Integration of Extended Reality with a Cyber-Physical Factory Environment and its Digital Twins

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In this paper, we present an example of complete integration of eXtended Reality technologies within a demonstration laboratory showcasing Industry 4.0/5.0 compliant machinery in realistic scenarios of use. We describe the design choices and the implementation of the augmented and virtual reality applications developed and potentially usable to support different real-world tasks, featuring advanced gesture-based interaction modes. We also describe the optimized communication architecture used to synchronize data between the cyber-physical factory environment with all its components, its industrial digital twin, and the augmented and virtual replica of the factory.

Example tasks supported with the tools in public demonstrations allow users wearing Microsoft HoloLens 2 or Meta Quest 2 headsets to monitor the status of the prototype production line and operate on it, locally or remotely.

An example video showing the applications is available in the supplementary material.

CCS Concepts: • **Human-centered computing → Mixed / augmented reality**; **Virtual reality**; • **Applied computing → Service-oriented architectures**; **Enterprise applications**.

Additional Key Words and Phrases: Cyber-Physical Factory, Digital Twin, Gestural interfaces, Computer Graphics

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1 INTRODUCTION

Virtual Reality (VR), Augmented Reality (AR), and, more in general, eXtended Reality (XR) are fundamental enabling technologies for Industry 4.0. As pointed out in [6], "the accessibility and

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accelerated progress in technological devices, incorporating advanced algorithms, ergonomic features, built-in cameras, and sensors, have encouraged a massive adoption and extensive application development in a wide spectrum of industry 4.0 domains.". They are also important for the more recent Industry 5.0 paradigm, focused on sustainable, resilient and human-centric solutions, as they can be considered "Individualized human-machine interaction technologies that interconnect and combine the strengths of human and machines" [17]. Thanks to the new interaction paradigms leveraged by XR, workers can be supported by assistive tools enhancing their safety and adapting to their needs and diversity [16].

If a manufacturing plant environment is transformed into a "Cyber-Physical Factory" (CPF) [15], with all the processes monitored and synchronized between the physical factory floor and the cyber computational space, workers can be helped in their tasks with smart visualization and advanced interfaces, and remote operators can monitor in real-time the status of the production process and possibly perform actions on machines.

The concept of "Digital Twin" (DT) [12] is used to indicate the creation of a numerical representation (and simulation) of a production plant. Specific software tools are available in the industrial domain to support the organization of the work, allowing the digital control of production recipes, process monitoring and analytics, predictive maintenance, etc.

The integration of these tools with eXtended Reality (XR) technologies, allowing immersive visualization and advanced interaction is, however, still limited and requires both the development of new interaction paradigms, tools and a careful user evaluation.

One of the problems limiting the research on these aspects is related to the lack of Cyber-Physical Factory demonstrators where the combination of all these technologies can be tested and evaluated.

In this paper, we present the design of a complete framework to test applications of XR in a realistic industrial context. The framework has been created within the Industrial Computer Engineering laboratory (ICE laboratory) of the University of Verona, an advanced demonstrator for Industry 4.0 and 5.0 technologies.

The laboratory is a functional replica of an advanced manufacturing environment with specialized hardware devices and software tools, allowing students and researchers to work with up-to-date instruments in different technological areas. In this environment, the use of XR technologies to develop and test novel Human-Centered interaction design solutions can be studied in a realistic scenario, interfaced with a complete cyber-physical factory provided with state-of-the-art industrial digital twins.

In this paper, we describe the development of the XR applications specifically created to support interaction research in this environment and show a few examples of their use.

The paper is structured as follows: in Section 2, we present a brief analysis of the literature on the integration of XR technologies with CPF/DT. In Section 3, we describe the main features of our laboratory. In Section 4, we discuss the creation of the 3D model of the plant reproducing the environment and all the machines. Section 5 describes the VR application allowing users to navigate in the laboratory, visualize real-time information on its equipment, and possibly trigger actions on the production management. In Section 6, we describe the AR application that allows users to walk in the physical environment, visualize information superimposed on the different machines, operate on them with simple gestures, and have feedback and alerts related to the production processes. Section 7 provides some final comments.

2 RELATED WORK

Many research papers describe the integration of Augmented Reality and Digital Twins/Cyber Physical factories, and several literature surveys have already been published in the field.

