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Combined Use of eXtended Reality Technologies for Training the Operator 5.0 – The PROXIMA Project

Simone CANTARELLI[a], Margherita PERUZZINI[a], Gian Maria SANTI[a], Alessandro POLLINI[b]
[a] *University of Bologna, Dept. Industrial Engineering, Viale del Risorgimento 2, Bologna, Italy*
[b] *BSD Design, via Lazzaretto 19, 20124 Milan, Italy*

Abstract. Extended Reality (XR), combining Virtual Reality (VR) and Augmented Reality (AR), is transforming human-machine interaction in manufacturing by facilitating complex system design and operator training. Traditionally, VR and AR have been utilised separately- VR for virtual simulations and validation, and AR for on-site assistance. Training operators in modern manufacturing (Operator 5.0) demands integrated approaches that merge virtual scenarios with real-world applications, enhancing learning outcomes and user experience (UX). The PROXIMA project introduces an integrated XR platform designed explicitly for Operator 5.0 training, combining VR and AR into a seamless, collaborative environment. PROXIMA addresses technological and educational gaps by enabling smooth interaction between physical and virtual contexts through spatially aware multimedia content generated in AR and used within immersive VR scenarios. The platform's usability and educational effectiveness were assessed through a structured pilot study involving 35 apprentices, utilising the System Usability Scale (SUS) and qualitative feedback. Results indicated strong usability (average SUS score of 73.2), high participant engagement, improved procedural knowledge, and positive educational outcomes. User feedback informed system enhancements, particularly for AR content creation and VR navigation. PROXIMA thus significantly advances integrated XR training solutions, effectively bridging technological innovation and pedagogical practice within Industry 5.0.

Keywords. Extended reality, Virtual training, Operator 5.0, User experience, Proximity.

Introduction

The increasing complexity of modern manufacturing environments needs innovative and integrated training solutions capable of effectively bridging physical and digital contexts. Extended Reality (XR), comprising both Virtual Reality (VR) and Augmented Reality (AR), has emerged as a promising technology with the potential to enhance human-machine interactions and improve operator training [7]. Conventionally, the use of VR has been focused on system design validation and virtual simulations, while AR has been instrumental in providing real-time assistance in on-site scenarios. However, current XR applications rarely integrate these modalities comprehensively, resulting in fragmented user experiences and limited educational effectiveness.

The PROXIMA project addressed this gap by proposing an integrated XR platform explicitly designed for the Operator 5.0 training. The project aim is to combine the

strengths of VR and AR into a cohesive, seamless learning environment. The central research question to be addressed in this paper is as follows: *How can an integrated XR platform effectively support training activities by blending virtual and physical contexts, thus enhancing usability, user experience, and educational outcomes?*

Employing a transdisciplinary approach that intersects technology development, human factors, and pedagogical methodologies, PROXIMA facilitates the creation, management, and interactive manipulation of multimedia content (textual, audio, and video) generated within AR environments and seamlessly transitioned into immersive VR scenarios. The project methodology incorporated iterative design and evaluation cycles, which resulted in a structured pilot study. This study involved novice apprentices, with the objective of assessing both system usability (measured through the System Usability Scale (SUS)) and the educational impact (through qualitative feedback and performance observations).

The present paper sets out the technical architecture of the PROXIMA system, the results of the pilot study, and discusses critical insights to inform future developments, thus contributing significantly to integrated XR training solutions aligned with the Industry 5.0 paradigm, promoting human-centricity and resilience.

1. State of the Art

XR, encompassing VR, AR, and MR, is progressively acknowledged as a transformative technology in the domain of industrial training. Recent literature demonstrates that XR not only facilitates the integration of theoretical learning and practical experience but also enhances safety, efficiency, and user engagement in high-risk industrial contexts [1, 2, 6].

