for AI processing, XR visualization, and XR application orchestration. Components such as **AI Models** (including generative AI and explainable AI) and **XR Visualization Tools** ensure modularity, enabling flexibility and customization. These tools interoperate through defined interfaces and APIs, ensuring seamless communication across systems while being adaptable to future technological advancements.

Technology Layer: Interoperable Infrastructure

The technology layer emphasizes scalability, security, and performance. It incorporates cloud repositories, IoT integration, and high-performance computing environments to support the computational demands of AI and XR. By leveraging cutting-edge hardware and software standards, this layer ensures robust and efficient operations.

Alignment with Industry Standards

The XR5.0 Reference Architecture doesn't exist in isolation; it aligns with established frameworks and standards to ensure compatibility, compliance, and interoperability. For example:

- **RAMI 4.0** provides a structured approach to industrial systems, which XR5.0 mirrors in its layered design [4].
- **OpenXR** ensures cross-platform XR compatibility, seamlessly integrating immersive experiences into the workflow [5].
- **XRSI** emphasizes security and privacy, which are embedded in the XR5.0 architecture to protect sensitive industrial data.
  This alignment not only boosts confidence in the architecture's adaptability but also facilitates its adoption across diverse industrial settings [6].

Driving Innovation with Enterprise and Solution Architecture

To make the architecture accessible to diverse stakeholders, XR5.0 employs two complementary approaches:

- **Enterprise Architecture**: Offers a strategic view of the system, showing how business objectives align with technological capabilities. This is essential for senior stakeholders and decision-makers who need to understand the "big picture."
- **Solution Architecture**: Provides operational-level detail, breaking down the system into components and workflows. This aids developers and implementers in translating the vision into practical solutions.

Together, these views ensure that the architecture is not only visionary but also actionable.

From Vision to Reality: Industry 5.0 in Action

The XR5.0 architecture is more than a theoretical framework—it's a practical guide for building systems that embody Industry 5.0 principles. For instance, in troubleshooting scenarios, AI analyzes sensor data or images in order to identify failures, while XR visualizes this information in real-time, enabling operators to act swiftly. Similarly, in training environments, AI-driven adaptive workflows combined with XR's immersive simulations empower workers with contextualized and hands-free guidance.

Such use cases demonstrate the tangible benefits of integrating AI and XR through a well-structured architecture, showcasing how Industry 5.0 can enhance both human and machine capabilities.

The Road Ahead

As industries continue to adopt AI and XR solutions, the role of architectures like XR5.0 will become increasingly critical. By ensuring interoperability, scalability, and alignment with global standards, XR5.0 provides a pathway for industries to embrace the full potential of Industry 5.0. This architecture is not just about technology, it's also about creating systems that empower humans, improve efficiency, and drive sustainable growth.

With XR5.0, the future of Industry 5.0 is within reach, promising smarter, safer, and more connected industrial environments.

- The Open Group, *TOGAF® Standard, 10th Edition: A Pocket Guide*. The Open Group, 2022.
- The Open Group, ArchiMate 3.2 Specification. The Open Group, 2023. [Online]. Available: https://pubs.opengroup.org/architecture/archimate3-doc/
- S. Brown, "C4 Model for Software Architecture," [Online]. Available: https://c4model.com/. [Accessed: 28-Nov-2024]
- Adolphs, P., Bedenbender, H., Dirzus, D., Ehlich, M., Epple, U., Hankel, M., Wollschlaeger, M. (2015) "Reference Architecture Model Industrie 4.0 (RAMI 4.0)". VDI/VDE and ZVEI. Retrieved from https://www.zvei.org/en/subjects/industry-4-0/the-reference-architectural-model-rami- 40-and-the-industrie-40-component/ [last accessed 21/05/2021]
- Khronos Group, "OpenXR Specification," The Khronos Group, [Online]. Available: https://www.khronos.org/openxr/. [Accessed: 16-Dec-2024].
- XRSI, "XRSI Privacy and Safety Framework," [Online]. Available: https://xrsi.org/. [Accessed: Dec. 7, 2024].

Evolving the Future: Advancing the XR5.0 Architecture for Industry 5.0 Applications

As industries continue to evolve, Industry 5.0 is gaining momentum, focusing on human-centric approaches, sustainability, and the integration of advanced technologies. In this context, XR5.0 is developing a cutting-edge architecture that integrates Extended Reality (XR), Artificial Intelligence (AI), and cloud systems to empower the next generation of industrial applications. By combining these technologies, the architecture aims to transform traditional processes into more efficient, intelligent, and adaptable workflows, offering companies new ways to enhance their operations, training, and maintenance strategies.

Bridging the Gap Between Digital and Physical Worlds

At the core of XR5.0's architecture is the seamless integration of XR technologies, AI models, and various industrial systems. The architecture provides a flexible, scalable framework for industrial applications, particularly in areas such as maintenance, troubleshooting, human-centric training, and optimization of workflows. These capabilities are not only expected to improve operational efficiency but also enhance the human experience in complex industrial settings.

By leveraging XR technologies, the architecture allows users to engage with digital representations of physical environments, such as 3D models, human digital twins, and virtual training simulations. These models are augmented with real-time data and insights, powered by AI, to deliver actionable outcomes. This offers industries a new level of interactivity and engagement with their operational systems.

Key Developments in the Architecture

XR5.0's architecture includes several important developments:

- **Human-Centric Training**: At the heart of this architecture is a personalized training framework that uses human digital twins to create customized learning experiences. This allows for the development of tailored training programs that adapt to the individual's skills and learning progress, resulting in more effective training outcomes.
- **Sensor-Driven Intelligence, Operational Guidance and Process Optimization**: By combining AI-driven recognition with XR technologies, the architecture enables seamless interaction between the physical and digital environments. Sensor data is automatically identified and rendered on top of corresponding equipment via XR interfaces, allowing users to visualize real-time values. Damaged components can be precisely located and linked to their digital twins, enabling detailed inspection and visualization. Operational procedures, such as maintenance checklists and safety protocols, are rendered step-by-step within immersive training sessions. Users are guided through complex tasks, like machine handling, disassembly, or part identification. Moreover, interactive overlays and AI-powered recognition of parts, streamline operations and enhance safety and understanding.

- **Security and Scalability**: Security is a top priority, and the architecture has been designed with OAuth 2.0 to ensure robust user management across multiple tenants. The use of multi-tenancy ensures that data and resources are securely isolated between different industries or organizations, providing scalability as the system expands to serve more customers.

Recent Advancements: New Diagrams and Views

As part of ongoing efforts to refine and extend the architecture, XR5.0 has recently developed several new views and diagrams to better represent and visualize the workflow and functionality of the system as follows:

- **Training Workflow View**: This specialized diagram, developed using ArchiMate [1] and aligned with the TOGAF [2] enterprise architecture framework, depicts the full workflow for creating a training project. It integrates both business and application elements, allowing for a clear understanding of how training projects are created, managed, and delivered. It outlines the various components involved, from content creation to real-time assessment and feedback.
- **Security View**: Another key diagram focuses on the OAuth 2.0 workflow for the entire system. It illustrates how secure authentication and authorization are handled across various components, ensuring that users have the right level of access to training programs, AI models, and industrial data.
- **Personalized Training View**: This diagram emphasizes the use of human digital twins to create personalized training experiences. By using real-time data from sensors, AI models, and XR technologies, it enables the design of adaptive training workflows that respond to the learner's progress and specific needs.

Key Benefits and Real-World Impact

By adopting XR5.0's architecture, industries can expect to see a significant transformation in their operational processes. The integration of XR and AI models allows for smarter, more responsive systems, capable of predicting and addressing potential issues before they arise. Human-centric training through personalized workflows offers more engaging and effective learning experiences, reducing the time required for skill development. Predictive maintenance powered by AI ensures that equipment remains operational, reducing downtime and extending asset lifecycles.

The architecture is not just about improving operational efficiency; it is also about making the workplace safer, more adaptable, and more human-centric. By empowering workers with personalized training and real-time insights, XR5.0 fosters a more collaborative and productive working environment.

In conclusion, XR5.0's architecture represents a significant leap forward in the convergence of XR, AI, and industrial technologies. With its emphasis on personalized training, intelligent troubleshooting, and system optimization, this architecture is poised to drive impact across diverse industrial sectors. As development progresses, XR5.0 aims to empower businesses to fully harness the potential of Industry 5.0.

- The Open Group, *TOGAF® Standard, 10th Edition: A Pocket Guide*. The Open Group, 2022.
- The Open Group, ArchiMate 3.2 Specification. The Open Group, 2023. [Online]. Available: https://pubs.opengroup.org/architecture/archimate3-doc/

Standards-based XR Architectures for Industrial Use Cases

With the advent of Industry 4.0, it became clear that the design of architectures achieving digitalization to all major parts of the industrial process had to move beyond standard enterprise design approaches, which focused solely on IT components or treated them as standalone solutions to be embedded into an industrial setting. Architecture paradigms, such as RAMI (Figure 1), define a three-dimensional structure in which the first axis defines the hierarchy, the second is the product life cycle, and the third is the architecture layer. This organization achieves two main goals: a) the solution involves all aspects of the production cycle, from machine to digital components, and b) it can be understood by all involved stakeholders as it can break down complex concepts.

As we are moving towards the 5.0 era, it is evident that new architecture paradigms and standards need to be leveraged to achieve the goal of putting worker well-being at the center, promoting sustainability, and reinforcing the contribution of the industry to society. The socio-economic component needs to be emphasized via appropriate extensions, such as the redefinition of layers, modifications of the product life cycle aspects to specifically target sustainability, etc. Even more drastically, new viewpoints may be added to the traditional architectural design paradigms that are specific to social and worker well-being aspects.

While a full Industry 5.0 reference architecture may be a huge endeavour that requires the collaboration of many standardization bodies, in XR5.0, we make an effort to contribute towards this direction by focusing on a subset of Industry 5.0 enablers, having to do with extended and augmented reality, as well as with AI. XR5.0 focuses on providing the means that enable workers to assess the situation remotely using minimal effort and commuting, receive help via digital helpers and real-time consultation, reproduce scenarios, train via digital twins, etc.

As such, the architecture that will support these aspects will be a flexible schema for incorporating existing and future extended reality solutions while also preserving the main characteristics that materialize a successful Industry 4.0 or Industry 5.0 solution.

As the field of reference architectures for Industry 5.0 is relatively new, there exist few propositions. One of the most prominent ones is the STAR Architecture (Figure 2), which was designed with a focus on AI-based Industry 5.0 systems. STAR defines three vertical domains, namely Cyber Security, Human-Robot Collaboration, and Safety. These are all served by the Explainable AI and Open Analytics functionalities. All these are very relevant to XR5.0; however, a new horizontal functionality, that of "Extended and Augmented Reality," is added. This functionality is used to account for all the technological enablers that are going to be implemented in XR5.0 having to do with XR and AR. The functionality will be implemented by components using the ever-developing OpenXR standard that allows the integration of XR hardware with a multitude of devices, browsers, and engines. This flexibility can allow for easy integration of new XR solutions, which, in turn, can allow for easy addition of new domains, should the need arise.

For the design process itself and to ensure that the complex use cases that XR5.0 aspires to fulfill are materialized, standard practices of iterative architecture design will be used, namely the TOGAF ADM cycle. Each cycle will aim to cover a greater percentage of the evolving user requirements. The Archimate modelling language will be used to code the architecture and to present the necessary viewpoints. Specifically, designated viewpoints will highlight the alignment of the architecture with RAMI and STAR as well as the new extensions our methodology proposes for incorporating extended reality into existing standards and reference architectures.

Last but not least, our architecture will present all the necessary business and application interfaces for connecting to third-party solutions. These interfaces will also serve as a staging point to integrate XR5.0 into the EU XR Platform, which is one of the main goals of our project.

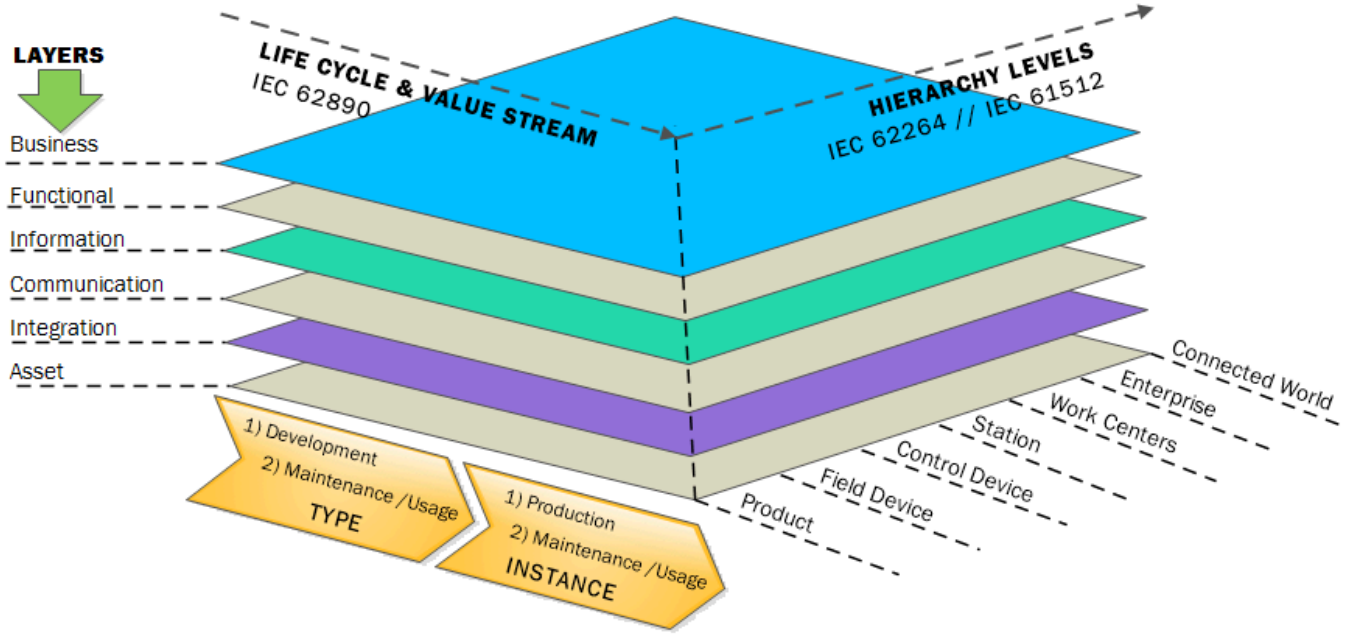


Figure 1: The RAMI Architecture

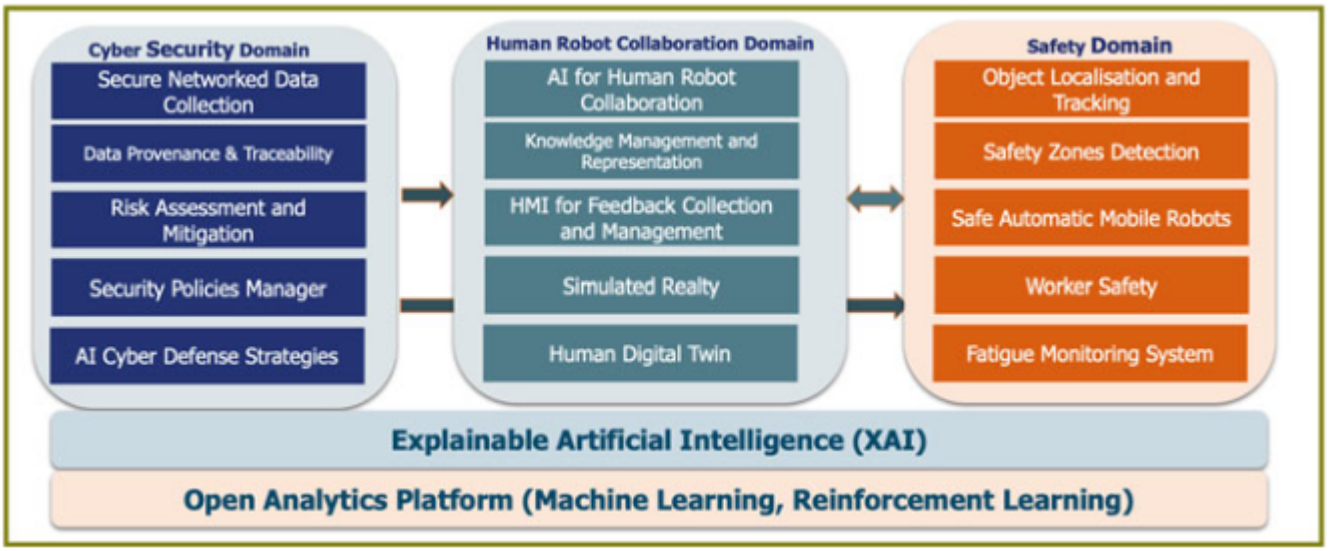


Figure 2: The STAR Industry 5.0 Architecture

XR Standards Landscape

Standards provide important benefits to industrial organisations and one of the most important is enabling interoperability of components and technologies coming from different suppliers making possible complex solutions, but also ensuring consistency of implementation across deployments so information and services can be easily shared. Standards enable efficient markets where buyers of technology have a choice of suppliers, also greater confidence when technologies utilise widely adopted standards - both in reliability and also their evolution through open and transparent industry consensus processes. Standards also provide protection for people and organisations by ensuring technologies and providers comply with required practices for safety, security, trustworthiness and ethics. Industries such as Manufacturing, Healthcare, Automotive, Aviation, and others have many technology standards, but also many other standards for protecting workers, patients, pedestrians and passengers.

Standards for eExtended Reality (XR) technologies provide similar benefits for buyers of XR technologies for new products and services. As XR encompasses immersive technologies including Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR) there are many XR-related standards published by government sponsored standards organisations such as IEEE, ISO, IEC, ETSI, CEN-CENELEC, and also industry sponsored groupings such as W3C, XRSI and the OpenXR consortium. There are so many that it is not possible to list all of the XR-related standards, but to give an indication of the extent to which standards have been specified the following is a sample of relevant standards grouped by their focus on components, interoperable frameworks or compliance. It should be noted that some broader framework standards also address specific components and safety compliance.

Component Standards

- *ISO/IEC* 18038:2020 – defines the framework and information reference model for representing sensor-based 3D MR worlds.
- *ISO/IEC* 18039:2019 – defines the scope and key concepts of MR and AR, the relevant terms and definition, and generalised system architecture for MR applications, components, systems, services, and specifications.
- *ISO/IEC* 18040:2019 – defines a reference model and base components for representing and controlling single or multiple Live Actors and Entities in an MR scene.
- *ISO/IEC* 18520:2019 – identifies the reference framework for the benchmarking of vision-based spatial registration and tracking methods for MR and AR.
- *INCITS/ISO/IEC* 23000-13: 2021 – specifies mechanisms to connect to local/remote sensors and actuators and remote resources, such as maps and compressed media.
- *ISO/IEC* 23488:2022 – specifies an image-based representation model for target objects/environments using a set of images and optionally the underlying 3D model for accurate and efficient objects/environments representation at an arbitrary viewpoint.

- *ISO/IEC* 19775:2023 – architecture and base components of X3D, which is a software system that integrates network-enabled 3D graphics and multimedia for a 3D time-based space that contains graphic and aural objects that can be dynamically modified through a variety of mechanisms.
- *ISO/IEC* 23884:2021 – specifies physical and material parameters of virtual or real objects expressed to support comprehensive haptic rendering methods, such as stiffness, friction and micro-textures. It supplements other standards that describe scene or content description and information models for VR and MR.

Framework Standards

- *ETSI* Augmented Reality Framework (ARF) – defining a framework for the interoperability of AR components, systems and services that specifies relevant components and interfaces required for an AR solution.
- *W3C* WebXR Device API – provides access to input and output capabilities commonly associated with VR and AR devices. It supports development and hosting of VR and AR experiences on the web.
- *Khronos Consortium* OpenXR – an open-source reference providing a common set of APIs for developing XR applications that run across a wide range of AR and VR devices allowing developers to easily adapt solutions to XR platforms for device manufacturers that adopt OpenXR.
- *IEEE* 1589-2020 – specifies an overarching integrated conceptual model that describes interactions between the physical world, the user, and digital information, the context for AR-assisted learning and other parameters of the environment. Two data models are defined with their binding to XML and JSON.
- *IEEE* 2048.101-2023 – specifies the general technical framework, components, integration, and main business processes of AR systems applied to mobile devices including technical requirements, performance requirements and corresponding test methods.

Compliance Standards

- *ISO/IEC* 5927:2024 – specifies how AR and VR devices are to be set up and used in the enterprise workplace in a manner that ensures health and safety is maintained.
- *UL* 8400 – addresses the safety of VR, AR and MR equipment including head-mounted displays, holographic displays, smart glasses, handheld devices, and interactive virtual simulators.
- *XRSI* Privacy and Safety Framework – a baseline set of XR specifications, guidelines, and regulation-agnostic best practices incorporating requirements from the General Data Protection Regulations (GDPR), National Institute of Standards and Technology (NIST) guidance, Family Educational Rights and Privacy Act (FERPA), Children's Online Privacy Protection Rule (COPPA), and other evolving laws.
- *IEEE* Global Initiative on Ethics of Extended Reality – provides guidelines to protect user data and ensure privacy in AR and VR environments, and emphasising the importance of informed consent and transparency in data collection and usage.
- *XR Association* Developer's Guide – provides developers with fundamental design principles to improve applications across all platforms and achieve better user comfort and safety.

There are over 600 publications that address XR standards, guidelines and recommendations, including specifications that target specific vertical sectors such as XR standards for Oil/Gas/Electric, Construction, Education, Healthcare and other industries, as well as for horizontal XR use cases such as Training. ISO has developed the most XR-related standards and guidelines with over 200 publications. Still, there are further areas where new XR standards are being discussed, which are in various stages of preparation including:

- **Streaming XR from the Cloud**: Interfaces and protocols to enable XR experiences delivered over the Internet and reducing the need for substantial local processing capabilities for users. Standardisation in XR streaming will make XR more accessible and scalable for large organisations and for products with high customer volumes such as automobiles.
- **XR for Collaboration Tools**: Remote working has become the norm in many organisations. However, the market is fragmented with multiple collaboration platform suppliers each approaching inclusion of XR and immersive environments with different often proprietary technologies. While multiple providers is important for the market and competitive pricing, standards are needed that enable users to establish and retain familiarity in their XR environments when moving between different supplier collaboration platforms.
- **XR Devices**: There is on-going development of hardware standards to ensure compatibility and performance across different XR devices, which will lower the development costs for XR solutions and provide interoperability of applications across different devices. Work in this area includes standards for display resolution, field of view, and tracking accuracy.
- **Virtual Worlds and Digital Twins**: The concept of the metaverse, a collective virtual shared space, is gaining traction and multiple groupings are addressing technology standards for the development of metaverse spaces, as well as safety, security and ethical standards that should be applied to protect XR users in metaverse environments. Digital twins, which are virtual replicas of physical objects or systems, are also becoming more prevalent in XR applications and standards for how digital twins integrate within XR solutions are needed.

The broad range of available XR standards and initiatives addressing emerging standards are helping to create more immersive, accessible, and versatile XR experiences across various industries. The work within the XR5.0 project is strongly committed to using existing XR standards, and also has specific tasks for introducing the research and innovation results that will be validated within the six industrial pilots as extensions to existing or emerging XR standards.

Co-Creation Workshops: A Methodology to Support Innovation in the XR5.0 Project

Introduction

The XR5.0 Project, a groundbreaking initiative in the Industry 5.0 era, leverages Extended Reality (XR) and Artificial Intelligence (AI) to redefine industrial applications with a human-centric approach. A key element in this transformation has been the co-creation workshops, designed to align technological advancements with real-world industrial needs. These workshops have proven instrumental in shaping the XR5.0 project by bringing together diverse stakeholders to define user requirements, validate technical feasibility, and ensure seamless integration of XR and AI technologies across multiple pilot sites.

The Role of Co-Creation Workshops in XR5.0

Co-creation workshops serve as a collaborative platform where industry experts, technical leaders, pilot representatives, and research institutions converge to shape the development of XR5.0 solutions. These sessions follow a structured methodology to:

- Identify and refine user stories that highlight the specific needs of each pilot project.
- Define Key Performance Indicators (KPIs) to measure the success of technological implementations.
- Determine the technical components and human factors essential for enhancing industrial applications.
- Ensure alignment between pilots and XR5.0 management, fostering seamless integration and effective deployment of solutions.

The XR5.0 Co-Creation Methodology

The co-creation workshops are designed to prioritize pilots' needs using:

- Structured Execution: Ensuring each co-creation session follows a clear workflow, from presenting pilot needs to preparing the final reports.
- Engaging Stakeholders: Bringing together pilot leaders, technical experts, and task coordinators to foster collaboration.
- Iterative Refinement: Reviewing use cases, user stories and requirements through multiple sessions to refine solutions based on industry needs.
- Cross-Pilot Comparisons: Aggregating results from multiple workshops to support identifying common challenges and synergies across different industrial settings.
- Remote Sessions: Using a digital platform to host remote co-creation sessions to facilitate engagement from all XR5.0 partners that are spread across several time zones thorough Europe.

Key Outcomes and Impact

An important objective of the XR5.0 Project is to establish a shared body of knowledge that accelerates the industry adoption of advanced technologies, such as XR and AI. This initiative aims not only to promote technological innovation but also to ensure that solutions are thoughtfully designed to address human needs and tailored to individual states, enhancing usability and impact across diverse applications.

To ensure practical relevance and support data aggregation, the outcomes of the six co-creation workshops were synthesized in the following table. This table provides a consolidated view of the selected Key Performance Indicators (KPIs), human factors, software tools, hardware requirements, and XR5.0 components, offering a clear framework that integrates technical, human-centric, and performance considerations. This synthesis serves as a foundational resource for aligning project outcomes with industry expectations while maintaining a strong focus on user-centric design and operational efficiency.

Points	Pilot 1 - KUKA	Pilot 2 - SH	Pilot 3 - EKSO	Pilot 4 - TAP	Pilot 5 - SPACE	Pilot 6 - LNS
XR5.0 Components	Hololight Hub/Stream, Generative AI, Active Learning Human Digital Twin, Training Programmes	AI-enhanced XR environments, Virtual Assistance Software, Neurosymbolic AI	AI-powered anomaly detection	AI-assisted training environments, Human Digital Twin, AI assistant	Personalized XR training, Real-time remote support, AI for personalization	AI-enhanced XR environments, Real-time remote support, Personalized maintenance instructions
KPIs	>50% faster troubleshooting >30% reduction on physical testing >25% reduction on consumption of test parts/waste	Reduced on-site maintenance, Decreased task completion time, Enhanced technician satisfaction	XR object latency < 1s, 30% training time reduction, Reduced failure identification time	Reduced maintenance time, Error reduction, Stress reduction	20% assembly time reduction, 50% increased engagement, Reduced repair time	35% troubleshooting time reduction, 50% documentation efficiency, 20% reduced learning time
Hardware	KUKA Renovation Robot HoloLens 2, Meta Quest 3	Smart Glasses (HoloLens 2), Smartphones/ Tablets	HoloLens 2, Magic Leap, Mobile devices, Eye-tracking devices	VR headsets, Wearable sensors	VR headsets (Quest 2/3), AR devices (Smartphones/ Tablets), Eye-tracking devices	AR glasses (Almer AR Glasses), Smartphones/ Tablets
Software	Hololight Stream/Hub, Generative AI Active Learning Human Digital Twin Training Programmes	OCU SHARE software, Local AI hosting	Generative AI, CYENS mobile AR app	IML's VR platform, AI-driven XR content	XR5.0 platform, Hololight HUB and Stream, Cloud-based repository	AI-driven XR interface, Cloud-based documentation BynderSync DAM TicketFlow CRM (Salesforce) SmartChat Assist (Chatbot) MyLNS Portal PowerInsights Suite
Human Factors	Fatigue and task load monitoring, Attention capture, Digital skills	Task load and fatigue monitoring, Digital skills, User experience (UX)	Fatigue, Task load, Stress, Attention capture, Digital skills, User experience (UX)	Task load and stress management, Real-time feedback, Cognitive load management	Cognitive load and fatigue monitoring, Digital skills, Stress monitoring, User feedback, Perception of effectiveness	Task load optimization, Adaptive learning based on real-time feedback

Conclusion

The co-creation workshops have been a pivotal element in the XR5.0 project, ensuring that technological innovations are aligned with industry requirements. By fostering collaborative engagement and iterative refinement, these workshops have laid a strong foundation for supporting new industrial practices with XR and AI that are centered on human factors. As the project moves forward, these insights will continue to drive efficiency, safety, and innovation, shaping the future of Industry 5.0.

Challenges in Databases and Data Management Systems to Support Modern XR Applications



The world of Extended Reality (XR) brings compelling new opportunities: immersive training, remote collaboration, digital twins, 3D holographic communication, location-aware AR experiences, and more. But these advances also impose demanding requirements on the underlying data infrastructure. XR applications tend to generate large volumes of heterogeneous data (sensor streams, user interactions, spatial tracking data, telemetry, state synchronization), at high velocity and often with real-time / low-latency constraints. Managing, storing, querying, and making sense of this data — often across distributed, edge and cloud environments — challenges traditional database systems.

XR systems typically produce a continuous stream of data: user movements, head/hand tracking, spatial anchors, telemetry from sensors, environment mapping updates, state changes — often for many concurrent users. This creates a classic "velocity" challenge: the data ingestion rate may spike dramatically (e.g. when many users interact, or a scene rapidly changes), requiring a system capable of absorbing many writes per second without becoming a bottleneck. Traditional relational databases often struggle under such workloads: write operations may be slow due to I/O, indexing, concurrency control, and transaction overhead. As a result, XR developers sometimes rely on NoSQL, time-series, or custom data stores — but those come with trade-offs in query flexibility, consistency, or integration complexity. A database designed for high ingestion velocity and massive throughput is critical for XR backends.



XR applications often demand real-time processing: whether for synchronizing state between users in a shared virtual environment, responding to sensor or user input, providing analytics or telemetry dashboards, or updating spatial anchors and environmental data. Latency must remain low to preserve interactivity and immersion. Moreover, building meaningful XR experiences may require combining real-time data with historical data: for example, aggregating user interactions over time, analytics on usage patterns, or performing spatial queries referencing previously stored environment data. Achieving real-time ingestion and real-time analytics over large volumes of data is notoriously difficult. Many traditional systems separate "operational" databases (for fast writes) from "analytical" databases/warehouses (for complex queries), requiring data pipelines or nightly ETL jobs, which introduces delays, increases complexity, and reduces freshness.



XR projects often start small — a pilot, a proof-of-concept, a limited user base — but if successful, they may scale to many concurrent users, or be deployed globally. This growth implies a dramatic increase in data volume (space, interactions, telemetry) and load (concurrent reads/writes, analytics, queries). Traditional relational databases may scale vertically (bigger server), but vertical scaling hits limits quickly. Scaling out introduces complexity, risks of inconsistency, and maintenance overhead. On the other hand, purely NoSQL solutions often sacrifice transactional integrity, query flexibility, or strong consistency guarantees. XR data systems that fail to scale gracefully risk breakdowns, high latency, uneven performance, or unsustainable operational loads — all detrimental to user experience and product reliability.

XR data is not uniform. A single XR application might store: positional tracking data, spatial mapping / 3D environment data, user profiles and preferences, interaction logs, time series telemetry, analytics data, possibly geospatial data (for location-based AR), and metadata. Queries over this data can be complex: temporal queries, spatial queries, aggregation across different data types, joins across user, session, environment, historical archives, analytics & summary tables. Many NoSQL stores lack the expressive power to perform complex joins, relational queries, or efficient aggregations. This leads developers to combine multiple data stores — e.g. one store for time-series telemetry, one for user data, one for spatial indexes, another for analytics — complicating architecture, increasing maintenance overhead, and fragmenting data view. Given how dynamic XR applications are, such data heterogeneity is the rule, not the exception.

In distributed, globally deployed XR systems — possibly spanning edge devices, cloud instances, multiple regions — ensuring data consistency and availability is challenging. Network partitions, server failures, write conflicts all become realistic risks. For XR experiences that require real-time collaboration or synchronized state across users, weak consistency can lead to divergent views, state corruption, or user confusion. Moreover, for analytics or audit use cases, losing data or having inconsistent records undermines reliability and trust. For production-grade XR services, you need a data system with strong consistency, reliable replication, high availability, and robust fault tolerance.Finally, many XR data workloads combine both high write volume (telemetry, streams) and complex reads (analytics, historical queries), which can stress concurrency control mechanisms, leading to contention, performance degradation, or even data loss in naive systems.



This is where LeanXcale enters the picture: a database engineered to address many of the above challenges, combining high ingestion rates, scalable distributed architecture, full SQL support, real-time analytics and operational workloads in a single system.

- **High ingestion & throughput**: LeanXcale uses a specialized storage engine (KiVi), optimized for fast writes, with a dual interface (key-value + SQL) that can ingest data efficiently even under heavy load.
- **Real-time analytics & aggregation**: Thanks to online aggregation and real-time KPI computation built into LeanXcale, it's possible to ingest data and have aggregated metrics or analytics queries immediately available — avoiding separate data pipelines or batch processing delays.
- **Scalable architecture — from small to large**: LeanXcale is designed as a distributed, "shared-nothing" database, with its storage, transactional manager, and query engine all able to scale horizontally and independently. This avoids bottlenecks and supports growth from a single-node MVP to hundreds of servers.
- **Full relational model + flexibility**: Because LeanXcale is ANSI-2003 SQL compliant, supports JOINS, secondary indexes, covering indexes, and integrates with standard BI tools, you can store heterogeneous XR data and query it relationally — combining telemetry, user data, spatial metadata, historical logs, analytics tables — without mixing multiple different data stores.
- **Simplified architecture & lower maintenance overhead**: By consolidating operational workloads (real-time ingestion, transactional data) and analytical workloads (historical queries, KPIs, analytics) into a single database, LeanXcale reduces the need for multiple systems, ETL pipelines, or complex orchestration — which lowers total cost, reduces architectural complexity, and speeds up development/troubleshooting.
- **Reliability & high availability**: LeanXcale offers active–active high availability, replication, hot/cold backups, encryption, access control, essential features for production-grade XR services with critical data or compliance requirements.

Thus, for XR projects, from research prototypes to large-scale deployments, LeanXcale provides a data backbone that aligns well with XR's demanding requirements of velocity, variety, latency, scalability and consistency.

As XR applications mature, from experiments and prototypes to production-ready systems, multi-user platforms, and global-scale deployments, the demands on data management grow considerably. High ingestion rates, real-time analytics, large and heterogeneous data volumes, spatial and temporal complexity, scalability, and strong consistency are not optional: they are prerequisites for delivering good user experience, reliability, and maintainability.

In this context, choosing a data management system that is purpose-built to handle high throughput, scalable distributed workloads, real-time analytics and flexible querying is a strategic decision. A database like LeanXcale aligns well with these demands: by offering a unified, scalable, ACID-compliant SQL database that can function both as operational and analytical backend, LeanXcale can significantly reduce architectural complexity, improve performance, and future-proof XR data infrastructures.

How LeanXcale Can Solve the Major Challenges of Data Management for XR Applications

In the XR (Extended Reality) domain, effective data management is crucial but challenging. The top challenges faced in this area are mostly related with the data volume and variety, the real-time data processing and the data integration and interoperability.

Regarding data volume and variety, XR applications often involve high-resolution video, 3D models and detailed textures, which require substantial storage space. Moreover, XR devices use various sensors (e.g., cameras, gyroscopes, accelerometers) to capture real-time environmental data, while detailed logs of user interactions, such as gestures, eye movements, and voice commands, contribute to the data volume. In fact, efficient storage solutions are needed to manage this data. Traditional storage systems might not be sufficient, requiring scalable cloud-based solutions or specialized databases designed to handle large volumes of diverse data types. To make things worse, XR applications necessitate advanced processing techniques, combining visual data with sensor data to create a coherent and interactive XR experience that is always computationally intensive.

Regarding real-time data processing, XR applications require minimal latency to maintain immersion and prevent user discomfort. Delays in data processing can lead to lag, which can be particularly problematic in VR and AR experiences. Real-time data streaming from sensors to the processing units and back to the display devices is also crucial. This involves not only capturing the data quickly but also transmitting it efficiently. Analyzing data in real-time to provide immediate feedback is critical. For example, an AR application that provides real-time navigation assistance needs to process GPS and visual data instantaneously to offer accurate directions.

For what concerns data integration and interoperability, XR applications often need to integrate data from multiple sources, having different data formats and protocols. The lack of standardized data formats and communication protocols can hinder integration efforts. Developing and adopting industry-wide standards is essential for seamless interoperability, while using APIs and middleware solutions can help in bridging the gap between different systems and devices. These tools facilitate data exchange and integration, but they must be designed to handle the specific requirements of XR data.

LeanXcale can play a crucial role in dealing with all these challenges. The LeanXcale database is a novel distributed database, which can be cloud based, ultra-scalable with elasticity capabilities. It can handle the vast volume of data that XR applications necessitate and scale out its data nodes horizontally as the size of the data grows. Its novel indexing mechanism, which includes global, local and covered indexes, allows for efficient query processing with minimum latency. LeanXcale also allows for data ingestion at very high rates, making it ideal for XR devices that generates data with high velocity and requires the transmission and capture of this data effectively with no delays. It is an SQL compliant database, thus supports the rich expressity of the relational query language to be used for complex query processing. This can be combined with one of its most important innovations, the *online*

aggregates, which calculate aggregation operations incrementally, thus enabling real-time processing and analytics, providing immediate results, a critical challenge in the XR domain. Last but not least, the LeanXcale database is compliant with industry standards and popular analytical frameworks, facilitating the integration and interoperability.

The Role of an XR Streaming Platform for Industrial Training: Exploring Hololight Hub in XR5.0

In today's rapidly evolving industrial landscape, organizations are turning to Extended Reality (XR)—encompassing Augmented, Virtual, and Mixed Realities—for immersive and cost-effective employee training in low-risk industrial environments. XR addresses the unique challenges faced by industries such as manufacturing, healthcare, construction, and aerospace, where traditional training methods like classroom sessions, simulations, and manuals often fall short. By offering interactive, hands-on learning experiences, XR allows employees to safely train in high-stakes scenarios involving hazardous materials or complex machinery without disrupting production. With features like rapid feedback, performance tracking, and scenario-based learning, XR ensures better knowledge retention, making it a critical tool for workforce development. However, while XR has a lot of potential, scaling it can be difficult. Here's where XR streaming platforms such as Hololight's Hololight Hub come in.

Hololight Hub: The XR Streaming Platform

Hololight Hub is a cloud-based system that hosts, manages, and streams XR applications in real time to devices, whether from the cloud or on-premises servers. It ensures high-quality, low-latency streaming, enabling smooth experiences regardless of device capabilities. Features like application version control, user management, analytics, and robust security protocols make it an efficient solution for industrial training. By centralizing XR application management, organizations can quickly update their content and provide access to users across multiple locations, simplifying operations while enhancing scalability.

Hololight Hub, deployed in the XR5.0 project as the XR5.0 training platform, uses Amazon Web Services (AWS) to host XR5.0 apps, leveraging Hololight Stream, a remote rendering solution for immersive, lag-free and secure streaming. Administrators manage access, track progress, and update content through a centralized dashboard, ensuring seamless delivery. The platform supports various devices enabling enterprises to select the device that best aligns with their specific use cases as well as adapting to device capabilities while offering other device features like spatial mapping hand and eye tracking for enhanced AR experiences. With high-fidelity 3D content streaming and secure data management within controlled networks, Hololight Hub delivers immersive XR experiences while minimizing IT workloads.

The Benefits of Using an XR Streaming Platform for Industrial Training

1. Centrally Managed Infrastructure

Hololight Hub allows organizations to centrally manage all training applications and user data, making it easier to deploy training content across multiple locations. This capability is particularly useful for industries with a geographically dispersed workforce. A new training module can be uploaded once and streamed to employees worldwide, ensuring uniform training experiences and avoiding discrepancies that could occur with localized training.

2. Device-Agnostic Access

Industrial environments often consist of a range of devices with varying capabilities. Hololight Hub streaming platform enables training to be accessed on different devices, including AR headsets such as Microsoft HoloLens 2, VR headsets such as Meta Quest 3, Windows Desktop and iOS devices. By streaming content from the cloud, the platform allows even lower-end devices to access high-quality XR applications, thus reducing the need for expensive, specialized hardware.

3. Cost Savings

Physical simulations and custom hardware setups can be prohibitively expensive to create and maintain. By taking a cloud-based approach Hololight Hub reduces cost by eliminating the need for complex on-site installations. Moreover, since training is hosted and managed in the cloud, hardware requirements are minimized on the user side, allowing companies to deliver immersive training on a larger scale without a substantial upfront investment.

4. Scalability and Flexibility

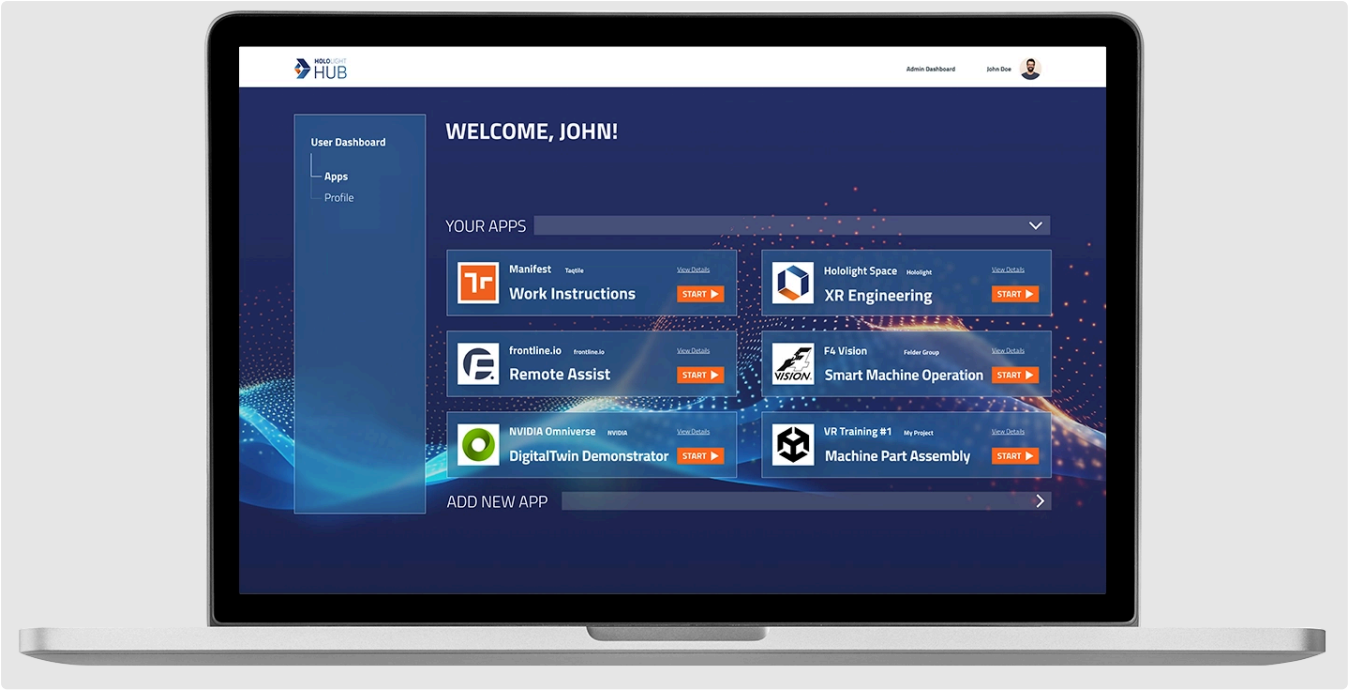
One of the most valuable aspects of XR streaming platforms such as Hololight Hub is their scalability. As companies grow, they can easily scale their training programs to match their expanding workforce without needing additional local hardware. Training modules can be customized to meet the specific needs of various job roles, and employees can access them from anywhere with an internet connection. This flexibility is invaluable in dynamic industrial settings.

5. Enhanced Security

Industrial training often involves sensitive information, from proprietary processes to safety protocols. XR streaming platforms offer robust security measures, including encrypted data transfer and user access management, ensuring that confidential information remains secure. By managing access to applications and monitoring data flows, companies can comply with regulatory standards and protect their valuable intellectual property.