Künz et al. [14] reviewed selected literature on AR applied to DT, finding that the main research topics considered are the visualization of information and data, the guidance of participants through given tasks, and the interaction with DT through AR. A clear weakness in the literature surveyed is that it focuses mostly on technical aspects neglecting human factors, and more than half presents only descriptions of the proposed implementation or concept as results.

Yin et al. [21] also conducted a state-of-the-art survey from the AR-assisted DT perspective across different sectors of the industrial field. They reviewed 118 papers and identified three levels of AR-assisted DT: Virtual Twin, Hybrid Twin, and Cognitive Twin, with only the latter including effective integration of machine and human intelligence and high-level support of human work. They considered the readiness level of this kind of DT as low. They also pointed out several implementation challenges, related to the limited use of human interaction with AR for DT control, the difficult adaptation of CAD-based 3D models to the AR environments, the problems in the management of real-time data communication in the integrated AR-assisted DT system.

Another literature review of papers discussing augmented reality and DT was presented by Böhm et al. [4]. Their survey focuses on how cybersecurity could benefit from the combination of the two technologies. AR can, in fact, provide situational awareness, including the actual physical situation, allowing insights derived from DT data and simulations to be visualized together with the physical assets. They also discuss on how AR and DT can be integrated with existing security mechanisms.

The use of Virtual Reality simulation integrated with smart manufacturing environments has been investigated in [11], who developed an early prototype of a VR application visualizing the data of the real-time operations of a forklift for a user equipped with a VR headset and performed preliminary evaluation of delays and acceptability.

Chandra et al. [7] surveyed papers on the usage of virtual reality (VR) in simulating a digital factory gathering recommendations for developing effective tools. They highlighted that although "VR provides the best visualization, interaction, and immersion, it still lacks in becoming a high-fidelity, industrial-grade digital factory tool".

Pirker et al. [19] reviewed recent papers on immersive VR applied to Digital Twins. They identified various applications fields for digital twins combined with VR that is not limited to industry, but has been extended to other domains like health, automotive, BIM, education, or even gastronomy. They found that primary use cases for VR associated to DTs are remote operation, remote collaboration or guidance, training. However, a particularly interested case where VR can play an important role is related to evaluation and to the possible use of virtual environments as safe spaces for user studies. The surveyed papers pointed out also the issues related to the usability of VR (cybersickness, user acceptance, ergonomy), to the network efficiency and security) and the specialized hardware requirements.

Many of these surveys reveal that, despite the amount of literature in the field, it seems that VR and AR technologies are still not as exploited as they could in the cyber-physical factory domain. In this context, the development of a demonstrator where different solutions are integrated with standard industrial software solutions and a rich set of machines can be a relevant contribution that can stimulate the implementation of new research for the improvement of the instruments themselves and show the potential of the technology to the industries.

3 THE ICE LAB OF THE UNIVERSITY OF VERONA: A COMPLETE INDUSTRY 4.0/5.0 TECHNOLOGY DEMONSTRATOR

The Industrial Computer Engineering laboratory (ICE lab) is a research facility of the University of Verona, designed to serve as a demonstrator for a wide set of computational technologies applied

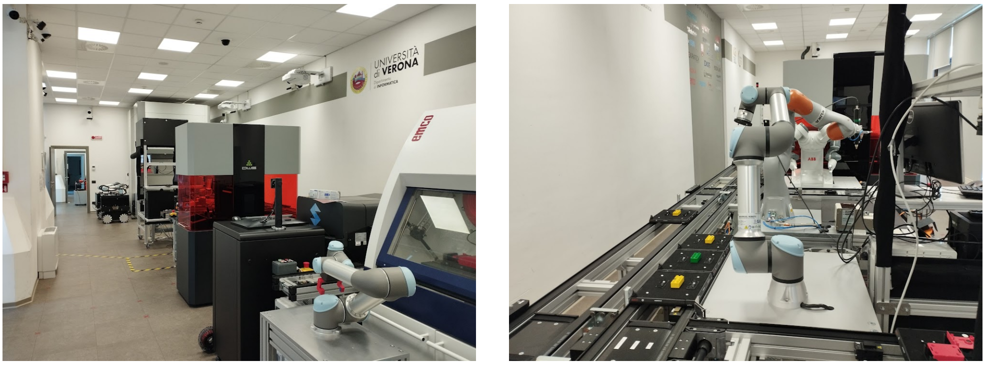

(a) (b)