Current operator training methods frequently employ physical simulations, classroom instruction, or traditional e-learning, which can be deficient in replicating real-world complexity or providing adaptive, on-demand feedback. This discrepancy assumes particular significance within the context of Operator 5.0, a pivotal figure in the transition towards Industry 5.0, which emphasises human-centric, resilient, and sustainable manufacturing [3, 5]. Operators 5.0 are envisaged as empowered workers supported by digital tools, able to interact flexibly with smart systems, robots, and adaptive processes. Several system frameworks have been recently defined to support the integration of the operator 5,0 needs with the digital tools, enhancing human integration in smart factories according to a transdisciplinary approach [9]. However, conventional training methodologies are found to be deficient in adequately preparing personnel for this highly dynamic environment.

A body of research has been dedicated to the exploration of XR in industry, with studies examining the potential of VR-based simulations for machine operation, the efficacy of AR-based maintenance support, and the integration of mixed-reality digital twins [4, 5]. These studies have yielded encouraging results, demonstrating the capacity to enhance learning outcomes and minimise errors. For instance, within the construction sector, XR has been employed to simulate hazardous conditions safely [1], while in manufacturing, cloud-based VR leveraging 5G has enabled responsive, real-time simulations [2].

However, there is a lack of systems that achieve a unified integration of VR and AR, where learning activities transition smoothly between virtual environments and physical workspaces. The majority of XR applications are oriented towards either VR or AR in

isolation, thereby overlooking the potential for creating a unified user experience that encompasses both domains. Furthermore, while numerous studies have examined usability or technical performance, there is a lack of research exploring how such integrated XR systems support educational methodology, adaptive learning, and personalised skill acquisition in the industrial context.

The PROXIMA project has been developed to address this gap by proposing an integrated XR system explicitly designed to support Operator 5.0 training. This system embeds both technological and educational innovation into a coherent, transdisciplinary framework.

1.1. Evaluating Usability in XR Systems: SUS

The evaluation of the usability of XR systems is of crucial importance in ensuring effective adoption, user satisfaction, and educational success. The SUS is a widely utilised instrument for the evaluation of usability. This questionnaire-based method has been validated and provides a comprehensive perspective on subjective assessments of system usability. The SUS is comprised of 10 standardised Likert-scale questions, on which users indicate their level of agreement with various statements on a scale ranging from 1 (strongly disagree) to 5 (strongly agree).

The SUS score is calculated by converting raw responses to a 0–100 scale, where a score above 68 is considered average usability [8]. More specifically:

Table 1. Curved Grading Scale for the SUS [8].

SUS score range	Grade	Percentile Range
84.1–100	A+	96–100
80.8–84.0	A	90–95
78.9–80.7	A-	85-89
77.2–78.8	B+	80-84
74.1–77.1	B	70-79
72.6–74.0	B-	65-69
71.1–72.5	C+	60-64
65.0–71.0	C	41-59
62.7–64.9	C-	35-40
51.7–62.6	D	15-34
0.0–51.6	F	0-14

SUS has been adopted by a wide range of industries, including those involved in software development, web services, and, with increasing frequency, XR applications. This approach enables the establishment of benchmarks against industry standards, thus facilitating the identification of key areas for system improvement. The simplicity, cost-effectiveness and speed of the software make it a powerful tool for iterative design and user-centred development processes.

2. PROXIMA System Architecture

To implement the goals outlined in the introduction, the PROXIMA system was designed as an integrated XR platform combining AR, VR, and a central data management layer. Its architecture ensures seamless interoperability between physical and virtual environments, supporting both technical functionality and educational objectives.

The system architecture comprises three primary components (see Figure 1):

- AR-based Authoring Application;
- Server Application for Centralised Data Management;
- VR Training Application.

The overall architecture and process flow are summarised in Figure 1, which illustrates the sequential interactions between AR authoring, server data management, and VR-based training.

