XR-Enabled Immersive Training for Industry 5.0: The XRTwinScape Platform

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Abstract

Immersive eXtended Reality (XR) offers a powerful solution to the challenges of vocational education: limited lab access, heterogeneous skill levels, and low engagement. The XRTwinScape platform addresses these challenges by streamlining the creation of photo-realistic digital twins from simple smartphone captures using Gaussian splatting, integrating spatially anchored multimedia annotations, delivering adaptive XR lessons linked to real-time learner analytics. In this paper, we introduce XRTwinScape's architecture, interface and interaction mechanism, and analyze its educational impact through a pedagogical lens and a pilot use case course (Industrial Electrician training). Our findings show that XR pre-lab simulations boost familiarity, equalize baseline skills, and increase learner confidence, aligning with the human-centered goals of Industry 5.0.

Keywords

eXtended Reality, Digital Twin, Vocational Training, Industry 5.0, Pedagogical scenarios

1. Introduction

Vocational education in industrial domains often faces three core challenges: learners lack access to specialized labs or equipment [1], incoming cohorts present widely varying prior skills, and fully online courses suffer from low engagement and poor retention [2]. Immersive eXtended Reality (XR) can address these by delivering realistic virtual laboratories accessible remotely, increasing emotional engagement and knowledge assimilation [3, 4]. However, existing commercial digital-twin solutions (e.g., Matterport[1], Cupix[2]) require expensive hardware or extensive manual processing, limiting uptake by small and medium-sized training providers.

The XRTwinScape project overcomes these barriers with a streamlined, cloud-native pipeline: instructors or trainers record video of a physical workspace on a standard smartphone, a server-side Gaussian-splatting workflow reconstructs a navigable 3D environment within hours, trainers then author XR lessons by placing spatial annotations (text, images, audio, video) through a web-based editor, finally, learners engage in adaptive Virtual Reality (VR) simulations where tasks progress as annotations are reviewed. By enabling a pre-lab stage, XRTwinScape standardizes baseline familiarity: every learner experiences the same virtual orientation before hands-on practice and frees instructors to focus on higher-order skills. A preliminary assessment has been performed within an Industrial Electrician course, reporting encouraging results.

The remainder of the paper explores the details of the XRTwinScape platform (Section 2), presents its pedagogical impact through an industrial pilot study (Section 3) within the XR2Learn's educational

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[1]Matterport: https://matterport.com
[2]Cupix: https://www.cupix.com

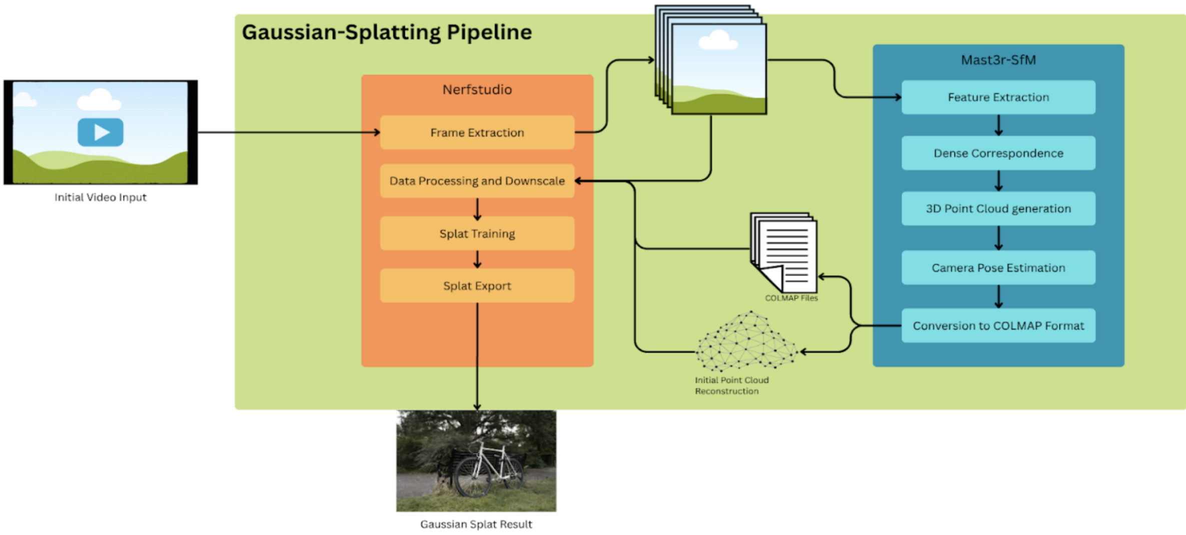

Figure 1: XRTwinScape end-to-end workflow, from the video upload to the automatic re-construction of the VR environment.

framework, and concludes with a discussion of key findings and future directions (Section 4).