Fig. 1. Two views of the ICE laboratory: (a) shows the milling machine close-by with the feeding arm in the forefront, the polyjet and stereolitographic printers in the middle, the autonomous ground vehicles and the vertical automated warehouse at the back; (b) shows the mini-pallet conveyor line on the left and the robotic arms in the middle.

to industrial manufacturing within the frameworks of the Fourth and Fifth Industrial Revolutions (Industry 4.0 and 5.0). Fig. 1 shows two views of the environment.

The main feature of the laboratory is a complete and reconfigurable production line equipped with an assortment of heterogeneous devices grouped into manufacturing cells: autonomous storage and logistics, robotic assembly, quality control, additive manufacturing, subtractive manufacturing, and functional testing.

The autonomous storage and logistics cell supplies and circulates materials (parts and products) between the cells: a vertical automated warehouse (Ferretto VERTIMAG EF), two autonomous ground vehicles (Robotnik RB-KAIROS 5), a mini-pallet conveyor line (Bosch-Rexroth) configured as a ring. The robotic assembly cell includes two collaborative robotic manipulators (ABB YuMi IRB14000 Collaborative Robot, Kuka LBR iiwa 14 R820) with different end-effectors, such as gripper, suction and screwdriver tools. The quality control cell includes a set of cameras (optical, infrared, laser scanner) to inspect materials and products for visible defects. The additive manufacturing cell is made up of a set of 3D printing machines based on different technologies, namely fused-deposition modeling (Prusa i3 MK3S+), polyjet (Stratasys J826), and stereolithography (DWS Systems XPRO S) for building product components. The subtractive manufacturing cell has a four-axis computerized numerical control (CNC) milling machine (EMCO ConceptMill 105). The functional testing cell has a flying probe testing machine to check the quality of electronic boards (SPEA 4050 S2).

Moreover, the production line is surveyed by an array of video surveillance and RGBD cameras mounted all around the room to monitor workers and guests in the laboratory. The first array feeds a customized neural-network based tracking system that robustly follows people even if partially occluded by the equipment. The RGBD cameras instead provide skeletal-based pose estimation to analyze interactions with the machines and the environment. The laboratory is also monitored by meters in every production cell to measure energy consumption, and environmental IoT sensors within the room to record temperature, humidity, and brightness.

This set of sensors enable us not only to perform research on the efficient use of automation in industry (4.0 paradigm), but also on sustainability and inclusiveness of the factory (5.0 paradigm) that will be particularly investigated in future work.

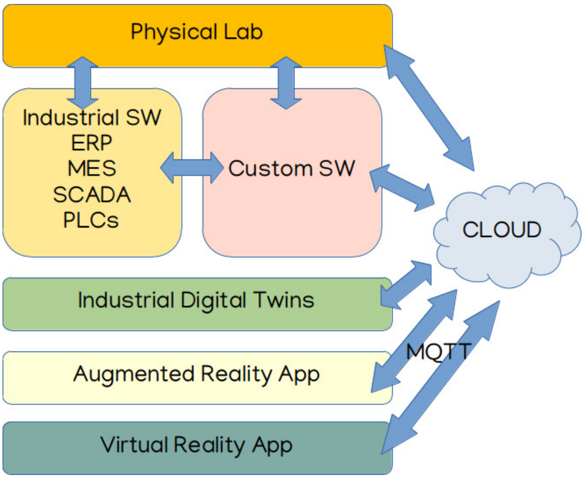


Fig. 2. Functional schema of the ICE lab. The AR and XR applications communicate both with the physical devices and the industrial digital twin, enabling augmented interaction, monitoring and control.

All the equipment and sensors in the laboratory are managed by a Service-oriented Manufacturing (SoM) software architecture based on containerization and virtualization, implemented as a Kubernetes cluster with two main components: the Data Integration Hub (DIH) and the Automation Manager. The DIH monitors the equipment, stores the gathered data, and propagates to the machines the commands requested by the Automation Manager. It acts as a service platform that provides a variety of functionalities: machine monitoring and control through OPC-UA servers and clients, communication between Kubernetes nodes with Industrial Internet of Things (IIoT) brokers (RabbitMQ, Kafka, MQTT), storage and retrieval of time series (InfluxDB).