Role of Streaming Platform within XR5.0 project

The XR5.0 project will design, build and provide a cloud-based XR platform to train industrial operators in an immersive environment. The XR5.0 training platform is based on HOLO's Hololight Hub streaming platform wherein XR5.0-enabled XR apps will be hosted and streamed. The platform will provide a cloud repository, developed by partner SYN, that will enable industrial enterprises to upload and store their training materials and assets. The repository will be integrated with the XR platform to enable streaming of XR training assets in real-time to end-users. In addition, XR5.0 training platform will offer the industrial enterprise the functionality to design and develop immersive training programs (developed by partner IML) that will address the needs of various operators based on expertise and level in industrial environments in alignment with XR5.0 pilots and use cases. As a result, it will enable industrial operators to be completely immersed during training sessions in a high-quality and robust virtual environment grounded in a real-world industrial context. In addition, the project via its XR5.0 apps hosted on the XR5.0 training platform will use AI technologies and the worker's digital image to personalise the XR training content and flows to the workers' needs.



Hololight Hub Admin View: The remote expert/admin utilises a web interface to upload and manage applications, training material, assets and users.



Hololight Hub User View: On the XR device, trainees/users can access a library of XR applications specifically assigned to them. Depending on the context of their task or training, they can select and run the appropriate application from this library.

Learn more:

- Hololight Hub – hololight.com/products/hololight-hub-industrial-metaverse-platform
- XR and AI Supercharged: Scaling Reality for Enterprises | XR Crisp LIVE – vimeo.com/1031869921
- Everything you need – Hololight Hub – vimeo.com/1017522894

Integrating Edge Devices with XR Environments for Personalized Training and Repairs Using Unity

In the fast-paced world of physical security, precision, safety, and efficiency are essential. Companies like SPACE, which integrate advanced edge devices into security systems, are constantly seeking ways to improve their workflows. These devices—equipped with sensors, actuators, and LTE modems—play a crucial role in real-time incident response for high-security environments. However, their complex configurations make assembly and maintenance challenging.

By adopting Extended Reality (XR) technologies, SPACE is transforming how its workforce engages with these complex devices. Leveraging SYN's Unity-based XR platform, SPACE provides workers with personalized, immersive training experiences and real-time remote support, boosting both productivity and accuracy.

The Challenge

SPACE's edge devices are integral to security infrastructures, such as those used in the banking sector. These devices are part of the Guardian™ 2.0 PSIM platform, which automates various incident response actions like:

- Triggering alarms
- Locking doors and safes
- Controlling lighting and other security measures

While essential to security operations, the diversity of components and the complexity of configurations make the assembly and repair processes both time-consuming and prone to errors.

The Solution: XR Integration

To overcome these challenges, SPACE and SYN turned to XR technologies. By integrating Unity-powered XR environments into their training and maintenance workflows, they've been able to:

- Provide personalized VR training experiences for assembling edge devices.
- Offer AR-guided remote repair instructions for technicians in the field.

Key Benefits of XR Integration

- **Tailored Learning for All Skill Levels:** Using AI-driven XR content, SPACE ensures that workers receive training tailored to their individual expertise.
  - Beginners get step-by-step, detailed instructions.
  - Experienced technicians receive concise, high-level guidance, reducing training and task completion times.

- **Enhanced Precision and Safety:** The immersive nature of the Unity-based XR platform allows workers to interact with 3D visualizations of the devices. This ensures:
  - Fewer assembly errors
  - Greater procedural accuracy
  - Improved safety during both assembly and maintenance
- **Real-Time Remote Support:** With AR-guided workflows, technicians can perform repairs on-site, guided by AI-enhanced instructions. This approach:
  - Reduces reliance on in-person support
  - Speeds up repair times
  - Lowers operational downtime and costs

How It Works

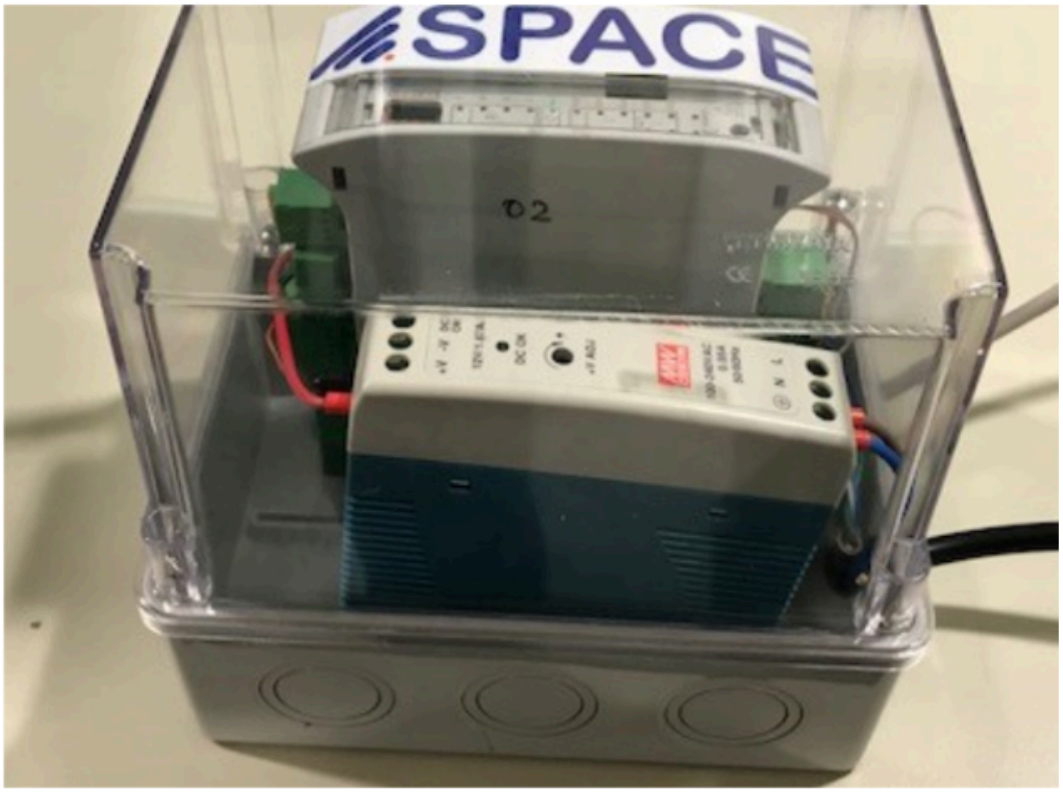
- **VR for Assembly Training:** Workers use VR headsets to interact with digital twins of the edge devices. Depending on their skill level, the AI adapts the training content, providing appropriate guidance through immersive 3D environments.
- **AR for Field Repairs:** Field technicians use AR glasses to view real-time instructions overlaid onto the physical devices they are repairing. The AI-driven system provides tailored recommendations based on the technician's expertise, ensuring quick and accurate defect resolution.

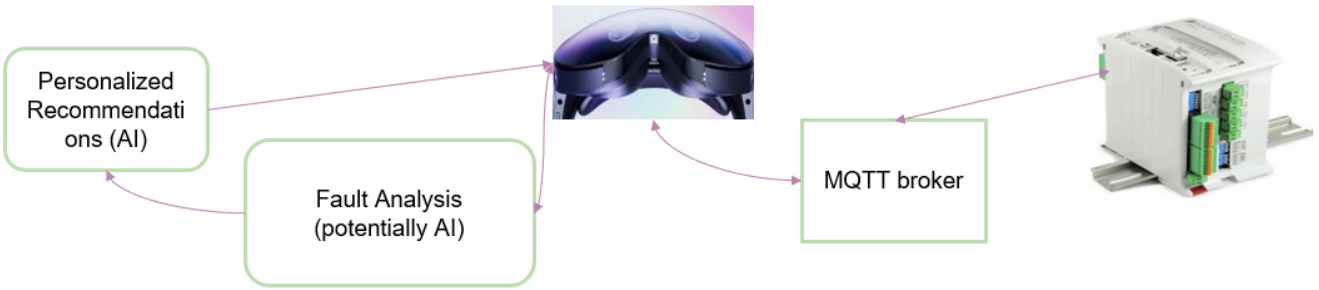
The Future of Industrial XR

The use of XR technologies, especially when combined with AI-driven personalization, is setting a new standard in industrial processes. For SYN, integrating Unity's XR platform into their operations has not only streamlined complex tasks but also ensured that workers are better prepared and more proficient in handling edge devices.

As industries continue to innovate, the role of XR technologies in optimizing workflows and boosting operational efficiency will only grow. Through its adoption of these cutting-edge solutions, SPACE and SYN are paving the way for the future of industrial training and maintenance, where immersive technologies and AI work hand-in-hand to drive results.




SPACE
02


Personalized Recommendations (AI)
Fault Analysis (potentially AI)
MQTT broker

Integrating Legacy Systems with XR5.0: Challenges and Solutions in Industrial Robotics

In the fast-evolving world of industrial automation, innovation often collides with reality. At KUKA Assembly and Test GmbH, we're proud to be at the forefront of robotics and smart manufacturing—but like many industrial leaders, we face a critical challenge: how to integrate cutting-edge technologies like XR5.0 into our existing legacy systems.

The Challenge: Bridging Old and New

Legacy systems, like PLCs, robot controllers, and factory IT infrastructure, are essential in manufacturing. They're reliable, proven, and deeply embedded in daily operations. But they weren't built with immersive technologies like XR (Extended Reality) or AI in mind.

This creates several challenges:

- Data accessibility: Systems often lack modern APIs or real-time data streaming capabilities
- Interoperability: Integrating XR devices like HoloLens with older control systems requires custom interfaces and middleware.
- Scalability: Architectures may not be the same thus individual approaches are needed to implement XR applications
- Security and compliance: Ensuring secure data exchange between old systems and new XR platforms is non-trivial

XR5.0 brings a suite of human-centric, AI-powered tools that are designed to work *with* existing systems—not replace them. Here's how it helps KUKA overcome integration barriers:

- Digital Twin Layering: XR5.0 enables the creation of digital twins that mirror kinematic behavior using signals from PLCs via OPC UA. This allows real-time visualization of machine states in XR environments without altering the underlying system.
- Modular Architecture: The XR5.0 platform supports modular integration, meaning we can selectively connect XR interfaces to specific parts of our legacy infrastructure—starting small and scaling up.
- Generative AI for Simulation: By generating virtual models of product variants and machine configurations, XR5.0 allows us to simulate and test scenarios without disrupting live systems
- Reduced reliance on physical test parts through virtual commissioning
- Faster troubleshooting via real-time fault detection and XR-guided diagnostics
- Improved training outcomes with immersive, personalized learning experiences

Looking Ahead

Integrating XR5.0 with legacy systems isn't just a technical upgrade, it's a strategic move toward a more agile, sustainable, and human-centric manufacturing future. At KUKA, we're excited to continue this journey, proving that innovation doesn't mean starting from scratch, it means building smarter on what already works.

Personalizing XR Applications and Human-Robot Interaction with Digital Twins

The rapid incursion of Extended Reality (XR) technologies, encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), is significantly transforming the landscape of Human-Robot Interaction (HRI) within industrial settings. This evolution transcends the mere physical cohabitation of humans and robots, venturing into a realm where deep integration is facilitated through multimodal interactions. Such interactions extend beyond traditional communication, involving vision, auditory signals, tactile feedback, and even physiological understanding.

At the forefront of this transformative wave is the concept of the Human Digital Twin (HDT). HDTs advance beyond mere virtual replicas of production systems [1], incorporating human characteristics and behaviors into digital models of complex systems (e.g., collaborative robotics work cells). Such characteristics and behaviors can include the perceived fatigue of workers, worker presence, and hand dominance, which can enhance task allocation and planning [2] (see video). Interpreting human intentions (e.g., human-robot object handovers) makes exchanges and interactions safer and more efficient [3].

The necessity for adaptive interfaces becomes apparent in the realm of XR applications, particularly when addressing diverse roles within a manufacturing system. For instance, in a simulated production setting, a maintenance technician focuses on the equipment's condition and wear levels, a production manager monitors the production line's key performance indicators, and a quality manager examines the output's conformity parameters [5]. Within such a framework, HDTs contribute to enhancing adaptiveness and personalisation, paving the way towards more dynamic and interactive collaborative spaces.

The XR5.0 project, funded by the European Union's research and innovation programme (GA: 101135209), aims to develop, demonstrate, and validate a novel Person-Centric and AI-based XR paradigm that will be tailored to the requirements and nature of I5.0 applications.

SUPSI will contribute to XR5.0 by providing Clawdite [6], an IIoT Platform that supports the easy and fast ramp-up of HDT and serve as a centralized repository for worker-related data fed by Artificial Intelligence (AI) modules to understand human intentions, preferences, and contextual cues. Clawdite, originally developed within the project STAR, will be extended in XR5.0 to provide contextual data and real-time sensory inputs needed to personalizing XR applications and human-robot interactions.

SUPSI will target the design of faithful digital images of workers to personalise XR functionalities. Additionally, specific mechanisms will be developed for dynamically adapting XR content based on the individual needs and contexts of users (e.g., operators, technicians), leveraging advanced AI techniques for real-time content modification. These efforts underline the commitment for creating a workplace where technology enhances human capabilities and where XR technologies serve as a bridge towards more intuitive and human-centric environments.

The integration between HDT and XR technologies marks a significant milestone in the evolution of HRI. This alliance signifies a shift towards work environments where technology is in harmony with human needs, guiding the industry towards new peaks of efficiency and satisfaction in spite of Industry 5.0.

Authors: Emanuele Fagnano, Davide Matteri, Vincenzo Cutrona, Elias Montini. SUPSI, SPS lab

[1] Montini, E., Bonomi, N., Daniele, F., Bettoni, A., Pedrazzoli, P., Carpanzano, E., & Rocco, P. (2021). The human-digital twin in the manufacturing industry: Current perspectives and a glimpse of future. *Trusted artificial intelligence in manufacturing: A review of the emerging wave of ethical and human centric AI technologies for smart production*, 132-147.

[2] Montini, E., Cutrona, V., Dell'Oca, S., Landolfi, G., Bettoni, A., Rocco, P., & Carpanzano, E. (2023). A framework for human-aware collaborative robotics systems development. *Procedia CIRP*, *120*, 1083-1088.

[3] Christen, S., Yang, W., Pérez-D'Arpino, C., Hilliges, O., Fox, D., & Chao, Y. (2023). Learning Human-to-Robot Handovers from Point Clouds. *CVPR 2023*.

[4] Sampieri, A., D'Amely, G., Avogaro, A., Cunico, F., Skenderi, G., Setti, F., Cristani, M., & Galasso, F (2022). Pose Forecasting in Industrial Human-Robot Collaboration. *ECCV 2022*.

[5] Greci L. (2022). XR for Industrial Training & Maintenance. *Chapter 13 - Roadmapping Extended Reality*.

[6] Montini, E., Cutrona, V., Bonomi, N., Landolfi, G., Bettoni, A., Rocco, P., & Carpanzano, E. (2022). An iiot platform for human-aware factory digital twins. *Procedia CIRP*, *107*, 661-667.

How Clawdite Human Digital Twins Empower the XR5.0 Ecosystem



Industry 5.0 (I5.0) places the human worker at the core of next-generation industrial systems, highlighting **well-being**, **safety**, and **personalization** as essential design principles. To achieve this, advanced digital infrastructures are required, capable of managing not only machine and process data but also highly dynamic human-related information.

Clawdite, an extensible Industrial Internet of Things (IIoT)-based platform, was developed to answer this need. Its modular and flexible infrastructure enables the creation of customized digital representations of production systems and their entities, including workers, easing the ramp-up of digital twins and their integration into real-world manufacturing scenarios. SUPSI's extension of Clawdite provides **highly realistic worker and machines avatars** for Extended Reality (XR) applications, creating a foundation for **personalized and adaptive XR functionalities**.

Data Collection and Visualization through Clawdite

At its core, Clawdite supports data collection and visualization from a variety of sources within XR5.0. Data is acquired through UNPARALLEL's gateway applications, such as:

- **Health Monitor** for wearable physiological data,
- **OPC-UA Robot** for robotic axis data, and
- **Pupil Labs Core** for eye tracking information.

This information is mapped through **NOVAAS Asset Administration Shell** and visualized in Grafana dashboards, such as the Worker and Cell Monitoring Dashboard (Figure 1 and Figure 2) and the KUKA Robot Dashboard (Figure 3). These dashboards enable both real-time monitoring and historical data analysis, ensuring **human- and machine-centric transparency**.



Figure 1. Worker Monitoring Dashboard



Figure 2. Cell Monitoring Dashboard



Figure 3. KUKA Robot Dashboard

Clawdite Functional Modules Supporting XR5.0 Pilots

Beyond monitoring, Clawdite plays a key role in directly supporting pilot-specific XR functionalities through dedicated functional modules.

- **Pilot 1 – KUKA (Workers Movement Prediction)**: this module leverages real-time position and orientation tracking of workers in industrial environments. By forecasting future human movements, it enables robots to adapt their behavior intelligently while ensuring safety in human-robot collaboration.
- **Pilot 4 – TAP (Worker Shadowing and Monitoring)**: this module combines expert knowledge transfer with process tracking. It stores and replays the "shadow" of expert Aircraft Maintenance Technicians while monitoring the execution of maintenance procedures. By tracking head and hand movements through XR visors, it provides real-time feedback and guidance.
- **Pilot 5 – SPACE (Training Scenario Adaptability)**: this module integrates user-related data (e.g., age, expertise level) and biometric inputs (e.g., heart rate, HRV). These data streams feed into XR applications and AI models that compute engagement and stress metrics. The training environment can thus dynamically adjust task difficulty, personalizing the learning curve for each user.
- **Pilot 6 – LNS (Troubleshooting Assistance)**: this module acts as a gateway, a central point of interaction for troubleshooting tasks. It integrates external services such as Innov AI Chat Engine, SIE Speech-to-Text, and Oculavis SHARE, delivering real-time support to workers through XR devices like RealWear.

Modularity as the Bridge to XR5.0 Pilots

HDTs were originally conceived to manage heterogeneous data collection and support worker fatigue monitoring. However, Clawdite is not confined to this scope. Its highly modular design has proven essential within XR5.0, enabling the seamless integration of diverse pilot-specific functionalities, ranging

from movement prediction to workers monitoring, while maintaining a unified backbone (Figure 4) allowing Clawdite to flexibly adapt to diverse pilot requirements. As modules continue to mature, this flexibility will keep empowering training, support, and monitoring scenarios, paving the way for truly personalized Industry 5.0 environments.

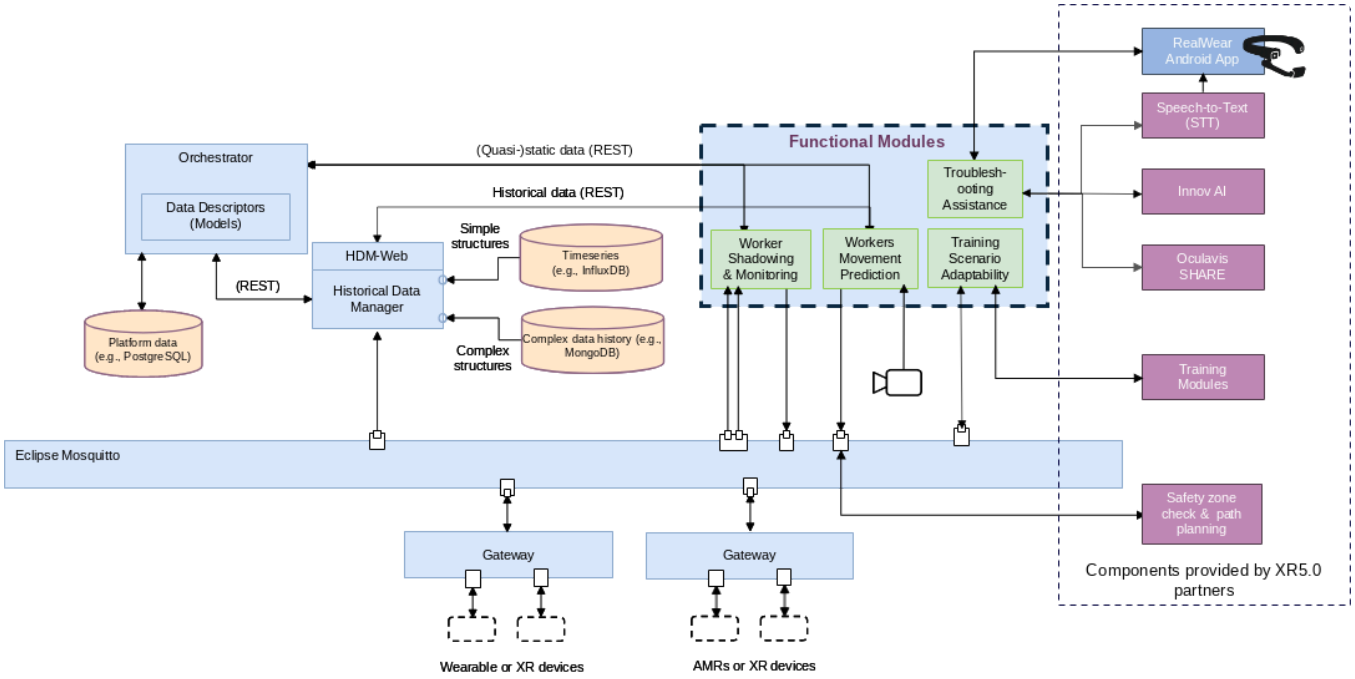


Figure 4. Clawdite Architecture

Authors: Samuele Dell'Oca, Davide Matteri, Vincenzo Cutrona, Elias Montini, Sara Masiero (SUPSI SPS lab)

Utilizing Databases for Knowledge Management in XR5.0 Remote Maintenance

Effective knowledge management is critical for industrial enterprises looking to optimize their maintenance and repair processes. As part of the groundbreaking XR5.0 research project, vector databases have emerged as a powerful solution for capturing, organizing, and delivering critical knowledge seamlessly to technicians working in augmented reality (AR) environments.

Traditional methods of knowledge management, such as document repositories and structured databases, often fall short when real-time context-aware information retrieval is necessary. This is particularly evident in remote maintenance scenarios where technicians require immediate access to precise and relevant procedural knowledge. The XR5.0 project addresses this challenge by utilizing vector databases—advanced, semantic-driven systems capable of delivering highly relevant and context-sensitive information in real-time.

Vector databases operate by converting text, images, and structured data into vector embeddings, effectively capturing the semantic meaning of the content (Figure 1). Within XR5.0's AR-based remote maintenance scenarios, this means technicians receive instant access to accurate, contextually relevant troubleshooting steps, historical maintenance logs, and detailed instructions tailored precisely to the current maintenance task. For instance, when a technician wearing an XR headset like the HoloLens 2 encounters an issue during equipment calibration, the vector database instantly retrieves and presents the most relevant knowledge artifacts, dramatically improving troubleshooting efficiency.

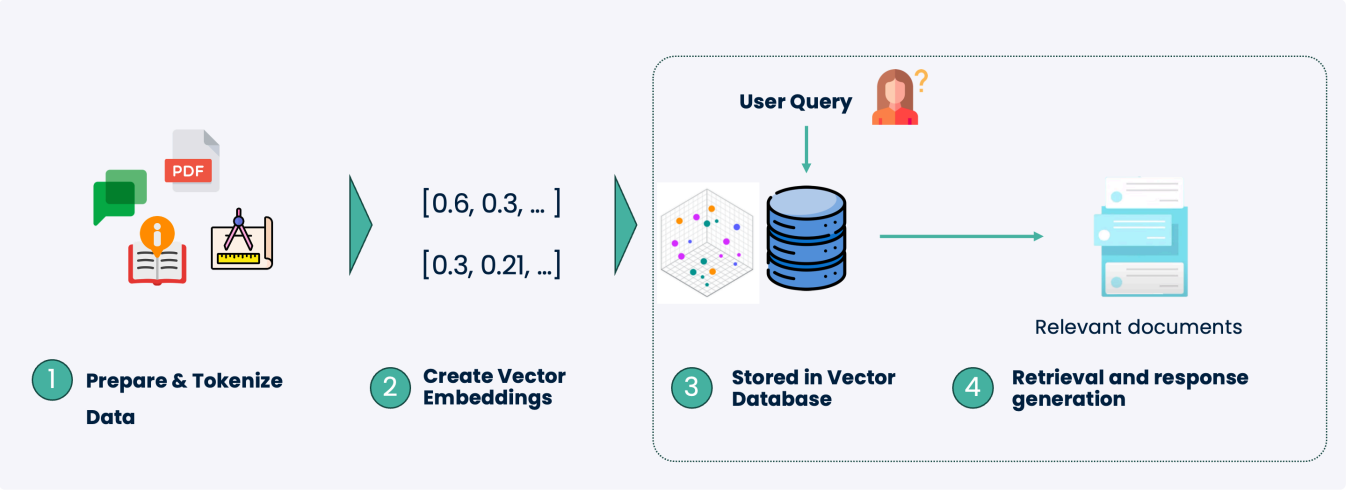


Figure 1: How a vector database works.

Integration with XR5.0's AI-driven features further enhances the capability of these databases. The AI component interprets the technician's context—location, equipment type, prior maintenance activities—and quickly searches the vector database to provide exactly the right guidance at the right moment. Additionally, this AI-enhanced knowledge retrieval continuously learns and adapts, refining its suggestions over time and ensuring a continuous improvement in maintenance procedures and technician performance.

This innovative approach implemented by XR5.0 significantly improves remote maintenance processes by reducing downtime, increasing first-time-fix rates, and enhancing technician satisfaction. Moreover, by ensuring that crucial expert knowledge remains readily available and instantly accessible, vector databases contribute to greater resilience and operational efficiency in modern industrial environments.

In essence, harnessing vector databases within XR5.0 represents a fundamental shift toward smarter, faster, and more reliable knowledge management—essential for the next generation of Industry 5.0.



Ensuring Legal and Ethical Compliance in XR5.0

The XR5.0 project is now entering its final year, making it particularly important to ensure that all project activities remain fully aligned with evolving legal and ethical standards. Over the past few years, the European regulatory landscape for artificial intelligence and digital technologies has undergone significant transformation. One of the most important developments is the adoption of the EU Artificial Intelligence Act, which establishes a comprehensive risk-based framework for the development and deployment of AI systems across the European Union. In parallel, the European Commission has introduced broader regulatory simplification initiatives, including the so-called Digital Omnibus packages, which aim to streamline and clarify the application of existing digital legislation while maintaining strong safeguards for fundamental rights, safety, and transparency.

For research and innovation projects such as XR5.0, these developments are particularly relevant. The Digital Omnibus initiative seeks to reduce regulatory fragmentation and improve coherence between different digital regulatory instruments, including the AI Act, the Digital Services Act, and the Data Act. By clarifying obligations and reducing unnecessary administrative burdens, these reforms are intended to support innovation while ensuring that emerging technologies remain trustworthy, safe, and aligned with European values. For XR5.0, this evolving framework reinforces the importance of embedding ethical and legal considerations directly into the design, testing, and deployment of extended reality (XR) technologies and AI-driven systems.

Against this evolving regulatory background, the XR5.0 consortium has taken a proactive approach to legal and ethical compliance. Rather than treating compliance as a final checkpoint, the project integrates ethical reflection and regulatory alignment throughout the entire lifecycle of the pilots. This approach reflects the principle of ethics by design, ensuring that ethical safeguards and legal requirements are embedded from the earliest stages of system development.

To support this effort, the project relies on the European Commission's Ethics Guidelines for Trustworthy AI. In particular, the seven key requirements identified in the Assessment List for Trustworthy Artificial Intelligence (ALTAI) serve as the conceptual backbone of our evaluation framework. These principles provide a flexible yet robust structure for assessing AI systems, covering dimensions such as human agency and oversight, technical robustness and safety, privacy and data governance, transparency, diversity and fairness, societal and environmental well-being, and accountability.

From a methodological perspective, the assessment combined several complementary approaches. All pilot partners completed structured ALTAI self-assessment questionnaires, which were complemented by targeted interviews and a review of relevant technical and governance documentation. The evaluation included mapping of data flows within the pilots, identification of potential indirect identifiers in datasets, and verification of documentation related to the model lifecycle. Particular attention was paid to the existence of human oversight procedures, logging mechanisms, audit trails, and risk management processes.

This work has been carried out within Work Package 1, Task 1.4, and has been conducted in close collaboration with the project's Ethics Advisory Board. Their involvement ensures that the assessment does not remain purely theoretical but instead directly informs both day-to-day engineering practices and higher-level governance decisions across the consortium. The analysis also complements Deliverable 1.5, Ethical Management and Regulatory Compliance Framework, by translating high-level ethical principles into concrete operational guidance that partners can apply during design, testing, and pilot deployment.

Key Findings and Looking Forward

The review of the pilot activities revealed a generally strong commitment among partners to responsible AI development. Many teams have already taken important steps to clarify the role of human oversight in AI-assisted decision-making processes, and several pilots demonstrate early integration of privacy-by-design principles in their technical architecture. In addition, documentation practices for datasets and models have been taken into account, reflecting a growing awareness of the importance of transparency and traceability in complex AI pipelines.

Ensuring trustworthy and responsible AI is not a one-time exercise but a continuous process that must evolve alongside technological development and regulatory change. For this reason, the XR5.0 consortium views compliance not as a static requirement but as an ongoing commitment to responsible innovation.

As the project approaches its final phase, the consortium will continue refining its ethical and regulatory framework, updating the ALTAI self-assessments, and strengthening governance practices across the pilots. Ultimately, XR5.0 seeks to demonstrate that innovation and responsibility can advance together.

By embedding transparency, accountability, and human oversight into the design of emerging XR technologies, the project aims to help build systems that are not only technically advanced but also socially trustworthy. In doing so, XR5.0 contributes to the broader European vision of human-centric digital transformation, where technological progress supports fundamental rights, societal well-being, and sustainable innovation.

Integrating Ethics and Privacy by Design in XR5.0

The XR5.0 project has taken a significant step forward with the completion of its first deliverable on Ethical Management and Regulatory Compliance. This milestone, part of the project's two key deliverables (M12 and M36), lays the groundwork for integrating ethics and privacy principles into the XR5.0 architecture. The primary aim of this deliverable is to establish a robust framework that ensures compliance with legal and ethical standards while fostering innovation in extended reality technologies.

Understanding the Core Objectives

The core objective of this deliverable is to outline the legal and ethical requirements essential for the responsible development and deployment of XR5.0 tools. A key focus has been placed on incorporating the principles of "ethics and privacy by design" within the system architecture. This proactive approach aims to mitigate potential risks associated with data processing and enhance user trust in XR technologies.

Collaborative Development and Stakeholder Engagement

Creating this deliverable was a collaborative effort that involved active engagement with project partners, particularly those involved in tool development and pilot case implementation. To gather diverse insights, we conducted several questionnaires with partners, focusing on the specific requirements of various use cases (UCs). This process was supplemented with online meetings and email communications, ensuring a comprehensive and informed analysis.

We also leveraged previously completed deliverables to build upon existing knowledge and align the current work with the project's broader objectives. This inclusive approach has helped in identifying key legal and ethical challenges early on, enabling the development of tailored solutions.

Key Findings and Data Protection Insights

The analysis conducted as part of this deliverable revealed that the XR5.0 project tools and pilot demonstrations will process various data categories, including personal data related to technicians and workers. Some of this data may be sensitive, necessitating stringent data protection measures.

To ensure compliance with the General Data Protection Regulation (GDPR), the following measures have been recommended:

- **Obtaining Explicit Consent:** Ensuring individuals are fully informed about data processing activities and provide their explicit consent.
- **Data Minimisation:** Limiting data collection to only what is strictly necessary for the intended purposes.
- **Implementing Appropriate Safeguards:** Establishing robust technical and organizational measures to protect personal data.

Cybersecurity: A Core Consideration

Given the sensitivity of the data involved, cybersecurity remains a top priority. Compliance with the NIS 2 Directive is crucial, requiring a risk-based approach to incident handling and the implementation of security-by-design principles. The Cyber Resilience Act has also been highlighted as a critical regulatory framework, mandating the integration of security measures throughout the product lifecycle. Additionally, the certification scheme under the Cybersecurity Act may be considered where applicable to further enhance trust and reliability.

AI Governance and Ethical AI Deployment

The deliverable underscores the importance of aligning XR5.0's AI components with the EU AI Act. This involves adhering to requirements related to transparency, accountability, and data governance. The project also draws on the High-Level Expert Group (HLEG) Guidelines on Trustworthy AI and the Assessment List for Trustworthy AI (ALTAI), emphasizing principles such as:

- Human agency and oversight.
- Technical robustness and safety.
- Privacy and data governance.
- Transparency and fairness.
- Societal and environmental well-being.
- Accountability.

By integrating these principles, the project aims to foster ethical and trustworthy AI practices that enhance user confidence and regulatory compliance.

Looking Ahead: Continuous Improvement and Compliance

Recognizing the dynamic nature of legal and ethical frameworks, this deliverable will undergo regular updates. The team will continuously monitor regulatory developments and incorporate new guidelines to maintain compliance with evolving standards.

In conclusion, this first deliverable provides a comprehensive foundation for ensuring ethical and lawful practices within the XR5.0 project. Through proactive planning, collaborative efforts, and adherence to established guidelines, the project is well-positioned to achieve its goals while safeguarding individual rights and promoting societal well-being.

From Legal Requirements to Technical Solutions: Designing Responsible XR and AI Systems

Extended Reality (XR) and Artificial Intelligence (AI) are increasingly finding their way into industrial environments. From immersive training and remote maintenance to AI-assisted guidance and personalised learning, these technologies offer significant opportunities for the factories and workplaces of the future. Yet their adoption also raises an important question: how can organisations ensure that innovation develops in line with European requirements on data protection, cybersecurity and trustworthy AI?

Within the XR5.0 project, we have been exploring this question through a compliance-by-design approach. The underlying idea is relatively simple: legal and ethical requirements should not be considered only once a technology has been developed. They should influence the way technologies are designed from the beginning. This builds on the principle of data protection by design contained in Article 25 of the General Data Protection Regulation (GDPR), but extends the same logic to cybersecurity, AI governance and broader ethical considerations.

Compliance starts with design

The European regulatory landscape surrounding XR and AI has become increasingly complex. Depending on the application, organisations may need to consider not only the GDPR, but also the NIS2 Directive, the Cybersecurity Act, the Cyber Resilience Act and, increasingly, the EU AI Act. These frameworks are often discussed separately. In practice, however, many of their requirements overlap, particularly when XR platforms combine personal data, industrial information, cloud infrastructure and AI-enabled functionalities.

The XR5.0 Training Platform provides a useful example. It is a cloud-based system that hosts, manages and streams immersive training applications to workers using different XR devices. Although the platform is not itself a standalone AI system, it incorporates AI-enabled functionalities, including local large language model processing, an AI-assisted chat function and adaptive personalisation tools. Rather than addressing privacy, security and AI governance as separate compliance exercises, the platform attempts to translate these requirements into concrete architectural choices.

Protecting data and systems through architecture

XR environments can potentially generate large amounts of personal and operational data. This makes data minimisation particularly important. The XR5.0 Training Platform deliberately limits the personal information it processes. Another important design choice is pixel streaming: XR applications are rendered in the cloud and streamed to users as encoded video, meaning that sensitive industrial information does not need to be stored locally on XR headsets. Personal data processed by the platform are also stored within the European Economic Area. These choices reflect a broader approach to data protection and security by design.

The same principle applies to cybersecurity. The platform uses several layers of protection, including session-token authentication, encrypted communications, role-based access controls and tenant isolation. System access and user actions are logged, supporting both security monitoring and accountability. This illustrates one of the main advantages of compliance by design: a single technical measure can often serve several regulatory objectives. Audit logging, for example, can help investigate cybersecurity incidents while also providing the traceability expected under AI governance frameworks. Similarly, cloud-based rendering can improve system performance while reducing local data exposure and protecting AI components from certain forms of attack.

Keeping humans in control

Human oversight becomes particularly important when AI is introduced into workplace training. In XR5.0, training programmes remain under the control of human administrators. AI may assist with tasks such as structuring training material or suggesting personalised learning paths, but it does not independently determine what workers should learn. Administrators define programmes, assign skill levels and approve training materials. They can also monitor active XR sessions and stop applications when necessary. Even where AI-driven personalisation is used, final training assignments remain subject to human control. This approach reflects the human-oversight principles underpinning the AI Act and the broader human-centric philosophy of Industry 5.0.

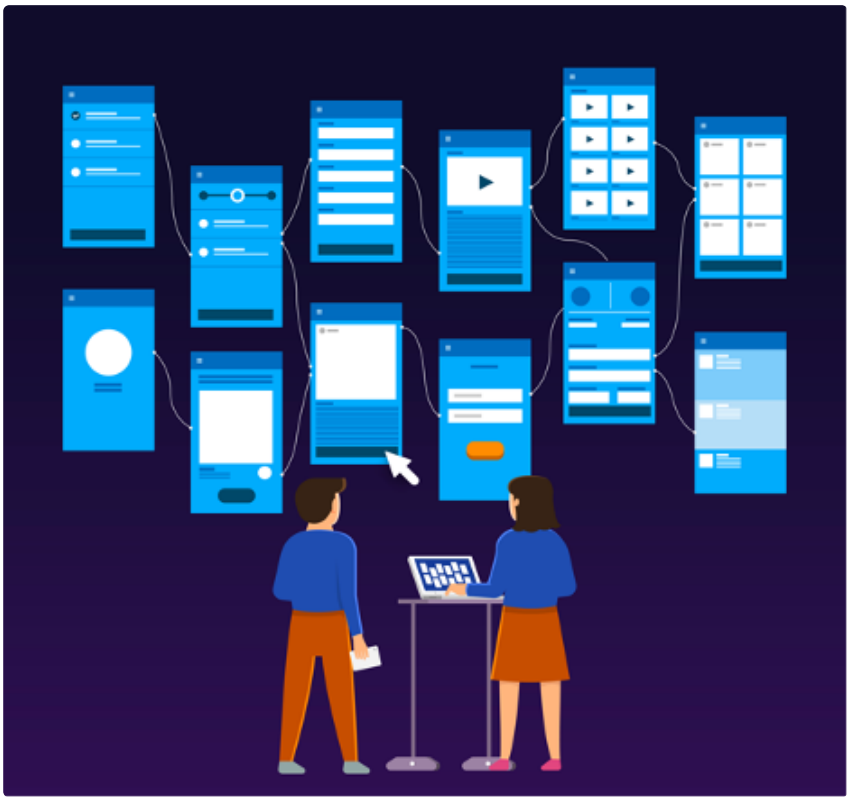
Transparency is equally important. Where workers interact with the XR-AI Assistant, AI-generated responses are identified as such so that users know when content comes from an AI-enabled functionality rather than human-authored training material. These measures also reflect the seven requirements of the European Commission's Assessment List for Trustworthy Artificial Intelligence (ALTAI): human agency and oversight, technical robustness and safety, privacy and data governance, transparency, diversity and fairness, societal and environmental wellbeing, and accountability. In XR5.0, these principles are not treated simply as abstract ethical aspirations; they are translated into platform features and governance mechanisms.

From compliance checklist to engineering principle

Perhaps the most important lesson from XR5.0 is that compliance should not be treated as a checklist applied at the end of technological development. Many legal and ethical requirements actually point towards the same good design choices. Data minimisation can improve privacy while reducing security risks. Human oversight can support regulatory compliance while improving training quality. Audit logs can contribute simultaneously to cybersecurity, transparency and accountability. In this sense, compliance by design requires lawyers, engineers, developers and other stakeholders to work together early enough for legal and ethical requirements to influence technological choices.

As XR and AI become increasingly integrated into industrial workplaces, compliance will remain a moving target. Technologies evolve, use cases change and regulatory obligations continue to develop. Building compliance into the architecture from the outset does not eliminate this challenge, but it provides a much stronger foundation for adapting responsibly. The broader lesson from XR5.0 is therefore that regulation and innovation do not necessarily need to pull in opposite directions. When legal, ethical and technical considerations are aligned from the beginning, compliance can become part of good engineering rather than an obstacle added at the end.

What if User Interfaces Could Adapt to User Characteristics and State?



Industry 5.0 (I5.0) places human well-being, safety, and productivity at the heart of technological advancements [1]. However, the transition to I5.0 introduces new challenges and, even if the significant advancement in automation, workers continue to play a crucial role in managing the control and oversighting of production processes.

One of the key challenges is effective human-computer interaction (HCI) through User Interfaces (UIs). In high-pressure manufacturing environments, traditional static interfaces often fail to accommodate varying skill levels, task complexities, and real-time operational needs. This is where Adaptive User Interfaces (AUIs) come into play, dynamically adjusting to user needs to improve efficiency, usability, and safety.

The fundamental premise of AUIs is that the system continuously assesses contextual factors, such as the user's skill level, the complexity of the task, environmental variables, and past interactions the user had with the system, for altering the interface accordingly. By reducing the mismatch between the interface configuration and user expectations or abilities, AUIs enhance overall usability, promote learning, and mitigate the risks of user error, particularly in high-stakes, complex environments such as manufacturing or assembly lines.

This dynamic adaptation can take various forms and can include:

- Adjusting the complexity of the interface, by reducing non-essential information to minimize distractions and help the user focus on critical interface elements.
- Providing contextual assistance, by offering real-time guidance or tutorials tailored to the user's skill level.
- Modifying the interface, by rearranging different elements to prioritize the most relevant information based on the user's current task.
- Providing task-specific guidance, by delivering focused, step-by-step instructions tailored to the specific task at hand, ensuring that users are not overwhelmed with unnecessary information.
- Streamlining complex procedures to minimize errors and improve decision-making, by navigating complex workflows and breaking down intricate processes into manageable stages.
- Predicting the adaptation, by analysing past interactions and patterns to anticipate user needs and pre-emptively adjust the interface.

In this context, Augmented Reality (AR) and Virtual Reality (VR) open even more opportunities and possibilities for adaptation. These technologies not only provide immersive environments but also enable new type of interface adjustments.

When integrated with AI and Human Digital Twins, these technologies create truly personalized and adaptive work environments that enhance efficiency, safety, and user satisfaction.

Challenges in Adopting Adaptive User Interfaces

However, several challenges remain in fully harnessing the potential of AUIs. One significant issue is the lack of a unified framework. Currently, there is no standardized architecture governing the development of the AUI life cycle. A review of 212 studies of the last decade revealed that only 10 focused on frameworks and just 4 addressed methodologies, underscoring the pressing need for structured and systematic approaches in this domain, particularly regarding user experience (UX) and usability[2]. Another challenge lies in the insufficient application of human-centered design principles. Traditional interfaces often fail to present data in ways that align with the operator's immediate tasks, leading to slower decision-making and potential mistakes. Operators need systems that are not only capable of presenting data but also of presenting it in a way that is meaningful and actionable in real-time. A low level of human-centered design also leads to a low level of worker acceptance. Early involvement of workers in the design process has been shown to improve adoption rates; however, designing solutions that are universally applicable remains a challenge due to the wide variety of systems and socio-technical contexts in which they operate. This diversity complicates efforts to create adaptable solutions that meet the needs of all users effectively.