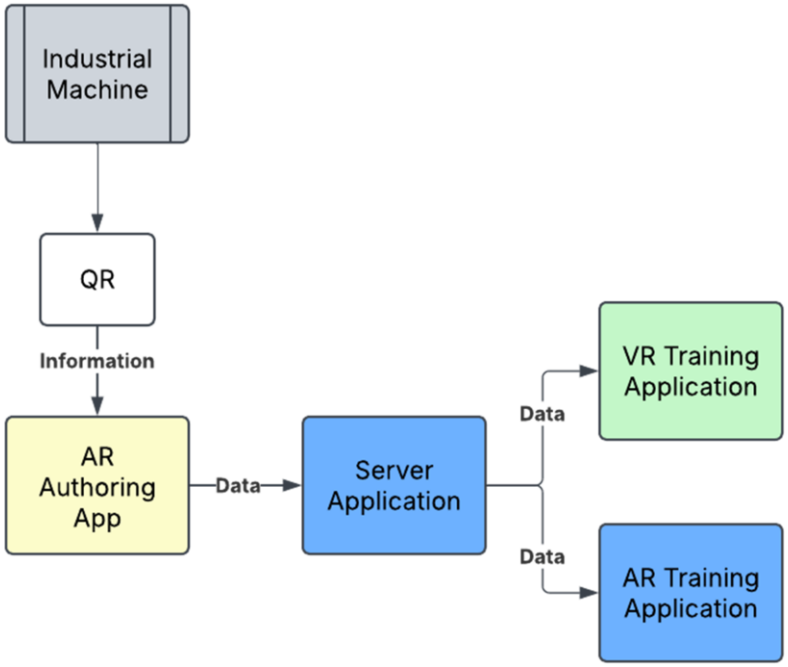

Figure 1. Flowchart of the PROXIMA training process.

2.1. The AR Authoring Application

The process commences within an AR application wherein users can generate multimedia notes (henceforth referred to as "Media Notes") comprising text, images, audio, and video. Each media note is enriched with metadata, including but not necessarily limited to:

- Position and Scale: To determine its placement and size in the VR environment;
- Rotation: To ensure the correct orientation of the media note;
- Unique Identifiers: To distinguish each note and link it to user-generated content.

Once a media note is created, it is uploaded to the server through an API according to the positions the markers have in the physical environment, ensuring that all relevant data is available for future retrieval in both the AR and VR environment.

2.2. The Server application for centralised Data Management

The server is the system's central component, responsible for data storage and management, user authentication, and facilitating communication between the AR and VR applications. It exposes several RESTful API endpoints that allow the AR application to upload Media Notes and the VR application to retrieve them. The server performs two main functions:

- Authentication: Users are required to initiate a session via the /api/authenticate/{email}/{password} endpoint. Following the successful user authentication, the server will generate a unique token, which will grant the user access to their media notes. It is imperative that this token is included in all subsequent API calls;
- Retrieval of Media Notes: The /api/get_tag_medianotes/{token} endpoint is utilised by the VR application to retrieve media notes. In response, the server provides a JSON file comprising an array of media notes, each accompanied by its associated metadata. The JSON structure thus ensures the precise reconstruction of each media note within the VR environment.

```
AUTHENTICATION
    /authenticate {email, password}
        if {status: "ok", token, project}
        else {status: "fail", msg}

FETCH TAGS
    /get_tags {token}
        {status: "ok", tags: [{id, name, position}, ...]}

FETCH NOTES FOR A TAG
    /get_tag_medianotes {token, tag_id, [categories]}
        {status: "ok", notes: [ {id, text, official}, ...]}

FETCH SINGLE NOTE
    /get_medianote {token, note_id}
        {status: "ok", note: {id, text, author, position}}

UPDATE NOTE
    /set_medianote {token, note_id, updated_fields}
        {status: "ok", updated_note}

LOGOUT
    /logout {token}
        {status: "ok"}
```

2.3. The VR training application

The VR Training App, a constituent element of the PROXIMA project, has been developed for the purpose of enhancing industrial training through the integration of augmented and virtual reality technologies into a unified learning platform. The application, developed in Unity, enables users to interact with digital replicas of industrial machinery in an immersive 3D environment. Trainers can import textual, video, and audio-based media notes created in an AR environment using QR codes into the VR system, ensuring a seamless transition from on-site annotation to virtual exploration. The application then allows users to access, modify, and rearrange these notes dynamically

within the VR space, thereby facilitating a personalised and interactive training experience. This approach was proven to enhance knowledge retention, improve operator engagement, and provide a risk-free environment for skill acquisition and system familiarisation.