The Automation Manager works between the Manufacturing Execution System (MES) and the DIH to control the production plant and dynamically execute work orders, reacting to changes in the plant and in the production plan in real time. It receives from the Siemens OPCenter Execution Discrete MES the desired production data and the associated production recipes, and schedules the activities of the production cells by employing the services of the DIH.

The industrial Digital Twin for the whole production line has been created with the Siemens Tecnomatix Plant Simulation. Two DTs are actually available. The first is the Digital Shadow, communicating with the OPC-UA servers of the machines to monitor their status and visually replicate it in real-time, and allowing real-time control over the entire system. The second is the Autonomous Digital Twin, designed to simulate the plant as a whole. The information flow connecting the physical devices, proprietary and custom software layers, and the DT, is represented in Fig. 2. Selected data can flow from the physical factory to the digital layers and vice-versa to ensure monitoring and control.

The communication between applications and services relies on RPC and events subscriptions that generate a stream of messages managed by IIoT brokers. In particular, RabbitMQ handles the control infrastructure and Apache Kafka the data distribution. These technologies have a recognised industrial appeal for their scalability and high reliability. Alongside these systems, a lightweight messaging system based on MQTT allows communication from outside the laboratory, specifically designed to provide remote monitoring and control of the production line with mobile devices.

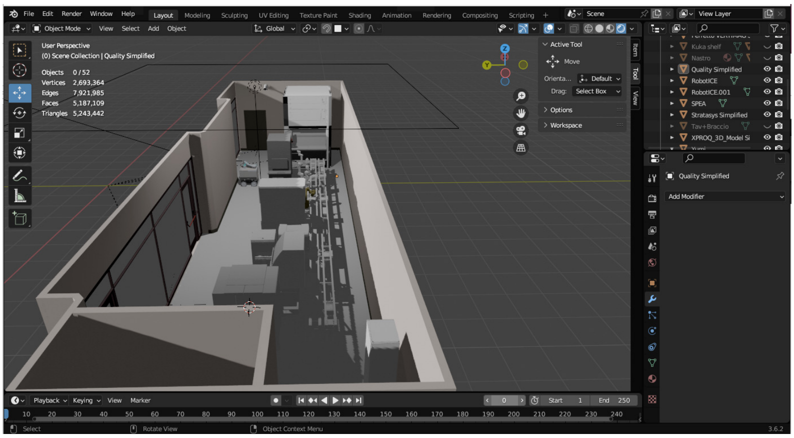
In the context of the ICE lab, we developed Virtual Reality and Augmented Reality applications that showcase the different opportunities that the technologies offer to train and assist workers.

These applications can be considered additional digital twins and directly communicate in both directions with the physical laboratory and the industrial digital twins.

They leverage the creation of an accurate graphical modeling of the laboratory elements, efficient network communication, and advanced interaction design solutions. The MR application is designed to help workers in the laboratory, while the VR application is designed for training but also for remote monitoring and control.

The AR and the VR applications currently run on the Meta Quest 2 and HoloLens 2 stand-alone HMDs, respectively. They can be ported easily on different platforms. The current AR application rely on the Hololens 2 spatial mapping, but, not only similar high quality inside out tracking capabilities are available on other AR glasses (Magic Leap, Meta Quest 3, VarjoXR), but it could be also possible to use VIVE base stations mounted in the lab to provide accurate headset tracking. The interaction in AR and VR is based on gestures, and also in this case, most of the recent AR and VR headset comes with finger tracking capabilities, that can in any case added to the setup with a low cost Ultraleap device. The porting of gesture recognition algorithms based on hand skeleton data needs attention but we have successfully ported applications from Leap Motion data to the Hololens even without the need to retrain the recognizer.

In the following sections, we describe the graphical model of the laboratory, the main characteristics of these applications, and the example demonstrations that have been performed with them and are available for the visitors.