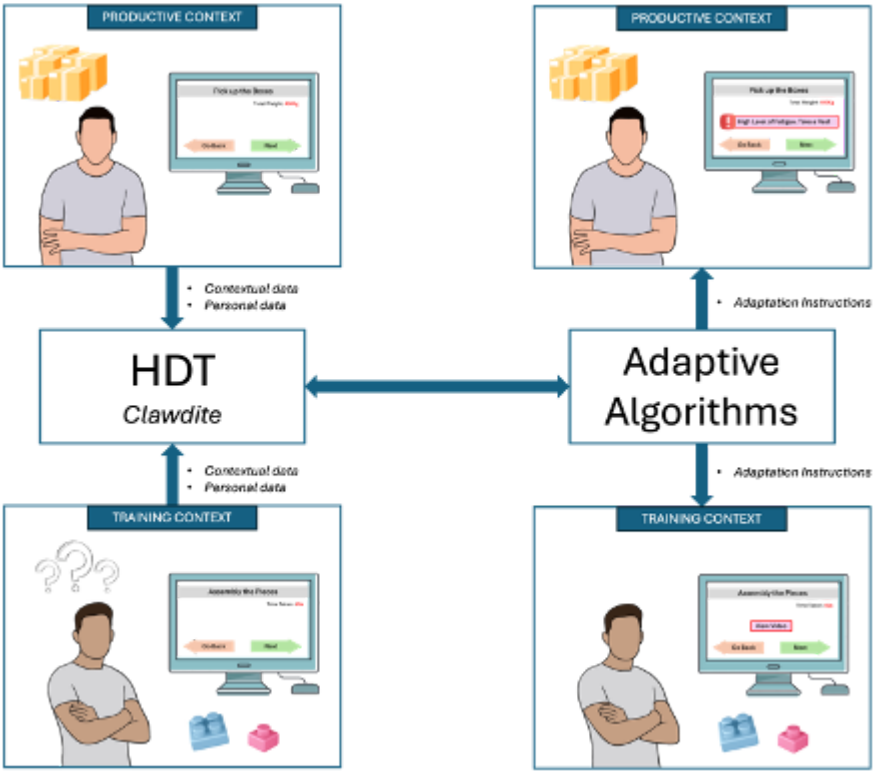
XR5.0 paradigm combining Human Digital Twins for Adaptive Interfaces

Human-centricity, a pillar of I5.0, emphasizes prioritising human needs, including safety, health, self-actualization, and personal development, within production processes. In this context, Human Digital Twins (HDTs) are proposed as one of the critical methods for empowering operators in smart manufacturing systems. They integrate models fed by dynamic, real-time data with static or quasi-

static data of the user, enabling a comprehensive representation of the human entity, the so-called ‘digital avatar’, that aims to revolutionize human-system integration by embedding human traits into the system’s architecture and functionality.

HDTs are emerging as a transformative solution in the manufacturing industry, particularly for addressing the challenges of physically and mentally demanding tasks. By creating real-time virtual replicas of workers, these systems enable continuous monitoring of physical and physiological conditions to proactively manage worker fatigue, prevent hazardous situations, and adapt workflows to individual needs.

Acting as a repository of each worker’s information and contextual factors, the HDT is representing the optimal solution to design interfaces with a clear human-centered view. Adaptation algorithms, which define the rules to be applied for an interface change, can directly interact with the HDT to enable the provision of effective, personalized modification to the User Interface. For example, in a manufacturing training scenario, the HDT can be used to monitor and adapt the learning process for a worker being trained to operate a robotic assembly line. The information stored by the HDT, i.e., worker’s current skills, learning pace, cognitive load, and so on, is then exploited by the adaptation algorithm to modify the training interface in real-time to help the user, e.g., when a worker struggles with understanding a specific task. Adaptations might involve simplifying the user interface or providing more detailed step-by-step visual instructions. Additionally, if the HDT is enabled to automatically detect unpleasant situations, e.g., workers feeling high levels of fatigue or stress, targeted alerts can be shown to them, e.g., to recommend breaks or adjust the training intensity to ensure optimal learning conditions.



The XR5.0 project, funded by the European Union’s research and innovation programme (GA: 101135209) and the Swiss State Secretariat for Education, Research and Innovation (SERI), aims to develop, demonstrate, and validate a novel Person-Centric and AI-based XR paradigm that will be tailored to the requirements and nature of I5.0 applications.

SUPSI will contribute to XR5.0 by providing Clawdite, an IIoT Platform that supports the easy and fast ramp-up of HDTs and serve as a centralized repository for worker-related data fed by Artificial Intelligence (AI) modules to understand human intentions, preferences, and contextual cues. Clawdite will be exploited to personalize XR functionalities of the pilot applications to ensure workers can experience a complete and personalized environment built around them. In fact, through the analysis of data collected from workers through sensors and wearable devices, specific mechanisms will be developed for dynamically adapting XR content based on the individual needs and contexts of users (e.g., operators, technicians), leveraging advanced AI techniques for real-time content modification.

Authors: *Davide Matteri*, *Vincenzo Cutrona*, *Elias Montini*, *Samuele Dell'Oca*, *Sara Masiero*, SUPSI, SPS lab

[1] Lu, Yuqian, et al. "Outlook on human-centric manufacturing towards Industry 5.0." Journal of Manufacturing Systems 62 (2022): 612-627.

[2] Brdnik, Saša, Tjaša Heričko, and Boštjan Šumak. "Intelligent user interfaces and their evaluation: a systematic mapping study." Sensors 22.15 (2022): 5830.

Why XR's Next Step Is Not a Better Headset

For more than a decade, Extended Reality has been described as the next phase of human-computer interaction. Keyboards gave way to mice, mice gave way to touchscreens, and touchscreens will give way to displays that follow our eyes and hands. That is the promise. Everyday adoption is something else.

After working on Almer (now part of RealWear) at SIPBB since the first 3D-printed prototype in 2021, and now contributing to the XR5.0 EU project, we have come to a different reading of why XR has stalled at the threshold. The bottleneck is not hardware. Weight has dropped, optics have improved, batteries last longer. The bottleneck is interaction itself.

Where XR has already worked. XR has produced its clearest wins in tightly bounded training and simulation. The XR5.0 Pilot 3 targets a 30 % reduction in training time and cost. The Pilot 5 targets a 20 % reduction in assembly time and a 50 % increase in the engagement of lower-skilled technicians. The Pilot 4 replays the actions of skilled technicians for the Wing Anti-Ice Valve repair so trainees can rehearse the procedure without grounding an aircraft. These are real results. They also share a pattern: they are for now tightly scoped, run on dedicated training devices, and live in controlled environments. Outside that envelope, XR rarely becomes the primary interface for daily work.

The interaction problem. Every successful computing paradigm has had a stable interaction grammar. The mouse pointer and the touchscreen tap each took decades to settle and then carried across millions of applications without retraining. XR has converged on nothing equivalent. A user crossing from VR to MR to a head-worn smart-glasses device meets a different input set each time: controllers here, gaze plus pinch there, hand tracking elsewhere, voice on a fourth device. For an industrial worker whose hands stay on the task, most of those options are not even available. In the first Almer prototypes, the choice was constrained to voice. There was no controller in hand, no surface to touch, and no spare bandwidth for learning a gesture set. Voice worked because there was nothing else, and because language models had finally become tolerant enough of free-form requests that workers could speak as they would to a colleague rather than memorise commands.

AI changes the role of XR. This is where AI rewrites the script. Large language models, multimodal context understanding, and persistent memory together collapse the fragmented input channels into a single interaction layer that sits above the device. The worker speaks, looks, or moves their head. The model fuses these signals with what it sees through the device's camera. The output is whichever modality fits: a spatial overlay, a spoken answer, a triggered hardware action. In XR5.0 Pilot 6, Innov's AI module holds the troubleshooting knowledge for a specific piece of industrial equipment and emits step-by-step instructions, which the Oculavis assistance app renders on a RealWear headset. SUPSI's middleware orchestrates the traffic between the components. The whole stack is tested against a real machine, the LNS Barfeeder Express 126, installed in the SSF Demonstration Factory. It behaves as one assistant rather than four bolted-together tools.

The hard parts are not the model. When we look at what actually broke during these years, the binding constraints were operational, not algorithmic. A device is useful only if it is charged and ready to grab. That is why we built a docking station that doubles as a charging cradle and gives the device a fixed, visible home in the workspace. By fitting into the existing workflow instead of asking workers to remember a separate routine, the station also makes the glasses easier to adopt at the organisational level. The headband form factor that solved compatibility with prescription glasses and hard hats made weight distribution a dominant concern, which constrains every future feature, AI included, before it exists. Around the device itself we have been building the surrounding system: AriOs as the on-device operating system that abstracts hardware peripherals and lets the same headset play tutor, co-pilot, or remote-expert proxy by configuration; and Ari Cloud as the enterprise-integration layer that connects to the customer's documentation, asset records, and ticketing.

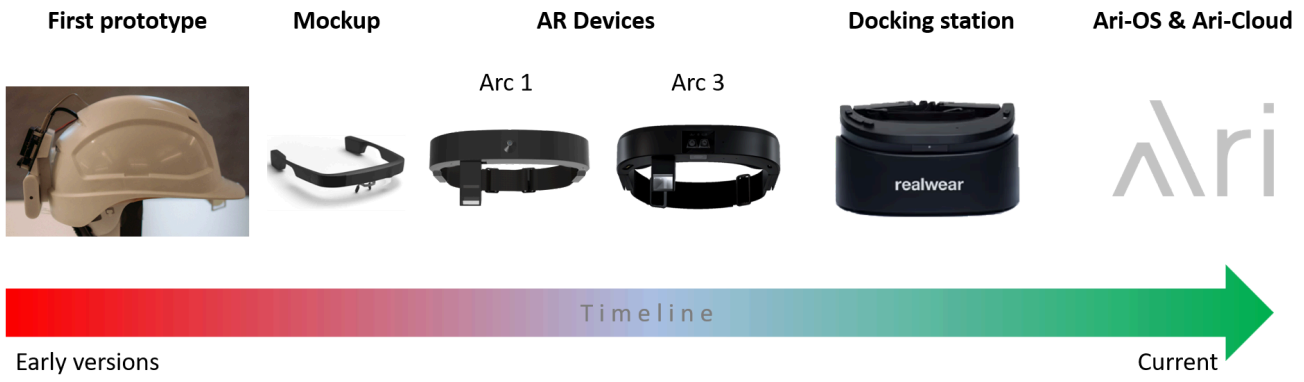


Figure 1. Evolution of the Almer/RealWear XR ecosystem from joint SIPBB–RealWear research projects to industrial deployment, including XR hardware, Ari-OS, and Ari-Cloud.

What to watch. LLM hallucination in safety-critical guidance is a real risk, and the literature has it right; we manage it by scoping the model to the equipment's documentation and keeping an explicit fallback to a human expert. Privacy concerns around biometric capture and prompt injection are mostly latent in a voice plus head-movement device that does not track gaze, but they would become live the moment the form factor changes. The risk profile shifts with the device class as much as with the model.

The point. The next jump in XR is not a smaller, lighter headset that runs a bigger model. It is an integration spine that connects the worker, the device, the AI, and the surrounding enterprise systems into one assistant, one workflow, and one stable interaction layer. That is the part of the puzzle worth building.

PART TWO · 16 ARTICLES

AI Integration

How XR5.0 deploys and advances Artificial Intelligence—from Explainable AI and Generative AI to LLM agents, adaptive learning, conversational assistants, and on-premises language models—to create trustworthy, human-centric industrial experiences.

2.1 AI INTEGRATION

Advancing XR Training with AI: Toward Intelligent and Adaptive Learning in Industry 5.0

Industrial training is undergoing a significant transformation as the transition to Industry 5.0 places greater emphasis on human-centric approaches and collaboration between humans and intelligent machines. Technologies such as Extended Reality (XR) and Artificial Intelligence (AI) are playing a key role in enabling more immersive, adaptive and personalized learning experiences [1]. As highlighted in recent research, the combination of XR and AI allows the development of training environments that adapt dynamically to the needs and performance of individual users [2].

The XR5.0 Training Platform focus on the integration of AI-driven tools that enhance both the creation and delivery of XR-based training. These developments represent a shift from static and predefined training experiences to intelligent systems capable of supporting users in real time and improving learning outcomes [3].

From Immersive Training to Intelligent Training Systems

The XR technologies have already demonstrated their value in visualizing complex systems and enabling interactive learning, but traditional XR-based training solutions often rely on predefined content and fixed workflows. This approach can limit scalability, particularly in industrial environments where tasks, user profiles, and learning needs vary significantly. The XR5.0 Training Platform addresses these limitations by incorporating AI capabilities that transform XR training into a more dynamic and responsive process. This allows for intelligent interaction, contextual guidance and adaptive learning pathways, supporting human capabilities and aligns with the Industry 5.0 vision.

AI-Enhanced Content Creation and Management

A key advancement in the XR5.0 Training Platform is the introduction of AI-supported tools within the Training Programs Authoring Tool (TPAT). These tools assist training managers in transforming traditional training materials, such as PDF manuals into structured XR-native content.

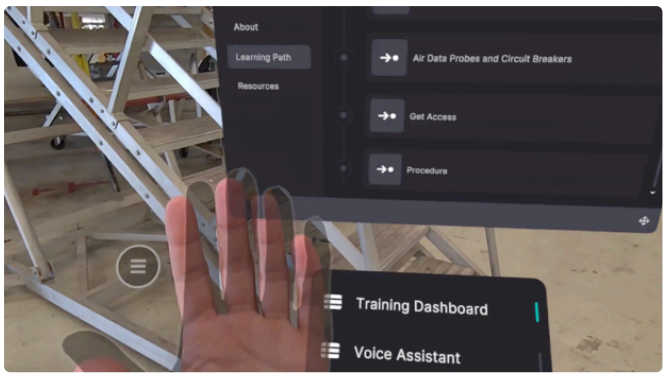
Using AI-based text extraction and processing mechanisms, procedural information embedded in documents can be automatically converted into structured elements such as checklists and workflows which significantly reduces the time and effort required to create XR training programs.

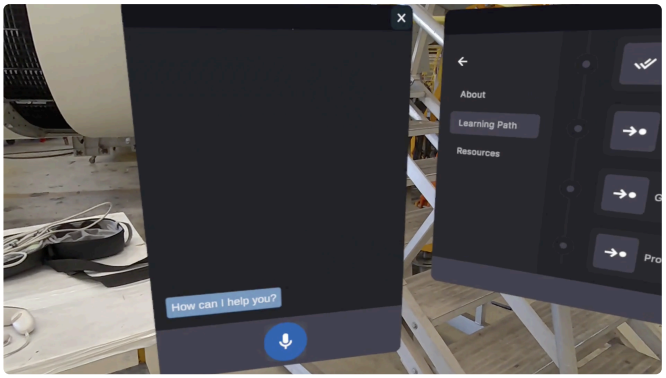
Intelligent Assistance in Immersive Environments

Another important feature is the integration of an AI-based assistant within the XR Training Plugin (XRTP). This assistant provides real-time, context-aware support to users during immersive training sessions.

Operators can interact with the assistant through natural language, receiving explanations, guidance and clarifications related to specific steps in a procedure. This reduces reliance on external documentation and allows users to remain fully engaged within the XR environment. The left image

shows the panel used to trigger the voice assistant in the context of the TAP pilot, while the right image shows the voice assistant interface.





Adaptive and Personalized Training Experiences

Beyond content creation and real-time assistance, the XR5.0 Training Platform introduces mechanisms for personalization and adaptation of training experiences. These mechanisms operate at two levels.

1) Static personalization allows training programs to be tailored based on user profiles, such as experience level, ensuring that content is aligned with the needs of each operator.

2) Dynamic adaptation, on the other hand, is driven by user interaction during training sessions. Metrics such as task completion time can be used to adjust the training experience in real time.

For example, when a user encounters difficulties in a specific step, the system can recommend additional supporting materials, such as a 3D model visualization or an instructional video. This adaptive approach contributes to more effective learning by providing targeted support exactly when it is needed.

Integration within a Scalable XR Infrastructure

These AI-driven capabilities are supported by the underlying architecture of the XR5.0 Training Platform, which combines cloud-based XR streaming, centralized asset management and modular training program design. The core components of this platform, namely the Hololight Hub, XR Training Asset Repository and XR Training Management System, work together to enable a device-agnostic delivery of XR training experiences.

Future Directions

Future work will primarily focus on the deployment and validation of the XR5.0 Training Platform across the industrial pilots, where the platform has already reached a level of maturity that enables end-to-end testing in real operational contexts. The pilot deployment will provide critical insights into performance, usability, and scalability, as well as the effectiveness of immersive training workflows in supporting complex industrial tasks.

In addition, a key focus of ongoing development is the finalization and integration of the adaptive training mechanisms. These advancements will complete the development of the full integrated version of the XR5.0 Training Platform, an intelligent and responsive training system aligned with the human-centric principles of Industry 5.0.

References

[1] Moser, T., Schlager, A.: Training and Assistance in Industrial Environments Using Extended Reality IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW) pp. 97-103 (2024).

[2] Kiourtis, A. et al.: XR5.0: Human-Centric AI-Enabled Extended Reality Applications for Industry 5.0. 36th Conference of Open Innovations Association (FRUCT), Lappeenranta, Finland, 2024, pp. 314-323 (2024).

[3] Oliveira, J., Saraiva, T., Shah, H. M., Mavrogiorgis, E., Mavrogiorgou, A., & Kiourtis, A. (2025). XR training in Industry 5.0: Advancing human-machine collaboration with the XR5.0 training platform. In Proceedings of the International Conference on Extended Reality (pp. 93–100).

2.2 AI INTEGRATION

XR and AI Integration: Five Industrial Cases You Need to Know

The Horizon Europe XR 5.0 project is developing and promoting a novel paradigm for Industrial Extended Reality (XR) Applications, where Artificial Intelligence (AI) models are used to enhance and improve XR cyber-representations. Specifically, the project has been motivated by the potential benefits of the convergence of Extended Reality (XR) and Artificial Intelligence (AI), which opens up interesting possibilities for enhancing industrial use cases such as use cases linked to operational efficiency, worker training, and maintenance processes. Based on combinations of AI algorithms and XR technologies, modern industrial organizations can change the ways they interact with their environments, products, and workforce. In this blog, we will present five categories of use cases where AI and XR intersect to drive innovation and improvements in industrial applications. The presented facilities of use cases include use cases that are implemented in the scope of the XR5.0 pilots, yet they are not limited to them.

1. AI-Powered Synthetic Datasets for XR Environments

One of the fundamental challenges in XR development is the scarcity of high-quality training data. AI comes to the rescue by enabling the creation of synthetic datasets that enhance the training of XR applications. Using machine learning algorithms industrial organizations can nowadays develop virtual environments that mimic real-world scenarios with precision. These synthetic datasets play a crucial role in creating XR systems for tasks such as object recognition, spatial understanding, and motion tracking. As a prominent example, AI algorithms can be used to create synthetic images of factory floor layouts or virtual equipment assemblies, which enable diverse training and testing scenarios in XR environments.

2. Generative AI for Content Creation in XR Cyber-representations

Generative AI algorithms, including Large Language Models (LLMs), empower XR developers to dynamically generate content for immersive cyber-representations of industrial settings. Based on state of the art generative models, organizations can create product variations, design prototypes, and virtual objects that seamlessly integrate into XR environments. This enables rapid prototyping and customization without the need for manual and time-consuming content creation. For instance, generative AI can be used to produce an array of car models in varying colors, shapes, and features. The latter can then be superimposed into XR simulations for design reviews or virtual showroom experiences.

3. AI-Driven Personalized Recommendations and Instructions in XR Training

AI's ability to analyze user behavior and preferences allows for personalized recommendations and instructions within XR training applications, such as industrial training for maintenance and repair tasks. Based on machine learning algorithms, XR systems can adapt their content and guidance based on

individual user interactions, towards making the learning process more engaging and effective. Consider an XR-based maintenance training program that provides real-time step-by-step instructions tailored to the technician's skill level and knowledge. Such an XR program can significantly enhance learning outcomes and reduce errors in industrial settings. Most importantly, it can enhance employed satisfaction as well, in line with the Industry 5.0 vision of human-centered manufacturing.

4. Human-AI Collaboration through Active Learning in XR Cyber-representations

AI paradigms that facilitate human-AI collaboration, such as active learning, can enable intelligent interactions of humans with XR cyber-representations. As a prominent example, the integration of active learning techniques into XR systems enables users to provide feedback and corrections to AI models in real-time. Such correction can greatly enhance a system's accuracy and adaptability, while fostering effective human-machine interaction and human robot collaboration. For example, in a collaborative design environment, engineers can interact with AI-generated prototypes in XR, refining and iterating on designs through natural interactions, fostering a seamless human-AI design process that is empowered by active learning.

Beyond active learning integration, human-centred XR applications can also benefit from the integration with other novel AI paradigms such as neurosymbolic learning.

5. AI in Digital Twins and the Industrial Metaverse

Digital twins, virtual replicas of physical assets or processes, can nowadays enhanced by AI technologies to create intelligent metaverse-like environments for industrial use cases. Based on the integration AI capabilities into digital twin ecosystems, organizations gain insights into predictive maintenance, operational optimization, and scenario planning. This facilitates data-driven decision-making in real-time.

As an example, consider an AI-powered digital twin of a manufacturing plant that uses machine learning algorithms to predict equipment failures, optimize production schedules, and simulate what-if scenarios to improve overall efficiency and productivity. The integration this AI-based digital twin within an immersive XR environment can greatly enhance the ergonomics and overall effectiveness of the respective industrial metaverse simulations.

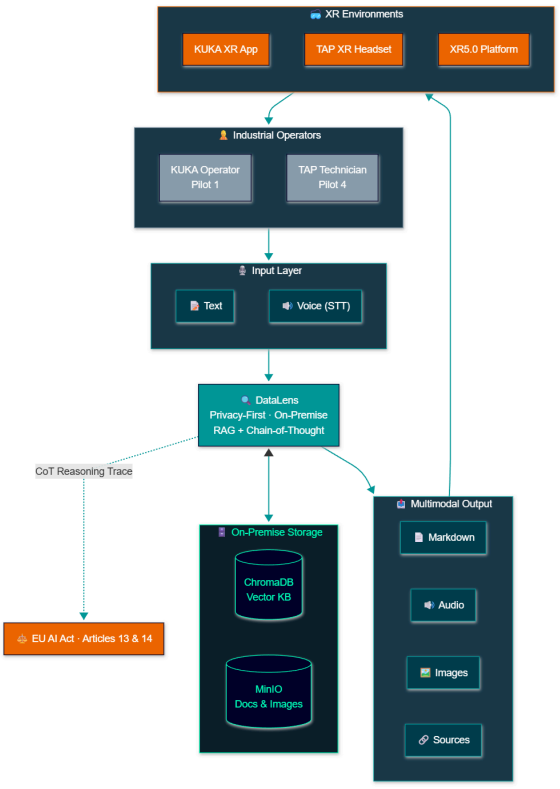
Overall, the fusion of AI and XR technologies holds immense potential for transforming industrial applications across various sectors, including manufacturing, logistics, and engineering. XR5.0 is currently working on an architecture paradigm for integrating AI-driven innovations in XR environments. At the same time it is co-creating novel pilot applications that demonstrate how the integration of XR and AI unlocks new possibilities for workforce training, operational efficiency, and decision-making.

2.3 AI INTEGRATION

DataLens: A Privacy-First Conversational AI Framework for Industrial Documentation

Every industrial company accumulates documentation at a rate that far outpaces anyone's ability to actually use it. Maintenance manuals, engineering schematics, commissioning procedures, safety protocols — the knowledge exists, usually in abundance. The problem is access: finding the right piece of information, at the right moment, in a form that is actually usable by someone whose hands are occupied and whose attention is already stretched thin.

This is the problem that DataLens was built to address. Developed by Siemens (SIE), DataLens is a privacy-first, on-premise conversational AI framework that allows industrial operators to query their own technical documentation through natural language inside Extended Reality (XR) environments. It has been deployed in two distinct industrial pilots: a robotics commissioning context with KUKA, and an aircraft maintenance training programme with TAP Air Portugal. Both deployments offer useful lessons, not just about what the system can do, but about the conditions under which AI assistance in industrial settings actually earns the trust of the people using it.



DataLens Integration within XR5.0

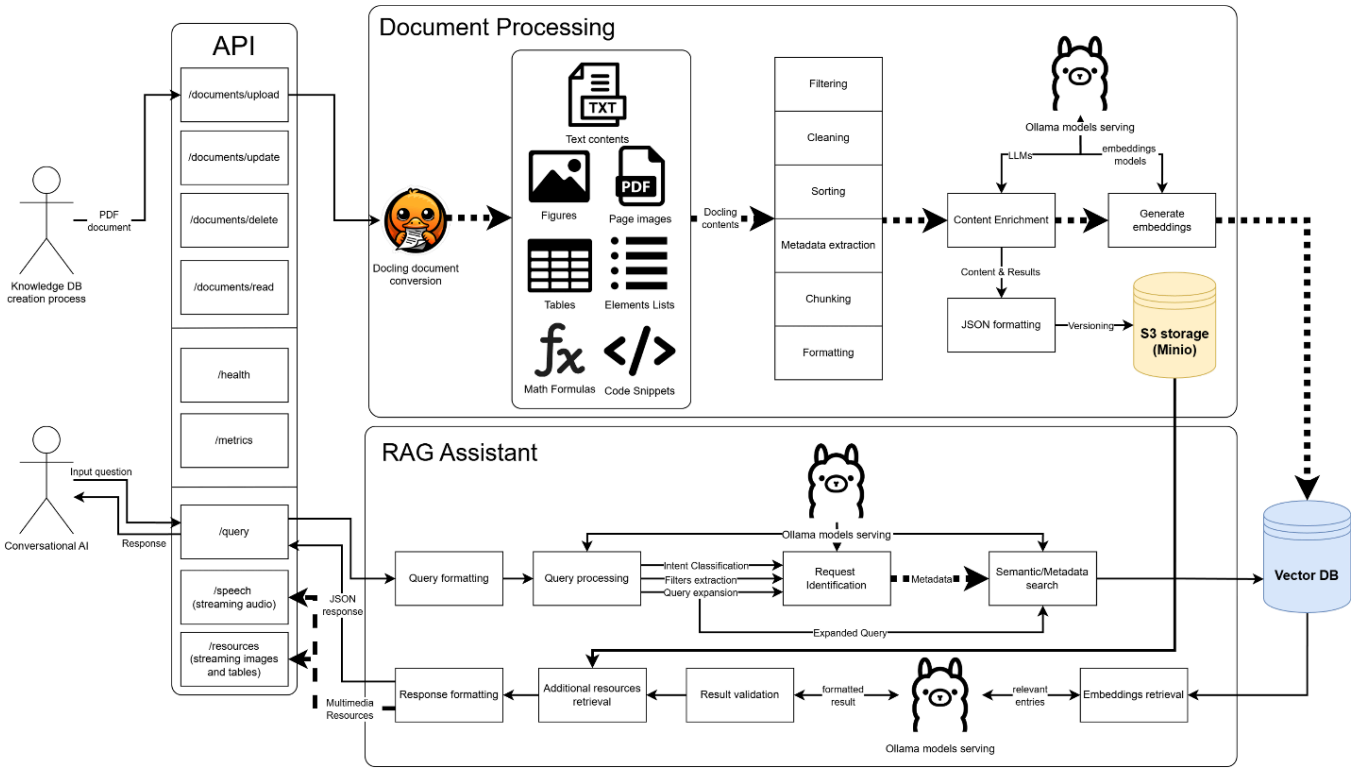
The Privacy Constraint as a Design Driver

Before getting into what DataLens does, it is worth understanding why it was built the way it was. Most conversational AI products today rely on external cloud infrastructure — queries leave the organisation, get processed somewhere else, and responses come back. For many consumer applications, that is an

acceptable trade-off. For an aerospace maintenance company or a robotics manufacturer with proprietary engineering documentation, it is not.

DataLens runs entirely on private cloud instances. No data leaves the organisation's infrastructure. This is not simply a compliance checkbox — it is the architectural foundation from which everything else follows. The system is built on open-source components precisely because they can be audited, deployed locally, and operated without dependency on any external service provider. The stack includes Ollama for serving locally-running language models, Docling for structured PDF extraction, MinIO for document and image storage, and ChromaDB for managing the vector-based knowledge bases that power semantic search.

The result is a system that organisations can actually trust with sensitive documentation — which, in turn, is what makes the conversational AI layer meaningful. An assistant that cannot be trusted with the documents is not much of an assistant.



DataLens High-Level Architecture

What the System Actually Does

DataLens is structured around two core components. The first is a document processing pipeline that ingests PDF documents, extracts their content in structured form — text, tables, images, metadata — and commits everything to a vector database through an embedding process. The second is a Retrieval-Augmented Generation (RAG) assistant that accepts user queries, classifies their intent, expands them where necessary, retrieves semantically relevant content from the knowledge base, and generates a structured response.

The system accepts both text and voice input, which matters considerably in XR contexts where typing is not a realistic interaction mode. Responses are multimodal: formatted text, synthesised audio, optional reference images, and source metadata indicating exactly which document and section the

answer came from.

The API layer sits above all of this, exposing a versioned REST interface that allows the system to be integrated into any external application — including XR headset environments — without requiring the consuming application to know anything about the underlying AI infrastructure.

The Harder Problem: Trust and Explainability

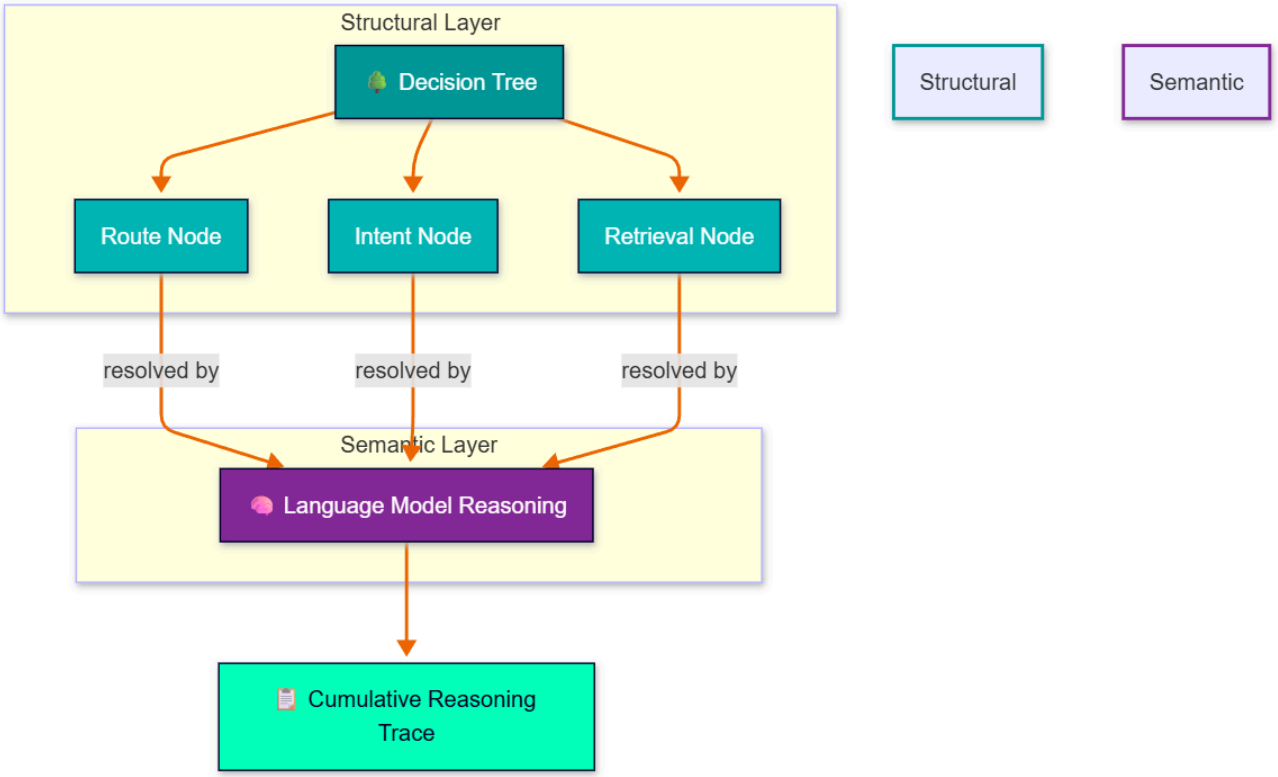
Retrieving a relevant document chunk and presenting it as an answer is, technically speaking, not that difficult. The harder problem is giving the person receiving that answer a reason to trust it — and, when they should not trust it, a way to know that.

This is where DataLens goes beyond being a search interface. The system incorporates Chain-of-Thought (CoT) reasoning as its primary mechanism for explainability. Rather than routing a query through a single model call and returning whatever comes out, the pipeline decomposes query resolution into a sequence of discrete, auditable stages. Each stage has a specific responsibility: route classification, intent resolution, query expansion, retrieval, response generation. At every stage, the reasoning produced by the language model is captured and appended to a cumulative reasoning trace, which is returned alongside the final answer as a dedicated field in the API response.

The practical effect is that the system's decision path — from the user's original query to the generated response — is fully visible. A human operator, or a downstream application, can inspect exactly how the system interpreted the query, what it retrieved, and why it generated the response it did. This is not a minor feature. In environments where AI-generated guidance may inform safety-critical decisions, the ability to trace a response back through its reasoning chain is an operational necessity, not an optional transparency enhancement.

The pipeline's design is also directly aligned with Articles 13 and 14 of the EU AI Act, which mandate transparency and human oversight for high-risk AI systems. The structured JSON outputs and multi-stage reasoning architecture ensure that every response can be audited, attributed to its source, and reviewed by a human operator.

Internally, the CoT implementation combines two complementary layers. The first is a system-defined decision tree — a deterministic structure that routes queries through a predictable sequence of specialised prompts and metadata filters. The second is the language model's own reasoning mechanism, which resolves each node of the decision tree and produces fine-grained semantic reasoning at every inference step. Together, these layers make the system's behaviour both structurally auditable and semantically interpretable. All pipeline configuration — route definitions, intent classifiers, system prompts, and model parameters — is centralised in a single rag_runtime.yaml file, which simplifies debugging and makes extending the system with new query types a contained operation.



DataLens XAI Reasoning Report

Pilot 1 — KUKA: Starting with Robotics

The first real-world deployment of DataLens happened within KUKA's pilot, focused on virtual commissioning and generative AI in robotics. DataLens was deployed here as **KUKABot**, a conversational knowledge assistant built on top of a dedicated knowledge base populated with KUKA's internal technical manuals — equipment datasheets, operating manuals, and electrical design schematics, five documents in total.

Operators interacted with the system through a natural language interface inside an XR application, querying component specifications and commissioning procedures. The system handled documents navigation, summarisation, question and answer, content lookup, and comparisons— 40 recorded interactions across the pilot evaluation. Retrieval performance was strongest for queries that used explicit technical terminology, where the vector similarity search consistently surfaced relevant entries.

Pilot 4 — TAP Air Portugal: Aircraft Maintenance Training

The second deployment moved DataLens into aircraft maintenance training, which represents a considerably higher-stakes environment. Aircraft Maintenance Technicians work with complex, safety-critical procedures where the cost of an error is not measured in downtime but in airworthiness. The pilot focused on training procedures related to the Wing Anti-Ice Valve (WAIV).

In this context, DataLens was deployed alongside the XR-Enabled AI Assistant — an enterprise platform providing speech-to-text, text-to-speech, and conversational AI capabilities through a unified API. The two components form an integrated voice-driven pipeline: the XR-Enabled AI Assistant handles audio

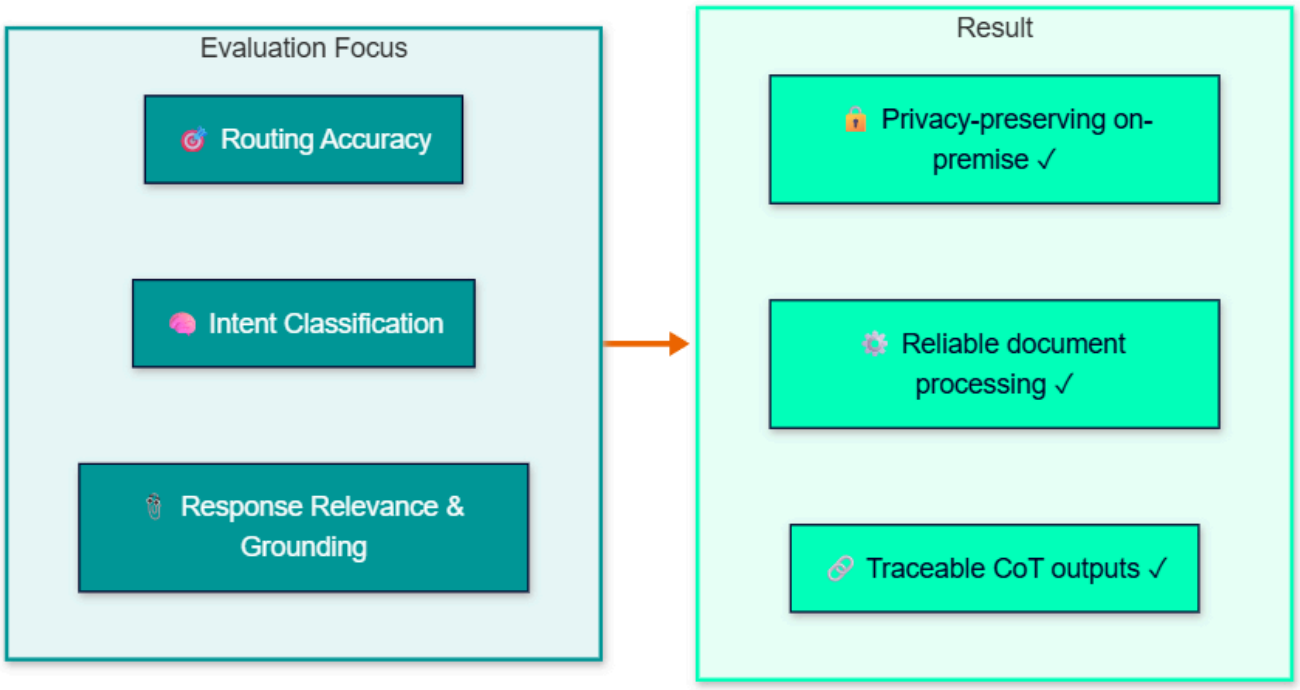
capture, transcription, and speech synthesis, while DataLens serves as the document intelligence layer, retrieving contextually relevant information from the ingested knowledge base and grounding every response in verified source documentation.

Technicians interacted with the system through voice and gesture, submitting queries such as "What are the steps involved in the WAIV installation?" The system processed the voice input, forwarded the transcribed query to the DataLens retrieval engine, and returned a response — both in text and synthesised audio — derived from the ingested technical documentation.

What the Evaluation Actually Showed

Across both pilots, evaluation confirmed the technical viability of the system as a privacy-preserving, on-premise conversational AI solution for industrial document querying. The document processing pipeline performed reliably on well-formed, born-digital technical documentation. The multimodal response format — combining synthesised speech, formatted content, and source references — was well received in both operational contexts.

The CoT pipeline evaluation focused on conversational routing accuracy, intent classification correctness, and the relevance and grounding of generated responses against their source documentation. The CoT structure consistently produced more reliable and traceable outputs than earlier single-prompt approaches, with the reasoning trace providing a transparent basis for identifying and correcting failure cases during iterative refinement.



DataLens Evaluation and Results

A Broader Point About Industrial AI

The lessons from DataLens extend beyond the specifics of the framework. The transition from a single-prompt architecture to a structured CoT pipeline demonstrated that explainability and reliability in RAG systems are best achieved through deliberate decomposition of the reasoning process, not through reliance on model capability alone. The model evaluation process reinforced that raw reasoning

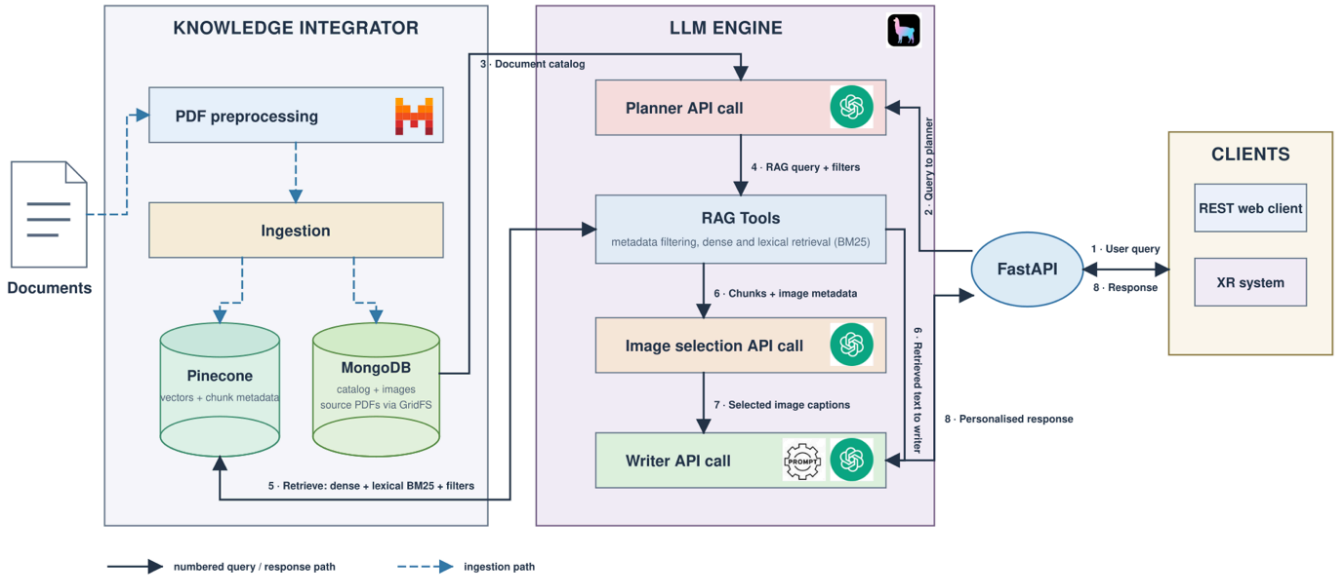
capability does not necessarily translate to pipeline suitability — stability, predictability, and token efficiency are equally critical selection criteria when deploying language models within structured conversational workflows.

More broadly, the pilot deployments confirmed something that is easy to understate: architectural decisions need to be grounded in real operational feedback. The version of DataLens that exists after two pilots is substantially different from the version that entered them, and that evolution was driven by what actually happened when real users, in real environments, tried to use the system to do real work.

That, in the end, is probably the most transferable lesson. AI systems for industrial use do not arrive fully formed. They are shaped — sometimes significantly — by the gap between what designers anticipate and what operators actually need.

2.4 AI INTEGRATION

Bringing Industrial Knowledge to the Point of Work with Multimodal AI



Extended Reality (XR) is transforming the way industrial workers are trained and supported. New recruits can learn to operate a machine before working on the real one, new equipment can be explored in a virtual environment, and hazardous procedures can be rehearsed where a mistake carries no cost or risk.

Throughout these activities, workers need precise guidance, such as the steps of a procedure, the meaning of an alarm code or the limit that applies to a specific component. An AI assistant integrated into the XR environment can provide this guidance at the point of work. However, the required knowledge lies in hundreds of company manuals and technical procedures that are not publicly available, so general purpose language models cannot provide it reliably.

This is where retrieval augmented generation (RAG) plays a crucial role. The documentation is ingested into a searchable knowledge base, and every answer is generated from the passages retrieved from it, so that guidance remains faithful to the documentation. Within the XR5.0 project, Innov-Acts has developed a multimodal RAG assistant for industrial documentation and evaluated how each design decision affects its answer quality, cost and response time, as presented in our paper.

Industrial manuals combine technical text with diagrams, schematics, screenshots and parameter tables, and much of the information a worker needs is carried by these figures rather than by the text. A text-only assistant discards this material and leaves some questions unanswered. For this reason, Innov-Acts created a multimodal assistant. It processes figures together with text and returns them to the worker alongside the written answer.

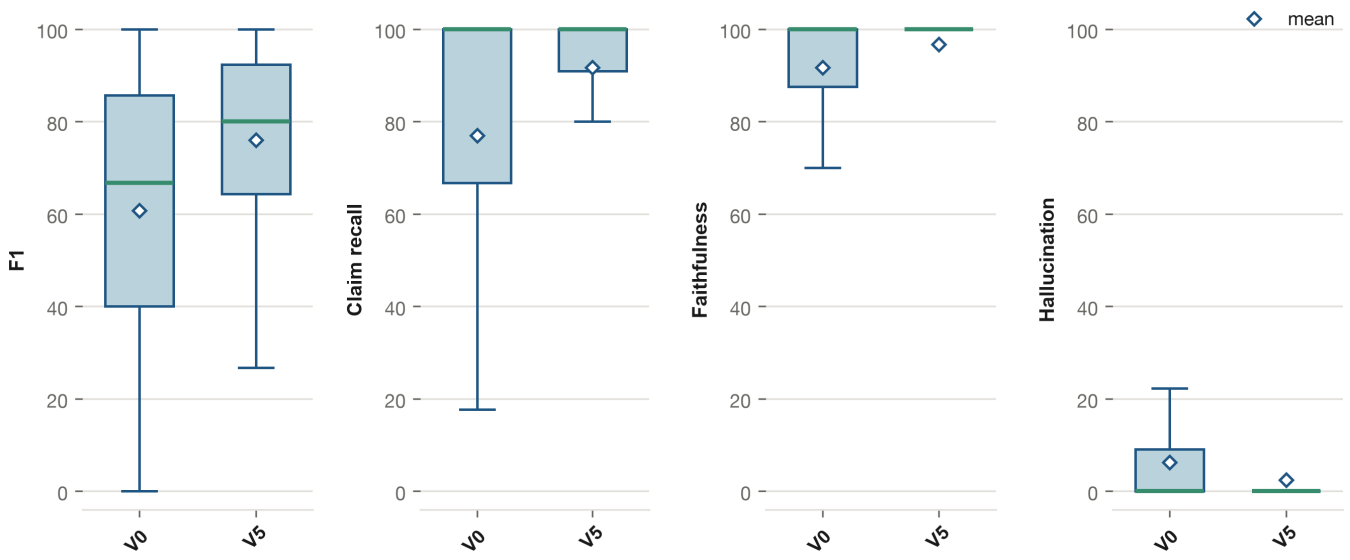
During ingestion, each manual is converted into structured text, and every figure is passed to a vision language model, that creates a short description of the image. This description is appended to the document text at the position the figure occupied, which makes the figure searchable in the same way as the text. Each passage also keeps references to its figures, so the corresponding images can be returned whenever the passage is retrieved.