2. XRTwinScape Platform

At the heart of XRTwinScape lies an end-to-end workflow (visible in Figure 1) designed to simplify digital twin creation and XR lesson delivery. The platform is open-source and its source code is publicly available on a GitHub repository[3]. The process begins when a user uploads a video of a real workshop. This video triggers an automated pipeline, orchestrated by Celery[4] and Redis[5], which extracts high-quality frames and runs a modern Structure-from-Motion algorithm (mast3r_sfm[6]) to estimate camera poses. These outputs feed into Splatfacto/W [5], a Gaussian-splatting library that produces an efficient volumetric representation of the scene. All processing occurs in a GPU-enabled Docker container exposed via a FastAPI interface, ensuring that even complex environments are reconstructed in under four hours on commodity hardware with an NVIDIA RTX 4060 GPU and 32 GB RAM.

[3]GitHub repository: https://github.com/isislab-unisa/XRTwinScape
[4]Celery: https://docs.celeryq.dev/en/stable
[5]Redis: https://redis.io
[6]Mast3r: https://github.com/naver/mast3r

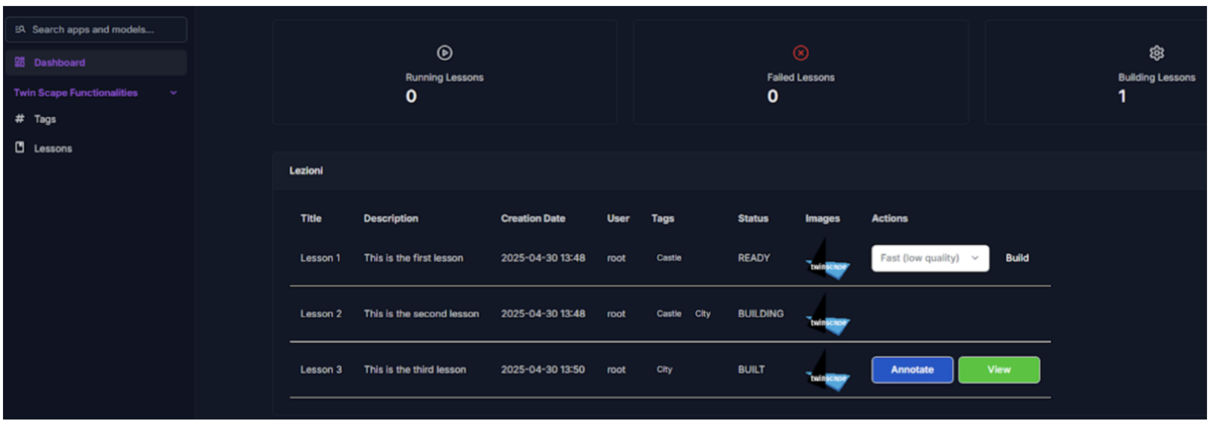

Figure 2: The XRTwinScape dashboard. It allows users the creation and editing of XR Lessons.