User Perspective
(0) Scene Collection | Quality Simplified

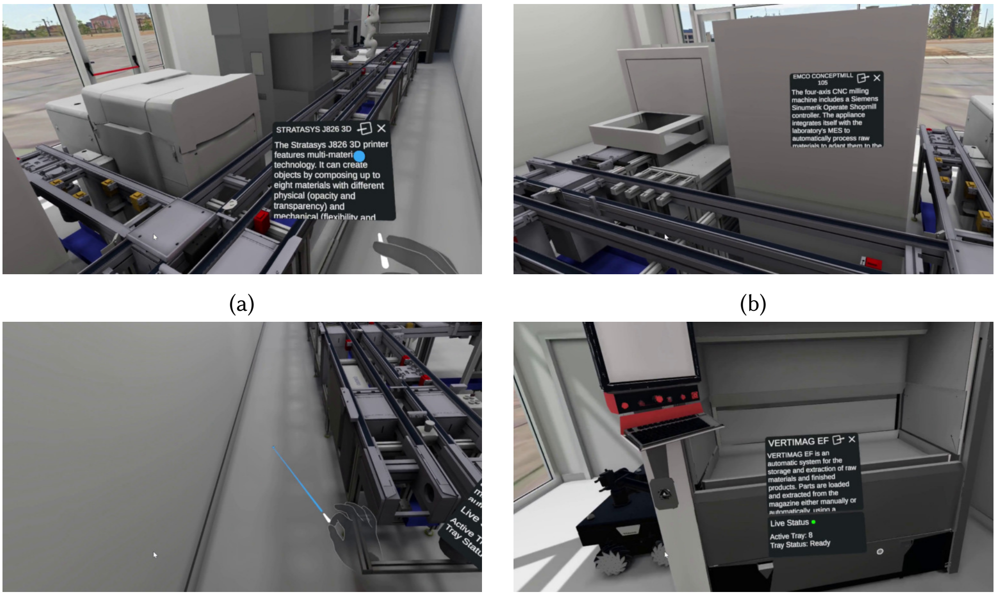
Objects 0 / 52
Vertices 2,693,364
Edges 7,921,985
Faces 5,187,109
Triangles 5,243,442

Fig. 3. The graphical twin of the ICE lab includes all the laboratory assets modeled as triangle meshes at different levels of detail to support rendering on low-end devices adapting the quality to the hardware resources. The full-resolution model is currently composed of approximately 5.1M triangles.

4 THE LABORATORY GRAPHICAL TWIN

A 3D digital replica of the laboratory was created to support the realization of the immersive VR tools and the creation of spatially referenced augmentations. The complete model has been designed and optimized with Blender [2], using the floor plan and on-site measurements to reproduce the room accurately (Fig. 3). We modeled most of the machines starting from the CAD files provided by the manufacturers, exported as surface meshes using Autodesk Fusion 360 [1], and put into a hierarchical structure. The meshes had to be processed to make them manageable in interactive graphical applications running on low-end hardware, as the single parts often had several millions triangles. Due to the large diversity in models quality and complexity, the simplification had to be specialized for each model. The process was organized into two steps: i) removal of internal/non-relevant parts and possible re-meshing of the external surface; ii) simplification of the mesh with edge collapse.

With the creation of the room and the generation of the models, we obtained a basic version of the scene with all the geometric models, totaling 5.1M triangles. This amount is still very high for interactive applications on several platforms, especially for the stand-alone VR headset (Meta Quest 2) used as a target platform in our VR app (Section 5). For this reason, we created meshes for the different elements at four different resolutions (100%, 50%, 30% and 10% the original models' triangles) that can be used changed dynamically using the Level Of Detail (LOD) mechanism in the rendering step. The LOD mechanism adapts the resolution to the distance from the point of view. For the most complex piece, the minipallet conveyor line, which is a unique structure covering most of the room space, we had to split the model into three segments along its major length, and create a multi-resolution version of each to optimize the performances of the LOD management. To obtain a realistic rendering of the scene, we also had to assign reasonable materials to the modeled surfaces. The original CAD data mostly lacked Physically-Based materials that have been, therefore, assigned in the modeling phase and still need to be completed/optimized. We plan to develop specific image-based methods to further improve realism in future work.