Each question is handled by three dedicated AI stages.

- **Retrieval Planning.** The planner receives the user question, chat history and a catalogue of the available documents in the database. It then decides in which documents it should search and what the query should be. Hybrid retrieval then combines dense and lexical retrieval over both the planner's query and the worker's original wording, so that exact terms such as alarm codes and part identifiers are always preserved.
- **Figure Selection.** A dedicated stage reviews the retrieved passages and their figures and selects those that should accompany the answer.
- **Answer Generation.** The writer produces an answer grounded in the retrieved text and the descriptions of the selected figures, and states when the documentation is insufficient.

The same pipeline serves unrelated industrial domains through configuration rather than redevelopment.

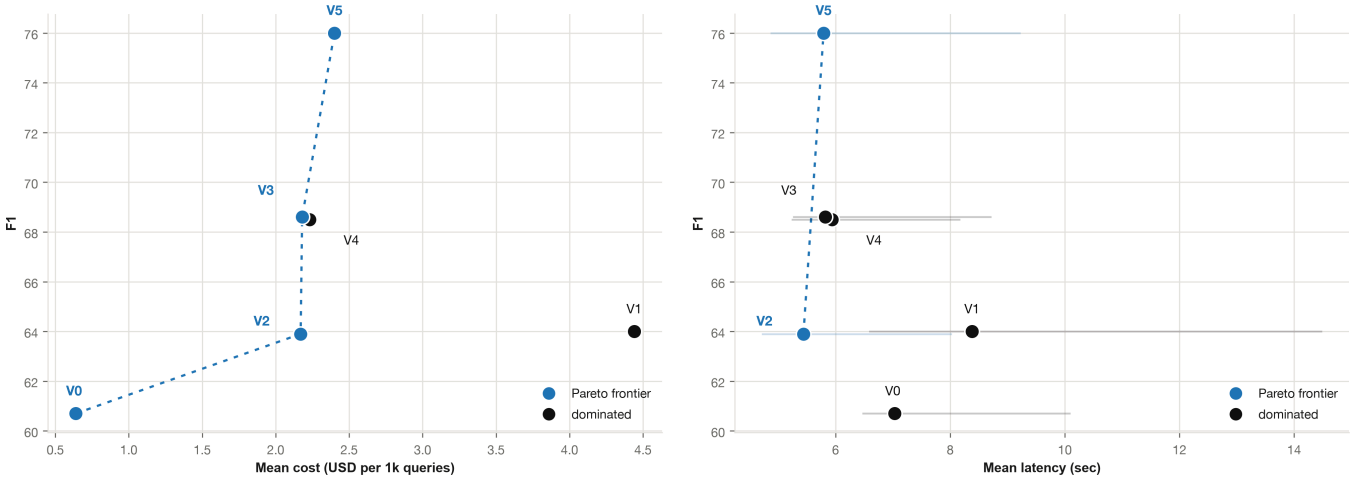
We evaluated six successive configurations, starting from a single function calling agent (FCA) baseline and ending with the deployed system. All configurations used the same index of 41 manuals from two unrelated industrial domains, pipe rehabilitation and bar feeder service, deliberately combined to increase its heterogeneity. The test set consists of 145 questions phrased as a technician would ask them, with handwritten ground truth answers. Answers were scored at claim level with the RAGChecker framework, and cost and response time were recorded for every configuration. Figure selection was evaluated separately on 22 questions against manually annotated figure sets. The box plots below show the scores of the baseline (V0) and the final deployed system (V5), while the full comparison of all six configurations is presented in the paper.



Key Results

- **Improved Answer Quality.** From the baseline to the deployed system, F1 increased from 60.7 to 76.0 and claim recall from 76.9 to 91.7.
- **Stronger Grounding.** Faithfulness to the retrieved documentation increased from 91.7 to 96.7, while hallucination decreased from 6.2 to 2.4.
- **Robust Retrieval for Difficult Questions.** The retrieval optimizations had the strongest effect on the weakest cases, with the lower end of the claim recall distribution rising from 17.7 to 80.0.
- **Efficiency in Cost and Latency.** The deployed system responds in 5.8 seconds compared with 7.0 seconds for the baseline, at approximately USD 2.40 per thousand queries. Separating planning from answer generation preserved answer quality while reducing cost and latency.
- **Accurate Figure Selection**. The assistant returned 92.1% of the relevant figures without any image specific retrieval optimization. The main remaining error is the inclusion of an additional figure.
- **Reliable Abstention**. All configurations correctly mentioned the lack of available information to the questions not covered by the documentation.

A key finding is that the largest single improvement came from the final instructions given to the planner and writer, which increased F1 by 7.5 points without additional latency while claim recall remained almost unchanged. Answer quality therefore depends not only on the evidence retrieved but also on how that evidence is used. Plotting answer quality against operating cost and response time shows that the deployed configuration lies on the Pareto frontier in both cases, combining the highest answer quality with a response time faster than the baseline. The same analysis provides a practical basis for selecting a configuration according to the budget and response time requirements of each deployment.



This work is closely aligned with the goals of the XR5.0 project, which aims to advance AI driven, human centric XR applications for Industry 5.0. The assistant can serve as the knowledge layer behind XR training and support, delivering grounded answers and the relevant figures at the point of work.

Our ongoing work within XR5.0 focuses on further improving figure selection and extending the assistant to additional pilot documentation. Innov-Acts thereby contributes to trustworthy AI support that helps industrial workers carry out their tasks more safely, accurately and efficiently.

2.5 AI INTEGRATION

Enhancing Human-AI Collaboration in XR Environments to Increase Trust and Human Cognition

Since 2021 the European Commission (EC) highlighted the need to build on top of the digital focus introduced in Industry 4.0 standards, with the intention to generate a globally competitive and world-leading industry which speeds up investments in research and innovation but is also sustainable and resource-efficient. This new strategy, known as Industry 5.0 (I5.0), introduced new initiatives concentrated on the adoption of human-centric approaches for digital technologies including Artificial Intelligence (AI) and Extended Reality (XR) solutions and the up-skilling / re-skilling of European workers' digital skills.

Although the adoption of AI and XR solutions is progressing in an accelerated pace in multiple industrial scenarios, many challenges arise. The high level of complexity encountered in AI models remains a drawback for widespread industrial adoption. AI models are defined by large numbers of interconnected parameters which tend to decrease the understanding of a model's decision-making processes from a human perspective, thus generating an issue of trust. Furthermore, state-of-the-art XR applications are built based on an "one-size-fits-all" philosophy that does not consider the characteristics of individual workers. Hence, they fall short when it comes to supporting the emerging wave of Industry 5.0 (I5.0) applications that are destined to be human-centric and emphasise trustworthy human-machine collaboration.

The XR5.0 project demonstrates and validates novel Human-Centric concepts and AI-based XR paradigms tailored to the requirements of I5.0 applications. It combines a unique blend of XR technologies and advanced AI paradigms, including AI technologies that foster human-machine cooperation such as eXplainable Artificial Intelligence (XAI), NeuroSymbolic Artificial Intelligence (NSAI), Active Learning (AL) and Generative AI (GenAI). The research, development and combination of these paradigms, empower novel XR environments that visualise recommendations, classifications, and explanations to provide human experts with access to enriched, detailed, and more accurate information.

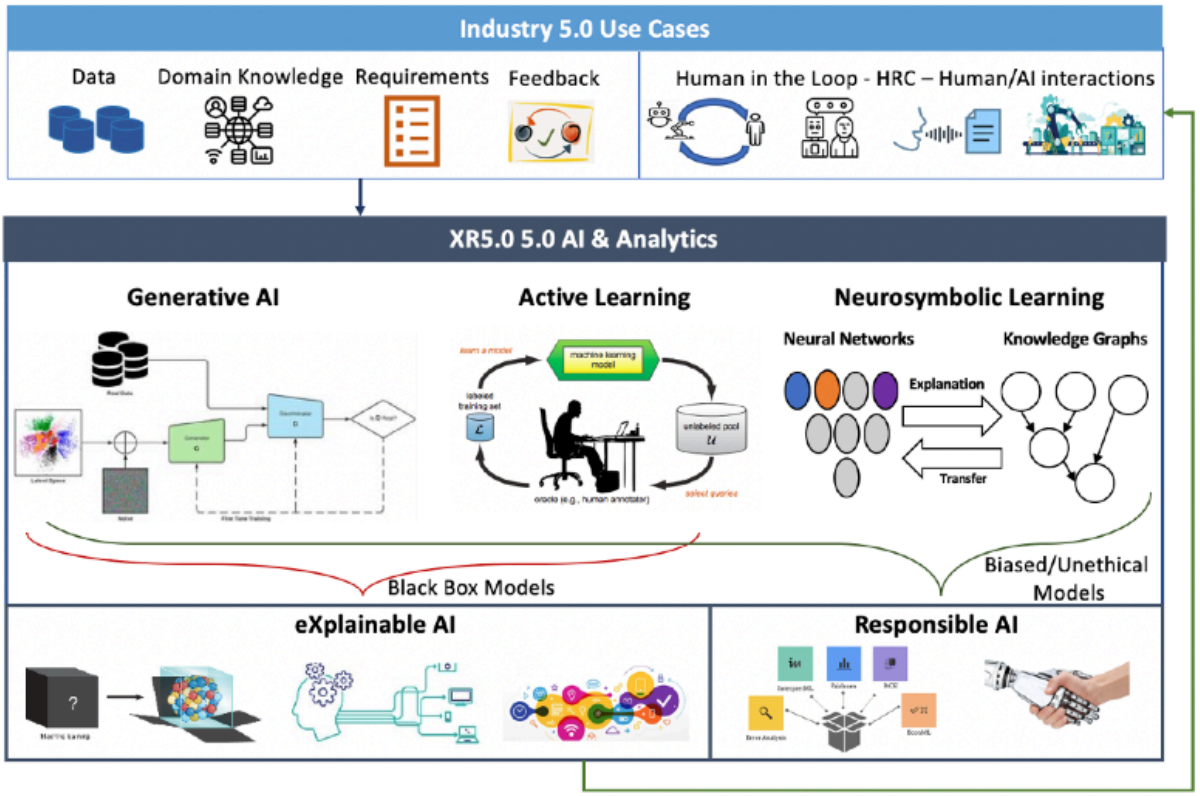


Figure 1: XR5.0 AI paradigms.

eXplainable Artificial Intelligence (XAI)

The XAI components developed for the purposes of the XR5.0 project are designed to provide useful insights and clarity into complex AI models that can be seen as "black-boxes". To serve a variety I5.0 applications and assist human experts in cases such as Rapid Human Centric AI-Enabled Product Design and Human Centered Remote Maintenance and Asset Management, the XR5.0 project provides solutions for three distinct types of XAI models:

- Glass-Box Models: Designed for inherently interpretable outputs through human-centric, concept-driven models that embed interpretability directly into the AI process.
- Post-Hoc Methods: Advanced tools that provide explanations for black-box models, allowing integration into existing workflows without retraining.
- Human-Centric GPT-Based Interaction: A conversational interface leveraging large language models (LLMs) for intuitive and interactive AI explanations.

NeuroSymbolic Artificial Intelligence (NSAI)

For the purposes of the XR5.0 project, the NeuroSymbolic AI (NSAI) components introduce a symbolic reasoning level to traditional AI models allowing domain experts to generate and/or extract semantic rules and reasoning out of "black-box" models. To further elaborate, the NSAI solution consists of 2 modules; a Neural Network (NN) that is responsible for tasks like object detection / image recognition and a symbolic reasoning part that is responsible for generating rules that will guide the training of the NN. Such rules are derived from human interaction, thus placing the human experts at the core of the AI modeling and training. The XR5.0 project utilizes NSAI in multiple I5.0 scenarios such as Anomaly detection of complex Water Pipe Networks based on XR streaming environments and Increased Effectiveness and Safety of Product Assembly and Repair Processes.

Active Learning (AL)

The rapid advancements in the field of Artificial Intelligence (AI) and Machine Learning (ML) have imposed the necessity for development of new ways of human-machine interactions. The XR5.0 has created a novel paradigm that enhances human – AI collaboration by combining immersive environments (XR applications) with Active Learning (AL) approaches, such as human-in-the-loop. The AL component empowers domain experts to be in the forefront when using AI as it allows them to directly interact with the AI models (e.x. NSAI models) in immersive environments, thus enhancing algorithmic accuracy, expert knowledge and human cognition. This approach is utilized in I5.0 scenarios such as Rapid Human Centric AI-Enabled Product Design, Anomaly detection of complex Water Pipe Networks based on XR streaming environments, Object Detection in XR streaming environments and Increased Effectiveness and Safety of Product Assembly and Repair Processes.

Generative Artificial Intelligence (GenAI)

The landscape of artificial intelligence has been transformed by Large Language Models (LLMs) and Generative AI (GenAI), fundamentally changing human-computer interaction through natural language interfaces. The XR5.0 project integrates GenAI technologies with XR environments to enhance human-AI collaboration, aligning with Industry 5.0 principles. The GenAI paradigm introduces a novel approach to industrial training and applications by combining AI-powered conversational capabilities with immersive XR experiences, aligned with Industry 5.0's human-centric vision. The GenAI component incorporates an LLM Chat Engine that delivers intelligent, context-sensitive guidance and a vector database for integrating proprietary or domain specific knowledge. The XR5.0 project employs the GenAI component in I5.0 scenarios such as Rapid Human Centric AI-Enabled Product Design, Human Centred Remote Maintenance and Asset Management, Operator 5.0 Training for Smart Water Pipes based on XR Streaming, Worker Centric Aircraft Maintenance Training and Human Centric Guidance and Troubleshooting for Customer Service.

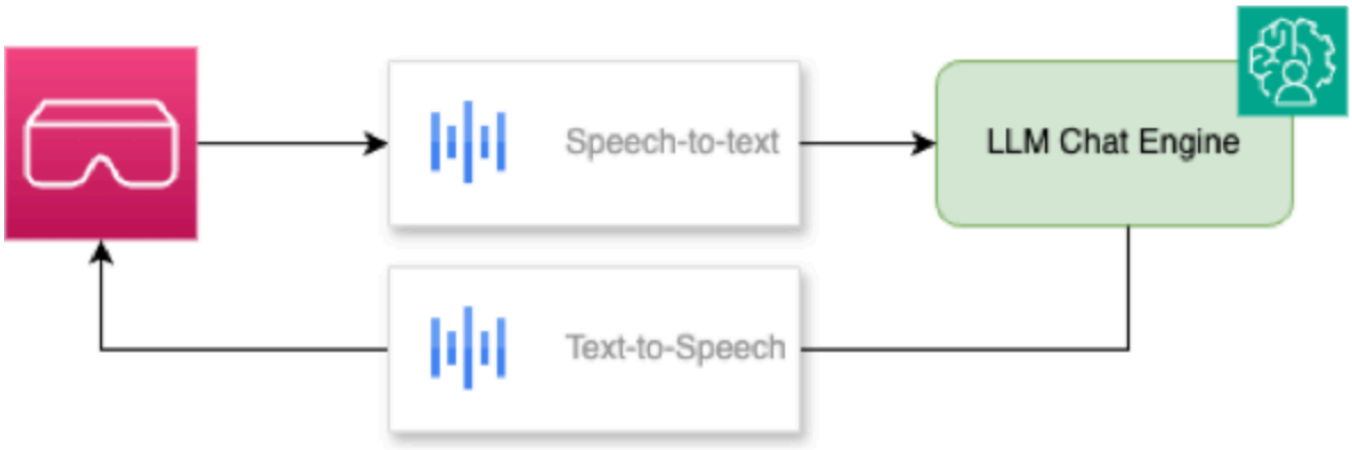


Figure 2: Indicative Workflow between XR and the LLM Chat Engine.

2.6 AI INTEGRATION

Enhancing XR5.0: Orchestration Pipelines for Smarter VR/AR Solutions

Introduction

The integration of Artificial Intelligence (AI) with immersive technologies such as Virtual Reality (VR) and Augmented Reality (AR) is reshaping how we experience digital environments. In this post, we explore how the using orchestration tools like Apache Nifi or Mage.ai can streamline the integration of AI into your VR/AR solutions and discuss the advantages of adopting this technology within XR5.0, particularly through Unity—one of the most versatile game engines for VR/AR development.

Why Mage.ai is ideal for XR5.0?

Mage.ai is an open-source, low-code AI tool that simplifies the development and deployment of machine learning pipelines. This tool allows developers to easily create modular, reusable components that make integrating AI functionalities within XR solutions more efficient.

Leveraging generative AI, it is possible to create pipelines that automate parts of the data transformation and model-building process. This makes it simpler for development teams to generate custom AI models tailored for specific VR/AR use cases, whether it's for user interaction, environment adaptability, or even content creation.

For this purpose, Mage.ai can easily integrate with XR environments built using Unity, via REST calls, providing a seamless experience from prototyping to production.

The processing pipelines can go beyond simply streaming 3D objects: it enables powerful real-time transformations of any type of model. For industries like manufacturing, this allows companies to dynamically adjust and optimize 3D models before deployment, enhancing both efficiency and adaptability in VR environments.

Generative AI to augment the pipelines

One of the most powerful features of Mage.ai is its ability to incorporate custom Python code. Naturally this means adding generative AI to build machine learning pipelines. Imagine having generative AI tools that help you quickly outline, adapt, and optimize a data pipeline that learns from users' behavior in a VR environment. Generative AI can automate tasks like data cleaning, feature extraction, and model selection—letting developers focus more on creating immersive experiences rather than managing tedious ML processes. This capability could be game changer for the XR5.0 project, enabling. Because of this, teams can generate tailored AI pipelines much faster, enabling rapid prototyping and iteration.

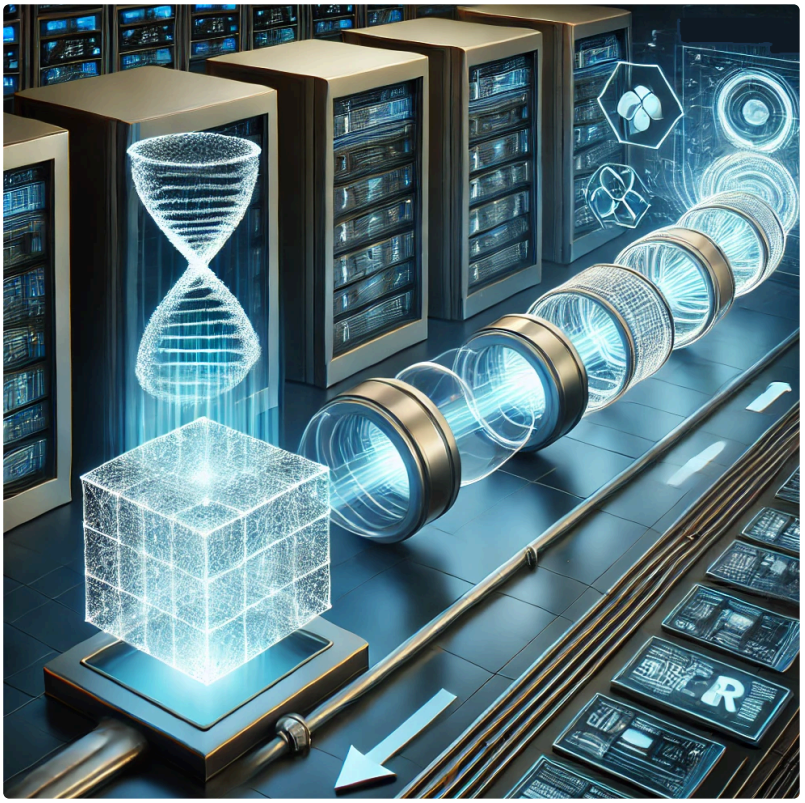
AI models can quickly learn user preferences, making the XR experience more personalized and responsive.

Another use of Generative AI is that it can automatically refine 3D models for better efficiency or adapt them in real time based on feedback. This means faster iterations of digital twins or machinery models, reducing downtime and accelerating innovation.

Seamless integration for maximum efficiency

The integration process is designed to be smooth. Using Unity's comprehensive support for C# scripting, you can connect to Mage.ai pipelines to process data from VR/AR sensors and feedback insights directly into Unity. This means you can create highly responsive environments—ones that learn, adapt, and improve interaction with every user.

Mage.ai offers a powerful and accessible solution for integrating machine learning into the XR5.0 project, providing Unity developers with the tools they need to enhance VR/AR experiences without getting bogged down by the complexities of AI development. With generative AI, rapid prototyping, real-time adaptation, and scalability, Mage.ai is an ideal partner for building the next generation of intelligent, immersive XR applications.



2.7 AI INTEGRATION

Generative AI in Extended Reality for Manufacturing: The 2026 Landscape (and What Comes Next)

A machine stops mid-shift. The operator hears a familiar tone—fault again. But this time, instead of hunting through manuals or waiting for a specialist, they look at the machine through smart glasses. The relevant panel is highlighted. A few sensor trends appear where they matter, not on a distant dashboard. A conversational assistant asks a clarifying question, proposes two safe intervention paths, and explains the trade-off. A remote expert joins the same view, drops a marker on a specific bolt, and the digital twin in the background runs a quick "what-if" check before the first tool is even picked up.

That is the feel of manufacturing XR in 2026: less "wow demo," more quiet competence—and more human-centric, consistent with the Industry 5.0 push toward tighter collaboration between people and intelligent systems [1].

It's also the direction behind **XR5.0**, our Innovation Action project, financed by the Horizon Europe Program, building a person-centric, trustworthy, AI-powered XR ecosystem for manufacturing—where human-centric digital twins, explainable AI, and generative AI tailor XR experiences to real workers, real contexts, and European values (privacy, security, data sovereignty).

What's changing isn't XR alone, but how three layers are starting to lock together: XR as a spatial interface [2], digital twins as living models of assets and processes [3], and generative AI as the "translation layer" that turns data and procedures into guidance people can act on.

XR is becoming the factory's user interface

Manufacturing has used XR for years—training, assembly guidance, inspection, remote support—because it reduces errors, improves safety, and speeds up learning [4]. What's new is how *operational* it's becoming: XR is moving from pilots into daily routines, while digital twin simulations are increasingly used for planning, optimization, and proactive decisions [3].

As this shift happens, expectations rise. Overlays alone aren't enough. Workers want systems that adapt to shop-floor reality—noise, gloves, time pressure, mixed skill levels, and constant change. That is where AI—especially generative AI—begins to change the experience.

What generative AI adds (beyond automation)

In 2026, the value of generative AI in XR is less about futuristic autonomy and more about three practical upgrades.

1) Procedures become situational guidance. Maintenance and repair are classic AR territory: diagrams, sequences, and in-context instructions to reduce guesswork and speed fixes [5]. The limitation is that procedures are usually written for an "average" scenario. Generative AI can make XR guidance more conversational and responsive: summarize what matters now, adapt steps to the observed situation, and answer follow-up questions hands-free.

2) Training feels less like content and more like coaching. XR training can reduce training time, improve retention, and allow safe practice without risking downtime or injury [4][5]. But scaling it has often meant scaling content production—slow and costly. Market signals increasingly point to AI as the way through this bottleneck: adaptive learning paths, real-time adjustment of difficulty, and faster creation/maintenance of training materials are becoming requirements for broad rollout [6]. Generative AI doesn't replace expertise, but it can compress the loop from expert know-how to usable training—especially when product variants and procedures change frequently.

3) Digital twins start to speak "human." Digital twins can be powerful yet hard to interrogate. XR already helps people "step into" complex twin data spatially [3]. Add generative AI, and the twin becomes easier to question: *What changed since yesterday? What's the likely cause? What's the safest intervention?*—with answers grounded in telemetry and history, not guesswork. This is where the "industrial metaverse" idea becomes tangible: real-time interaction with physical entities mirrored into a virtual space, enabling proactive problem-solving rather than reactive firefighting [1].

What's working on factory floors in 2026

The most convincing progress isn't one killer app—it's repeatable patterns.

- **AR inspection and maintenance toolkits** increasingly blend live data with contextual overlays and knowledge modules [7].
- **Collaborative maintenance** connects field technicians with control-room colleagues or remote experts, reducing risk and speeding resolution [7].
- **XR-based design reviews and virtual commissioning** reduce late-stage errors and accelerate iteration, especially where physical prototyping is expensive or disruptive [8].

Across all three, the goal is the same: compress the distance between *knowing* and *doing*.

The invisible infrastructure behind "it just works"

When AI-powered XR works well, the infrastructure disappears—but it's doing heavy lifting:

- **5G and edge computing** help erase latency barriers for real-time, multi-user collaboration and on-floor visualization [6].
- Research partnerships are explicitly exploring **XR + digital twins + AI over 5G/5G Advanced** for immersive training and real-time process optimization across sites [9].
- For high-fidelity twins, **hybrid approaches** (local + streamed rendering) are positioned as a way to scale realism without putting all compute on the device [10].
- And open standards such as **OpenXR** matter for interoperability and ecosystem maturity [6].

The hard part: trust, privacy, and human reality

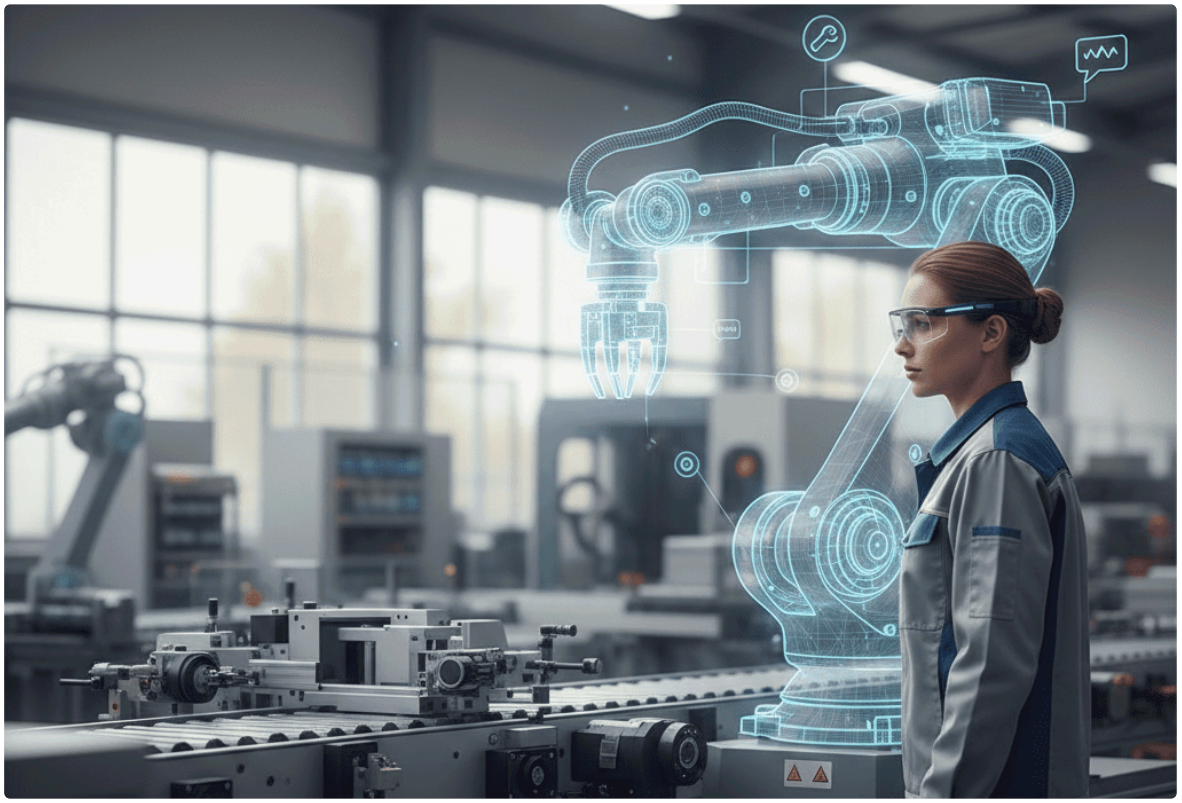
Industry 5.0 is not just about capability; it's about trust and human-centricity [1]. XR makes this unavoidable because headsets and smart glasses can capture sensitive environments and worker-related signals. Security and privacy concerns are real: XR devices can "see," and organizations need risk assessment, policies, and careful data management—especially where IP or personal data could be

exposed [11]. Adoption also depends on human factors; comfort and all-day wearability remain practical constraints for some users [6]. The next wave won't be won by the flashiest demo, but by solutions workers accept, supervisors trust, and IT can secure.

Where XR5.0 fits

Many deployments still assume a generic user and fixed workflows. XR5.0 starts from the opposite assumption: people differ, contexts change, and XR must adapt—safely and transparently. That means human-centric digital twins for real-time adaptation, generative AI inside XR (including a chat engine for context-aware assistance and maintenance), explainable AI for transparent human–AI collaboration, and a strong commitment to privacy, security, compliance, and data sovereignty. It is being validated through six real manufacturing pilots—where XR has proven ROI and where generative AI can remove scaling bottlenecks.

Closing thought. AI-powered XR is starting to feel less like "technology added to manufacturing" and more like manufacturing learning a new language: spatial, interactive, and collaborative. The best versions won't replace people. They'll raise the floor—safer work, faster learning, and more first-time-right execution. That's the promise of Industry 5.0 [1], and the trajectory XR5.0 is building toward.



References

[1] *Metaverse for Manufacturing: Leveraging Extended Reality Technology for Human-Centric Production Systems*.

[2] *What is XR, and how is it radically transforming industries?*

[3] Business Reporter — *Digital twins, extended reality and manufacturing's quiet revolution.*

[4] *How VR Technology Is Altering Manufacturing.*

[5] *XR/AR in Manufacturing: 7 Use Cases with Examples ('26).*

[6] *Extended Reality (XR) Market Size, Trends & Share Analysis, 2026–2031.*

[7] Unity — *How XR Reinvents the Manufacturing Factory Floor.*

[8] ABI Research — *Three Ways XR Revolutionizes Industrial Machinery Manufacturing.*

[9] Ericsson / Volvo Group / Airtel — *Research collaboration on Digital Twins & XR over 5G Advanced in India.*

[10] Immersive Learning News — *NVIDIA's New Superpowers: Digital Twins & AI-powered XR, partnership with Apple and Magic Leap.*

[11] VIVE Blog — *XR in Manufacturing: Considerations from Industry Professionals.*

2.8 AI INTEGRATION

Human-Centered AI: The XR5.0 Project and the Future of Adaptive Systems

Artificial Intelligence (AI) is rapidly transforming how we live, learn, and work. Yet, even as AI systems become more capable, they often they often lack real-time awareness of users' cognitive and affective states. What if our AI systems could understand users' signals — attention, stress, or fatigue—and adjust their behavior to help us perform better and feel better?

At the **Insight Research Center** of Instituto Piaget, Portugal, this question lies at the heart of an ambitious initiative - **the XR5.0 Project** – a Horizon Europe collaboration, involving 23 partners from nine countries. We are exploring how **AI, multimodal sensing and assessment, and human factors research** can enable systems that adapt in real-time to the user's cognitive and emotional states.

From Industry 5.0 to Human-Centered AI

Industry 5.0 envisions a future where technology and people work together harmoniously. Unlike the automation-driven vision of Industry 4.0, the new paradigm emphasizes *human-centric, sustainable, and resilient* systems. XR5.0 embodies this principle by developing **extended reality (XR) technologies** —virtual and augmented environments—that are not only functional but also **responsive to human conditions**, reducing mental workload and stress to sustain wellbeing.

The project's core idea is simple yet transformative: use **AI-driven sensing and adaptation** to make XR environments responsive of their users' mental, emotional and physical states. Whether a worker is fatigued, stressed, or overloaded, the system detects these cues and adjusts the interaction accordingly—simplifying interfaces, modulating training pace, or providing supportive feedback.

Understanding and Measuring Human Factors

To understand how the system adapts to the user, XR5.0 assesses the user state across three complementary dimensions —cognitive workload, affective state , and physiological signals—grounded cognitive ergonomics and applied psychophysiology:

- **Cognitive factors**, such as attention, workload, and decision fatigue - govern how users process information, allocate attention, and make decisions in complex environments.
- **Affective factors**, such as frustration, motivation, and trust – influence engagement, **confidence, and readiness to learn or perform under varying emotional conditions.**
- **Physiological indicators**, including heart rate variability (HRV), eye movements, electrodermal activity, and pupil dilation – provide objective, real-time signals that support inference of **cognitive load and emotional state.**

Integrating multimodal signals provides a precise, holistic understanding of the user's condition, enabling an AI-driven adaptive engine to tailor the XR environment in real time—modulating visual complexity, pacing, task difficulty, and information flow.

Use Case: Adaptive Training in Extended Reality

One of XR5.0's most promising use cases is **adaptive worker training**. In traditional XR-based training, every user follows the same scenario at the same pace, regardless of skill level or mental fatigue. XR5.0 changes that by adapting content and pacing to the user's moment-to-moment state.

Imagine a worker wearing a lightweight XR headset connected to wearable sensors such as a smartwatch and ring. As the worker performs a maintenance simulation, the system continuously monitors eye-tracking data and physiological signals. When the AI-driven adaptive engine estimates high cognitive load or stress, it **reduces task complexity**, **slows the pace of instruction**, and **highlights key visual cues** to maintain comprehension and comfort.

Conversely, if the user shows signs of confidence and low cognitive strain, the system increases challenge—introducing more advanced steps, tighter tolerances, or time constraints—to sustain engagement and accelerate learning. This **closed feedback loop**—from sensing to inference to adaptation—delivers a personalized, effective, and well-being-aware training experience.

Why It Matters

Human adaptability has always been our greatest strength, but in the digital age, the cognitive demands placed on us can exceed our limits. The XR5.0 Project shifts the paradigm toward *technology that adapts to people*, rather than the other way around. By integrating **AI, human factors assessment, and immersive technologies**, XR5.0 has the potential to:

- **Improve learning outcomes** through adaptive pacing, and feedback.
- **Reduce mental workload, fatigue and stress** in industrial and training environments.
- **Improve safety and performance** by aligning digital systems with human capabilities.

These outcomes are not just technological goals—they reflect a deeper human aspiration: to build intelligent systems that respect our limits and amplify our strengths, supporting both performance and well-being.

Toward a More Human Future

The XR5.0 Project exemplifies a new era of **Human-Centered Systems**, where intelligent systems act as responsive collaborators – able to sense and adapt to our cognitive and emotional realities. **It marks a concrete step toward AI that enhances not only productivity but also human well-being, empathy, and resilience.**

In a world increasingly mediated by algorithms and automation, XR5.0 reminds us that the most advanced technology is the one that adapts to human – respecting our limits and amplifying our strengths. It is a tangible step toward the broader vision championed by Instituto Piaget's Insight Research Center for Human and Ecological Development: AI systems that enhance human wellbeing, not just productivity.

2.9 AI INTEGRATION

When XR Training Understands Stress: Building Adaptive Human-Centric Digital Twins

What if a training system could understand when an operator is becoming stressed and adapt in real time to provide additional support?

This is one of the key questions being addressed in the XR5.0 project through the development of Human-Centric Digital Twins (HDTs). Rather than treating all workers the same, XR5.0 aims to create systems that continuously monitor human factors and adjust XR experiences according to the operator's current condition.

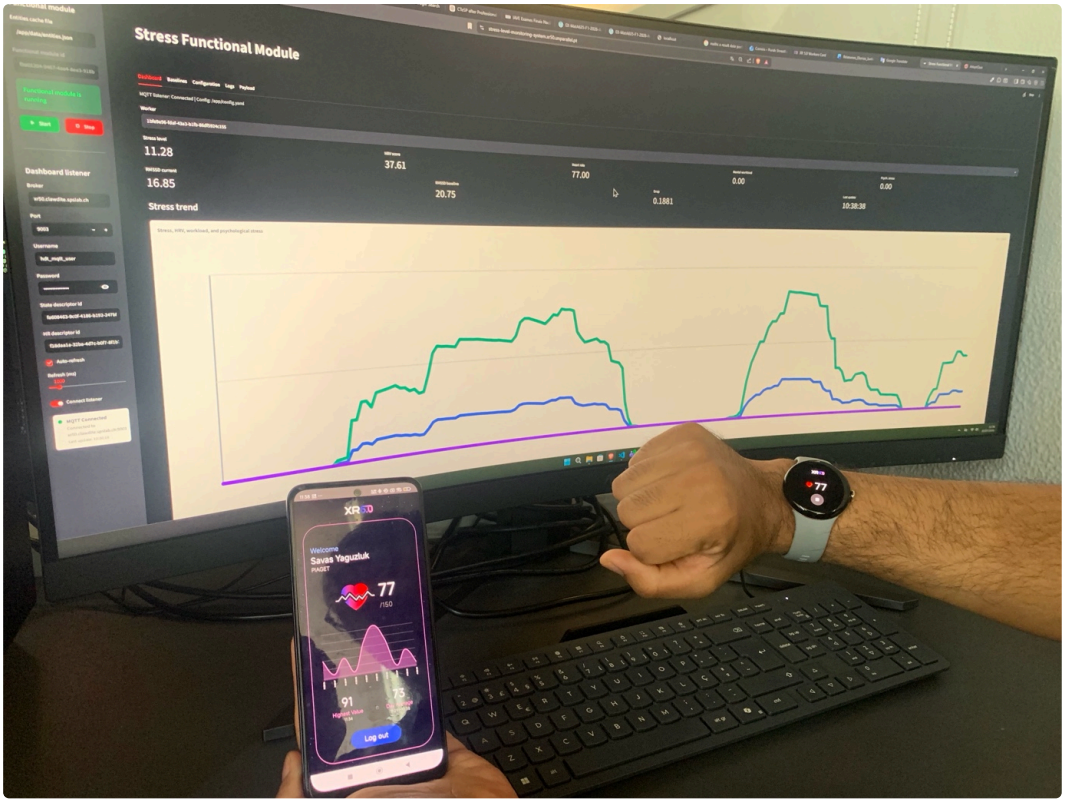
The Instituto Piaget team proposed a framework for assessing operators' stress levels through real-time multimodal assessment. The objective is not simply to collect physiological data, but to combine multiple indicators into a robust representation of the operator's psychophysiological state.

The framework relies on three complementary sources of information:

- Physiological indicators, such as heart rate and heart rate variability (HRV);
- Behavioural indicators, including eye-tracking metrics;
- Self-report measures provided directly by the operator.

Together, these inputs contribute to the calculation of a Composite Stress Index, a dynamic measure that evolves over the course of task execution. Because the index is derived from several simultaneous indicators, it provides a more reliable assessment than any individual measurement alone. This multimodal approach allows the system to better distinguish between temporary fluctuations and meaningful changes in the operator's workload and stress level.

The image below shows one component of this broader framework: the acquisition of physiological data via a wearable smartwatch. Heart rate measurements are continuously collected and transmitted to the Clawdite platform, where they can be analysed and used to derive heart rate variability metrics. The dashboard visualises these values and their evolution over time, enabling real-time monitoring of the operator's state.



However, it is important to note that the XR5.0 stress assessment framework goes far beyond heart rate alone. In parallel with physiological monitoring, XR5.0 integrates lightweight self-assessment mechanisms directly into XR environments. During pilot activities, operators can provide quick evaluations of their perceived stress and cognitive workload using simple in-situ questionnaires embedded within the training experience. These subjective assessments complement the objective data collected from wearable devices and contribute to a more complete understanding of the operator's condition.

The value of this approach lies in its ability to support adaptation. As the Composite Stress Index changes, the Human-Centric Digital Twin can detect situations where stress levels exceed predefined thresholds. When this occurs, the system may trigger adaptive responses designed to support the operator. Depending on the application, these responses could include modifications to training content, additional guidance, changes in information presentation, or other interventions aimed at reducing cognitive effort and improving performance.

This concept reflects one of the central principles of Industry 5.0: technology should adapt to people, rather than forcing people to adapt to technology.

Within XR5.0, the Human-Centric Digital Twin serves as the foundation for this vision. By combining physiological, behavioural, and self-reported information, the digital twin becomes capable of maintaining an up-to-date representation of the worker and supporting personalised XR experiences. The result is a training environment that can respond not only to task requirements, but also to the human being performing the task.

The demonstrations developed so far illustrate the general principle of adaptive human–digital twin interaction. While the smartwatch shown in the image represents the most visible part of the system, it is only one element of a wider real-time stress assessment and adaptation framework currently being developed within XR5.0.

As the project progresses, these capabilities will continue to evolve, enabling XR applications that are increasingly aware of human needs, workload, and well-being. By bringing together wearable sensing, behavioural analytics, subjective assessments, and adaptive XR technologies, XR5.0 is helping shape the next generation of human-centric industrial environments.

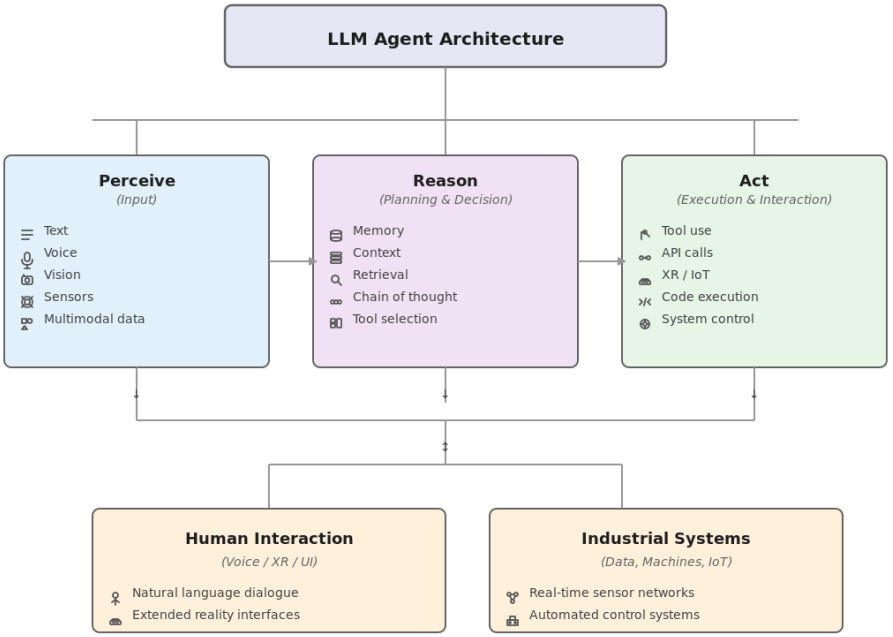
2.10 AI INTEGRATION

LLM Agents Go to Work: How XR5.0 Is Bringing the Age of Agentic AI to Industry

From Chatbots to Agents

Artificial Intelligence (AI) is entering its most transformative phase — the **era of agents** [1]. Large Language Models (LLMs) are evolving from passive chatbots into **goal-driven, reasoning systems** that can plan actions, use tools, and interact across modalities. OpenAI's GPT-models, Anthropic's Claude, and Meta's AI-enabled glasses all reflect this shift toward *Agentic* systems that perceive, reason, and act.

In industrial environments, this evolution is not a luxury; it's essential. Manufacturing, energy, and aerospace sectors face global skills shortages and complex data silos. Workers often lack immediate access to expert knowledge when diagnosing equipment faults or applying safety procedures. Traditional automation can process data but cannot explain or contextualize it. LLM-based agents can.