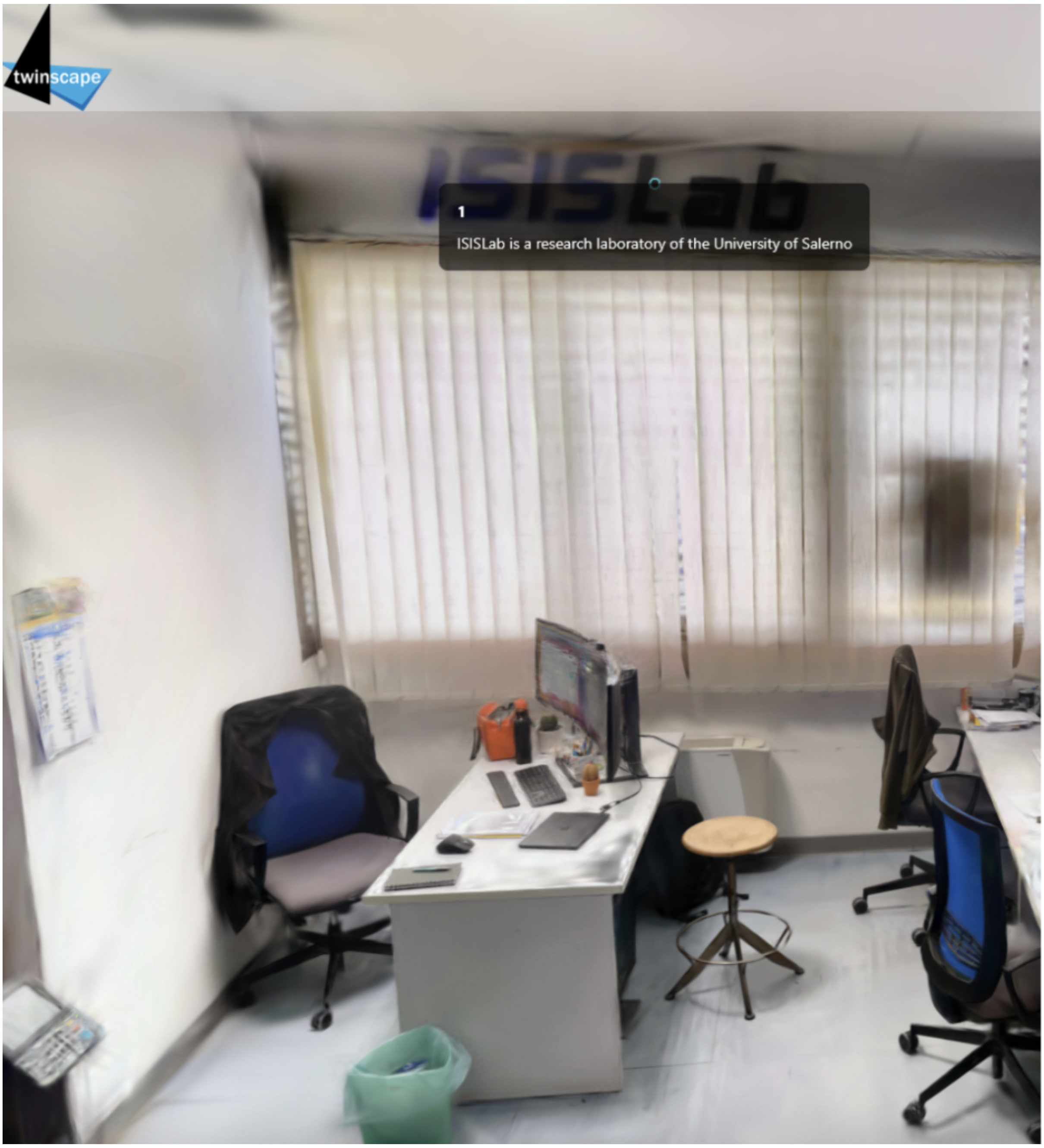

Figure 3: The XRTwinScape viewer displaying the digital twin of the ISISLab at the University of Salerno, created with the XRTwinScape pipeline. The inset at the top shows an open annotation containing descriptive text.

Interface and Interaction Mode. The Django-based **Dashboard** (visible in Figure 2) shows the digital twin creation status allowing trainers to monitor progress. The XRTwinScape Editor then provides a web interface in which instructors can navigate the digitized virtual work environment using familiar mouse and keyboard controls. On a contextual sidebar, they can insert spatially anchored annotations, selecting content types (text, image, audio, video), defining activity sequencing, and even specifying variant content tailored to different expertise levels. The variant mechanism, driven by the XR2Learn Personalization Enabler, allows beginner learners to view simplified diagrams or step-by-step videos, while advanced users see concise technical notes, all within the same lesson file.

Finally, the **Player** applications deliver these lessons either through a web browser (as visible in Figure 3) or a Meta Quest 3 headset. In VR mode, head and hands movement data stream in real time to the centralized Artificial Intelligence (AI)-based XR2Learn Personalization Enabler. Based on head and hands movements of the trainee, the enabler dynamically adjusts forthcoming activities, selecting appropriate content variants and modulating difficulty. We observed that both an unusually high number of interactions with the annotations and very limited interaction could reflect boredom or frustration, suggesting a possible misalignment in task difficulty. In the Industrial Electrician pilot, for example, revisiting an annotation containing a detailed specification of an electrical switch may result in it being replaced with a simplified variant that highlights core functionality rather than technical detail. This helps trainees grasp the basics before progressing to the full specification. Whether accessed on a PC or in immersive mode, learners experience a guided, adaptive journey through the digital twin, seamlessly progressing from one activity to the next as they engage with each annotation.