STRATASYS J826 3D

The Stratasys J826 3D printer features multi-materi technology. It can create objects by composing up to eight materials with different physical (opacity and transparency) and mechanical (flexibility and

EMCO CONCEPTMILL 105

The four-axis CNC milling machine includes a Siemens Sinumerik Operate Shopmill controller. The appliance integrates itself with the laboratory's MES to automatically process raw materials to adapt them to the

VERTIMAG EF

VERTIMAG EF is an automatic system for the storage and extraction of raw materials and finished products. Parts are loaded and extracted from the magazine either manually or automatically using a

Live Status ●

Active Tray: 8
Tray Status: Ready

(a) (b)

(c) (d)

Fig. 4. The VR application provides a realistic visualization of the simulated environment on the Head-Mounted display, with physically-based illumination effects and high-resolution details (a,b). The application allows to navigate inside the ICE lab using instant teleport by throwing a ray with a gesture and clicking when the ray intersects the floor in the desired position (c), and the interactive visualization of both offline description and real-time information on the single machines, as the active tray in the vertical warehouse (d).

5 VIRTUAL REALITY APPLICATION

The app was developed using Unity [3], and is based on the optimized scene created with Blender. We added the ceiling of the lab with area-based lights simulating the real LED light sources. A spherical texture representing the external view of the lab has been added to provide a visually plausible rendering of the scene behind the windows and a realistic illumination. The materials of the models were fine-tuned along with a Universal Rendering Pipeline asset to find the best compromise between performance and image quality. Global illumination has been baked into light maps. The application uses the Unity LOD management system, set up with the 4 different resolutions created, and setting distance thresholds to enable lower LOD models based on a preliminary test with subjects, asking them at which distance the change in detail seemed negligible. These settings and configurations allow the app to run at 60FPS on average on the Oculus Quest 2, with the lowest performance registered at roughly 50FPS with the camera observing the scene facing the full length of the virtual laboratory. The degree of realism of the visualization is good, as shown in Fig. 4.

5.1 Interaction Design

The user can navigate the environment by walking in the real space or by changing the viewpoint with the Point and Teleport technique [5, 10]. In this case, they must perform a pinch gesture that makes the hand cast a virtual ray that can be pointed to the target destination on the floor (Fig.4c). The camera movement is performed upon releasing the hand pose. The users can exploit the same pinch/ray casting action to point at the different machines spread throughout the laboratory. In this case, they can activate the visualization of specific information on their status, displayed on a floating panel. We implemented two modalities for the information panels: Follow or Anchored. In the Follow mode, the panel follows the user with smooth transitions when the camera rotates or when the user moves through the environment.

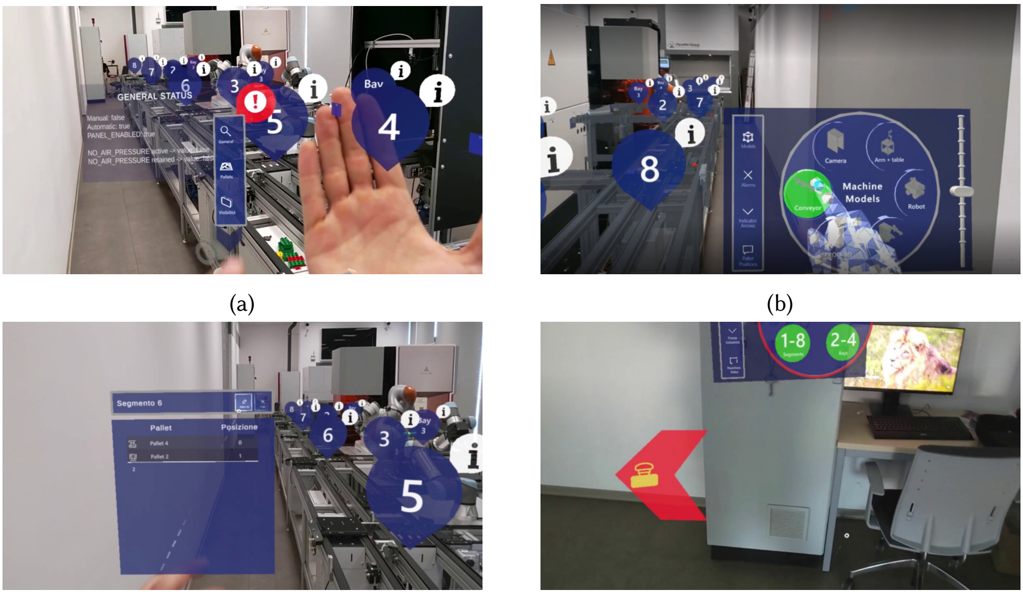
5.2 VR Demo: virtual visit with real-time machines' status visualization