From Chatbots to Agents — The New Architecture of Intelligent Collaboration

Why Industry Needs Agentic AI

LLM agents combine natural-language understanding, contextual memory, and tool orchestration to act as **intelligent intermediaries between humans, data, and machines**. An operator can ask, "What caused the pressure anomaly on Pump A-7?" and receive a response that merges sensor readings, maintenance history, and procedure steps cited from the right document. A technician wearing AR glasses can request, "Show me the torque pattern for this valve," and see the instruction projected

directly on the digital twin. Such examples illustrate a practical shift from static manuals and dashboards to **interactive, conversational, and situational intelligence**. The result is faster decision-making, safer operations, and continuous learning on the job.

XR5.0's Solution for Agentic AI

The EU-funded **XR5.0 project** brings this transformation to industry by merging **Extended Reality (XR)** with **LLM-powered agents**. Aligned with the **Industry 5.0** vision, XR5.0 focuses on *human-centric*, *explainable*, and *sustainable* AI enhancing human expertise instead of replacing it. Within XR5.0, Innov-Acts has developed the LLM Chat Engine, a scalable platform that delivers **industrial-grade agents** through secure APIs and XR interfaces. The system transforms large technical documents, manuals, and IoT data into an **accessible conversational layer** that workers can interact with via text or speech.

Inside the XR5.0 LLM Chat Engine

The Chat Engine implements a **Retrieval-Augmented Generation (RAG)** architecture enhanced with multi-agent orchestration [2]. Documents are parsed and semantically chunked before embedding, preserving technical structure and improving recall accuracy. Benchmarking demonstrated **99.07 % faithfulness** and **93.37 % recall**, achieving near-zero hallucinations — crucial for safety-critical domains [3].

The backend runs on FastAPI, integrates easily with enterprise systems, and supports cloud, edge, or on-premise deployments. **Data residency and security** are built-in: all indexing and retrieval can stay within the company's infrastructure, meeting GDPR and AI Act requirements.

LLM Agents Meet Extended Reality

Connecting the Chat Engine with XR devices makes knowledge access **hands-free and immersive**. Speech-to-Text (STT) and Text-to-Speech (TTS) components enable natural dialogue through headsets or AR glasses. A worker can talk to the agent, receive spoken guidance, and view annotated instructions within the physical workspace. This integration transforms XR from a visualization tool into an **interactive expert assistant** that understands context and supports real-time operations.

Design Principles

XR5.0's approach to LLM agents follows four guiding principles:

- **Human-in-the-Loop:** Operators remain in control, validating and refining AI suggestions.
- **Transparency:** Each answer can be traced to its source; XR5.0's XAI methods can be integrated as LLM tools.
- **Compliance and Security:** Local data handling ensures conformity with EU AI Act and GDPR.
- **Openness:** REST, MQTT, and WebSocket APIs make integration simple; XR5.0 effectively offers **LLM Agents-as-a-Service** for industry.

Agentic AI in XR5.0 is designed to **augment, not automate away** human expertise.Technicians and engineers collaborate with digital co-workers that provide explanations, recall past actions, and learn from feedback. This partnership model strengthens trust and accelerates upskilling. In addition, XR5.0's

LLM Chat Engine embodies open interfaces, transparent reasoning, and respect for data ownership. Thereby, XR5.0 ensures that **AI innovation remains both competitive and responsible**.

Conclusion

LLM agents are redefining how humans interact with machines and knowledge. Within XR5.0, these agents are **operational tools** that make industrial expertise accessible through natural conversation and immersive visualization.

The XR5.0 LLM Chat Engine demonstrates that **Agentic AI can be explainable, secure, and immediately useful** in real-world factories and infrastructures. It represents a practical step toward Industry 5.0 where technology empowers people, strengthens resilience, and keeps intelligence close to where work happens.

Learn more at https://xr50.eu or contact **info@innov-acts.com** for access to the XR5.0 LLM Chat Engine.

References

[1] McKinsey & Company (2025) Seizing the agentic AI advantage. Available at: https://www.mckinsey.com/capabilities/quantumblack/our-insights/seizing-the-agentic-ai-advantage (Accessed: 15 October 2025).

[2] Lewis, P., Perez, E., Piktus, A., Petroni, F., Karpukhin, V., Goyal, N., Küttler, H., Lewis, M., Yih, W.T., Rocktäschel, T. and Riedel, S., 2020. Retrieval-augmented generation for knowledge-intensive nlp tasks. Advances in neural information processing systems, 33, pp.9459-9474.

[3] Tomkou, D., Fatouros, G., Andreou, A., Makridis, G., Liarokapis, F., Dardanis, D., Kiourtis, A., Soldatos, J. and Kyriazis, D., 2025. Bridging industrial expertise and xr with llm-powered conversational agents. arXiv preprint arXiv:2504.05527.

2.11 AI INTEGRATION

From Extended Reality to Agentic Reality: When Virtual Worlds Start Acting on Our Behalf



From Extended Reality to Agentic Reality

Put on a headset today and you are, in a sense, still looking at an elaborate stage set. Objects wait to be picked up. Menus wait to be clicked. Scenes wait to be walked through. Extended Reality (XR) has spent most of its life as a *place* — beautifully rendered, increasingly responsive, but a place nonetheless, where the person is the only one actually doing anything.

Researchers now have a name for what changes when that stops being true: the "agent paradigm." One recent framework for understanding XR technology separates it from the rest of the stack — hardware, virtual-world content, embodiment — as its own layer, built from generalist agents, multi-agent planning, and dynamic adaptation to the environment [1]. Agentic AI, in other words, isn't being proposed as a feature bolted onto XR. It's being proposed as a fourth pillar of what XR *is*.

What makes an agent "agentic"

It helps to be precise about what separates an agent from a script:

- A **scripted character** follows a fixed decision tree. It reacts to input; it doesn't decide.
- An **agent**, as studied across XR and AI research, is expected to show some degree of autonomy — building trust with people, coordinating with other agents sharing the same space, and modelling behaviour like personality or gait rather than just animating pre-set poses [2].

A large scoping review covering 311 papers at the intersection of XR and AI found that interaction with intelligent virtual agents was one of only five major research directions in the field — as prominent as using AI to generate XR content in the first place [2]. Across that body of work, autonomy keeps surfacing as the property researchers actually care about measuring, more than realism of appearance or graphical fidelity [2].

Three places agentic AI is already showing up in XR

1. Agents that cross into the physical world. Most virtual agents are confined to the headset — whatever they do stays inside the scene. A research prototype called a "blended agent," tested in a mixed reality lab study, pushed past that boundary: the agent could act on real physical objects around the user, not just their virtual counterparts, so its behaviour had visible consequences outside the headset too [2]. It's a small-scale demo, not a shipping product, but the reaction is the interesting part — participants called the effect "amazing," and specifically pointed to seeing the *physical* consequences of the agent's actions as what made it feel more present, not less [2]. An agent starts to feel genuinely "there" less because of how it looks, and more because of what it visibly changes.

2. Agents you talk to instead of operate. Generative AI changes the interaction model itself: agents you *ask* for things in ordinary language, instead of triggering with a fixed input. In prototype AR systems, a vision-language model recognises what's in a fridge and suggests a recipe unprompted [3]; in mixed reality training, multimodal language models align instructions to a real physical workspace nearly as capably as a human assistant would [3]. A parallel review of generative AI in XR points to the same shift from the content side: systems like AIsop use a language model to autonomously generate an entire narrative experience in VR, deciding not just what things look like but what happens next [4].

3. XR as the place where agents are trained, not just deployed. The relationship also runs the other way. A systematic review of the AI–XR combination found that a large share of the field uses virtual environments precisely because they're a safe, repeatable place to develop autonomous behaviour: robots and self-driving cars trained entirely inside XR-style simulations through reinforcement learning, then deployed into the real world without further adjustment [5]. Agentic Reality runs both ways — agents act inside XR, and XR is where many of today's agents first learn how to act at all.

The part nobody has figured out yet

None of this is a solved problem, and the research is upfront about that.

Most of what we know about virtual agents comes from asking people how trustworthy or "present" an agent *feels* — not from measuring what it actually gets right [2]. An agent can come across as warm and capable while still quietly getting things wrong.

Then there's the practical stuff that shows up the moment you try to build one for real: agents that confidently make things up, responses slow enough to break the illusion, and the sheer computing power it takes to run a capable reasoning model in real time [3].

Put those together and you get the real question behind Agentic Reality — not "can we build agents that feel convincing," which is largely solved, but "how much should we actually let them decide," which isn't.

A backdrop that decides

Extended Reality asked how far a virtual world could stretch around a person. Agentic Reality asks a different question: what happens once that world can act — and decide — on its own initiative, both inside the headset and, increasingly, in training the very agents that will later act elsewhere.

It's a question projects like XR5.0 are already grappling with on the factory floor, not in the abstract: how much initiative a person-centric, AI-powered XR system should take on a worker's behalf — and how to keep that initiative transparent rather than just convenient.

Sources

[1] B. Zeng, "Recent Advances and Future Directions in Extended Reality (XR): Exploring AI-Powered Spatial Intelligence," 2025.

[2] T. Hirzle, F. Müller, F. Draxler, M. Schmitz, P. Knierim, and K. Hornbæk, "When XR and AI Meet – A Scoping Review on Extended Reality and Artificial Intelligence," *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*, 2023.

[3] M. Zhu, J. Chen, and B. Li, "When Generative AI Meets Extended Reality: Enabling Scalable and Natural Interactions," *IEEE Internet Computing*, 2026 (preprint arXiv:2601.15308v1).

[4] X. Ning, Y. Zhuo, X. Wang, C.-I. D. Sio, and L.-H. Lee, "When Generative Artificial Intelligence meets Extended Reality: A Systematic Review," 2025 (preprint arXiv:2511.03282v1).

[5] D. Reiners, M. R. Davahli, W. Karwowski, and C. Cruz-Neira, "The Combination of Artificial Intelligence and Extended Reality: A Systematic Review," *Frontiers in Virtual Reality*, vol. 2, article 721933, 2021.

2.12 AI INTEGRATION

Making AI Understandable in Extended Reality: A Human-Centered Approach

Artificial Intelligence (AI) is increasingly shaping the way industrial operations are managed, optimized, and monitored. From anomaly detection in pipelines to predictive maintenance in factories, AI offers speed, precision, and foresight that would be impossible for humans alone. Yet one critical barrier remains: trust. Operators often struggle to understand how AI systems reach their conclusions, especially when decisions impact safety, efficiency, and costs.

This is where the work of XR5.0's Work comes into play. Focus on integrating Explainable AI (XAI) into Extended Reality (XR) environments, creating solutions that not only visualize outcomes of AI models but also empower human operators to interpret, validate, and act upon them in real time.

From Black Box to Transparent Insights

Traditional AI often functions as a "black box," producing outputs without offering clear reasoning. For industrial operators, this can be a serious challenge. If an AI model flags an anomaly in a pipeline, simply knowing that "something is wrong" is not enough. Operators need to know why the anomaly has been detected, what data contributed to that decision, and how confident the system is.

Through immersive AR and VR applications, XR5.0 is making this process more transparent. Anomalies and recommendations generated by AI are no longer just numbers on a dashboard, they are placed directly into the operator's field of view, linked to digital twins of equipment, and enhanced with explanations that highlight causes, contributing sensor data, and suggested next steps.

Building Human-Centric Interfaces

A key part of this work is the design of lightweight, modular user interfaces tailored for XR. Operators need fast, intuitive access to AI explanations without being overwhelmed by information. Popups, contextual menus, and interactive markers allow workers to call up details only when needed, reducing cognitive overload.

Equally important is the integration of AI-powered assistants within XR environments. Instead of searching through complex datasets, operators can simply ask the system, in natural language, questions such as: "What aquipment is essential for cleanning the pipeline?" or "What maintenance action is recommended?" The assistant can then provide explanations drawn from the AI models, displayed in both text/voice and visual overlays.

Handling Real-World Complexity

Integrating AI explanations into XR is not without challenges. Industrial environments are complex, and XR devices vary widely in terms of performance, sensors, and tracking capabilities. To address these issues, the XR5.0 team has focused on several strategies:

Device adaptability: Ensuring that explanations remain correctly aligned and stable, even when device tracking accuracy differs.

Information filtering: Designing adaptive visualization strategies that present only the most relevant details, preventing cognitive overload in information-rich scenarios.

Performance optimization: Developing rendering pipelines that allow mobile-class XR devices to display complex recommendation-rich environments without sacrificing responsiveness.

By addressing these challenges, the framework ensures robustness across different XR platforms and readiness for deployment in real-world industrial contexts.

Human-in-the-Loop Intelligence

One of the most powerful aspects of this approach is its emphasis on human-in-the-loop methods. AI is not designed to replace operators, but to work alongside them. Immersive technologies provide operators with the context and clarity they need to evaluate AI outputs, challenge or validate recommendations, and ultimately make informed decisions.

This collaboration improves both sides of the equation: AI models become more accurate through human feedback, and operators enhance their decision-making with the support of transparent and explainable insights.

Towards Smarter and Safer Industry

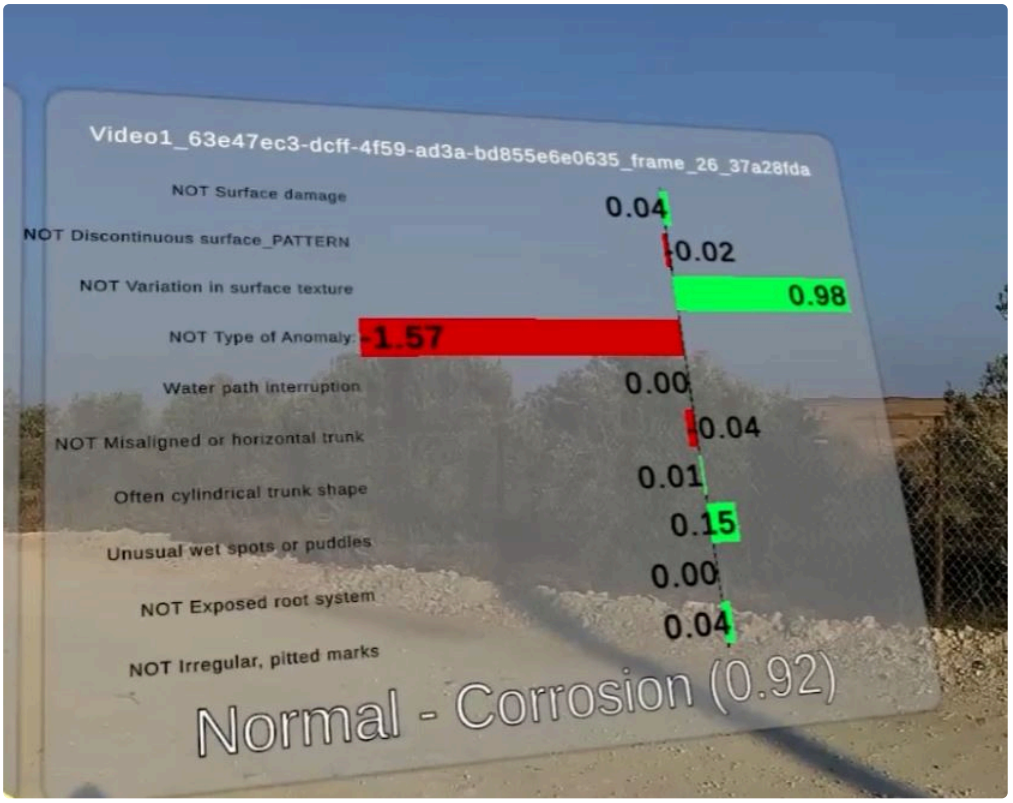
The integration of explainable AI into XR is more than a technical innovation, it is a step toward reshaping industrial workflows. By allowing operators to see, understand, and interact with AI-driven insights in the context of their daily tasks, the solution increases trust, safety, and efficiency.

Looking ahead, testing and validation with industry experts will play a crucial role. Their feedback will guide refinements, ensuring that interfaces are intuitive, explanations are clear, and the technology delivers value where it matters most: on the factory floor, in the field, and in real-world operations.

Conclusion

AI has the potential to revolutionize industry, but only if humans can trust and understand its outputs. By embedding explainable AI within XR environments, the XR5.0 project is bridging the gap between advanced algorithms and human expertise. The result is a new generation of tools that empower workers, enhance safety, and build confidence in AI-enabled decision-making.

In short, this work ensures that the future of industry is not just intelligent, but also transparent, collaborative, and human-centered.



AI-generated anomaly explanations visualized in AR

2.13 AI INTEGRATION

On-Premises AI Utility Stack: Implementing Secure Local Language Models with Speech Processing

The landscape of Extended Reality (XR) has evolved dramatically, and voice-enabled interactions are no longer a luxury, they're becoming essential for creating truly immersive and accessible XR experiences. Today, we're excited to share how Siemens has developed a comprehensive on-premises AI utility stack within the XR5.0 project that brings together cutting-edge speech synthesis, recognition, and local language model capabilities into a single, powerful platform designed specifically to enable secure, enterprise-grade XR, AR, and VR applications.

The Enterprise XR Challenge: Balancing Innovation with Security

Extended Reality applications in industrial environments face unique challenges that go beyond traditional user interface considerations. In AR/VR environments, users often have their hands occupied with controllers, tools, or physical objects, while enterprises demand strict data security and compliance with industrial regulations. Cloud-based AI services, while powerful, introduce latency, dependency risks, and data sovereignty concerns that are unacceptable in mission-critical industrial operations.

The XR5.0 project, with its focus on human-centric Industry 5.0 applications, identified the need for a completely on-premises AI utility stack that could deliver enterprise-grade voice interaction capabilities without compromising security or requiring external internet connectivity. Whether it's an operator wearing a HoloLens 2 on an assembly line, a maintenance technician using AR guidance in a secure facility, or a trainee learning complex procedures in VR, our local AI stack provides the natural voice bridge between human intent and digital response, all while keeping sensitive data within the enterprise perimeter.

Our on-premises AI utility stack addresses this challenge head-on by providing XR applications with unified voice and language processing capabilities that operate entirely within the enterprise infrastructure, ensuring data sovereignty while delivering the responsiveness required for immersive experiences.

Enabling Secure XR5.0 Use Cases Through Local AI Intelligence

Hands-Free Industrial Operations with Data Sovereignty

In XR5.0's assembly line production use cases, operators wearing AR headsets need to access technical documentation, request real-time data, or report issues while their hands remain free for physical tasks, all while ensuring that proprietary manufacturing data never leaves the facility. Our on-premises AI stack enables natural language interactions like:

- "Show me the torque specifications for component B-47"
- "What's the current temperature reading from sensor 3?"

- "Log a quality issue with the bearing assembly"

The system processes these requests through locally hosted language models, retrieves relevant information from on-premises technical documentation systems, and provides responses either as AR overlays or synthesized speech, all without any external data transmission.

Secure Immersive Training Experiences

XR5.0's training platforms leverage our local AI utility to create engaging and effective learning environments while maintaining complete control over training content and learner data. Trainees can ask questions about procedures, request clarification on safety protocols, or interact with virtual instructors, all through natural speech processed entirely on local infrastructure. The document-aware capabilities mean the system can reference proprietary training materials, safety manuals, and procedural guides without exposing sensitive content to external services.

Air-Gapped Remote Maintenance and Support

For XR5.0's remote assistance use cases in secure environments, our on-premises stack enables voice communication and AI assistance even in air-gapped networks. Field technicians can describe problems verbally while an expert views their AR feed through secure internal networks. Our local voice synthesis capabilities enable the remote expert to provide audio guidance that's naturally integrated into the technician's AR experience, all while maintaining complete network isolation.

What Makes Our On-Premises AI Stack Different?

Local Language Models with Enterprise Security

At the heart of our utility stack lies a carefully orchestrated deployment of local language models running on enterprise hardware. Through seamless integration with Ollama, we support various open-source models including Llama, Gemma, DeepSeek, and Qwen, all running entirely within the customer's infrastructure. This approach ensures:

- **Complete Data Sovereignty**: No sensitive information ever leaves the enterprise network
- **Zero External Dependencies**: Operations continue even without internet connectivity
- **Compliance Ready**: Meets strict regulatory requirements for data handling
- **Customizable Models**: Ability to fine-tune models on proprietary documentation and procedures

Rich Voice Synthesis Designed for Secure Industrial Environments

Our Text-to-Speech (TTS) engine, built on the powerful Coqui-TTS framework with VITS architecture, delivers natural-sounding voice synthesis that operates entirely on local hardware. With 48 unique speaker voices representing diverse demographics and linguistic backgrounds, XR applications can select voices that match user preferences or cultural contexts, critical for global industrial deployments, while ensuring voice data never leaves the premises.

Advanced Local Audio Processing for XR Environments

XR applications operate in challenging acoustic environments from factory floors to secure facilities. Our sophisticated audio enhancement pipeline ensures voice interactions remain clear and reliable while processing everything locally:

- **Spectral Gating Noise Reduction** eliminates industrial background noise using local processing power
- **Dynamic Speed Control** adjusts speech delivery for optimal comprehension without cloud dependencies
- **Multi-format Support** ensures compatibility with various XR platforms and devices
- **Local Streaming Optimization** provides real-time voice responses with minimal latency, crucial for maintaining immersion

Robust On-Premises Speech Recognition

Our Speech-to-Text (STT) capabilities leverage locally deployed OpenAI Whisper "turbo" models, delivering exceptional accuracy even when users are wearing XR headsets or speaking in noisy industrial environments. The system handles diverse audio conditions typical in XR scenarios and supports automatic translational processed on local hardware without sending audio data to external services.

Document-Aware Conversations with Local Storage

Perhaps our most innovative feature for secure XR5.0 use cases is the integration of document-aware conversational AI that operates entirely on local infrastructure. Through seamless integration with locally hosted language models and MinIO object storage deployed within the enterprise network, XR applications can access vast technical documentation libraries and provide contextual information on demand without any external data exposure.

Imagine an AR maintenance application where a technician can upload equipment manuals to local storage and ask questions like "What are the safety procedures for replacing the hydraulic pump?" The system reads the documentation using local AI models, understands the context, and provides accurate, referenced answers either as AR text overlays or synthesized speech, all without the documentation or queries ever leaving the secure facility network.

Architecture That Scales Across Secure XR Platforms

Microservices Design for Enterprise Integration

Our platform follows a clean microservices architecture built on FastAPI, ensuring high performance and easy integration with diverse XR applications while maintaining security boundaries. Each service TTS, STT, and Chat operate independently on local infrastructure while sharing common security frameworks, allowing XR developers to integrate only the voice capabilities they need without compromising the overall security posture.

This modular approach is particularly valuable for XR5.0's diverse use cases, where different applications may require different combinations of voice services while maintaining strict data isolation requirements.

Local Service Integration Optimized for Enterprise Workloads

Rather than relying on external cloud services, we strategically deploy best-in-class open-source technologies optimized for local enterprise requirements:

- **Ollama** handles LLM inference locally with support for various open-source models
- **MinIO** provides distributed S3-compatible storage within the enterprise network
- **Local CUDA acceleration** ensures optimal performance on enterprise GPU infrastructure
- **Container orchestration** enables scalable deployment across enterprise Kubernetes clusters

Real-World Secure XR5.0 Applications

The versatility of our on-premises AI utility stack enables numerous security XR5.0 scenarios:

Smart Manufacturing with Secure AR Guidance

Assembly line workers use voice commands to access work instructions, report quality issues, and request assistance while maintaining focus on their physical tasks. The system integrates with local PLCs and manufacturing execution systems to provide real-time operational data through voice queries, ensuring all proprietary manufacturing data remains within the facility.

Air-Gapped VR-Based Industrial Training

Trainees interact with virtual instructors and equipment through natural speech in completely isolated networks, asking questions about procedures and receiving contextual explanations. The document-aware capabilities ensure training content remains current with the latest technical documentation while maintaining complete data sovereignty.

Secure Mixed Reality Maintenance

Field technicians use voice to describe problems, access troubleshooting guides, and receive step-by-step repair instructions while viewing AR overlays of equipment internals and sensor data, all processed through local AI infrastructure without external connectivity requirements.

Compliant Accessible XR Experiences

The voice capabilities make XR applications more accessible to users with visual impairments or motor limitations while meeting strict compliance requirements for data handling, supporting XR5.0's human-centric design principles in regulated environments.

The Technology Stack Powering Secure XR5.0 Voice Services

Under the hood, our platform combines several cutting-edge open-source technologies specifically selected for enterprise deployment and XR compatibility:

- **Coqui-TTS with VITS models** for high-quality local speech synthesis
- **OpenVoice v2** for voice conversion and adaptation on local hardware
- **OpenAI Whisper** for robust speech recognition without external dependencies
- **FastAPI** for high-performance, low-latency web services
- **Ollama** for flexible local LLM deployment and management
- **MinIO** for scalable on-premises document storage

This carefully selected open-source stack ensures we deliver both quality and performance while maintaining complete control over data and processing, meeting the stringent requirements of enterprise XR deployments.

Looking Forward: The Future of Secure Voice-Enabled XR

As XR technologies mature and become more prevalent in industrial settings, the need for secure, on-premises AI capabilities will become increasingly critical for creating natural, efficient, and compliant user experiences. Our on-premises AI utility stack is designed to evolve with these advances, providing a stable foundation for building secure voice-enabled XR applications of tomorrow.

We're particularly excited about expanding local multilingual capabilities for global manufacturing environments, advancing on-premises voice cloning for personalized XR experiences, and deeper integration with emerging open-source AI models that will make secure XR interactions even more natural and intelligent, all while maintaining complete data sovereignty.

Building the Secure Voice-First XR Future

Voice interfaces represent a fundamental shift in how users interact with Extended Reality applications, but enterprise adoption requires solutions that don't compromise on security or compliance. They're more natural than gesture controls, more accessible than visual interfaces, and more efficient than traditional input methods, and now they can be deployed with complete data sovereignty. By providing this comprehensive on-premises AI utility stack within the XR5.0 ecosystem, we're empowering enterprises to create next-generation XR experiences without the complexity of managing multiple external AI services or compromising security requirements.

Whether you're building AR guidance systems for secure manufacturing facilities, VR training platforms for sensitive procedures, or mixed reality maintenance applications for regulated environments, our on-premises AI utility stack provides the foundation you need to bring secure voice-enabled XR experiences to life.

The future of XR is voice-enabled and secure, and through XR5.0, we're helping build that future today.

2.14 AI INTEGRATION

Revolutionizing Industrial Knowledge Access with AI-Powered Conversational Agents

The future of industrial expertise is now accessible through conversation. The XR5.0 project has successfully launched a novel **LLM Chat Engine** that transforms how workers access critical industrial knowledge, making expert-level guidance available instantly through natural language interactions.

The Challenge: When Industrial Expertise Isn't Available

Industrial sectors worldwide struggle with a fundamental problem: the right expertise isn't always available when and where it's needed. Consider the costly scenario when a major manufacturing facility relocates operations, requiring experts to be flown in from other regions for essential maintenance and operational support, leading to significant downtime and logistical complications. This scenario illustrates a widespread challenge across manufacturing, infrastructure, and aerospace industries.

Traditional industrial documentation sits locked away in lengthy manuals and technical specifications that are difficult to navigate during critical moments. Workers often need immediate answers to complex questions about equipment troubleshooting, safety protocols, or maintenance procedures, but finding the right information quickly remains a persistent bottleneck.

Introducing the XR5.0 LLM Chat Engine

Our platform, developed by Innov-Acts, addresses these challenges head-on by embedding domain-specific industrial knowledge into an intelligent conversational interface. The **LLM Chat Engine** leverages advanced Retrieval-Augmented Generation (RAG) technology to provide instant, accurate responses to complex industrial queries.

Unlike generic AI assistants, our system is specifically engineered for industrial environments. The platform processes comprehensive technical documentation and transforms it into an accessible knowledge base that workers can query using natural language. Whether you need troubleshooting guidance, safety procedures, or maintenance instructions, the engine delivers precise, contextual responses tailored to your specific industrial domain.

The system's architecture centers on dynamic tool orchestration, where specialized agents work together to provide comprehensive answers. The Query Router Agent intelligently directs questions to the most relevant knowledge sources, while additional agents fetch real-time data from predictive maintenance systems, IoT sensors, and explainable AI services. This multi-agent approach ensures that responses aren't just accurate but also current and actionable.

High Response Accuracy

Rigorous evaluation demonstrates the platform's exceptional reliability for industrial applications. Our semantic chunking approach achieves 99.07% faithfulness in technical responses, meaning virtually no hallucinations when providing safety-critical information. As presented in our research paper, the

system maintains 93.37% recall accuracy for knowledge retrieval, ensuring that relevant information is consistently found and delivered.

These performance metrics matter enormously in industrial contexts where incorrect information can lead to safety incidents, equipment damage, or costly downtime. The engine's balanced embedding models and efficient vector database architecture deliver not just accuracy but also the speed required for real-time operational support.

Real-World Applications Across Industries

The LLM Chat Engine is already transforming operations across multiple industrial sectors. In manufacturing environments, technicians access commissioning checklists and troubleshooting guides through simple conversational queries. Instead of searching through hundreds of pages of documentation, workers can ask specific questions and receive step-by-step guidance immediately.

For infrastructure maintenance, particularly in smart water networks, the system integrates with IoT sensors and predictive maintenance algorithms to provide comprehensive operational insights. Maintenance teams can query the system about anomaly detection alerts, historical performance patterns, and recommended resolution procedures, all through natural conversation.

In aerospace applications where precision and safety are paramount, the engine provides access to component-specific maintenance procedures, safety protocols, and regulatory compliance information. The system's ability to cross-reference multiple technical documents ensures that workers receive complete, verified guidance for complex procedures.

Architecture Built for Industrial Reality

The platform's FastAPI-based architecture ensures low-latency responses essential for real-time operational support. The system maintains conversation context across extended interactions, enabling workers to ask follow-up questions and receive progressively more detailed guidance as needed.

Security and reliability are fundamental to the design. The engine operates with robust authentication systems and can function in environments with limited connectivity. Document processing pipelines can handle technical specifications of 100s pages, automatically creating semantic chunks that preserve the logical structure of industrial documentation.

The modular architecture allows for easy integration with existing industrial systems. Organizations can upload their specific technical documentation, safety procedures, and operational guidelines, creating customized virtual assistants that reflect their unique requirements and standards.

Available Now

The XR5.0 LLM Chat Engine is fully operational and ready for industrial deployment. You can experience the platform immediately at https://chat.xr50.eu/ or integrate it into your existing systems using our comprehensive API at https://chat-api.xr50.eu/.

The system supports multiple deployment options, from cloud-based solutions for immediate access to on-premises installations for organizations with specific security requirements. Complete API documentation and interactive testing environments make integration straightforward for technical teams.

Transforming Industrial Operations

The XR5.0 LLM Chat Engine represents a fundamental shift toward democratizing industrial expertise. By making complex technical knowledge accessible through natural conversation, we're eliminating barriers that have traditionally separated workers from the information they need to perform effectively and safely.

As industries continue evolving toward smart manufacturing and Industry 5.0 principles, the ability to access expert knowledge instantly becomes increasingly critical. Our platform doesn't just solve today's skills shortage; it creates the foundation for more resilient, efficient, and human-centric industrial operations.

Watch our demonstration video on the XR5.0 YouTube channel to see how the XR5.0 LLM Chat Engine transforms industrial knowledge access, making expert guidance available through simple conversation.

For access requests or more information about implementing the XR5.0 LLM Chat Engine in your organization, contact us at ***info@innov-acts.com****.*

2.15 AI INTEGRATION

The Role of AI Chatbots in Modern Maintenance

AI-driven chatbots are rapidly changing how maintenance teams handle service requests, communication, and daily workflows. What once relied on phone calls, emails, or manual ticket entry is now increasingly automated through intelligent, conversational interfaces. For organizations in manufacturing, facility management, healthcare, and infrastructure, chatbots act as a digital first point of contact, capturing issues immediately, guiding users through structured questions, and ensuring that maintenance requests are complete and consistent from the start.

Unlike traditional rule-based systems, AI chatbots use natural language processing and machine learning to understand context and intent. When a machine operator, tenant, or employee reports a problem, the chatbot records essential details such as location, asset, symptoms, and urgency. In many cases, it can also provide instant troubleshooting guidance for simple issues, reducing unnecessary technician dispatches. This not only accelerates response times but also helps maintenance teams focus on complex and high-impact work.

The real strength of AI chatbots emerges when they are integrated with a CMMS. Maintenance requests collected by the chatbot are automatically converted into structured work orders, enriched with historical context, and relevant asset data. As new information becomes available, the system updates in real time, improving transparency and coordination. Over time, chatbot-driven data supports better prioritization, reveals recurring issues, and enables a shift from reactive maintenance toward more predictive and preventive strategies.

From a user perspective, chatbots significantly improve the maintenance experience. Requests are acknowledged instantly, progress can be tracked at any time, and communication remains consistent regardless of shift schedules or staff availability. For maintenance managers, this means clearer visibility into workloads, failure patterns, and resource allocation, ultimately leading to higher asset availability and lower downtime.

Maintastic supports this evolution toward smarter, more connected maintenance. As a modern CMMS software, Maintastic combines artificial intelligence with human collaboration to digitize maintenance processes end to end. With features such as AI-supported ticketing, mobile maintenance, digital work orders, and centralized asset management, Maintastic helps organizations increase efficiency, shorten repair times, and improve transparency across teams. Used by more than 150 companies across manufacturing, pharma, construction, and mining, Maintastic enables maintenance teams to work more proactively while keeping systems simple and intuitive.

In conclusion, AI-driven chatbots are not about replacing people in maintenance but about removing friction from everyday processes. By automating communication, improving data quality, and integrating seamlessly with CMMS platforms like Maintastic, chatbots help maintenance teams respond faster, plan smarter, and build a more resilient maintenance operation for the future.

2.16 AI INTEGRATION

KUKABot in Action: Voice-Driven AI Support for KUKA Technicians Inside RoboSpace

As industrial automation and robotics systems grow in complexity, technicians are increasingly required to handle large volumes of technical documentation, configuration data, troubleshooting procedures, and machine-specific knowledge is needed often under time pressure and directly on the shop floor. In the XR5.0 project's Rapid Human-Centric AI-Enabled Product Design KUKA pilot is addressing this challenge by integrating the voice-driven AI assistant KUKABot directly into the immersive XR application RoboSpace. Together, these technologies transform how technicians interact with robots, access information, and execute tasks in real industrial environments.

This KUKABot enhances technician workflows through natural-language interaction, Retrieval-Augmented Generation (RAG) capabilities, and seamless integration within spatial XR interfaces.

A Unified XR Workspace for Robot Interaction

The XR application RoboSpace is built as a high-fidelity, spatially aligned interface for interacting with KUKA robotic systems on the shop floor. It combines true-to-scale robot visualization, real-time OPC UA data streaming, and interactive engineering tools into a single immersive environment based on the HoloSpace Software by Hololight.

Technicians can:

- Walk around the full-scale digital robot model
- Inspect the robotic cells from any angle
- Compare digital and physical configurations
- Use advanced tools such as cross-sections, measurements, annotations, and collision checks

This interactive 3D environment replaces the traditional reliance on multiple software systems, terminals, printed documentation, and separate engineering tools. It also provides the foundation on which KUKABot operates.

AI Assistant Embedded Directly Into XR

Integrated as part of RoboSpace's AI Service Layer, KUKABot provides natural-language access to robot-related documentation and technical knowledge. It allows technicians to request information while keeping both hands free for inspection or operation tasks. This is an essential capability in industrial environments where handheld interaction is often impractical.

What KUKABot Can Deliver

Through simple voice commands, technicians can request:

- Technical specifications

- Motion range and workspace tables
- Troubleshooting procedures
- Datasheet excerpts
- Visual diagrams displayed inside XR panels

This makes it possible to retrieve information without navigating complex menus or returning to a workstation.

RAG for Industrial Documentation

KUKABot uses a Retrieval-Augmented Generation (RAG) approach. It retrieves relevant documentation and generates structured responses, including tables, images, and summaries displayed as contextual XR overlays.

This architecture enables:

- Faster access to information
- Reduced cognitive load
- Consistent and context-aware guidance
- Hands-free task execution
- Because KUKABot is implemented as an API-based service, its knowledge base can be updated continuously without requiring changes to the XR interface.

Voice-Driven Interaction for Real-World Conditions

RoboSpace includes a voice-driven interaction layer, combining speech-to-text for recognizing commands and text-to-speech for delivering system responses. Users can activate tools, switch views, request documentation, or navigate the interface without needing to use physical controllers or hand menus.

This interaction model is essential for:

- Environments with limited mobility
- Situations requiring protective equipment
- Tasks where technicians cannot remove their hands from the machine
- Reducing interruptions and context switching
- By integrating KUKABot with this layer, RoboSpace becomes a seamless conversational and operational environment.

Impact on the Technicians Workflows

- Faster Troubleshooting

With KUKABot available directly in XR, technicians no longer need to step away from the machine to search for commissioning instructions and specifications. The system fetches relevant troubleshooting steps and displays them.

- Reduced Cognitive Load

Context-dependent visualizations, such as OPC UA sensor values overlaid on the correct components, combined with on-demand explanations from KUKABot reduces the cognitive load.

- Improved Safety and Task Accuracy

Technicians can confirm procedures verbally while observing the machine in XR. This minimizes errors that can occur when switching between devices or reading documentation away from the equipment. Combined with predictive safety alerts from the Human Digital Twin module, the overall system strengthens safe and effective human-robot collaboration.

- Enhanced Training and Onboarding

During Training sessions inside RoboSpace, trainees can ask KUKABot for clarifications or additional instructions. This enables richer and more adaptive learning experiences.

Insights From Pilot Evaluation at KUKA

The XR5.0 pilot evaluation at KUKA's facilities confirmed the strong operational relevance of integrating KUKABot into RoboSpace. Technicians appreciated the intuitive interface, hands-free access to structured information, and the clear potential for long-term efficiency gains.

Toward AI-Supported, Human-Centric Robotics Workflows

The integration of KUKABot into RoboSpace demonstrates a powerful vision for the future of human-robot interaction. An environment where technicians engage directly with physical and digital systems through natural language, contextual spatial visualization, and AI-driven support.

By embedding intelligence, safety awareness, and documentation access inside an immersive XR workspace, the XR5.0 pilot showcases a scalable, Industry-5.0-aligned approach to technician empowerment. As KUKA continues to refine performance and expand capabilities, KUKABot and RoboSpace represent a major step toward highly adaptive, efficient, and human-centric robotics operations.

PART THREE · 22 ARTICLES

Applications and Use Cases

Real-world deployments across six industrial pilots—from robot assembly and aircraft maintenance to water utility operations and remote commissioning—demonstrating the tangible impact of XR5.0 technologies for workers, companies, and society.

3.1 APPLICATIONS AND USE CASES

From Manuals to Mixed Reality: AI-Powered XR for Robot Assembly Line Production

Modern assembly lines are becoming more complex, with increasing demands for customisation, speed, and precision. Operators are expected to work with advanced machines and robots, while also handling large amounts of process data and documentation. Extended Reality (XR) can help reduce this cognitive burden by placing information directly in the operator's field of view and allowing for intuitive, hands-free interaction.

Hololight (HOLO) is building an XR application, RoboSpace, for the end-user KUKA, within the Use Case 1 "Personalised XR in Assembly Line Production" of the XR5.0 Pilot 1 "Rapid Human Centric AI-enabled Production Design". RoboSpace is built on Hololight Space and is securely streamed to the Microsoft HoloLens 2 using Hololight Stream, bringing the above-mentioned capabilities into real-world production settings.

True-to-Scale Robot Visualization

The application provides a high-fidelity digital representation of a KUKA robot in true scale (Figure 1). Operators can walk around it, view it from any angle, and place it in their physical workspace for comparison with the real machine (Figure 2). This spatially accurate representation is critical for both training and day-to-day operation, as it enables workers to develop a deeper understanding of robot behaviour and positioning in their environment. The operator can align the virtual model with the real physical space using markers such as QR codes or a Two Point Alignment Tool that allows users to precisely align the 3D model to real-world references using two connected points ensuring the virtual model matches both the position and orientation of physical objects.

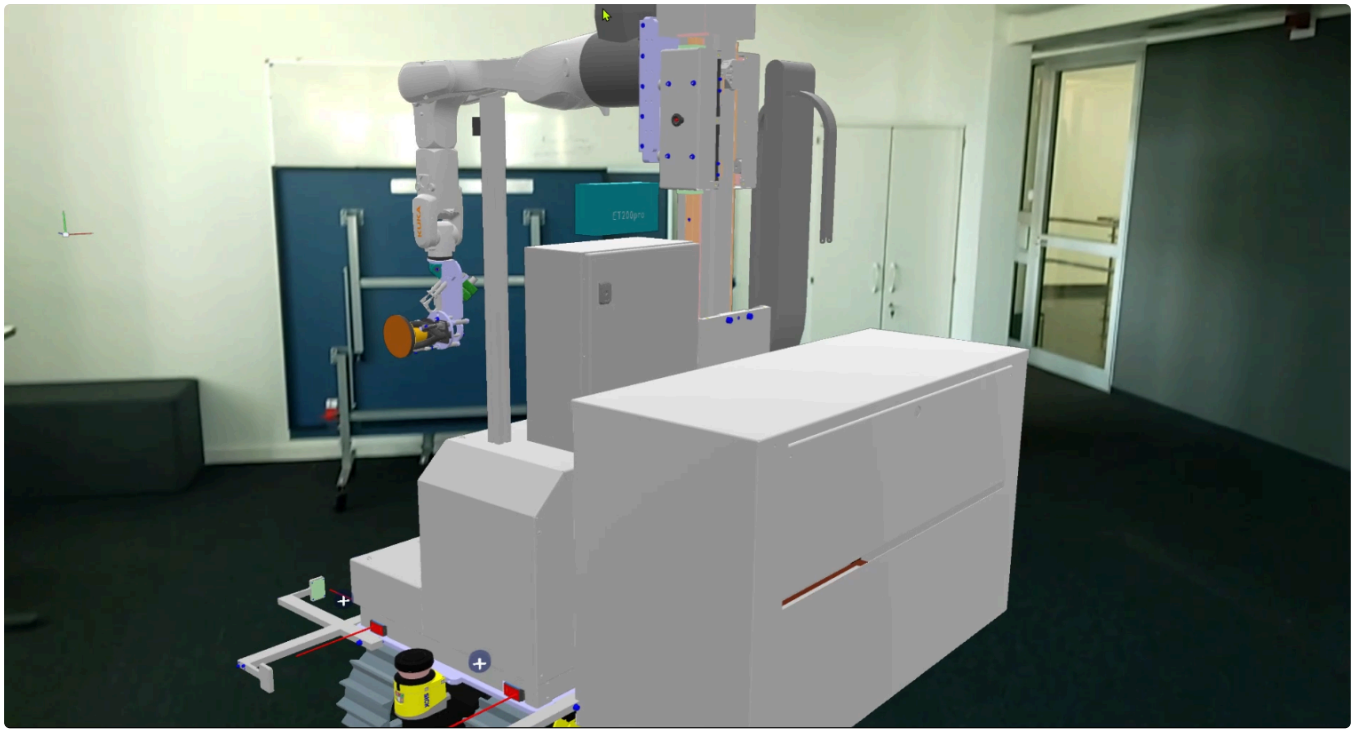


Figure 1 The true-to-scale 3D robot model visualised on the HoloLens 2 and streamed from a powerful server.