The PROXIMA VR application has been developed on Unity [2022.3.33f1] to revolutionise industrial training by allowing trainers to import notes into an immersive 3D environment. Starting with an initial login screen (Figure 2a), users can select the desired machinery (Figure 2b) and access a virtualisation of the real machine within a 3D environment (Figure 2c).

The user can download textual, video, and audio information directly from a server through a dedicated menu. These notes, displayed in the VR environment (Figure 2d), accurately reflect those on the real machine, enabling operators to move in a 1:1 scale, explore, and update information for a comprehensive and interactive learning experience.

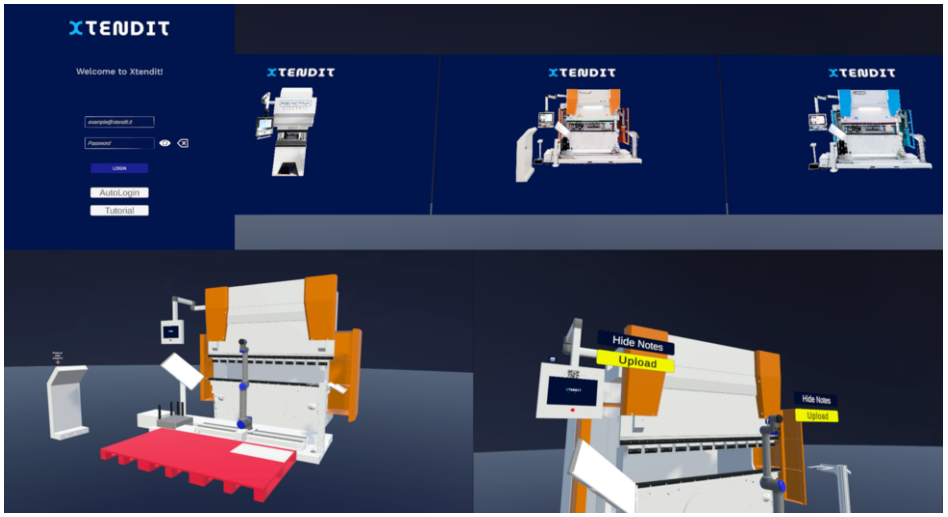

Figure 2. (a) Log-in Screen; (b) Machinery Selection; (c) Real Machine model; (d) Note icons on the machine.

The VR application can modify the notes and their positioning not only in the virtual scene, but also on the server to be further read and used by a following AR application dedicated to support the operators' training at the shop floor, close to the real machine.

3. Testing with users

A pilot testing campaign involving 35 novice apprentices from industrial training academies was conducted to evaluate and refine the PROXIMA XR training kit.
Participants took part in controlled simulation sessions under realistic conditions, then completed the System Usability Scale (SUS) and provided open-ended feedback on educational relevance.

Although two pilot phases were originally planned, this paper focuses on the primary study, laying the groundwork for further refinement of PROXIMA.

3.1 Training Tasks and User Activities

During the testing sessions, apprentices were introduced to a simulated environment designed to replicate a modular robotic cell used in metal sheet-bending operations. The key tasks assigned to participants included:

- Exploring virtual representations of industrial machinery using the VR headset;
- Accessing, interpreting, and reorganizing Media Notes (text, video, audio) integrated into the VR environment;
- Using AR authoring tools to create or modify Media Notes linked to specific machine components;
- Simulating typical operator activities such as system calibration, tooling checks, and basic maintenance procedures.