The current version of the application allows remote users to easily navigate in the laboratory, learning its layout and visualizing panels with the description of the different "virtual" machines. Furthermore, these panels can display live information retrieved from the corresponding "real" equipment. The live information update is gathered by an MQTT module that connects the application to the MQTT broker in the laboratory infrastructure that exposes data retrieval and command functions to authorized users. In Figure 4d, the panel displays the currently active tray in the vertical automated warehouse.

6 AUGMENTED REALITY APPLICATION

AR applications can be easily created using a see-through headset with spatial mapping capabilities like the Microsoft HoloLens 2. By using the mentioned AR headset, we built a MR system that augments the experience while being in the ICE lab, by showing real and up-to-date information about the state of the machines. Similarly to the VR app (Section 5), the software is developed using Unity Engine [3], importing 3D models of the machines created in Blender. Because these 3D models are superimposed over physical machines, there is no need to render them, but they can be used for visualization purposes in case of specific application requirements.

The spatial alignment of the virtual and real spaces exploits the Space Pins feature of World Locking Tools (WLT) for HoloLens 2. WLT provides a stable and reliable world-locked coordinate system. By scanning with the headset camera QR codes located in the physical world and corresponding to known virtual world coordinates, the system can recover the optimal transform matching the 3D model of the lab and the spatial map created by the headset. For high-quality alignment accuracy, it is recommended to scan two or more QR codes, so we placed two QR codes in the physical lab, annotating the corresponding position in the virtual space. We estimated an alignment error of ±5*cm* between the virtual model and the real machines, which we considered to be acceptable given the extent of the laboratory. The application must be initialized at startup by scanning these QR codes with the HoloLens 2 camera.



(a)

(b)

(c)

(d)

Fig. 5. Example headset views of the basic AR application of the ICE lab. The user can see augmentations (a) and/or semitransparent models of the selected (b) devices. In the examples in the bottom row, the operator checks the status of a segment of the conveyor (c). In case of alarm, a red arrow guides the operator to the critical point (d).

6.1 Interaction Design

We designed a set of augmentation options controlled by UI elements realized with the MRTK 2 toolkit. A hand menu allows the selection of the different visualization options. The user can select the augmentation panels enabled and hidden. The 3D models of the machines can be rendered with variable transparency, superimposed on the real ones, or not displayed (default option). The information panels associated with the machines are clickable with the local or remote (ray-casting) standard pinch-based interaction of MRTK to visualize related information, updated in real time.

Furthermore, our AR application features a custom gesture-based interaction system. This system detects and segments in real-time static and dynamic gestures, captured by the HoloLens 2 finger-tracking system and can map them to specific actions. The system exploits a client-server architecture and a neural network recognizer [8] to provide a low-latency detection and recognition of a dictionary of 16 heterogeneous gestures, including static (e.g., fixed hand poses) and dynamic ones, including hand articulation (pinch, grab), or whole hand movement (swipe left and right, circle). The gestures dataset used to train the network has been released for a recognition contest in 2022 [9]. The related dictionary includes gestures typically used for interaction and communication (see Fig. 6).

Our network could be, however, trained on different datasets/dictionaries with specific gestures and non-gestures examples, with classes optimized for the desired task.

By mapping gestures with system actions, it is possible to create easy-to-use control systems for specific tasks. This allows a touchless control (that is also optimal for hygiene) and we expect to be faster and less error-prone than clicking in mid-air. We plan to perform usability tests to verify this, comparing our gesture-based solutions to traditional mid-air clickable menus provided by the MRTK2 framework in the near future with a user study on a controlled task, measuring efficiency, errors and fatigue. The preliminary feedback of the ICE lab visitors testing the gesture-based solutions is really promising, and the fact that menu item selection with simple gestures can be faster and not less accurate than mid-air clicking has been already shown in previous work [13].