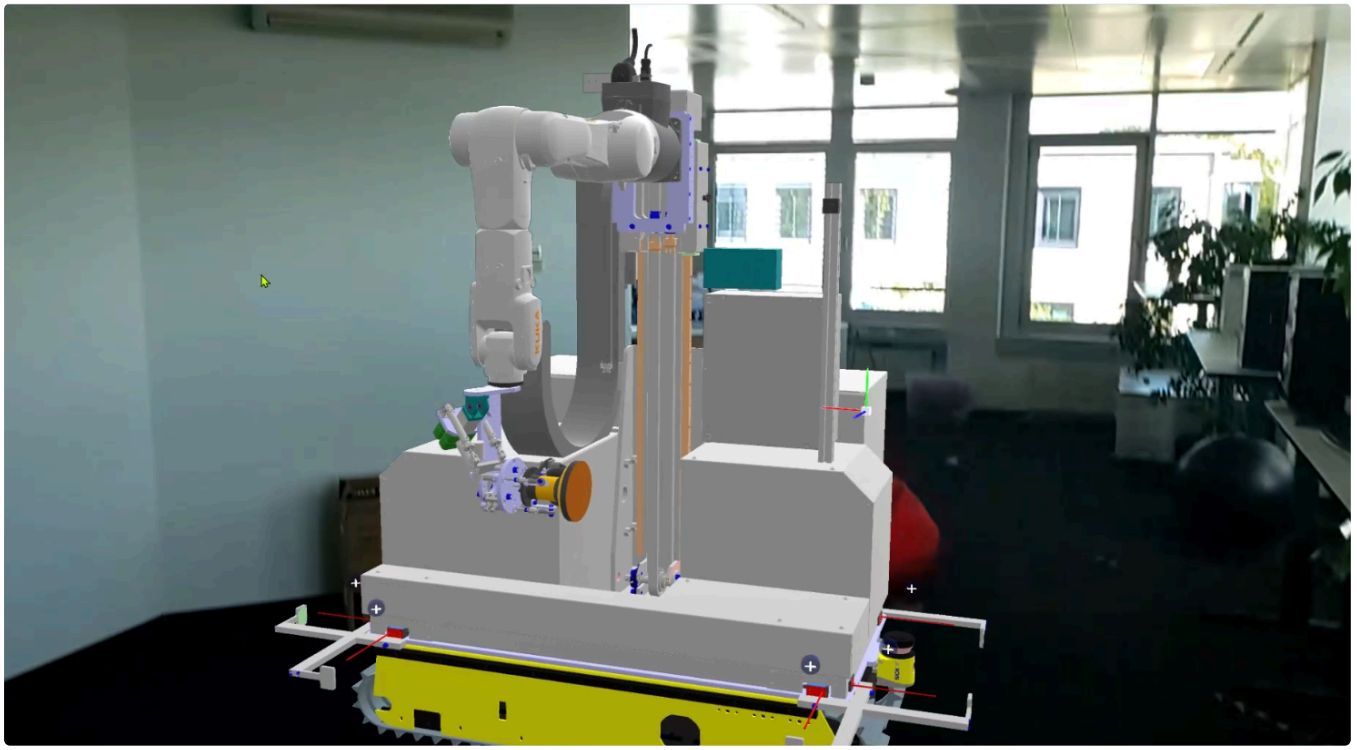


Figure 2 A high-quality 3D model of robot overlayed on the real environment.

Interactive Tools for Inspection and Analysis

The application has a set of interaction tools designed for industrial workflows:

- **Explosion view**: Disassemble the robot virtually to understand its internal components without any physical teardown (Figure 3).
- **3D model manipulation**: Use tools such as bounding box, grab, rotate, scale and move to manipulate virtual 3D models in real environment.

- **Cross-sectional views**: Slice through models using 2D plane, cube or sphere to analyse hidden structures (Figure 5).
- **Measurement and annotation tools**: Take measurements within the model and leave notes for colleagues.
- **Collision detection**: Identify potential clashes between robot parts or with external equipment before they become real problems.

Together, these tools transform XR from a simple visualization platform into a workspace where analysis and decision-making can take place directly on-site.

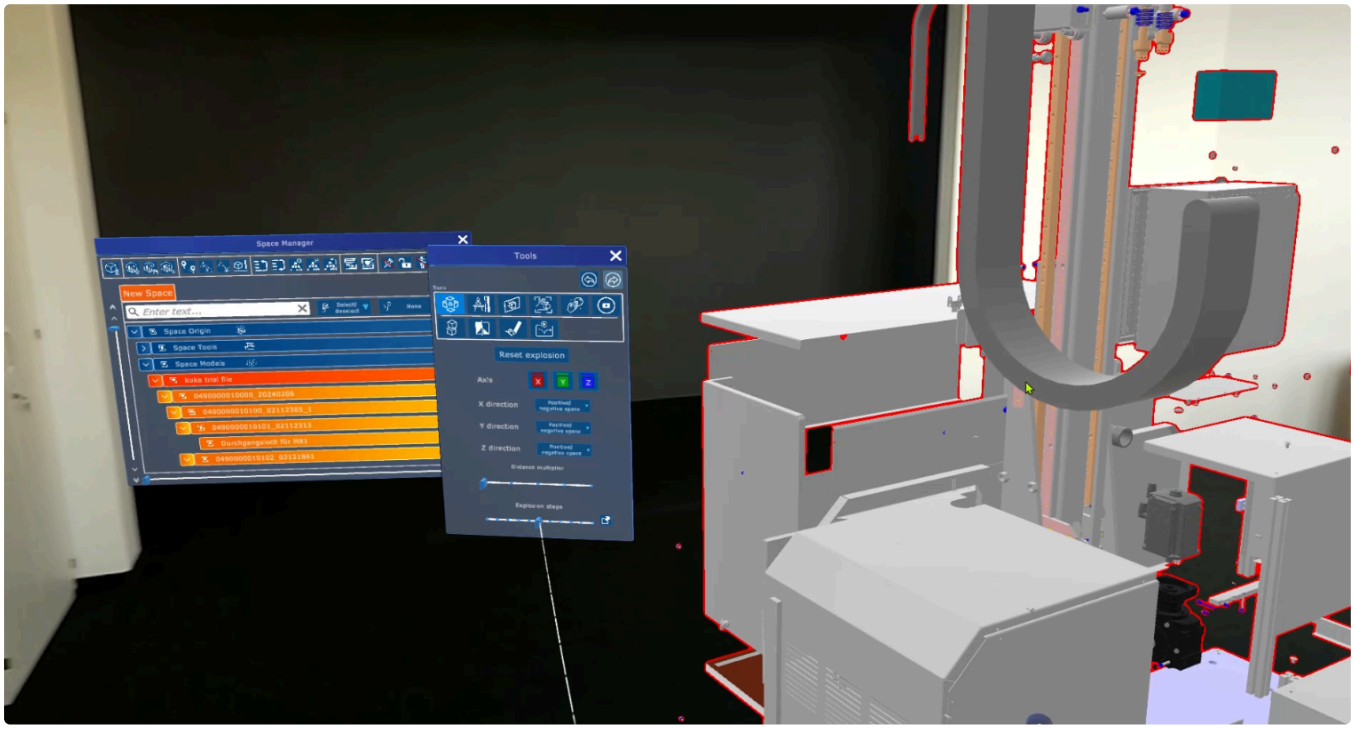


Figure 3 RoboSpace application allowing the user to explode the 3D model to understand the internal components.

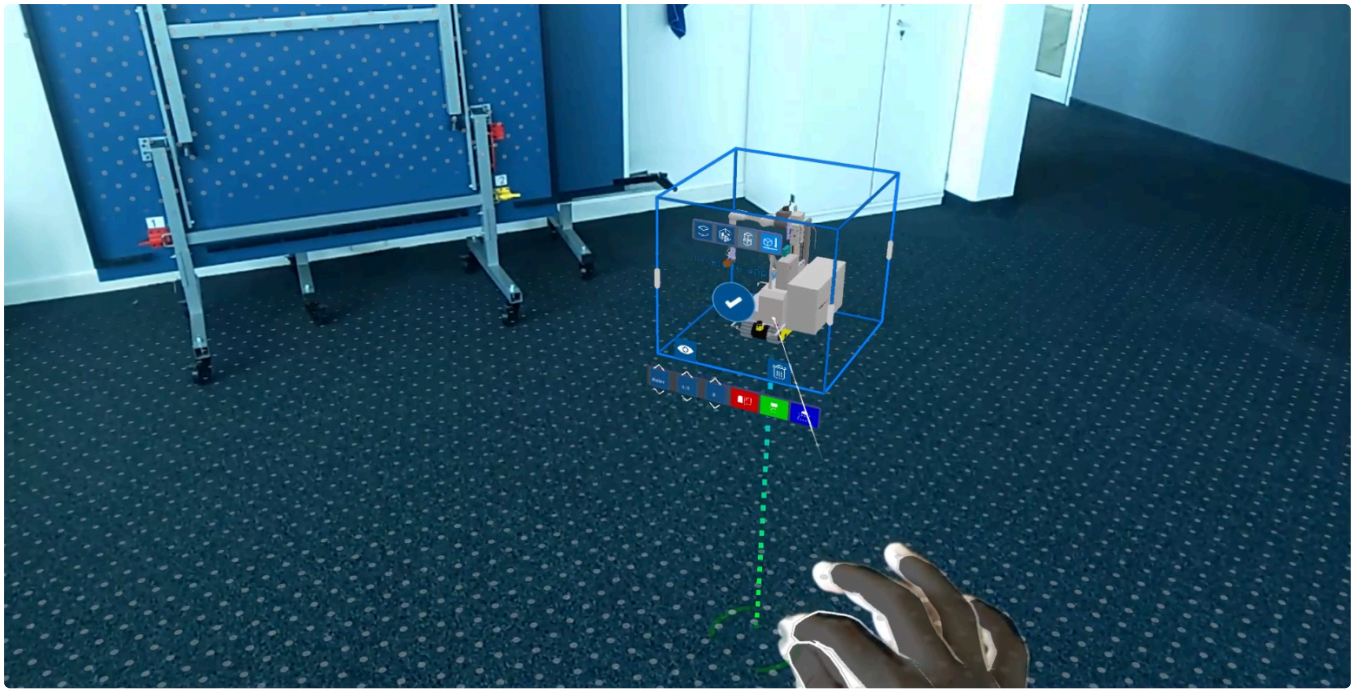


Figure 4 Users have several methods to load the 3D model onto the physical space. In the image the user is loading it by aligning to the physical ground.

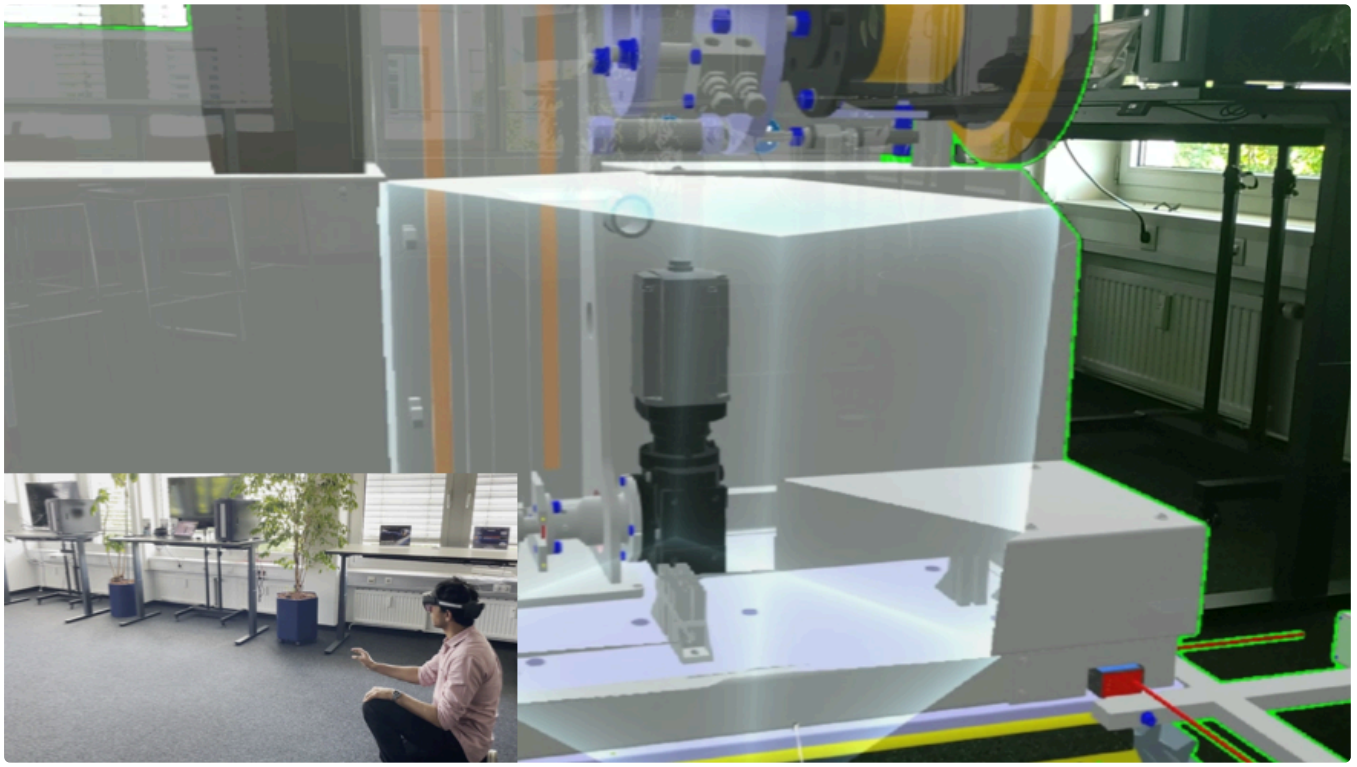


Figure 5 The user is using a cube cross section to view the internal parts of the robot model.

Real-Time Data Visualization with OPC UA

A major strength of the application lies in its integration with KUKA's OPC UA servers. By connecting to machine controllers and sensors, the XR model becomes a live digital twin that overlays real-time data onto the robot. For example, operators can see readings of the distance sensors displayed directly on the robot arm. Instead of switching between screens or terminals, the operator experiences the data where it matters most—on the machine itself.

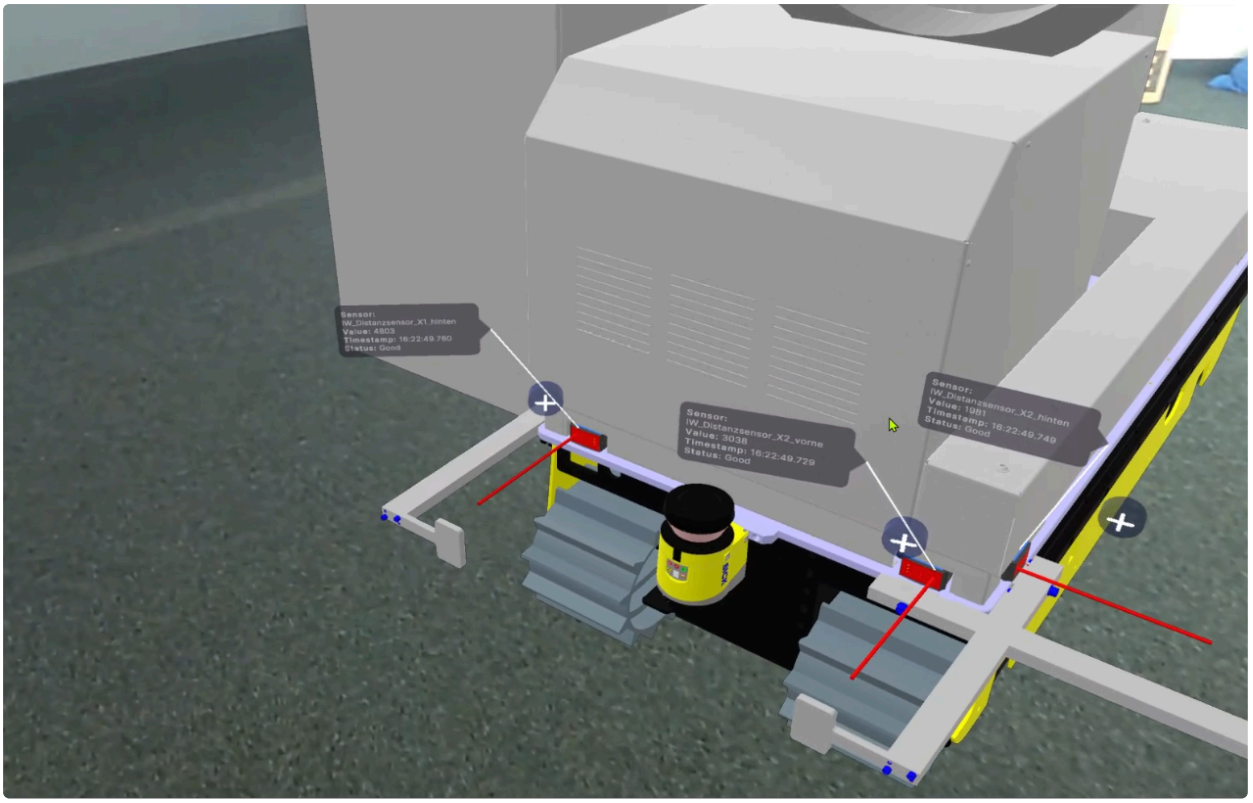


Figure 6 The user, by voice or hand gesture, can view the real-time sensor data of the 3D robot model.

AI-Powered Assistance for Documentation

Industrial robots come with extensive technical documentation, manuals, and troubleshooting guides. Searching through these during operation is inefficient. To address this, the application integrates AI services, developed by partner Siemens, that allow workers to ask natural language questions such as *Show me the technical specifications of the robot arm?"* or *"Display the commissioning manual of the robot arm?"* The system retrieves and summarizes relevant documentation, providing immediate answers in XR (Figure 7).

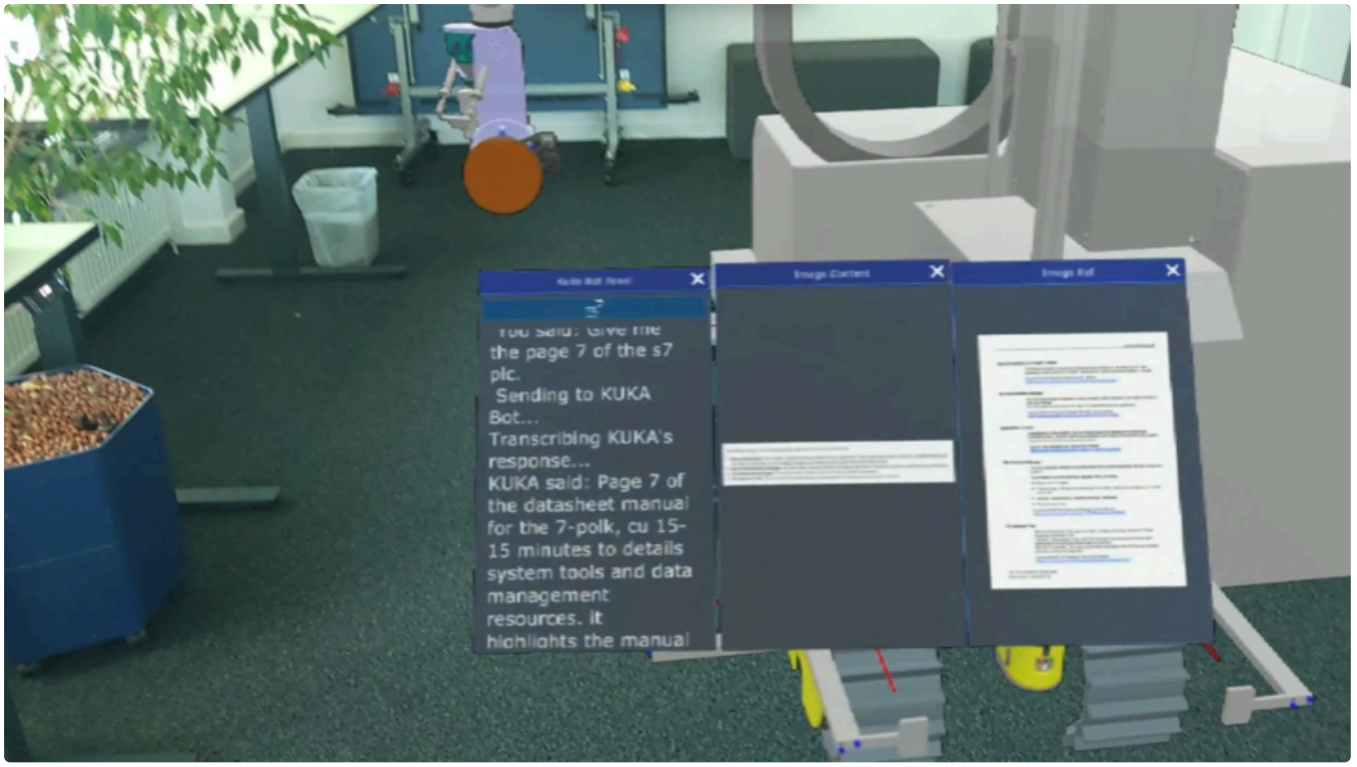


Figure 7 The user can prompt the chatbot, KUKABot, regarding technical details and specifications about the robot. Here the user is viewing a page from the PLC manual.

Voice-Driven UI for Industrial Environments

In production settings, hands are often occupied, and using controllers or touch interfaces is impractical. Our application supports voice-driven interaction, enabling users to control the interface, switch tools, or request information through simple spoken commands. For example, the application allows users to visualise all the distance sensor values via voice. This feature makes the system far more usable in noisy, hands-on environments.

Practical Applications on the Assembly Line

The combined features enable:

- **Guided assembly** using AR overlays directly on machines.
- **Monitoring of live operational data** for predictive maintenance.
- **Remote assistance**, where an expert can guide on-site staff in real time.
- **Personalized voice-driven workflows**, improving efficiency and safety.

Together, these features support assembly line workers with contextual information, data visualization, and hands-free operation ensuring that operators are empowered with information and tools exactly when and where they need them, reducing downtime and enhancing productivity.

3.2 APPLICATIONS AND USE CASES

Making Robot Programming Easier with Extended Reality

Robot programming has traditionally required engineers to work with a combination of code, simulation tools, controller interfaces, and physical hardware. While these tools are effective, they often create a gap between what the engineer programs and what the robot actually does. Understanding robot behaviour usually involves switching between multiple software environments and interpreting abstract data such as joint positions, kinematic values, or controller states.

Within the XR5.0 project, we are exploring how Extended Reality (XR) can help bridge this gap by allowing engineers to interact with robot systems in a more intuitive and visual way. Instead of analyzing robot motion through numerical data, users can directly observe robot behaviour inside an immersive environment and better understand how a robot executes its programmed tasks.

One example of this approach is the latest update of the KUKA Robot Arm model integrated into the XR environment. When the robot model is loaded, an interactive motion control panel is automatically created, allowing users to immediately work with available robot motion data. The goal is not to replace existing programming tools but rather to complement them by presenting robot behaviour in a way that is easier to understand and evaluate.

A key aspect of modern industrial automation is the increasing availability of cloud-based services and centralized data platforms. Robot programs, simulation results, and operational data are no longer limited to local engineering stations. Instead, they can be shared across teams, facilities, and locations. This trend creates new opportunities for XR applications, where users can access and visualize robot information from different sources within a single environment.

To support this vision, the updated robot model can work with different motion data sources like OPC UA Interface or the simulated KUKA Smart Pad so that Engineers can observe robot movements. This flexibility makes it possible to compare planned robot behavior with data obtained from development, testing, or operational environments. As cloud infrastructures continue to evolve, such approaches can simplify collaboration between software developers, automation engineers, and commissioning teams.

One practical advantage of XR-based visualization is the ability to inspect robot motion from any perspective. During development, engineers frequently need to verify trajectories, analyze robot accessibility, or identify unexpected movements. Conventional visualization tools often provide only limited viewpoints or require extensive navigation through complex interfaces. In contrast, XR allows users to walk around the robot, zoom into specific areas, and inspect movements in a natural way. This makes it easier to understand how a programmed trajectory is executed and to detect potential issues early in the development process.

The recently updated motion panel also supports simple interaction with recorded robot motion data. Users can start, pause, and reset motion sequences directly within the XR environment. Although these features may appear straightforward, they are particularly useful when validating robot behaviour. Being

able to repeatedly inspect a specific movement from different viewpoints allows engineers to focus on details that may otherwise be overlooked. This is especially valuable during debugging, testing, and training activities.

Another important benefit of immersive visualization is communication between different stakeholders. Robot programmers, automation engineers, project managers, and customers often have different levels of technical expertise. Explaining a robot program using source code or controller parameters can be difficult for people who are not directly involved in robot development. XR provides a common visual representation that all participants can understand. As a result, design reviews and technical discussions become more productive because everyone can observe the same robot behaviour within the same virtual space.

Cloud-enabled XR solutions also support more distributed engineering workflows. Teams located in different countries can access the same virtual environment and evaluate robot applications without the need to meet physically at the production site. This can accelerate decision-making processes during engineering and commissioning and reduce the effort required for reviewing changes or validating new programming concepts. As industrial systems become increasingly connected, the combination of XR and cloud technologies has the potential to make robot engineering more collaborative and efficient.

The current implementation is still evolving, and further optimizations are planned. For example, improvements in motion streaming and visualization performance will help create even smoother representations of robot movements within XR environments. Nevertheless, the current results already demonstrate how immersive technologies can make robot programming more accessible and transparent.

Looking ahead, Extended Reality is likely to become an important part of future engineering workflows. By combining intuitive visualization, connected data sources, and cloud-based collaboration, XR offers new ways to interact with robotic systems throughout their lifecycle. Rather than relying solely on traditional engineering interfaces, future robot programmers may increasingly use immersive environments to develop, validate and understand robot behaviour. XR5.0 provides an opportunity to explore this possibility and to demonstrate how digital technologies can simplify complex automation tasks while improving productivity and collaboration across our engineering teams.

Enhancing Aircraft Maintenance Training with AI-Powered XR Environments

The air transportation industry faces significant challenges nowadays in maintaining high safety standards and providing timely aircraft maintenance technician (AMT) training. Most importantly, this industry must meet strict regulatory requirements, prevent unscheduled equipment failures and deal with shortage of workers, many in advanced age according to a previous report of the Aeronautical Repair Station Association [1]. In addition, as aircraft systems become more complex, the demand for advanced training tools like XR-based solutions has increased.

A critical element of the Minimum Equipment List is the Wing Anti-Ice Valve (WAIV) that must be working for the airplane to operate safely. Failure in the WAIV leads to extended grounding times, while repairing also requires specialized maintenance procedures.

XR5.0 aims to address this issue by providing a solution for training AMTs to properly disassemble the WAIV through an interactive XR environment. This solution allows AMTs to practice each step of the disassembly process in a realistic 3D simulation, providing detailed guidance on safety procedures, tools and the correct steps to dissemble this component. This solution is tailored to each user based on the profile (experience) and performance metrics (execution time, errors). **XR5.0's AMT Virtual Training** aims to improve technicians' skills and to reduce the likelihood of errors by providing a customized and hands-on virtual training.

The choice of XR technology is driven by the advantages it offers in visualizing and interacting with complex objects. XR-based visualizations provide a more intuitive understanding of visual information [2], allowing AMTs to see the WAIV from multiple angles and levels of detail. This immersive approach is especially valuable for this procedure where AMTs must understand complex mechanical parts and steps to perform WAIV maintenance accurately.

The inclusion of 3D manipulation and interaction in XR environments improves the training experience by simulating the motor coordination and interactions users experience in real-world settings [3]. These features allow AMTs to inspect the different components that represent the actual physical tasks. The intuitive interaction in such XR environments will help trainees get familiarity with the equipment, potentially contributing to skill refinement and confidence when performing the task in the real environment.

Key Features of the XR5.0 AMT Virtual Training Solution

a) Personalization/Adaptation

This feature focuses on adapting the training experience to each user. The application will provide a priori personalization and real-time adaptation of content according to the user profile which ensures that the training is tailored for the level, background, and specific needs of the technician.

b) XR-based Training

This feature offers a step-by-step virtual guide to support technicians to complete maintenance procedures. This guide is structured to provide users with information for each step of the task, using different materials such as text and images from PDF manuals or even videos to detail specific steps in the procedure.

c) 3D Visualization Tool

The 3D visualization tool allows users to visualize and interact with a virtual model of the WAIV, promoting a better understanding of the equipment's structure and function. Additionally, this component also contains the virtual models of tools and equipment including tool selection and manipulation, which helps ensure user familiarity with each step in the procedure.

d) AI Voice Assistant

The application includes a speech-based voice assistant equipped with procedural knowledge. It uses a specific knowledge database to answer in real-time to the operators' questions, providing verbal guidance and feedback.

In sum, the **XR5.0 AMT Virtual Training** combines various features as step-by-step guidance, 3D visualizations and AI-driven tools to train AMTs through a multi-faceted approach. The solution provides detailed instructions with real-world context to help AMTs for competence development, improve procedural accuracy, and confidence in performing maintenance tasks, making it a valuable tool for both off-the-job and on-the-job training of AMTs.

References

[1] ARSA (2022). Not Enough Aviation Mechanics: How the industry can address this decade's shortage in aircraft maintenance workers. Retrieved from: https://arsa.org/wp-content/uploads/2023/03/OW-2023WorkforceAnalysis-Technicians.pdf

[2] Abrash, M. (2021). Creating the Future: Augmented Reality, the next Human-Machine Interface. 2021 IEEE International Electron Devices Meeting (IEDM). doi: https://doi.org/10.1109/IEDM19574.2021.9720526

[3] Sundstedt, V. & Garro, V. (2022) A Systematic Review of Visualization Techniques and Analysis Tools for Eye-Tracking in 3D Environments. Front. Neuroergon. 3:910019. doi: https://doi.org/10.3389/fnrgo.2022.910019

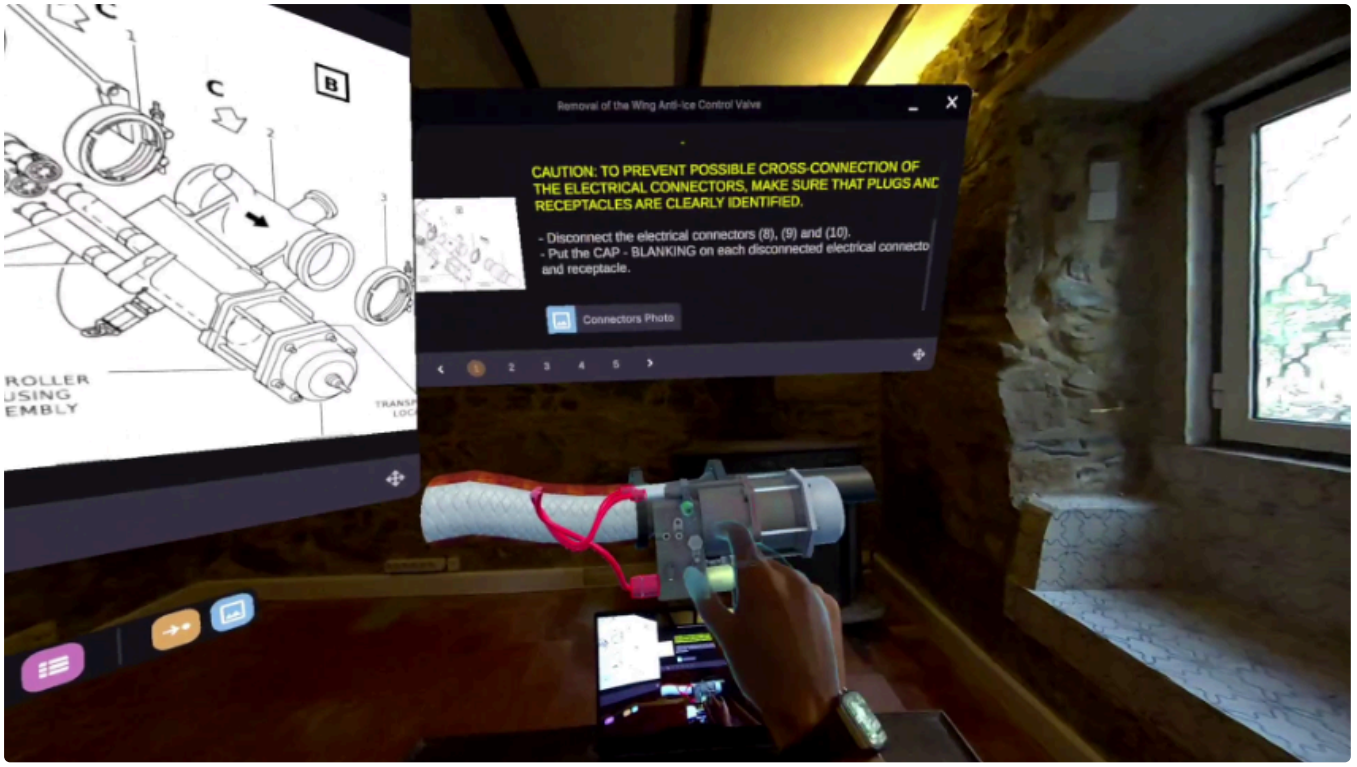


Figure. Screenshot depicting the XR5.0's AMT Virtual Training

Advancing Industry 5.0 through Human-Centric XR and AI: Progress and Results from Pilot 5

Transforming Industrial Training and Maintenance

The transition towards Industry 5.0 is redefining the relationship between humans and technology, placing workers at the center of digital transformation. Within the XR5.0 Horizon Europe project, Pilot 5 demonstrates how Extended Reality (XR), Artificial Intelligence (AI), Human Digital Twins, and intelligent training platforms can be combined to enhance the effectiveness, safety, and quality of industrial assembly and maintenance processes. The pilot focuses on the assembly, deployment, configuration, and repair of industrial edge devices used in security-critical environments. These devices play an important role in monitoring and controlling physical security infrastructures, supporting functions such as alarm activation, access control, and operational monitoring. While highly valuable, their installation and maintenance often require specialized knowledge, creating challenges for both inexperienced and experienced technicians.

Use Case 1: Personalized XR Training for Edge Device Assembly

The first use case focuses on Personalized Training for Edge Device Assembly. Technicians can access immersive training scenarios through Meta Quest devices, allowing them to interact with virtual representations of industrial equipment in a safe and controlled environment. Training content is adapted according to the technician's experience level, providing detailed guidance to beginners while offering more concise instructions to experienced users.

By combining 3D visualizations, interactive workflows, and contextual documentation, the platform enables technicians to acquire practical skills before interacting with physical equipment. A key innovation of this use case is the integration of AI-driven personalization. Training scenarios are generated and adapted based on technician profiles, enabling individualized learning paths. The platform also incorporates Human Digital Twin technologies that consider indicators such as user engagement and stress levels, allowing the training experience to dynamically adjust its level of detail and support. This approach aims to improve learning effectiveness while maintaining user engagement throughout the training process.

Use Case 2: AI-Assisted Remote Support for Repairs

The second use case focuses on Remote Instructions for Edge Device Repairs. In this scenario, technicians receive intelligent support while performing maintenance and troubleshooting activities. Through XR interfaces, users can execute diagnostic procedures, identify faults, and receive contextual repair recommendations. AI-powered assistance helps technicians perform device commissioning, operation verification, and fault resolution more efficiently.

Building the Technological Foundation

Significant technical progress has been achieved during the latest project period. The pilot currently exploits several XR5.0 technological building blocks, including workers' data analytics, Human Digital Twins, personalized XR content development, cloud-based XR training repositories, training material management services, Hololight Hub integration, and XR training programs. Together, these components create a complete ecosystem capable of supporting adaptive industrial training and maintenance workflows. The integration of AI services, XR applications, cloud-based content repositories, and connected edge devices enables a seamless training and support experience that can be scaled across different industrial environments.

Progress Towards Key Performance Indicators

The pilot has demonstrated tangible progress in terms of maturity and readiness. Several user stories have already reached Technology Readiness Levels (TRLs) between 4 and 6, reflecting successful integration and validation of core functionalities. These developments contribute directly to the pilot's targeted Key Performance Indicators, including a reduction of assembly and repair times by more than 20%, increased engagement of lower-skilled technicians by more than 50%, and significant reductions in operational costs. The achieved results indicate that personalized XR and AI-assisted workflows can deliver measurable improvements in workforce performance and operational efficiency.

Validation Through Real Demonstrations

Beyond technical development, Pilot 5 has also been actively validated through dissemination and demonstration activities. In November 2025, a live demonstration session was organized with technicians who experienced hands-on XR training using Meta Quest devices. Participants explored personalized assembly and repair workflows, gaining practical experience with immersive learning and AI-assisted maintenance support. Feedback from the session confirmed the potential of XR technologies to improve technician familiarization, operational confidence, and remote assistance capabilities. The pilot has additionally been presented to the wider research and innovation community through a demonstration paper at the IEEE NFV-SDN 2025 Conference in Athens, highlighting the application of XR technologies to industrial assembly and repair processes.

Towards a Human-Centric Industry 5.0 Future

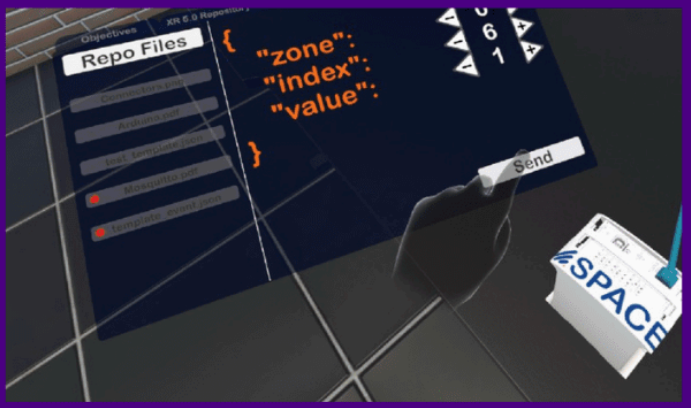
By combining immersive XR experiences, adaptive AI, Human Digital Twins, and intelligent maintenance assistance, Pilot 5 provides a compelling example of how Industry 5.0 technologies can support both organizational objectives and workforce development. The pilot showcases how digital innovation can be applied in a practical and measurable manner, creating safer workplaces, supporting continuous learning, and enabling technicians to perform complex tasks with greater confidence and efficiency. As XR and AI technologies continue to mature, their role in shaping the future industrial workforce is expected to become increasingly significant.


XR5T
Key Objectives


XR5T
Key Objectives


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Key Objectives


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3.5 APPLICATIONS AND USE CASES

Bridging Hands and Systems: XR Training for Real-World Industrial Work

There is a category of industrial work that resists clean categorisation. Think programmable controllers, IoT gateways, embedded systems sitting at the boundary between software and the physical world. The people who work on these systems operate with two kinds of knowledge at once:

Image 1: The Problem of Isolated Skill vs. System.



- One lives in their hands: Routing a cable through a tight enclosure. Feeling when a connector is properly seated. Soldering a wire.
- The other lives in their head: Network addressing, protocol configuration, firmware sequencing, system logic that offers little feedback until it either works or fails.

Traditional training separates these, and for good reason: motor skills are learned through practice, often by shadowing an experienced technician while cognitive skills are documented and learned abstractly.

For edge device work, neither approach suffices alone.

Shadowing is slow and expensive and depends on experts who are already in short supply (and whose boss would prefer that they spent their time differently). Documentation captures procedure, but not judgment. It explains what to do, but not what “correct” looks like in practice, or how to recover when something breaks mid-process.

This creates a structural gap.

Devices evolve faster than expertise. Variants accumulate. Firmware changes. Technicians move forward with partial knowledge and no efficient way to close the gap. An expert who could help might no longer be available.

This is the problem addressed in XR5.0 Pilot 5, co-developed by SYN and SPACE Hellas.

The pilot focuses on an industrial IoT controller used in facility management. Complex enough to expose the problem, but representative enough to make the solution broadly relevant.

The key question is simple:
Can training environments handle both the physical and the procedural aspects of work at the same time?

The solution is a VR training application where the technician performs an assembly task inside a fully interactive 3D environment.

The device is not shown as a diagram, but as a manipulable object. It can be inspected, rotated, and handled spatially. Training content is delivered as structured objectives, guiding the technician through the process.

Crucially, physical and cognitive tasks are not separated. They occur together, as they do in real work.

What distinguishes this from a standard XR training scenario is its connection to real hardware. Through MQTT integration, the VR environment communicates bidirectionally with an actual physical controller.

- A configuration step in VR triggers a real response from the device
- Sensor readings reflect the real system state
- Actions in training produce actual system behaviour

This is not a simulation that precedes real work.
It is the work executed through a different interface. That distinction matters most for procedural knowledge. The feedback loop between action and result is no longer abstract or delayed. It is immediate and grounded in the real system.

For motor-cognitive tasks, the gap between knowing and doing has always been expensive to close.

- Documentation reaches the cognitive side but misses the physical
- Apprenticeship reaches both but does not scale

XR, when connected to real systems rather than isolated simulations, offers a third path. It keeps the task whole.

Training becomes less about preparation and more about controlled execution. The relevance extends beyond a single device. Industrial environments are full of programmable controllers, sensors, and embedded systems, and the same pattern appears repeatedly:

- Specialist knowledge concentrated in a few individuals
- Documentation that fails to transfer judgment
- Training cycles that cannot keep up with system evolution

With AI, the cost of creating training scenarios is also dropping. Generative models, trained on device manuals and procedural documentation, can assist in producing varied training scenarios, turning static instructions into interactive learning experiences.

Image 2: The Generative AI & Hardware-in-the-Loop Solution.



Pilot 5 demonstrates one instance of a broader approach.

Not replacing expertise, but compressing the distance between access to knowledge and the ability to act on it.

Empowering the Future of Industry: How XR, AI, and AR Are Transforming Workflows with RealWear

Extended Reality in the Smart Factory: Accelerating Innovation, Collaboration, and Efficiency

As we usher in the era of Industry 5.0, smart factories are becoming more than just automated production environments; they're transforming into digitally orchestrated ecosystems where people and machines collaborate seamlessly. One of the driving forces behind this shift is Extended Reality (XR), an umbrella term that includes Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). In the XR5.0 project, we explore how XR technologies are revolutionizing smart manufacturing, not just by making processes more efficient, but by reshaping how we train, troubleshoot, plan, and communicate.

XR as a Game-Changer in Workforce Training

One of the most impactful uses of XR in our smart factory initiatives is in worker training. As production systems become increasingly complex and customized, equipping new or existing employees with the skills to operate and maintain machinery safely and efficiently is more challenging than ever.

With XR, we're able to create interactive, immersive training environments that simulate real-world scenarios. Workers can explore and interact with digital twins of machines, rehearse maintenance procedures, and understand intricate machine operations, all in a safe and controlled environment.

This approach significantly reduces onboarding time and improves knowledge retention. More importantly, it allows trainees to fail safely, learning through experience without the risks or costs of downtime or damage to actual equipment.

Supporting Live Interventions and Remote Troubleshooting

XR doesn't stop at training; it extends into live support and operational assistance. During a real intervention, for example, AR headsets or tablets can overlay contextual information directly onto a worker's field of view, showing instructions, warnings, or sensor data. This greatly improves accuracy and reduces errors during complex tasks.

We also leverage XR to enable remote collaboration. When a technician encounters a machine fault, an expert can connect via a remote call, view what the technician sees, and guide them through the troubleshooting process. This approach minimizes the need for on-site visits and allows real-time problem-solving across locations.

Virtual Production Tours and Invisible Insights

Beyond operations and maintenance, XR has proven invaluable for showcasing and communicating smart factory processes, especially to visitors, partners, or stakeholders unfamiliar with the factory floor. Through virtual production tours, users can navigate a digital replica of the factory, explore different stages of production, and visualize workflows.

But XR can do even more. In a smart factory, many of the most critical interactions are invisible, like machine-to-machine communication, data exchanges over the industrial IT network, or the flow of orders through ERP systems. With XR, we can make these hidden layers visually accessible, offering insights into how the factory "thinks" and "communicates," not just how it moves parts.

This capability enhances transparency, trust, and understanding, particularly during client presentations, audits, or educational visits.

Spatial Planning and Layout Optimization

Smart factories are dynamic: machines get upgraded, layouts are reconfigured, and new workflows are introduced. In such an environment, planning spatial arrangements efficiently is crucial. This is where XR again proves its worth.

By importing CAD models of machines and installations into a shared 3D environment, teams can experiment with layout changes in real time. They can walk through the virtual production space, check for bottlenecks, simulate maintenance access, and ensure compliance with safety distances, all before moving a single machine.

This not only accelerates the planning process but fosters collaborative decision-making. Stakeholders, from engineers to operators, can all view and interact with the same virtual setup, reducing misunderstandings and aligning perspectives.

Current Limitations and Challenges

While the benefits of XR in smart factories are clear, we also need to acknowledge its current limitations.