3. Pedagogical Impact and Industrial Pilot

`XR2Learn`'s educational framework[7] highlights the importance of combining immersive technology with effective teaching methods. The sequencing of activities emphasises orientation, guided practice and transfer in order to reduce cognitive load and support mastery. Meanwhile, multimodal annotations (labels, images, audio and video) aid recognition and procedural memory. In vocational training, XR offers a unique blend of realism and safety, allowing learners to rehearse operational procedures, such as wiring electrical panels or configuring machinery, in a consequence-free environment. This pre-lab familiarization not only accelerates the initial learning curve but also fosters a uniform starting point for all participants, regardless of their prior experience. Empirical studies [6] involving 238 university students show the VR/AR hybrid significantly enhances learning and accommodates diverse learning styles, improving outcomes and highlighting its potential for broader integration into the curriculum. Learners trained with VR were up to 4 times faster to train than in the classroom and 275% more confident in applying what they learned [7], demonstrating how immersive technology enhances both learning speed and depth.

The Industrial Electrician course exemplifies these pedagogical gains. Before entering a physical lab (visible in Figure 4), 60 trainees explore a virtual laboratory rendered by `XRTwinScape`[8]. During the Industrial Electrician pilot, XRTwinScape will be deployed to the trainees in the form of a 20–40 minute VR pre-lab, followed by an instructor-led practical lesson. Evaluation will be based on a combination of pre- and post-questionnaires (assessing self-efficacy, usability and engagement), instructor observations and in-VR logs (annotation completion, time spent on the task and error events), in order to triangulate subjective and objective outcomes. At the start of the immersive lesson, participants locate the personal protective equipment and inspect the control panels. They are guided through this process by embedded annotations that explain the safety protocols and circuit schematics. This virtual orientation ensures that every learner arrives at the hands-on session with the same foundational knowledge, effectively bridging the gap between novices and those with electrical backgrounds. Formative assessment takes place within the VR environment itself: learners must interact with all target annotations, such as identifying the main breaker and reading its label, before unlocking subsequent tasks. The VR environment is good for perfecting work procedures or routines [8].

Beyond the electrician scenario, the pedagogical insights generalize across industrial training: XR pre-lab simulations scaffold learning experiences, promote equitable skill progression, and cultivate learner confidence. XR is also a highly scalable technology that can be used to develop soft skills, which are increasingly crucial for all professions, both industrial and non-industrial; in fact, it is also applied in a training path dedicated to enhancing problem-solving and decision-making skills. By continuously adapting to individual performance through the XR2Learn Personalization Enabler, XRTwinScape ensures that each trainee confronts challenges aligned with their evolving expertise [8]. This combination of technological innovation and instructional design is in line with Industry 5.0's human-centric ethos. It promotes technical competence, learner agency and engagement.

[7]The XR2Learn Educational Framework: https://github.com/XR2Learn/.github/wiki/The-XR2Learn-Educational-Framework
[8]A demo of the virtual laboratory for the Industrial Electrician course is freely accessible at https://drive.google.com/file/d/1YXOzhMOT4VK2YLxL6MCZFOlId4_opA71/view

Figure 4: Real-life photograph of the innovative training workshop used as the pilot site for the Industrial Electrician course.

4. Conclusion, Limitations, and Future Directions

XRTwinScape demonstrates that XR-enabled digital twins can transform vocational training for Industry 5.0. By lowering technical barriers (smartphone capture, cloud-based Gaussian-splatting, intuitive authoring) smaller institutions can create engaging, adaptive VR lessons at scale. Pedagogically, XR pre-lab experiences standardize learner readiness, boost engagement, and build confidence, as evidenced in the Industrial Electrician use case. We will integrate and compare lessons produced with XRTwinScape into conventional (non-XR) courses in order to evaluate real-world adoption. We will perform the assessment the impact through validated questionnaires targeting the following dimensions: learning outcomes, learner engagement and motivation, perceived usability and cognitive load, and self-reported transfer of skills to workplace tasks. We acknowledge the current limitations that could impact the wider use and replication of the technology, such as the varying familiarity with XR devices among trainees and trainers, the risk of motion sickness, and the lack of standardised evaluation protocols. These issues will be addressed in our ongoing work. As part of the long-term study, the work on XRTwinScape will continue over the next year, with the refinement of the pipeline and the personalization algorithms, we will then conduct controlled studies on long-term skill retention in various courses. Future work will extend XRTwinScape to other sectors: real estate, entertainment, cultural heritage.

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Declaration on Generative AI

During the preparation of this work, the author(s) used Chat-GPT in order to: Grammar and spelling check. After using these tool(s)/service(s), the author(s) reviewed and edited the content as needed and take(s) full responsibility for the publication's content.

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