The tasks were designed to assess the system's usability and its ability to support instructional objectives such as skill acquisition, knowledge retention, and procedural understanding.

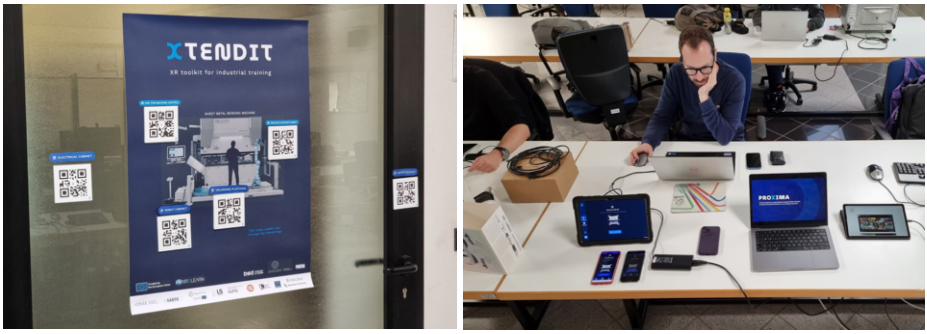

Figure 3. Positioning of the poster and QR codes (Left) and setup of the applications with connection and server communication verification (Right).

3.2 Test Session Protocol

Each test session followed a structured protocol:

- Introduction and Briefing: Presentation of the project, objectives, and team members.
- System Overview: Demonstration of the PROXIMA XR toolkit, explaining its AR, VR, and server components.
- Hands-on Training Simulation: Participants interacted with the system using posters with QR codes, AR tablets, and VR headsets, experiencing the full workflow from AR annotation to VR immersion.
- Post-session Assessment: Completion of the SUS questionnaire and open-ended qualitative feedback collection.

The full session lasted approximately 50 minutes, with groups of up to 8 participants per round.

Figure 4. Trainees listen to the training session before engaging with the XTENDIT app to take notes via the QR codes placed around the machine (Left) and Trainee testing the VR app (Right).

3.3 Results and Educational Evaluation

Quantitative evaluation using the System Usability Scale (SUS) yielded an average score of 73.2, indicating good usability and placing the system above the industry standard benchmark of 68. This finding suggests that the PROXIMA system offers a user-friendly and well-accepted interface for industrial apprentices.

In addition to quantitative data, the collection of qualitative feedback was undertaken to assess the educational impact. The following observations were reported by the participants:

- High engagement due to the immersive nature of the VR environment;
- Improved understanding of machine functions through hands-on digital interaction;
- Increased confidence in executing real-world tasks after simulated practice.

Educational evaluation was conducted through a combination of observation, task performance tracking, and post-session discussions. Key findings highlighted that the system effectively supported both instructor-led and self-paced learning, facilitating procedural learning, conceptual understanding, and experiential engagement. Areas identified for improvement included the intuitiveness of the AR authoring interface and the refinement of VR navigation controls to reduce cognitive load.