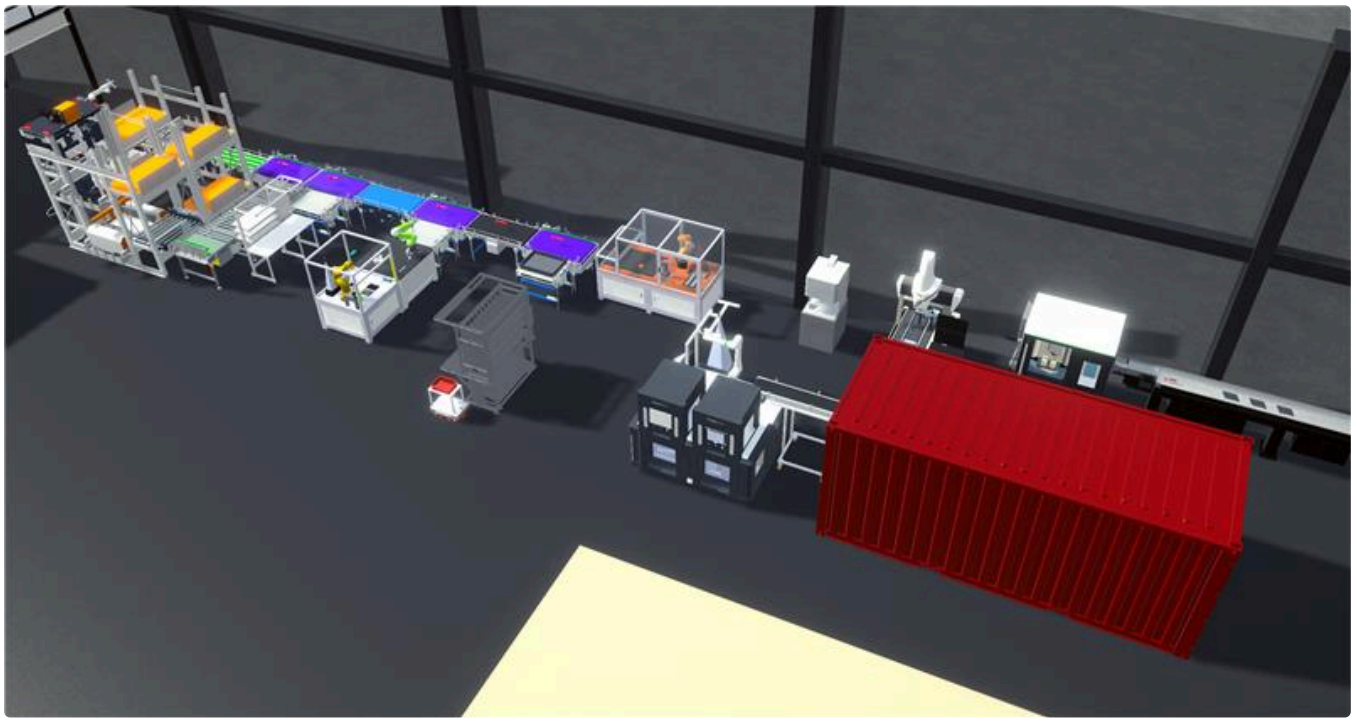
- Hardware constraints: XR devices can still be bulky, expensive, or limited in battery life and durability, especially in industrial environments.
- Content creation and maintenance: Developing accurate, interactive 3D content and keeping it up to date requires significant effort and expertise.
- Integration complexity: To be truly useful, XR needs to integrate with existing IT, IoT, and OT systems, something that can be technically and organizationally challenging.
- User acceptance: Some users may be hesitant to adopt XR tools due to unfamiliarity or concerns about comfort and usability.

However, these limitations are not showstoppers; they are areas of active research and development. With the XR5.0 initiative, we are continuously testing new devices, improving interoperability with factory systems, and developing best practices to ensure smooth deployment and long-term value.

Conclusion: XR as a Strategic Enabler

XR is no longer a futuristic add-on; it's a strategic enabler in the transformation of smart manufacturing. At XR5.0, we've seen how these technologies can enhance human capabilities, streamline collaboration, and unlock a new level of factory intelligence.

As we look to the future, the integration of XR with AI, edge computing, and real-time data analytics will only deepen its impact. The smart factory is not just automated; it's becoming intuitive, visual, and interactive, thanks to the power of Extended Reality.



3.7 APPLICATIONS AND USE CASES

AI-Enabled Smart Glasses in Industry: Future Potential for Context-Specific Workflows

Smart glasses have been used in industrial research and pilot projects for more than a decade. Their central benefit has remained consistent: workers can access digital information while keeping their hands available for the physical task. Recent progress in artificial intelligence could now expand this concept considerably. Instead of functioning primarily as wearable screens, future smart glasses may become context-aware assistants that interpret the working environment and provide support for specific industrial workflows.

A recent systematic review of assisted-reality applications in manufacturing identifies maintenance, visual work instructions, remote assistance, monitoring and quality control as particularly relevant use cases. The review also highlights artificial intelligence, industrial Internet of Things integration and improved human-machine interaction as important areas for further development.

The combination of smart glasses and AI is especially promising because the two technologies provide complementary capabilities. Smart glasses can capture the worker's visual perspective and present information within the field of view. AI can analyse images, speech, documents, sensor data and historical maintenance records. Together, these technologies can provide information that is more closely aligned with the current task.

Context-Aware Maintenance Support

Maintenance is one of the clearest application areas. A technician could look at a machine and ask the system to identify the asset, retrieve its maintenance history or display the correct service procedure. Computer vision could help recognise components, indicators or visible defects. An AI model could then connect these observations with equipment documentation, work orders and sensor data.

The system would not need to make autonomous maintenance decisions. Its role could be to organise relevant information, suggest diagnostic steps and explain why a particular action may be appropriate. The technician would remain responsible for evaluating the situation and approving the next step.

AI could also improve hands-free documentation. Spoken observations could be converted into structured maintenance notes, while images and videos could be assigned automatically to the correct asset and work order. Research into the integration of AI, speech processing and augmented reality has already explored hands-free task logging as a method for reducing interruptions during industrial maintenance.

Adaptive Work Instructions

Traditional digital work instructions usually follow a fixed sequence. AI-supported smart glasses could adapt instructions to the worker's experience, the machine configuration and the current process state.

An experienced technician may only require a checklist and safety confirmation. A new employee may benefit from detailed explanations, visual examples and verification after each step. If the system detects uncertainty or a deviation from the expected process, it could provide additional guidance or recommend assistance from a supervisor.

This could be particularly valuable for assembly, inspection, changeovers and less frequently performed maintenance tasks. Instead of replacing employee expertise, the system could make existing organisational knowledge available at the moment it is required.

Quality Inspection and Process Documentation

Smart glasses could also support visual inspection workflows. A worker might examine a product while an AI model compares visible characteristics with reference images, specifications or known defect patterns. Potential deviations could be highlighted for closer inspection.

The final decision should remain with a qualified employee, especially in safety-critical or regulated environments. However, AI could help standardise documentation, ensure that required inspection points are not missed and make previous quality information easier to access.

Remote Expertise and Knowledge Transfer

Remote assistance is already one of the established applications of industrial smart glasses. AI could make this workflow more efficient by summarising the situation before a remote expert joins, retrieving relevant documentation and recording the final solution.

Over time, recurring support cases could become part of a searchable organisational knowledge base. This would allow knowledge created during one intervention to support future technicians facing similar problems. The combination of AI-enhanced digital twins, real-time industrial data and maintenance information could further strengthen this connection between the physical asset and its digital history.

From General Technology to Specific Workflows

The future of industrial smart glasses is unlikely to depend on a single device that supports every activity. Adoption may instead progress through clearly defined workflows in which hands-free access, visual context and AI-supported information retrieval provide measurable value.

Human-centred implementation will remain essential. Devices must be comfortable, compatible with protective equipment and integrated with existing industrial systems. AI-generated recommendations must be traceable, secure and easy to verify. Workers should also be involved in the design of the workflows that affect their daily activities.

This approach corresponds closely with the objectives of XR5.0. The project combines human-centred extended reality, artificial intelligence and digital twins to develop applications for areas including training, assembly guidance, troubleshooting and remote maintenance. Six pilot applications are being developed and evaluated in realistic manufacturing environments.

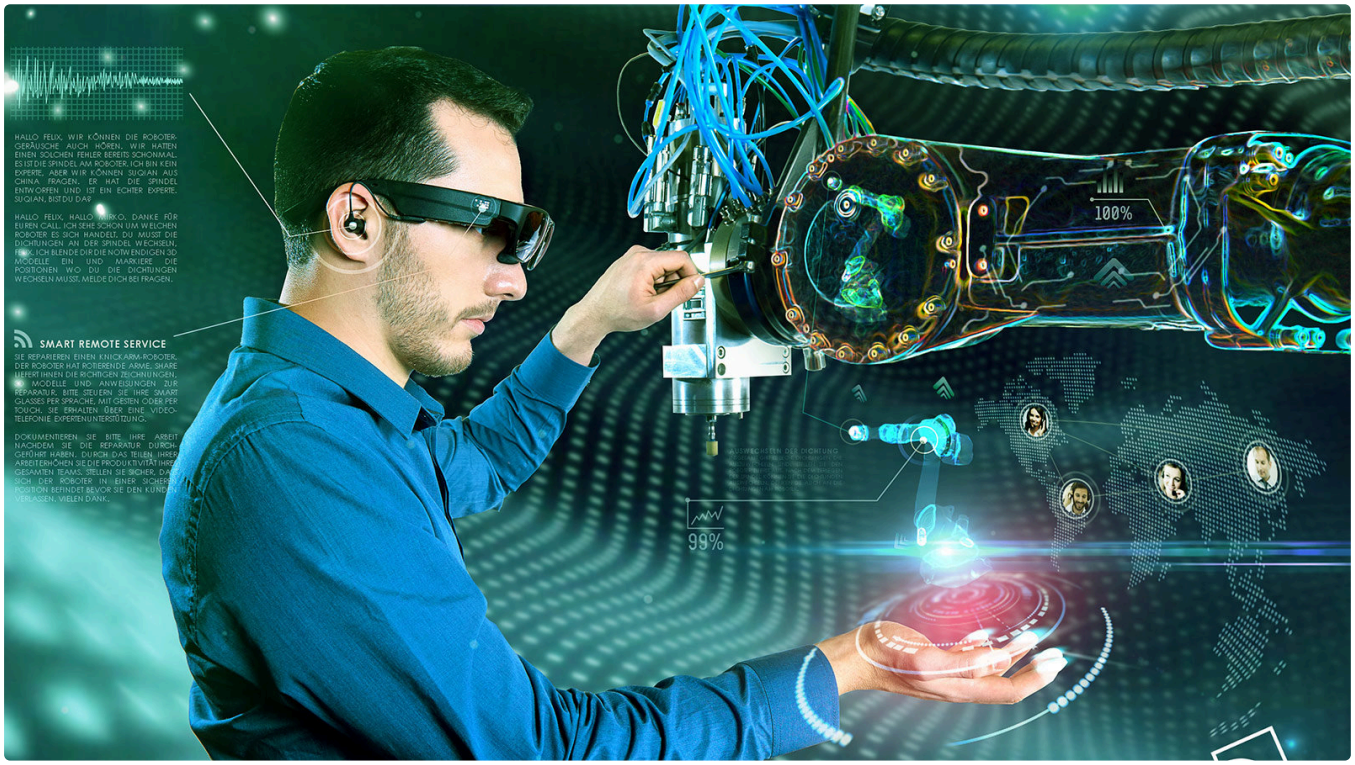
Smart glasses may therefore become most valuable not as replacements for computers, tablets or human expertise, but as a new interface between workers and industrial knowledge. When applied to carefully selected workflows, their combination with AI could make information more accessible, documentation more consistent and technical support more responsive.

Sources

Solomashenko, A. et al. “A systematic review of assisted reality applications in manufacturing.” Virtual Reality, Volume 30, 2026.

Chen, S. et al. “AI-enhanced digital twins in maintenance: Systematic review and future research directions.” 2025.

Khanna, P. et al. “Human-centric Maintenance Process Through Integration of AI, Speech, and AR.” 2025.



Evaluating Human-Centric XR in Practice: Lessons from the XR5.0 Early Prototype Pilots

As Industry 5.0 transitions from a strategic vision into day-to-day industrial practice, the success of Extended Reality (XR) and Artificial Intelligence (AI) is no longer defined by technological sophistication alone. Instead, it depends on demonstrable, measurable value in real working conditions—on the shop floor, in maintenance environments, and within safety-critical operational contexts. XR and AI must prove that they genuinely support workers by improving efficiency, accuracy, confidence, and safety, rather than adding complexity or cognitive burden.

The **XR5.0 project** directly addresses this challenge through the development and evaluation of **six early prototype pilots**, each deployed and assessed in realistic industrial environments across different domains, including manufacturing, maintenance, infrastructure, and training. These pilots were not laboratory demonstrations, but hands-on evaluations involving real users, real tasks, and real constraints, providing an authentic picture of how human-centric XR solutions perform in practice.

Rather than benchmarking isolated components or algorithmic performance in abstraction, the evaluations adopted a **socio-technical perspective**. They examined how workers experienced XR systems in their daily activities, how intuitively AI-supported guidance integrated into established workflows, and how factors such as usability, explainability, responsiveness, and ergonomics influenced trust and acceptance. At the same time, the evaluations identified concrete limitations and improvement needs, offering clear guidance on what must be refined before these solutions can move from promising early prototypes to scalable, deployable systems aligned with the principles of Industry 5.0.

Pilot #1: Early Validation of Human-Centric XR Design

Pilot #1 evaluated XR and AI support for human-centric product design and training in human–robot collaboration contexts. The early prototype demonstrated strong potential in terms of visual clarity, situational awareness, and perceived safety. Participants appreciated high-quality XR visualizations and real-time data integration, which supported understanding of complex systems.

However, the evaluation also highlighted limitations typical of early-stage prototypes. AI responsiveness and onboarding effort were identified as critical areas for improvement. The findings underline that while XR training is well suited for preparatory learning, performance optimization and usability refinements are essential for operational deployment.

Pilot #2: Comparing Maintenance Support Modalities

Pilot #2 focused on the evaluation of human-centred remote maintenance and asset management, comparing three support scenarios for the same real maintenance task. The results clearly showed that mobile and voice-based solutions were currently perceived as the most efficient and intuitive for simple tasks. Remote expert support significantly increased confidence for untrained technicians.

The XR workflow scenario demonstrated clear potential, particularly for more complex procedures, but also revealed higher cognitive demand and usability challenges. Importantly, explainable AI elements improved user understanding and trust, confirming that transparency is a decisive factor in AI-supported maintenance workflows.

Pilot #3: XR and AI for Smart Water Infrastructure

In Pilot #3, operators evaluated AR-based support for smart water pipe inspection and maintenance. The early prototype combined AI-based anomaly detection, AR visualization, and voice interaction. From a technical perspective, the system showed strong rendering performance and stable interaction, even in outdoor environments.

User feedback confirmed that XR visualization enhanced situational awareness and supported decision-making. At the same time, the evaluation revealed weaknesses in AI explainability and marker precision, which negatively affected trust. These findings emphasize that AI accuracy and clarity of visualization are prerequisites for XR adoption in infrastructure maintenance.

Pilot #4: Aircraft Maintenance Training in XR

Pilot #4 evaluated an XR-based training environment for aircraft maintenance technicians, focusing on a critical component of the Wing Anti-Ice system. Participants, including junior and senior technicians, reported positive experiences regarding visual quality, interaction, and content accuracy.

Although the lack of real equipment limited objective KPI measurement, qualitative feedback confirmed that XR training improved comprehension and reduced perceived stress. The evaluation also identified usability issues related to panel positioning and interaction, particularly for users with limited XR experience, reinforcing the importance of ergonomic and intuitive interface design.

Pilot #5: Adaptive XR Training and Repair for Edge Devices

Pilot #5 assessed adaptive XR training and repair support for industrial edge devices. The early prototype integrated immersive XR applications, biometric monitoring, and Human Digital Twins. The evaluation confirmed high system stability, good responsiveness, and reliable data integration.

Participants recognized clear benefits in task efficiency, error reduction, and safety. Adaptive content personalization based on expertise and physiological state was perceived as especially valuable. While large-scale KPI tracking was not yet possible, qualitative evidence strongly suggested improved assembly and repair performance, validating the technical and human-centric foundations of the solution.

Pilot #6: Predictive Maintenance and Troubleshooting

Pilot #6 evaluated XR-supported predictive maintenance and troubleshooting using voice-controlled interaction and AI-generated guidance. The system performed reliably even under challenging conditions, such as background noise and heavy network usage, with fast reaction times that users did not perceive as disruptive.

Participants reported high trust, clear task support, and reduced cognitive load, particularly appreciating hands-free interaction. At the same time, the evaluation highlighted areas for improvement, including voice recognition robustness and richer visual information. Overall, the pilot confirmed the feasibility of XR-based troubleshooting and strong user interest in continued development.

Cross-Pilot Insights and Readiness for Industry 5.0

A holistic view of the evaluations for all six early XR5.0 prototypes reveals a consistent and coherent representation of the strengths and maturity gaps pertaining to human-centred XR solutions. Across a broad spectrum of application domains, including product design, training, maintenance, troubleshooting and infrastructure operations, participants consistently reported distinctly perceived benefits. The aforementioned improvements included enhanced accuracy in task execution, increased confidence when performing unfamiliar procedures, more effective learning and knowledge retention, and greater process consistency when compared to conventional documentation-based or purely verbal support methodologies. In the preliminary prototype phase, extended reality (XR)-assisted guidance exhibited its potential to mitigate uncertainty, facilitate decision-making processes, and engender a heightened sense of control among employees undertaking complex or safety-critical tasks.

It is imperative to note that the findings of this study demonstrate that human-centred design principles are not discretionary embellishments, but rather constitute indispensable prerequisites for XR systems that are specifically engineered for Industry 5.0. In the field of technology, particularly in the context of artificial intelligence and voice-activated devices, there is a growing recognition of the importance of certain features in fostering trust, efficiency and safety. These features include explainable AI, which enables users to comprehend the rationale behind the recommendations received; hands-free interaction via voice and wearable devices, which enhances convenience and accessibility; and adaptive guidance, which is tailored to the user's level of knowledge and situational context. The significance of these features has been repeatedly emphasised in various studies and discussions within the academic community.

3.9 APPLICATIONS AND USE CASES

Beyond Efficiency: How XR5.0 Is Evaluating Whether AI-Enabled XR Actually Strengthens Industrial Skills

Industrial Extended Reality (XR) systems are often evaluated using familiar measures: Was a task completed faster? Were fewer errors made? Did the system respond reliably? These questions matter, but they capture only part of what Industry 5.0 aims to achieve.

If an AI-enabled XR system helps a technician complete a task more quickly, this represents an efficiency gain. But what happens to the technician's knowledge and competence over time? Does the system help workers understand their tasks, develop skills and become more confident when dealing with unfamiliar situations? Or can increasingly capable assistance make workers dependent on the technology?

As XR5.0 moves towards its final pilot evaluations, these questions are becoming an important part of the project's socio-technical evaluation work led by ATB.

Looking beyond technical performance

XR5.0 combines Extended Reality, Artificial Intelligence (AI) and Human Digital Twin technologies across six industrial pilots. Applications range from robot commissioning and maintenance to smart water infrastructure, aircraft maintenance, industrial training and customer support.

The project's early prototype evaluations already looked beyond whether the technology worked. The common evaluation framework combined technical performance with usability and user experience, work impact and effectiveness, task load, and social and economic aspects. This approach allows XR5.0 to examine technological performance together with the experience of the people expected to use these systems in practice.

This becomes increasingly important as XR5.0 applications combine several forms of intelligent assistance. Workers may receive visual XR guidance, interact with AI assistants through natural language, access recommendations based on technical documentation or receive personalised support adapted to their context.

Pilot 1 provides one example. Its RoboSpace environment combines augmented-reality visualisation of industrial robots with live operational data, the voice-controlled KUKABot assistant, XR training, worker-movement prediction and a Safety-Risk Zone Checker. Evaluating such a system therefore involves more than measuring response times or AI accuracy. It also raises questions about situational awareness, learning and safe human-robot collaboration.

What does the worker learn?

As AI becomes embedded more deeply into industrial workflows, the distinction between using a digital tool and collaborating with an intelligent system becomes less clear.

A conventional digital instruction might simply tell a technician which step comes next. An AI-enabled XR system can potentially explain a recommendation, retrieve relevant technical knowledge, answer questions or adapt information to the user and situation.

Within XR5.0, ATB also leads work on advanced AI paradigms for trusted Human-AI collaboration. The project investigates approaches including active learning, neurosymbolic AI and generative AI. A common principle is that humans should remain active participants in the interaction with AI rather than becoming passive recipients of automated decisions.

This changes an important evaluation question. Instead of asking only **"How much faster did the worker complete the task with AI?"**, we should also ask **"What did the worker learn while using the AI?"**

Connecting efficiency with skill development

The first XR5.0 evaluation cycle used qualitative and semi-quantitative indicators to identify strengths, limitations and development priorities across the pilots. For the final evaluation, the project is extending this work towards more precise measurements of efficiency, cost, safety and sustainability while strengthening its human-centred perspective.

One direction identified in this work is an **Efficiency-Skill Ratio**. The underlying idea is that productivity improvements should not be considered independently from their effects on human competence.

Consider two hypothetical assistance systems. The first substantially reduces task time, but the worker mainly follows instructions without understanding the reasoning behind them. Without the system, completing the procedure becomes difficult. A second system may provide a smaller immediate efficiency gain but helps the worker understand the process, recognise relevant patterns and deal with similar problems independently later.

If execution time were the only criterion, the first system would appear better. From an Industry 5.0 perspective, the assessment is less straightforward.

The Efficiency-Skill Ratio is therefore being explored as an evaluation direction rather than as an established standard metric. It highlights the balance between efficiency achieved through technological assistance and the human capabilities maintained or developed while using it.

Assistance should not always increase

This question becomes particularly relevant for personalised XR systems. A novice encountering a task for the first time may benefit from detailed instructions and explanations. An experienced technician performing the same task may need only occasional assistance.

Effective personalisation may therefore mean learning not only **what assistance to provide**, but also **when assistance should decrease**.

Reducing assistance can give workers opportunities to recall knowledge, make decisions and retain competence rather than continuously outsourcing these activities to an AI system. This perspective connects personalised XR with a broader objective of XR5.0: technology should augment human capabilities rather than simply replace them.

Towards the final XR5.0 evaluations

The final evaluation phase will put increasingly mature XR5.0 solutions into realistic industrial settings. The socio-technical evaluation work will build on the experience gained from the early prototypes to refine the common assessment approach across the pilots.

Technical reliability and industrial efficiency remain essential. But the project is also examining a broader measure of success.

Human-centred industrial AI should not be evaluated only by how much work technology can perform for people. We should also consider what people can **do with it, learn through it and still do without it**.

For XR5.0, this distinction is central to moving from more intelligent automation towards genuinely human-centred Industry 5.0.

3.10 APPLICATIONS AND USE CASES

Experience the Future: Tailored Training for Industrial Workers at EKSO I5.0

Extended reality (XR) is quickly evolving from just entertainment to becoming powerful operational tools.

Innovative hardware advancements, advanced software applications, and reduced costs have hastened this transformation, even for tasks carried out in challenging conditions and industrial environments.

XR, short for extended reality, encompasses all technologies that transform how we perceive and interact with the world around us, including AI technologies that foster the interplay between humans and AI such as explainable AI (XAI), Active Learning (AL), Generative AI (GenAI), and neurosymbolic learning.

XR significantly impacts industrial environments, particularly in Industry 5.0, by enhancing efficiency, safety, and training.

Various advancements are bringing industries closer to the virtual world, particularly in the realms of work and manufacturing. For instance, at Northumbrian Water in the UK, remote experts use AR headsets to guide field technicians. Bank of America employs VR for employee training. Additionally, the team responsible for restoring Notre Dame in Paris collaborates on a VR version of the fire-damaged cathedral, allowing them to work in a digital twin of the structure and, last but not least, XR technologies are finding applications in no-dig pipeline renovation and underground infrastructure work with trenchless technology, which are EKSO's core businesses.

EKSO Srl is a partner and a demonstrator in XR5.0. The company specializes in no-dig pipeline renovation methods designed to rehabilitate or repair underground pipes without the need for disruptive excavations. This means that EKSO already uses XR technologies to enhance efficiency, accuracy, and safety in this field. Furthermore, the project has a concrete impact, and the technologies involved, such as Augmented Reality (AR) and XR, revolutionize pipeline maintenance and repair processes. AR can overlay 3D models of underground pipelines onto the real-world view, aiding workers in understanding layouts and identifying areas for renovation. It also allows for real-time guidance during repairs and remote support from experts. On the other hand, XR enhances inspection by combining the physical and digital worlds, providing inspectors with real-time data and historical records for accurate assessments. Additionally, XR technologies enable the creation of digital twins for remote monitoring, predictive maintenance, and simulations of potential issues. XR tools also aid in 3D mapping and surveying of underground environments, facilitating accurate renovation planning and evaluation of different no-dig techniques.

EKSO is now moving towards offering personalized training and operations to its workers, such as maintenance technicians.

XR technologies and Virtual Reality (VR) are increasingly being utilized for Training and Simulation purposes, particularly in trenchless technology methods. This innovative approach involves simulating various scenarios in a virtual environment to provide workers with practical training and hands-on experience without the associated risks of working in real-world situations. By immersing workers in a risk-free virtual environment, XR allows them to practice complex procedures and gain valuable experience without the need to disrupt actual infrastructure. This not only enhances their skills but also reduces the potential for errors and accidents when working on real projects. XR5.0 integrates XR into Industry 5.0 applications, with a focus on creating cutting-edge "XR-made-in-Europe" technology that harmonizes with human-centric manufacturing technologies and upholds European values.

Moreover, XR is being utilized to simulate hazardous situations that workers in the no-dig pipeline industry may encounter. For example, VR simulations can replicate dangerous scenarios like ground collapse or accidental damage to existing utilities. By exposing workers to these virtual hazards, they can learn how to react appropriately and develop the necessary skills to avoid accidents in real-world scenarios. This proactive approach to training can significantly improve safety protocols and preparedness among workers, ultimately leading to a safer work environment for all involved.

In this regard, the activities in XR5.0 offer a more efficient way to train maintenance operators and support repair and servicing processes for smart pipes.

By integrating XR technologies into work environments, companies can drastically reduce accidents, improve emergency preparedness, and ensure workers stay safer, healthier, and more productive.

XR5.0 is not the only project within European-financed research that focuses on structuring principles and blueprints for using XR in I5.0 applications. Another initiative called Spirit - Scalable Platform for Innovations on Real-time Immersive Telepresence has a similar focus. SPIRIT's mission is to create Europe's first multisite and interconnected framework capable of supporting a wide range of application features in collaborative telepresence. Additionally, 6G-XR - 6G Experimental Research aims to strengthen European leadership in 6G technologies by enabling next-generation XR services and infrastructures that will provide capabilities beyond the current state-of-the-art towards the 6G era.

We believe that AI technologies will drive business innovation. Although it's still early days, the demonstrations in XR5.0 show that enterprises see AI and Extended Reality as the next step in their digitalization efforts and expect it to have a transformative impact on the way they do business. Conducted with individuals knowledgeable about AI across six demonstrations, XR5.0 presents a consistent global picture – that beyond the hype, enterprise and industrial metaverse use cases are being practically planned and deployed.





See relevant links:

- https://digital-strategy.ec.europa.eu/en/policies/extended-reality
- https://www.ekso.it/sandman
- https://www.ekso.it/evenflow
- https://www.ekso.it/ai4publicpolicy

3.11 APPLICATIONS AND USE CASES

From Data to Action: How XR Transforms Pipeline Intelligence into Real-Time Decisions

In today's industrial environments, the real challenge is no longer data availability, but the ability to translate it into timely action.

Across critical infrastructures such as water networks, vast amounts of data are continuously generated through sensors, inspections, and monitoring systems. Pressure fluctuations, temperature variations, structural anomalies, video inspection feeds: all this information is available. Yet, translating this data into timely, informed decisions on the field remains a major operational challenge.

For companies like EKSO, working in complex and often invisible environments such as underground pipelines, the gap between data and action can directly impact efficiency, safety, and sustainability. In a word: competitiveness.

This is precisely where the XR5.0 project is driving a transformative shift.

From fragmented data to operational intelligence

Traditionally, operators rely on multiple, disconnected sources of information. Sensor dashboards, inspection reports, and expert assessments are often consulted separately, requiring interpretation, experience, and time. This fragmented approach introduces delays and increases the risk of errors—especially in high-pressure or hazardous scenarios where rapid intervention is critical. Within the XR5.0 pilot, EKSO and the project's partners are contributing to a new paradigm: integrating AI, sensor data, and Extended Reality (XR) into a unified operational layer that supports real-time decision-making directly in the field.

XR as an enabler of real-time action

In the ongoing pilot activities, XR technologies are no longer used solely for visualization or training. Instead, they are becoming an active interface between complex data streams and human operators.

Through AR-enabled devices and immersive interfaces, field technicians can now:

- Visualize underground pipeline conditions directly on site, without the need for invasive interventions
- Access real-time diagnostics generated by AI models applied to sensor data
- Receive contextual alerts and guided instructions aligned with the specific operational scenario
- Interact with integrated video inspection outputs, enhanced by AI-based anomaly detection

This convergence of technologies allows operators to move beyond passive observation and into immediate, informed action.

Integrating intelligence across the pipeline lifecycle

A key advancement in EKSO's XR5.0 pilot lies in the integration of multiple data sources into a coherent operational workflow.

Sensorized smart pipes provide continuous monitoring of physical parameters. AI models—such as those developed in EKSO's broader innovation ecosystem—enable early detection of faults, including micro-leaks or structural stress. At the same time, robotic video inspection systems generate visual data that can be processed in real time. XR acts as the unifying layer, transforming these heterogeneous inputs into a single, intuitive experience. Rather than navigating across separate systems, operators are guided through a seamless flow where data becomes immediately actionable.

From decision support to decision execution

This shift represents more than a technological upgrade—it is a change in how decisions are made and executed.

In traditional settings, operators interpret data and then decide how to act. In the XR5.0 approach, decision-making is embedded within the operational context itself.

By overlaying insights directly onto the physical environment, XR enables:

- Faster identification of critical issues
- More precise localization of faults
- Reduced need for unnecessary excavation or inspection
- Improved coordination between field operators and remote experts

In this sense, XR is not just a visualization tool—it becomes a driver of operational intelligence.

Toward a human-centric, data-driven future

Aligned with the principles of Industry 5.0, the XR5.0 project places human operators at the center of this transformation. The goal is not to replace human expertise, but to augment it—providing workers with the right information, at the right time, in the most intuitive way possible. This means enabling a new generation of operators capable of navigating complex infrastructures with enhanced awareness, confidence, and efficiency.

Looking ahead

As the XR5.0 pilot progresses, the project's partners continue to explore how the integration of XR, AI, and smart infrastructure can redefine operational workflows in the water sector. The transition from data to action is no longer a future vision—it is becoming a practical reality. And in this evolving landscape, Extended Reality is proving to be a key enabler of faster decisions, safer operations, and more sustainable infrastructure management.

Within this context, the XR5.0 project stands as a key European initiative shaping the next generation of human-centric, AI-enabled industrial systems, where technologies are designed not only to optimize processes, but to empower people.

Mixed Reality and AI Technologies Enhance SCHMIDT + HAENSCH Service Processes



Halfway to XR5.0: Redefining Remote Maintenance with SCHMIDT + HAENSCH

As the XR5.0 project reaches its midpoint, SCHMIDT + HAENSCH continues to pioneer the future of smart maintenance in laboratory and process instrumentation. Together with more than 25 European partners, we are translating the ambitious vision of Industry 5.0 into real-world tools—tools that combine extended reality (XR), artificial intelligence (AI), and human-centric design to transform how industrial maintenance is performed.

From Vision to Validation: Where We Stand

Since the project's launch, SCHMIDT + HAENSCH has successfully integrated XR5.0 prototypes into real maintenance scenarios. With a global installed base of high-precision instruments—polarimeters, refractometers, and inline sensors—we've had ample opportunity to test XR-enhanced support in the field.

Key milestones achieved so far include:

- Successful Pilot Deployments: XR-enabled service procedures have been piloted with both internal service engineers and external partners. These pilots demonstrate significant reductions in troubleshooting time and improved first-time fix rates.

- AI-Based Skill Adaptation: Our system now recognizes technician experience levels and adapts instructions accordingly. Whether the user is an in-house expert or a new operator, the interface delivers step-by-step support that is context-aware and intuitive.
- Reduced Downtime, Reduced Travel: Remote troubleshooting, calibration, and validation have proven effective, minimizing the need for travel while keeping instruments operational even in remote or regulated environments.

Use Case Highlight: Supporting Global Partners

A major focus has been enabling distributors and field technicians across the globe to carry out diagnostics, retrofitting, and even complex maintenance—with guidance from SCHMIDT + HAENSCH experts in Berlin. Using smart glasses and AR overlays, technicians receive real-time instructions, diagrams, and verbal assistance in their local context—without needing to fly in a specialist.

This not only improves efficiency but also aligns with our sustainability goals, reducing the carbon footprint of service operations and making high-quality support accessible across time zones.

For instance, SCHMIDT + HAENSCH's Service Technician Experts can remotely oversee and assist Field Technicians or Equipment Operators via AI-enhanced visualizations, delivering step-by-step instructions that adapt to each user's skill level. This personalized assistance not only improves task accuracy and safety but also enables swift, informed decision-making in the field. Equipment operators can now independently handle basic maintenance tasks while having a reliable support network for more complex issues.

Challenges and Learnings

As with any transformative technology, implementation brings challenges:

- Connectivity Constraints: Reliable XR support depends on stable internet connections—especially in remote industrial environments.
- User Adoption: Training and onboarding remain critical to help users embrace new tools. We've found that once initial barriers are overcome, user satisfaction and confidence increase rapidly.

These lessons are shaping our ongoing development and are shared across the XR5.0 consortium to refine the overall platform.

Looking Ahead: Scalable, Smart Service for Industry 5.0

In the coming months, SCHMIDT + HAENSCH will continue:

- Expanding real-world deployments of the XR tools across additional service scenarios
- Collecting performance data to quantify improvements in service efficiency and sustainability
- Working with consortium partners to finalize a market-ready XR5.0 maintenance platform

Our goal remains clear: to provide a flexible, scalable, and intelligent maintenance solution that supports the transition toward more resilient, human-centered, and resource-efficient industries.

Want to See XR5.0 in Action?

We’re actively scheduling demonstrations and pilot partnerships. If you’re interested in how XR-enhanced maintenance could benefit your operations, reach out to our team or visit xr50.eu to learn more.

Revolutionizing Remote Assistance with Extended Reality for Commissioning Automation Solutions

In today's fast-paced industrial landscape, the demand for efficient and effective automation solutions is higher than ever. One of the most promising advancements in this field is the integration of Extended Reality (XR) technologies for immersive visualization in virtual commissioning and for remote assistance in real commissioning of automation systems, including robots. This blog post explores how XR is transforming the way we approach commissioning, the benefits it offers, and its potential future impact.

Extended Reality (XR)

Extended Reality (XR) is an umbrella term that encompasses Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). These technologies blend the physical and digital worlds, creating immersive environments that can be used for a variety of applications, from gaming to industrial automation.

- Virtual Reality (VR): Creates a fully immersive digital environment.
- Augmented Reality (AR): Overlays digital information onto the real world.
- Mixed Reality (MR): Combines elements of both VR and AR, allowing real and virtual objects to interact.

XR in Remote Assistance

Remote assistance using XR technologies is facilitating the troubleshooting process in commissioning automation solutions on-site. Commissioning involves the installation, testing, and validation of systems to ensure they operate as intended. Traditionally, this process requires on-site presence, which can be time-consuming and costly. XR technologies, however, enable experts to provide remote support, reducing the need for physical presence.

Virtual Commissioning

Virtual commissioning involves creating a digital twin of the automation system. This digital replica allows engineers to simulate and test the system in a virtual environment before it is physically implemented. XR technologies enhance virtual commissioning by providing immersive visualization and interaction capabilities.

- Simulation and Testing: Engineers can simulate the behaviour of robots and automation systems in a virtual environment, identifying and resolving issues before they occur in the real world.
- Training and Collaboration: XR enables remote training sessions where engineers can interact with the virtual system, gaining hands-on experience without the need for physical prototypes.
- Cost and Time Efficiency: By identifying potential issues early in the virtual environment, we can save significant time and resources during the actual commissioning phase.

Real Commissioning

Real commissioning involves the physical implementation and testing of the automation system. XR technologies play a crucial role in providing remote assistance during this phase as well.

- Remote Guidance: Experts can use AR to guide on-site technicians through complex tasks. For example, an engineer can overlay digital instructions onto the technician's field of view, providing step-by-step guidance.
- Real-Time Collaboration: MR allows remote experts to interact with the physical environment in real-time. They can manipulate virtual objects that appear in the technician's real-world view, facilitating precise and effective collaboration.
- Troubleshooting and Maintenance: XR technologies enable remote experts to diagnose and resolve issues quickly, minimizing downtime and ensuring smooth operation of the automation system.

Benefits of XR in Commissioning Automation Solutions

The integration of XR technologies in commissioning automation solutions offers numerous benefits:

- Enhanced Efficiency: XR reduces the need for physical presence, allowing experts to provide remote assistance from anywhere in the world. This leads to faster problem resolution and reduced downtime.
- Cost Savings: By minimizing travel and on-site visits, we can significantly cut costs associated with commissioning and maintenance.
- Improved Safety: Remote assistance using XR reduces the need for personnel to be physically present in potentially hazardous environments, enhancing overall safety.
- Better Training and Knowledge Transfer: XR provides immersive training experiences, enabling engineers to gain practical skills in a virtual environment. This leads to better knowledge preservation and transfer.
- Scalability: XR technologies make it easier to scale commissioning processes across multiple sites, ensuring consistent quality and performance.

Future Prospects

The future of XR in remote assistance for commissioning automation solutions looks promising. As XR technologies continue to evolve, we can expect even more sophisticated and seamless integration into industrial processes. Some potential future developments include:

- AI Integration: Combining XR with artificial intelligence (AI) can enhance predictive maintenance and automated troubleshooting, further reducing downtime and improving efficiency.
- 5G Connectivity: The rollout of 5G networks will provide the high-speed, low-latency connectivity required for real-time XR applications, making remote assistance even more effective.
- Advanced Haptics: Improved haptic feedback technologies will enable more realistic interactions with virtual objects, enhancing the training and simulation experience.

Conclusion

Extended Reality is transforming the way we approach remote assistance in the commissioning of automation solutions, including robots. By leveraging VR, AR, and MR, we can achieve greater efficiency, cost savings, and safety. As XR technologies continue to advance, their impact on the industrial landscape will grow, paving the way for a more connected and efficient future.

Smart Pipes, Smarter Workers: How EKSO's XR5.0 Pilot is Revolutionizing Water Infrastructure

In the ever-evolving industrial world, the future belongs to those who innovate at the convergence of sustainability, safety, and digital transformation.

EKSO, a cutting-edge company in trenchless pipe maintenance and smart pipe technologies, is doing just that with its participation in the XR5.0 project, funded under Horizon Europe and in collaboration with 24 partners of excellence.

As part of the XR5.0 pilot for Operator 5.0 training, EKSO is demonstrating how Extended Reality (XR), in combination with AI and real-time sensor data from equipped pipelines, can revolutionize the way operators monitor and maintain water infrastructure.

Why Smart Pipes Matter

EKSO's smart pipe system, equipped with embedded sensors and AI-enabled analytics, detects early signs of damage and supports predictive maintenance strategies.

But technology alone is not enough. That's where XR5.0 enters the picture.

XR Meets Predictive Maintenance

As the XR5.0 pilot continues, EKSO is now in a critical stage whereby the fusion of Extended Reality (XR) with predictive maintenance technologies is being tested in real-world settings.

Initial field tests demonstrate how XR complements EKSO's intelligent pipe systems by delivering real-time information and diagnostics to operators. The pilot uses sensorized composite pipes to track key parameters such as pressure and temperature. AI-powered predictive models offer early detection of possible problems, including micro-leaks and structural stress, before visible failure.

What's being experimented now is the way in which **this intelligence can be made more available to operators in a form that is intuitive and actionable. With XR devices like AR headsets and smart tablets, technicians are beginning to see how digital overlays and real-time alerts can lead them directly to areas of concern.**

Rather than referring to independent dashboards or relying on occasional inspections, operators now have the pipeline's health represented visually on site, in real time.

EKSO and its technical partners are considering adding a digital twin—a virtual representation of the pipeline that mirrors its present state based on sensor information. The model enables operators to run fault scenarios, examine past trends, and more effectively comprehend system alerts. Early feedback indicates it supports faster, smarter interventions, particularly when combined with personalized XR guidance.

Most exciting, perhaps, is how XR is facilitating a more collaborative maintenance experience. In the trials, the experts have already been able to participate in live XR sessions, providing guidance, confirming observations, and solving technical problems together—in real time, without ever leaving the office. This developing capability promises to cut downtime, travel expenses, and response times dramatically. While the pilot continues, EKSO is already starting to envision how **XR can transform predictive maintenance from a data-driven to a human-centered model, one in which operators are not simply alerted but actually empowered.** These initial trials are informing a new operating model in which AI, XR, and field know-how are combined in concert to safeguard critical water infrastructure and the ecosystems they support.

Training Operator 5.0: A New Era of Workforce Empowerment

In EKSO's XR5.0 pilot, **Operator 5.0** is not just a label—it's a vision for a new generation of field **technicians who are empowered by technology, driven by data, and trained through immersive learning experiences**. Using Extended Reality (XR), the pilot is transforming traditional operator training into a dynamic, responsive, more secure and highly personalized process.

Here's how:

- **Immersive Diagnostics Training**: Operators visualize internal states of smart pipes—such as temperature changes and pressure fluctuations—through XR overlays and digital twins, gaining real-time insights via AR glasses.
- **Scenario-Based Simulation and Decision-Making**: Training modules simulate scenarios like saltwater leaks or pipe corrosion, allowing workers to practice decision-making and emergency responses in a safe XR environment, enhancing preparedness and reducing stress.
- **Guided Maintenance and Task Automation:** Operators receive interactive AR instructions for maintenance tasks, making complex procedures easier for less experienced workers to navigate.
- **Real-Time Collaboration with Remote Experts**: The pilot features XR-enabled remote assistance, allowing operators to connect with experts for real-time problem-solving through live video and shared XR annotations, minimizing downtime and errors.
- **Performance Monitoring and Personalized Learning Paths**: Training data informs AI-powered analytics dashboards, offering tailored feedback and improvement recommendations to support continuous learning and adaptability.

Through these innovations, EKSO's Operator 5.0 training pilot is redefining how water infrastructure professionals are prepared—not only to operate today's smart pipelines, but to lead tomorrow's sustainable systems with confidence and skill.

Expanding XR with Image Detection Capabilities

Beyond predictive maintenance, **EKSO is now testing AI-based image detection capabilities across multiple real-world scenarios**—broadening the reach of XR technology in field operations.

In **Use Case 1**, XR guides operators in real time while working on sensorized pipes, enhancing spatial awareness and safety.

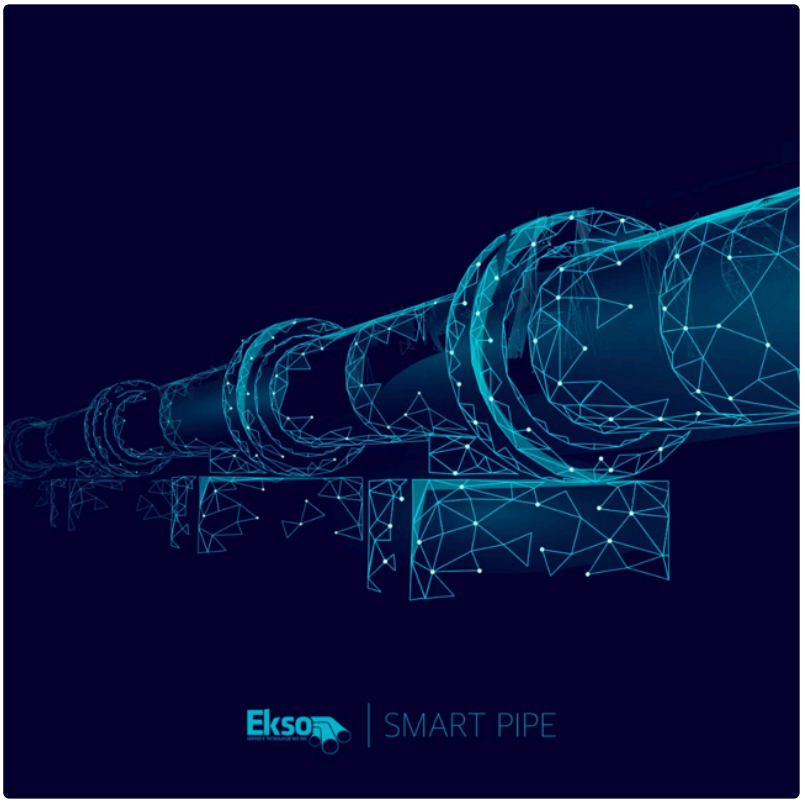
In **Use Case 2**, the company integrates AI image analysis into robotic video inspection workflows, enabling more efficient and accurate identification of anomalies captured via CCTV footage.