	SCORE for calculating SUS score																																		
	q1	q2	q3	q4	q5	q6	q7	q8	q9	q10	q11	q12	q13	q14	q15	q16	q17	q18	q19	q20	q21	q22	q23	q24	q25	q26	q27	q28	q29	q30	q31	q32	q33	q34	q35
1. I think that I would like to use this system frequently.	3	3	3	4	3	4	3	2	3	2	4	4	3	4	3	3	2	3	3	4	3	3	3	4	4	2	3	3	4	3	4	4	3	3	3
2. I found the system unnecessarily complex.	2	3	3	2	4	3	4	4	4	3	3	3	3	3	4	3	3	3	1	3	2	1	3	1	3	3	4	3	3	4	4	4	3	2	4	4
3. I thought the system was easy to use.	3	3	2	3	3	4	3	3	2	2	3	3	4	3	4	3	3	2	4	4	2	4	2	4	3	3	4	4	3	4	3	3	4	4	4
4. I think that I would need the support of a technical person to be able to use this system.	3	3	2	3	2	4	3	2	1	3	3	2	3	2	3	2	2	3	2	2	1	3	1	1	2	3	3	1	2	0	2	1	3	4	4
5. I found the various functions in this system were well integrated.	3	2	3	3	4	3	3	3	2	2	4	4	4	3	3	3	3	3	4	4	4	3	3	2	3	3	3	3	4	3	2	3	4	3	3
6. I thought there was too much inconsistency in this system.	2	2	3	2	3	4	4	3	3	2	3	3	3	3	3	2	3	3	3	1	1	4	1	2	3	3	2	1	4	0	4	3	3	4	4
7. I would imagine that most people would learn to use this system very quickly.	2	3	2	3	4	4	2	3	3	2	3	3	4	3	3	4	2	4	4	4	3	4	4	4	4	3	4	3	3	4	3	3	3	4	3
8. I found the system very cumbersome to use.	3	3	3	2	3	4	3	3	3	2	3	3	3	3	3	1	2	4	3	0	2	3	1	2	3	3	1	2	2	0	2	3	2	4	3
9. I felt very confident using the system.	2		2		4	4	3	4	3	2	3	3	4	3	2	3	3	4	4	4	3	4	3	4	2	3	3	2	4	4	4	4	3	4	4
10. I needed to learn a lot of things before I could get going with this system	1	4	2	3	2	4	3	3	3	2	3	4	3	1	3	3	1	2	4	2	0	3	2	3	3	3	4	1	3	0	3	3	3	4	4
	60	65	62.5	62.5	80	95	77.5	75	65	55	80	80	85	70	77.5	67.5	60	72.5	85	67.5	50	85	52.5	72.5	75	75	75	57.5	80	57.5	80	72.5	72.5	97.5	90

Figure 5. SUS Questionnaire results.

3.4 Critical Insights for Future Development

The pilot testing provided essential insights for further development. The most critical improvements identified were:

- Streamlining AR content creation workflows for trainers;
- Enhancing the feedback mechanisms within the VR environment to guide trainees in real time;
- Expanding the system's adaptability to accommodate different machine types and training scenarios.

These findings will inform the next iteration of the PROXIMA platform, ensuring that it not only remains technically robust but also pedagogically aligned to the evolving needs of Operator 5.0 training.

4. Conclusions

The present work has presented the PROXIMA platform, an integrated XR system designed to support the training of Operator 5.0 through the combined use of AR and VR. The system architecture successfully bridges physical and virtual environments, thereby enabling seamless creation, management, and immersive interaction with multimedia training content.

The pilot testing phase, which involved 35 industrial apprentices, provided substantial evidence to support the system's strong usability, as evidenced by an average SUS score of 73.2. Furthermore, the pilot testing phase demonstrated the system's effectiveness in enhancing procedural knowledge, conceptual understanding, and user engagement. The qualitative feedback indicated that immersive simulations are valuable, and that the integration of AR and VR is flexible. However, it also identified the need for refinement, including the improvement of AR authoring tools and the streamlining of VR navigation.

A notable finding of the study was that PROXIMA facilitates both instructor-led and self-paced learning, thereby addressing educational needs that are frequently overlooked by traditional training methods. This finding serves to substantiate the platform's pertinence, not only as a technological solution, but also as an educational innovation that is congruent with the objectives of human-centric Industry 5.0.

In future work, the focus will be on extending the system's adaptability to diverse industrial contexts, integrating real-time data streams to enable predictive and adaptive training scenarios, and exploring the incorporation of machine learning to personalise learning pathways. These developments will further consolidate PROXIMA's potential as a scalable, immersive, and pedagogically sound solution for next-generation industrial training.

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