Finally, **Use Case 3** explores new forms of field training and operator assistance, where AI-powered computer vision supports real-time learning and decision-making.

These applications represent a crucial step forward in EKSO's mission to embed intelligent automation into daily operations—turning video, voice, and sensory data into actionable insight for field professionals.

The Broader Vision

EKSO's pilot is not an isolated success—it's part of a broader XR5.0 mission to shape the future of Industry 5.0 through AI-powered, XR-enhanced, and worker-centric solutions. With its smart water pilot, EKSO exemplifies how small enterprises can lead big transformations—bringing European-made XR technology into critical infrastructure domains where impact matters most.



Strengthening Effectiveness and Safety of Product Assembly and Repair Processes Using XR Applications

Demo Highlight from XR5.0 Horizon Europe Project

As part of the XR5.0 Horizon Europe project, a collaborative effort between **SPACE HELLAS** and **SYN** is delivering innovative XR-based solutions to strengthen training and support in the industrial domain. A recent demonstration from the XR5.0 project highlights how immersive and intelligent technologies can significantly improve both the effectiveness and safety of product assembly and repair processes — particularly in the context of complex edge devices used in critical infrastructure environments.

Why This Matters:
Modern industrial systems increasingly rely on distributed IoT edge devices for automated control and security management. However, these devices often require complex configuration and maintenance, demanding high skill levels and consistent accuracy from field technicians. Errors in assembly or repair can lead to costly downtime, inefficiencies, or even safety risks. The demo showcases how AI-augmented XR applications can address these challenges by offering intuitive, adaptive, and immersive support experiences.

What Was Demonstrated?
The showcased solution is built around two core use cases (UCs), each reflecting a major operational need in industrial environments:

Use Case 1 – Personalized Training for Edge Device Assembly

This use case focuses on training technicians of various skill levels using personalized VR/AR workflows. By blending AI with 3D visualizations and interactive guidance, the system allows trainees to:

- Access contextual documentation and technical instructions,
- Interact with high-fidelity digital twins of edge devices in a virtual training environment,
- Follow tailored step-by-step procedures based on their experience level.

The key innovation lies in the **adaptive learning engine**, which uses AI to generate and adjust training paths in real time. From entry-level workers to more advanced technicians, each participant receives just the right amount of guidance through:

- Immersive, skill-specific XR modules,
- Embedded animations and simulation tools for better knowledge retention,
- Real-time performance monitoring and feedback mechanisms.

All XR content is delivered through lightweight, wearable headsets, with computational load handled server-side via cloud-based APIs — allowing for scalability, smooth user experiences, and lower hardware requirements.

Use Case 2 – Remote Instructions for Repairs

The second use case addresses repair operations through **AI-powered remote assistance**. Technicians are equipped with AR headsets that allow them to receive real-time, context-aware instructions while working directly on the hardware. This setup supports:

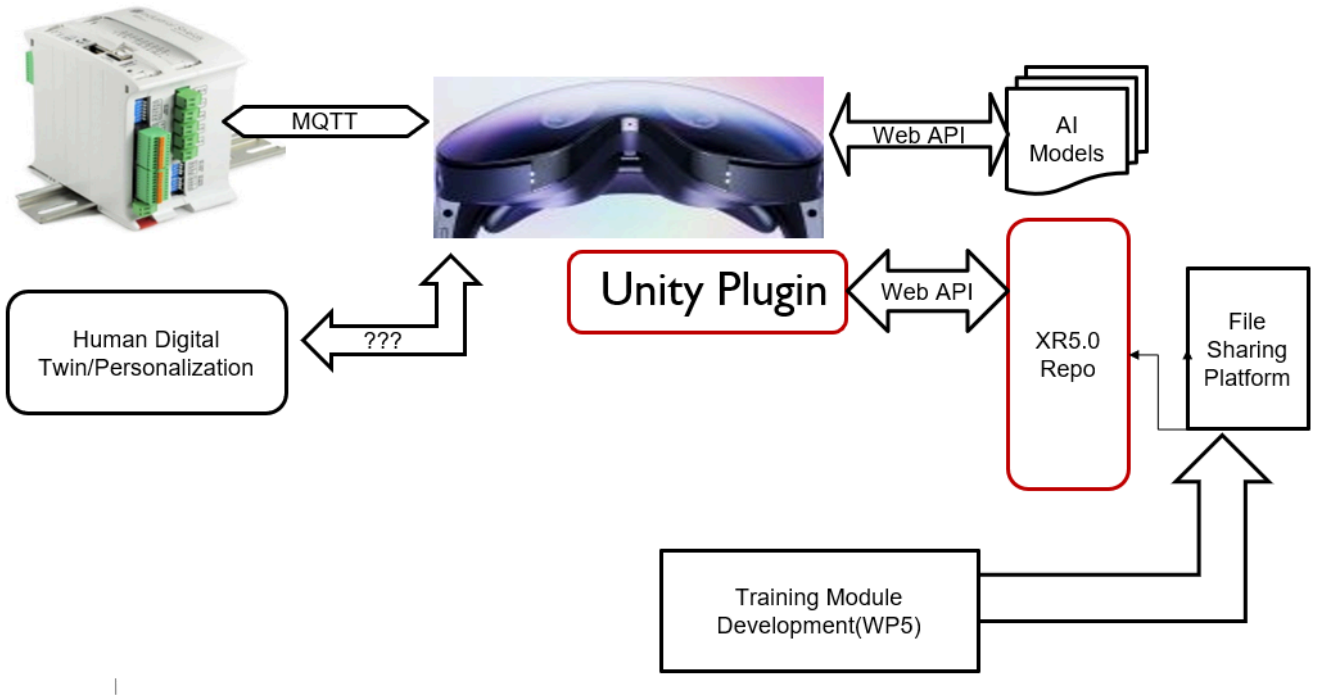
- Live support from remote experts with visual annotations overlaid in the technician's field of view,
- Integrated access to diagnostic data and sensor information in real time,
- AI-driven fault detection and repair guidance customized to technician expertise.

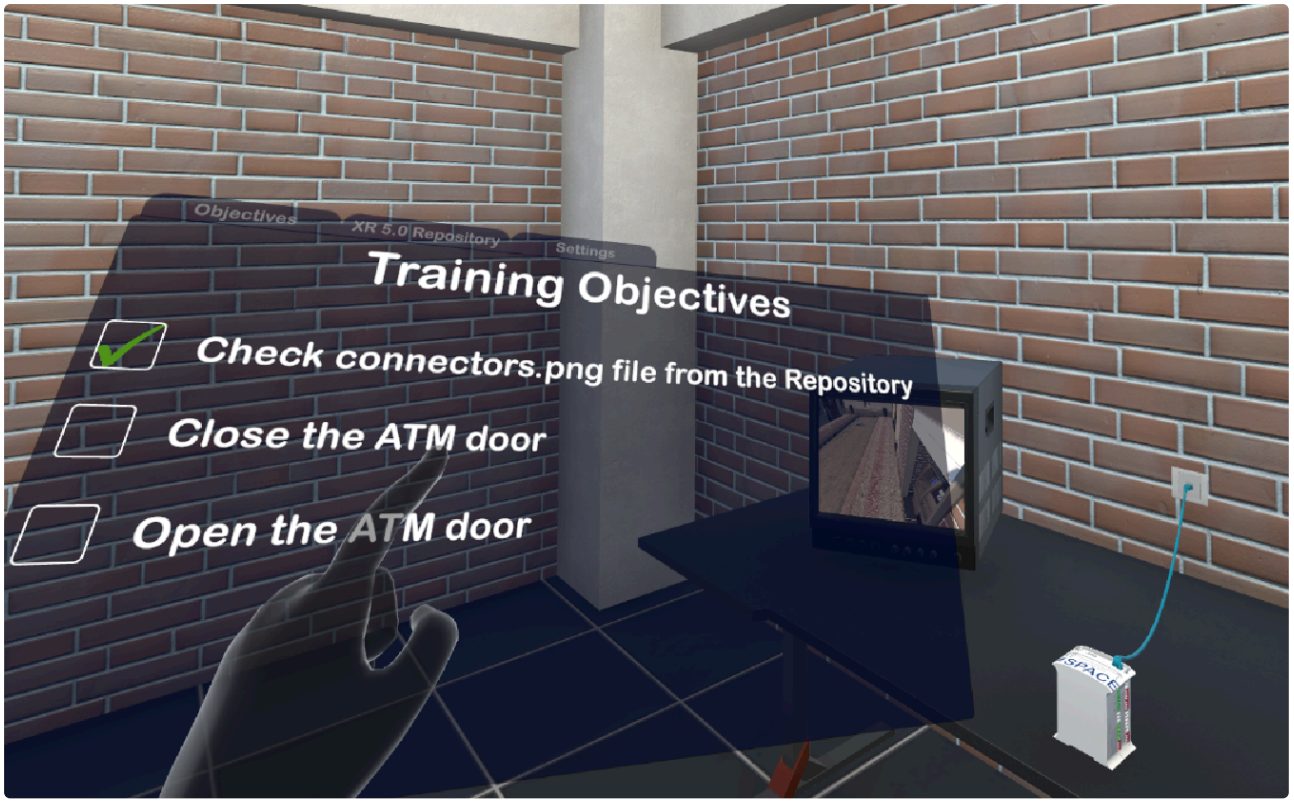
Whether it's identifying anomalies or applying corrective actions, the system adapts its content to the user's needs. Less experienced technicians receive in-depth walkthroughs, while experts get concise prompts — both of which significantly reduce troubleshooting time and prevent errors.

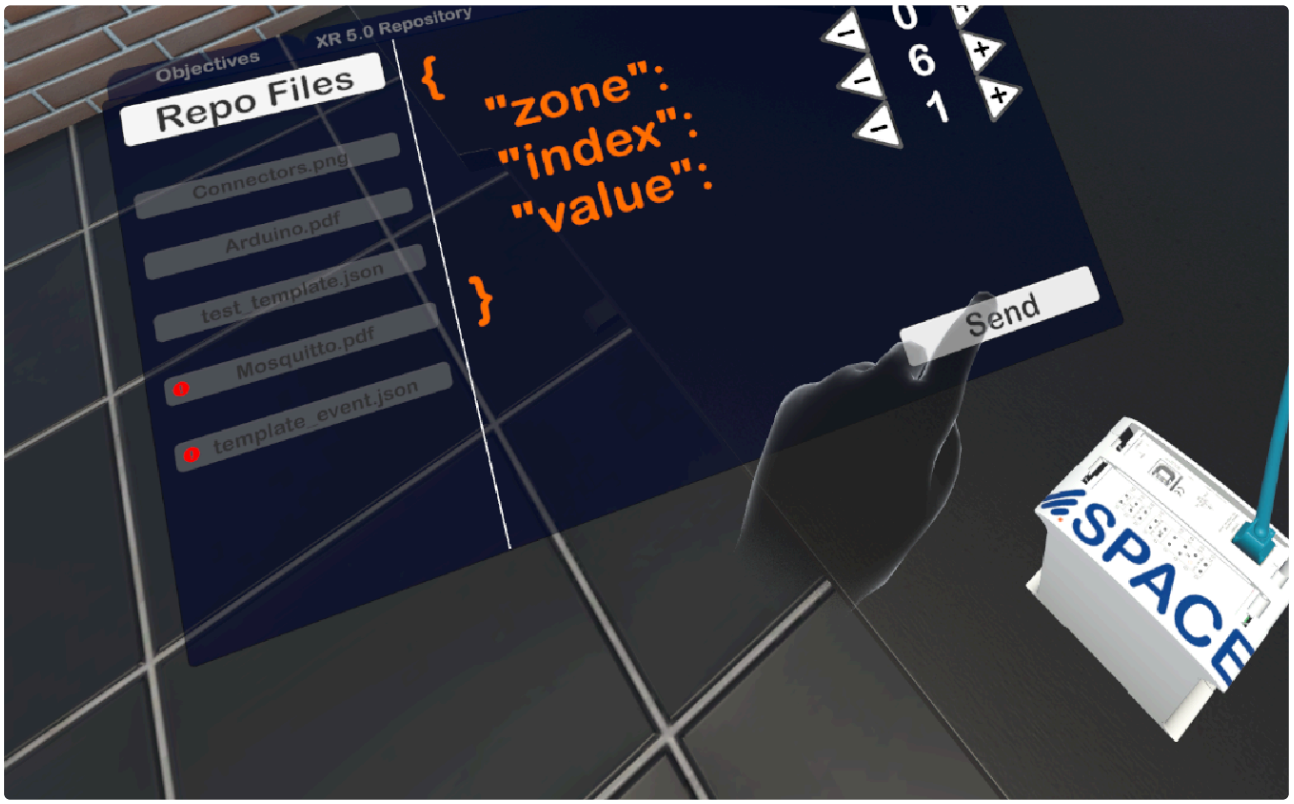
Impact and Added Value

The demo illustrates how XR and AI technologies can elevate operational resilience in industrial settings. The benefits are tangible:

- Reduced training and repair time,
- Increased task accuracy and technician confidence,
- Scalable support for diverse skill profiles,
- Enhanced safety and reduced equipment downtime.




Objectives
XR 5.0 Repository
Settings
Training Objectives
Check connectors.png file from the Repository
Close the ATM door
Open the ATM door


Objectives
XR 5.0 Repository
Repo Files
Connectors.png
Arduino.pdf
test_template.json
Mosquitto.pdf
template_event.json
{
"zone":
"index":
"value":
}
Send


VIRTUAL
REALITY

Transforming Industrial Maintenance with XR Applications

In today's industrial landscape, digital transformation is essential. oculavis is driving this change with its software solution oculavis SHARE. The device-agnostic software redefines customer service and maintenance for machinery, equipment, and other enterprise assets that connect complex products, experts, technicians, and end customers worldwide.

Coupled with advanced XR (Extended Reality) applications for devices like Microsoft HoloLens 2 and Magic Leap 2, oculavis SHARE is setting new standards in remote maintenance and support. As a technology and research partner for the XR5.0 project, oculavis is committed to advancing the integration of XR technologies in human-centered industrial settings.

Advanced XR Applications for HoloLens 2 and Magic Leap 2

The MR (Mixed Reality) application, developed by oculavis, is a cutting-edge solution optimized for the Microsoft HoloLens 2 and Magic Leap 2. The technology offers numerous application possibilities in human-machine interaction to improve processes and procedures:

- Device Compatibility: The MR app is fully compatible with Microsoft HoloLens 2 and Magic Leap 2, utilizing their advanced spatial awareness and gesture recognition features.
- Interactive User Interface: The application features a 'Hand Menu', activated by hand gesture detection, allowing users to interact with AR elements effortlessly.
- Augmented Reality Annotations and Navigation: The transformation of 2D dynamic annotations into interactive 3D MR Annotations is possible, enhancing task efficiency and accuracy.
- Communication and Collaboration Tools: The app supports robust video and audio communication via the oculavis SHARE platform, with features like in-call chat, HD freeze, and shared pointer mode.
- Privacy on the Shop Floor: In the visual assistance module of the oculavis smart service platform, special privacy features are activated in Mixed Reality, such as the display of virtual walls. These virtual walls make certain areas unrecognizable during a visual support session, ensuring privacy while maintaining effective visual assistance.
- Enhanced Maintenance: By integrating dynamic annotations and HD freeze capabilities, the MR app reduces machine downtime and improves first-time fix rates, enhancing productivity and safety.

Using Interactive Technologies to Facilitate Maintenance Operations

oculavis SHARE combines Augmented Reality (AR) and Virtual Reality (VR) technology to facilitate complex maintenance and service tasks remotely. The user-friendly interface is designed to enhance the experience of industrial workers by providing intuitive AR annotations. These annotations overlay virtual elements onto the real world, enabling machine and system experts to

offer remote guidance to technicians, ensuring precise and efficient support. But oculavis SHARE covers much more than just visual assistance. The software helps you to improve service to your global installed base, giving your customers and technicians access to information anytime and anywhere.

- Cases Module: Efficiently manage and track maintenance processes with the integrated ticketing and work order management system.
- Digital Work Instructions: Digital work instructions are used for operator training or to guide technicians through complex maintenance procedures.
- Asset Management: Your worldwide installed base can be managed. Machines can be enriched with service access and self-service offerings and assigned to experts, service teams, or dealers.
- Visual Assistance: Utilizing AR annotations within visual assistance calls allows experts to guide on-site technicians with precise, real-time instructions.
- Global Connectivity: This feature connects machines, experts, technicians, and customers worldwide, eliminating the need for physical travel and reducing operational costs.
- Flexible Integration: The oculavis API and standard connectors enable seamless integrations into any existing third-party systems.
- Maintenance Goals: Reducing machine downtime, improving first-time fix rates, and enhancing overall equipment effectiveness are critical goals achieved using oculavis SHARE.
- New Digital Business Models: Offering smart remote and self-service services opens up new opportunities for diversifying the service portfolio and implementing digital business models.

About the XR5.0 Project and Partnership

As a technology and research partner for the XR5.0 project, oculavis contributes to developing a novel Person-Centric and AI-based XR paradigm tailored for Industry 5.0 applications. Over the past decade, XR technologies like VR, AR, and MR have revolutionized digital manufacturing through applications in remote service & maintenance, process simulation, training, and safety. These immersive tools blend the physical and virtual, offering ergonomic digital representations of production processes for enhanced quality, flexibility, and safety. However, current XR solutions often adopt a generic approach that overlooks individual worker characteristics, falling short of Industry 5.0's human-centric, trustworthy collaboration ideals. The collaboration with all partners in the XR5.0 project aligns perfectly with oculavis' mission to enhance industrial maintenance and service operations through innovative XR technologies.

More information about the project, its consortium and pilots can be found on https://xr50.eu/.

If you would like to learn more about our solutions feel free to book a demo with our experts.



Transforming Maintenance with XR Technologies: SCHMIDT + HAENSCH's Role in the XR5.0 Project

In a world where precision and efficiency drive industrial operations, SCHMIDT + HAENSCH is leading the way in laboratory instrument maintenance with cutting-edge XR (Extended Reality) technologies. As a partner in the Horizon Europe XR5.0 project, we're reimagining how remote maintenance can enhance productivity, reduce costs, and support a more sustainable approach to service operations.

XR-Powered Maintenance for a Changing Industrial Landscape

Founded in 1864, SCHMIDT + HAENSCH is renowned for its high-precision laboratory instruments, such as polarimeters, refractometers, and advanced optical-electronic measurement technology. Our devices are integral to industries spanning agriculture, chemicals, pharmaceuticals, and more—across 100+ countries. Given the complexity and global reach of our technology, maintaining these instruments is both crucial and challenging. The XR5.0 project allows us to address these challenges head-on by integrating AI-driven XR solutions into our service model, enabling a leap towards Industry 5.0.

Human-Centered Maintenance and Expert Support

In partnership with European leaders in XR and AI technology, we're developing a remote maintenance solution designed for flexibility, personalization, and seamless interaction. Through XR5.0, we aim to empower our technicians, field partners, and clients' equipment operators with tools that simplify maintenance tasks. By integrating advanced XR functionalities, technicians receive tailored, real-time guidance and can visually interact with expert instructions, all from their location, reducing the need for travel-intensive, on-site support.

For instance, SCHMIDT + HAENSCH's Service Technician Experts can remotely oversee and assist Field Technicians or Equipment Operators via AI-enhanced visualizations, delivering step-by-step instructions that adapt to each user's skill level. This personalized assistance not only improves task accuracy and safety but also enables swift, informed decision-making in the field. Equipment operators can now independently handle basic maintenance tasks while having a reliable support network for more complex issues.

Key Features: Enhancing Efficiency and Safety

The XR5.0 project equips our maintenance teams with immersive AR tools that transcend traditional support:

• **Augmented Reality Support**: Field Service Technicians can access contextual AR instructions through devices like smart glasses, making complex repairs more manageable.

• **Real-Time AI Assistance**: AI models assess and guide users based on the task's difficulty and their experience level, minimizing risk and increasing success rates for on-site interventions.

• **Remote Retrofitting and Troubleshooting**: By providing a virtual layer over real-world equipment, our experts can guide technicians through critical upgrades, replacements, or calibrations without the need for physical presence.

Towards a Sustainable and Scalable Future

As an industrial pioneer, SCHMIDT + HAENSCH is committed to creating a more efficient, accessible, and environmentally friendly service model. Our participation in XR5.0 aligns with this mission by reducing travel, conserving resources, and providing scalable, remote service solutions that support global operations.

Learn More About the XR5.0 Project

The Horizon Europe XR5.0 project unites over 25 partners from industry, academia, and research institutions across the EU. Together, we're advancing Industry 5.0 by fostering AI-driven, human-centered XR applications that prioritize safety, efficiency, and adaptability. For more information about SCHMIDT + HAENSCH's role and our innovative maintenance solutions, visit xr50.eu or contact our team for a demonstration of our latest XR-enabled services.

XR Solutions for Industrial Training in the XR5.0 Project

Industry 5.0 represents a paradigm shift in manufacturing, where advanced technologies and human-centered principles converge to create more intelligent, sustainable, and collaborative workplaces. At the forefront of this movement is the XR5.0 project, which aims to develop and validate a person-centric, AI-driven Extended Reality (XR) framework for Industry 5.0 applications. By leveraging XR solutions, AI-driven insights, and cloud-based training platforms, XR5.0 seeks to revolutionize industrial training, making it more ergonomic, efficient, and personalized.

The Need for XR in Industrial Training

As industries evolve, the demand for skilled workers capable of operating complex machinery and systems is growing. Traditional training methods, such as classroom instruction and hands-on apprenticeships, can be costly, time-consuming, and often ineffective in preparing workers for real-world challenges. Extended Reality (XR) offers immersive, interactive, and on-demand training experiences that enhance learning retention, improve worker safety, and boost overall productivity.

The XR5.0 project focuses on creating a cloud-based XR training platform that enables industrial workers, known as Operator 5.0, to gain hands-on experience in realistic virtual environments. This approach aligns with the European vision of human-centric manufacturing, ensuring that technological advancements support workers rather than replace them.

Core Innovations of XR5.0 in Training

Human Digital Twins (HDTs)

Human Digital Twins are digital representations of workers that capture biometric data, skill levels, and ergonomic preferences. These twins personalize XR training applications, adapting to individual needs and optimizing the learning experience for each worker.

AI-Powered XR Technology

Artificial Intelligence is integral to enhancing XR training experiences within the XR5.0 framework. The project incorporates several advanced AI technologies:

Explainable AI (XAI): Ensures that AI-driven decisions in XR training are transparent, understandable, and trustworthy, providing insights into AI reasoning.

Generative AI (GenAI): Creates realistic and customizable industrial training scenarios, allowing trainees to practice responses to complex challenges in a safe environment.

Neurosymbolic AI (NSAI): Combines symbolic reasoning with machine learning for more effective AI-human collaboration in immersive environments.

Active Learning (AL): Continuously refines training content based on real-time user performance and feedback, offering personalized guidance and optimizing industrial operations.

These AI-driven enhancements ensure that industrial training in XR is both efficient and adaptive, and enables workers to upskill rapidly in response to industry demands.

Cloud-Based XR Training Platform

The core of XR5.0's training solutions is a cloud-based XR streaming platform designed for Operator 5.0 training. This platform enables industries to deploy XR training applications on demand, allowing workers to train in Augmented Reality (AR) and Virtual Reality (VR) environments with real-time interactions.

Key benefits include:

Ergonomic Training: Tailors training experiences to individual worker needs and workplace conditions.

Remote Accessibility: Allows workers to train from any location, reducing downtime and travel expenses.

Scalability: Supports large-scale deployment of XR training modules across multiple industries and geographies.

The platform leverages Hololight's enterprise streaming technology, Hololight Hub, ensuring seamless access to immersive training applications for industries across Europe.

The Future of Industrial Training with XR5.0

The XR5.0 project aims to set new standards in industrial training by combining AI-driven insights with immersive XR experiences. By focusing on human-centered innovation, the project ensures that XR-based technological advancements support workers in enhancing their skills and ensuring workplace safety while aligning with European values.

With its cloud-based XR training platform, XR5.0 envisions future industrial training that is continuous, adaptive, and deeply integrated into operational workflows. As the project progresses, it will deliver valuable insights into how XR can effectively build a more skilled, efficient, and empowered workforce for Industry 5.0.

Conclusion

The integration of XR solutions in industrial training marks a transformative step toward a smarter, safer, and more efficient manufacturing ecosystem. XR5.0's AI-driven, human-centric, and cloud-based innovations ensure that industries can create immersive training and learning environments that enhance worker competencies, improve operational efficiency, and strengthen the European industrial landscape.

XR5.0 Training Platform: Immersive Industrial Training for the Human-Centric Industry 5.0 Era

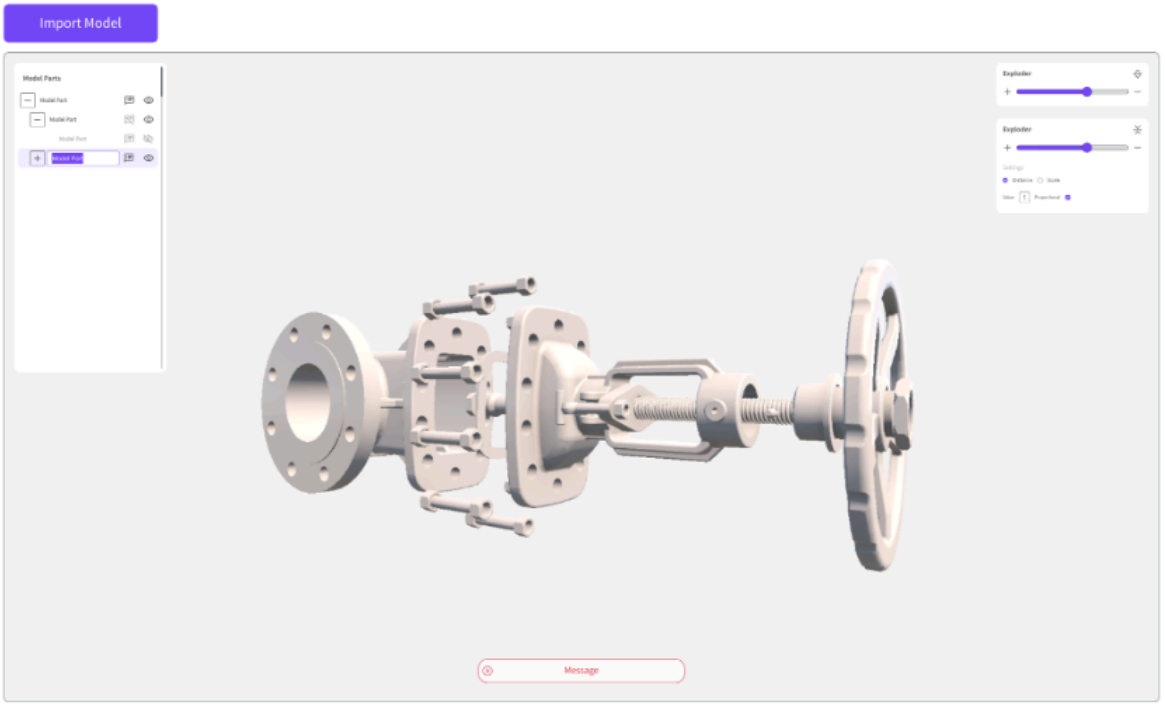
The evolution of industrial training has reached a critical stage as organizations transition toward Industry 5.0, emphasizing synergies between humans and intelligent machines [1]. The complexity of actual industrial systems demands new types of training options and delivery methods not restricted to conventional formats such as PDFs, videos, and in-person instruction that limit personalization, scalability, and adaptability of industrial training [2]. To address these challenges, the XR5.0 Training Platform introduces an innovative, revolutionary approach consisting of personalized, immersive, and AI-supported learning through a cloud XR infrastructure.

The XR5.0 Training Platform: From static manuals to immersive and dynamic learning

Developed within the XR5.0 project, the XR5.0 Training Platform is a multi-component ecosystem designed to transform traditional training content into interactive, immersive training experiences.

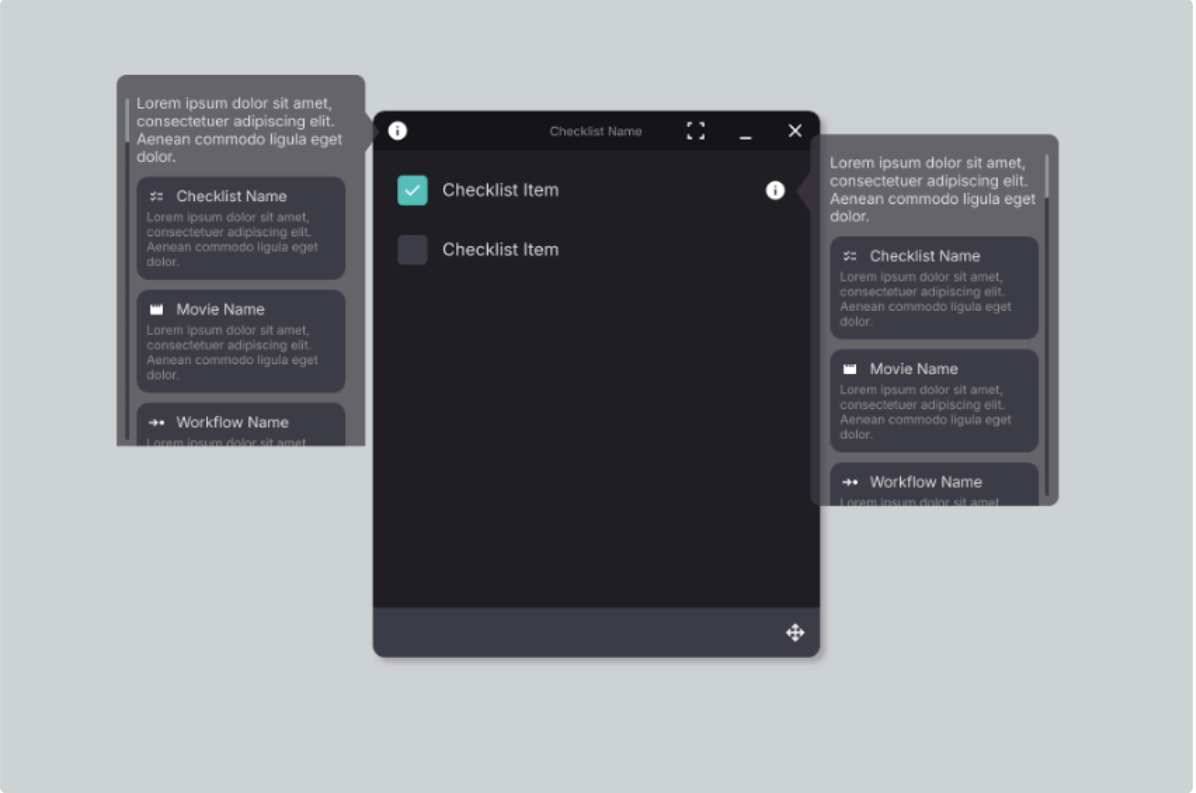
At the core of the XR5.0 Training Platform there is the XR Training Management System that allows for content creation and tailors training programs according to the user skill level and performance comprising two main components:

- **Training Programs Authoring Tool (TPAT)** - A web-based tool that allows training managers to upload and convert traditional materials into XR content. It provides an intuitive interface to build immersive programs using learning paths, quizzes, and workflows. As planned features it will include AI-driven content generation tools for extracting and producing the XR training materials [3]. The figure below shows the TPAT interface for configuring 3D materials.



- **XR Training Plugin (XRTP)** - A Unity-based plugin for XR devices compatible with HoloLens, Magic Leap and Meta Quest, renders XR training programs created with TPAT. As planned features it will provide personalized interactions, and adaptive interfaces based respectively on the user's skill level and task performance [4].

For achieving these features, this system offers a simple and flexible structure for combining the training materials into training programs, consisting of many-to-many relations which is crucial for creating scalable, modular, and personalized training programs. The figure below depicts the XR panels displaying related training materials associated with both the checklist and individual checklist items.



The XR5.0 Training Platform supports the following modules for converting traditional training materials into XR-based training materials:

- **XR Image** - Enables trainees to view static diagrams and illustrations in immersive environments, with zoom capabilities for exploring details.
- **XR Checklist** - Converts procedural instructions from traditional documents into step-by-step bullet points within XR dashboards to guide user actions.
- **XR Workflow** - Offers sequenced task guidance using rich text, enhancing procedural clarity during a complex task.
- **XR Video** - Integrates annotated instructional videos with chapters, allowing real-time visualization inside XR environments.
- **XR Assistant** - An AI voice assistant included in the XR interface trained on training materials to provide real-time guidance, answer procedural questions and help users in navigating the training content.
- **XR 3D Model Explorer** - Provides exploded views and interactive part visualization, supporting users in exploring 3D content from industrial assemblies.
- **XR 3D Workflow** - Extends the XR Workflow concept by integrating animated 3D models to offer a sequenced task guidance using 3D models.
- **XR Quiz** - Implements assessment modules to evaluate user knowledge, task performance, and training retention.

Conclusion:

The XR5.0 Training Platform may contribute to significant advancements in industrial training by shifting from static and conventional formats to immersive, interactive, and personalized learning experiences. Through its suite of XR modules, ranging from XR visualizations and workflows to AI-guided assistance, it equips operators with the tools needed to perform complex tasks more effectively. This platform aims to enhance training engagement, retention, and adaptability to individual learning needs. As the platform evolves, incorporating AI-driven automation and advanced personalization will further strengthen its capabilities and alignment with Industry 5.0 principles. This positions XR5.0 as a scalable, human-centric solution that meets the demands of novel industrial environments.

References:

[1] Zalozhnev, A.Y. and Ginz, V.N. (2023). Industry 4.0: Underlying Technologies. Industry 5.0: Human-Computer Interaction as a Tech Bridge from Industry 4.0 to Industry 5.0. 9th International Conference on Web Research (ICWR).

[2] Kiourtis, A. et al. (2024). XR5.0: Human-Centric AI-Enabled Extended Reality Applications for Industry 5.0. 36th Conference of Open Innovations Association (FRUCT), Lappeenranta, Finland, pp. 314-323.

[3] Oliveira, J., Saraiva, T., Manoj Shah, H., et al. (in press). XR Training in Industry 5.0: Advancing Human-Machine Collaboration with the XR5.0 Training Platform. XR Salento 2025. Lecture Notes in Computer Science. Springer, Cham.

[4] Matteri, D., Masiero, S., Dell'Oca, S., Montini, E., Cutrona, V., & Canetta, L. A. (2025). Protocol for Human-Centric Adaptive User Interfaces: From Static Interaction to Behaviour-Driven Adaptation. [pre-print].

3.20 APPLICATIONS AND USE CASES

XR4ED and XR5.0 EU Projects: Synergies for Revolutionizing Training and Education with Made-in-Europe XR Solutions

The XR4ED EU project (https://xr4ed.eu/) aims to connect the Educational Technologies (EdTech) and Extended Reality (XR) communities via the establishment of a European platform that will constitute a reference for stakeholders wishing to deploy XR technologies for training and learning. The platform, currently under development, will make widely accessible components and tools, both existing and upcoming. It is therefore expected that the project will contribute towards making Europe a leader in the rapidly evolving cutting-edge XR technologies for education. As such, XR4ED project will support start-ups, SMEs and industry active in the education sector, as well as providing training and education (schools, high schools, universities and VET institutions) via two Open Calls. Each call will fund up to 10 projects, each lasting 12 months. The First Open Call will be aimed at developers to make use of the XR4ED platform and create their own solutions, which will address any level of learning and all categories of learners. The purpose is to test and validate the platform to be created by the project. It will also make it possible to demonstrate the level of its usefulness in the learning process, as well as its societal and economic impact. All the software created will have to build upon Open Standards (such as WebXR, OpenXR), open APIs and frameworks and any third-party projects. All of them will have to be published in the European XR4ED solutions catalogue. The instances funded by the Second Open Call will work towards developing mini pilots for testing XR solutions in real environments. The trials will employ Minimum Viable Product (MVP) design approaches, targeting various end-users. The pilots will call for the participation of schools, high schools, universities, teachers, students, parents and VET institutions and companies. All 20 instances that will receive funding will go through an intensive process which will include mentoring, workshops, dedicated growth coaching and progress monitoring. The training will be provided by the Consortium members and its objective will be to enhance their business acceleration and incubation.

The XR5.0 EU project (https://xr50.eu/) works towards designing and implementing solutions that allow a unique blending of the entire spectrum of XR technologies and AI, with the aim to support the emerging wave of Industry 5.0 (I5.0). Designed to be human-centric (integration of Human Digital Twins) and provide trustworthy human-machine collaboration within industrial settings, these technologies will be made available to XR and AI integrators, data providers, SMEs, and citizens in developing and using the project's results in line with European values. Like XR4ED project, XR5.0 will make available its training content via a cloudbased platform that will be developed within the context of the project. It is therefore expected that both projects will support the establishment, growth and sustainability of a vibrant community of stakeholders interested in the uptake and further development of XR technologies, such as researchers, vendors, as well as providers/integrators of XR technologies and solutions. Furthermore, the sustainability and wider use of both projects' results will be boosted. In such a way, a rapid launch of both projects' developments will be enabled, which will allow the XR vendors of the Consortium to become the world's first providers of XR technologies, without overlooking issues of

accessibility. Moreover, it will contribute towards developing standards relevant to the issues of interoperability and standardization, while also overcoming fragmentation issues, which will undoubtedly encourage and boost the acceleration of innovation. What is thus anticipated is that the outcomes of the projects will be commercialised after their completion, with financial benefits for the partners, while also increasing the projects' value for EC money.

By leveraging potential synergies, both XR4ED and XR5.0 have the potential to revolutionize the way we learn, educate and teach/train using XR technologies that are more effective, engaging and accessible than before. And this, not only in Europe, but at an international level. XR4ED and XR5.0 projects could thus lead to a future where XR solutions are further integrated into training and education, since they have the capacity to boost productivity and further support skill-based teaching and learning, while providing a boost to the European and global economy.

XR5.0 at LNS: Making AI Work for People, Not the Other Way Around

At LNS, digital transformation is not about technology for its own sake. It is about solving real problems for our customers and for our teams. The XR5.0 project has been a strong driver in this journey, helping us move from ideas into concrete service improvements. A question that many industrial companies are facing nowadays is how to use AI in a way that really supports people — the customers, the technicians, and the service teams. The work around Helen S. is a good example of how we approach this.

From chatbot to real service tool

Helen S. started as a simple chatbot to answer frequently asked questions. Today, it has evolved into a much more practical tool: customers can access it on our website, in the customer portal, on the latest HMIs, and even when calling LNS by phone in some countries. When called, it provides structured, relevant answers based on real technical documentation and service data. What matters for us is not the technology behind it, but the impact:

- Faster answers for customers
- Less repetitive work for hotliners
- Better use and preservation of internal knowledge

We also made sure that Helen does not replace people. When needed, it quickly escalates to a technician, creates a ticket, and connects the customer with the right expert. This is what we mean by human-centric AI: it supports the interaction, it does not try to take it over.

Adding voice: a natural next step

A recent step was the addition of voice capabilities to Helen S. Instead of only typing, customers can now interact via phone or voice channels. This brings two advantages:

- It fits better with how many customers already work (calling instead of typing)
- It makes the service accessible even outside of normal working hours

At the same time, the rollout showed clearly that technology alone is not enough. We had to adjust how the bot communicates, how tickets are created, and how customers are informed. Early feedback from teams and customers helped to improve these points quickly, for example making sure customers understand that a ticket has been created and that someone will follow up. This iterative approach is key for us: test, learn, adapt.

Strong collaboration within XR5.0

The progress we made did not happen in isolation. The XR5.0 project brought together many partners, each with different perspectives and expertise. Through regular exchanges — from working group meetings to workshops — we challenged our ideas and improved our solutions. For example, discussions around XR-supported service, remote diagnostics, and user experience directly influenced how we position Helen S. and our digital service offering. What was particularly valuable:

- Open and constructive discussions with partners
- Sharing real use cases, not just concepts
- Learning from different industries and approaches

This helped us stay pragmatic. Instead of building “nice demos”, we focused on solutions that can be used in daily operations.

Moving the service offering forward

The combination of AI (Helen S.), XR concepts, and the learnings from XR5.0 is now clearly shaping our service model. We are moving towards:

- More remote support and fewer on-site interventions
- Better use of technician time
- Faster response times for customers

This also supports our sustainability goals, as less travel is required and resources are used in a more efficient way.

What comes next

We are still at the beginning of this journey.

The next steps will focus on:

- Further improving the quality and accuracy of AI answers
- Making the voice interaction more natural and clearer for customers
- Connecting Helen S. even more closely with our internal systems and processes
- Exploring how XR can be used together with AI in real service situations

The XR5.0 project will continue to support this work, not just through technology, but through collaboration.

Conclusion

XR5.0 is not just a research project for LNS. It is a practical framework that helps us test, learn, and improve how we deliver service. With Helen S., and now also with the voice extension, we have taken concrete steps towards a more modern and customer-focused service model. The key takeaway is simple: AI works best when it supports people.

3.22 APPLICATIONS AND USE CASES

XR5.0 Pilot 3 Advances AI-Powered Extended Reality for Water Utility Operations

The XR5.0 consortium continues to make strong progress in the development of Pilot 3, which explores how Artificial Intelligence (AI) and Extended Reality (XR) can support water utility operators in inspection, maintenance, and training activities. The pilot aims to improve situational awareness by combining AI-driven analytics with intuitive visualisation and natural interaction technologies, enabling operators to better understand underground infrastructure and make more informed decisions in the field.

Pilot 3 focuses on three complementary use cases addressing key operational challenges faced by water utilities. The first supports maintenance activities by visualising underground pipe networks together with real-time sensor information to facilitate the identification of potential leakages. The second enhances CCTV pipe inspection workflows by presenting AI-detected anomalies alongside explainable AI outputs, allowing operators to better understand the reasoning behind automated detections. The third use case provides an AI-assisted training and operational support environment through an intelligent conversational assistant that enables natural interaction using both text and voice.

Over the past development period, the CYENS team has implemented a broad range of functionalities that bring these use cases closer to operational deployment. These include real-world geolocation and underground pipe visualisation, integration of IoT sensor data, AI anomaly visualisation, conversational AI services, speech-to-text and text-to-speech capabilities, modular backend communication, and a flexible user interface designed to present contextual information when and where it is needed.

A key milestone has been the evolution of the platform through continuous user feedback. Initial prototypes were developed for Magic Leap augmented reality devices, allowing operators to visualise infrastructure directly within their surroundings. User evaluations, however, highlighted several practical considerations related to navigation, information density, readability, and safety during field operations. These findings guided a significant redesign of the platform, including support for mobile devices, simplified navigation, improved visualisations, enhanced AI explanation panels, redesigned information windows, and integrated chatbot functionality. The result is a more accessible and user-friendly solution that better reflects the needs of end users.

The pilot has also addressed several technical challenges associated with deploying XR applications in real-world outdoor environments. Development efforts focused on improving GPS positioning, reducing compass drift, managing heterogeneous backend services, handling network latency, and ensuring reliable speech interaction. A modular software architecture and reusable components have been adopted to facilitate future scalability and integration with additional services.

Development has now reached an advanced stage, with the maintenance support use case nearing completion, AI-assisted inspection capabilities entering their final validation phase, and the training environment continuing to mature through interface refinements and additional testing. Upcoming work will focus on further optimisation, expanded user evaluations, single sign-on integration, and preparation for the final pilot demonstrations.

By integrating AI, explainable decision support, and Extended Reality into everyday operational workflows, Pilot 3 demonstrates the potential of human-centric digital technologies to support more efficient infrastructure management while keeping human expertise at the centre of decision-making. As XR5.0 progresses towards its final demonstrations, the pilot continues to contribute valuable insights into the practical adoption of Industry 5.0 technologies within the water sector.

This booklet compiles the full blog posts and project updates from the XR5.0 consortium.

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