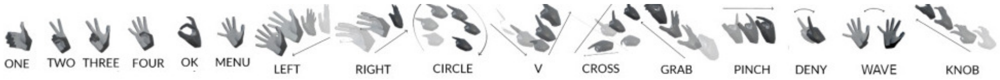


Fig. 6. The 16 static and dynamic gestures modeled in [9] that are used for touchless control.

6.2 Demo tasks for the AR app

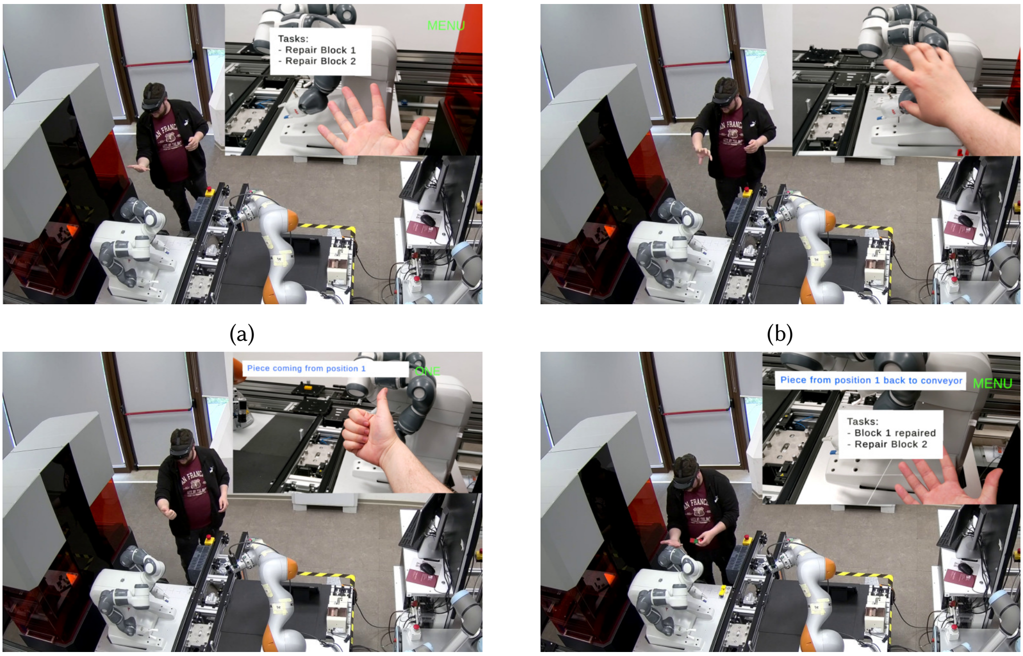
Using the framework developed, we demonstrated different tasks in public exhibitions showing the potential impact of the use of this technology in industrial environments and showing the effectiveness of the design and implementation choices adopted.

6.2.1 Transport line augmentation. The first demo of the augmented reality application allows the real-time visualization of the transport line data, as shown in Fig. 5. The user can check the status of the pallets and of the bays. In particular, they can gather general information about the conveyor line, and inspect in more detail the position, content and destination of each pallet. When the conveyor is operational, blinking arrows on each bay signal the direction of a pallet entering or exiting. Moreover, the application warns the user about any ongoing machine alarms by placing a marker on the conveyor line and enabling the operator to inspect them in a dedicated panel. At any time, the user can enable and disable the virtual machine models, information panels, alarms and arrows.

6.2.2 Active monitoring and control of the production workflow with AR and gestural interface. To demonstrate the integration of the XR interfaces with the production line management and the use of natural interaction with gestures, we implemented another demo for the visitors of the laboratory where users wearing HoloLens 2 glasses can control realistic production tasks with simple gestures having visual feedback on the effects of the actions on the system.

The demo simulates the action of an operator that can select pending tasks on a list (Fig. 7a), use a gesture (in this case "knob") to start the transport line (Fig. 7b), select one of the available actions with a gesture (Fig. 7c) and monitor the ongoing procedures (Fig. 7d).

6.2.3 Remote monitoring/control of single machines. We implemented a specialized XR application based on our framework in occasion of a big national technology exhibition on Industry 4.0, where the ICE lab staff had the opportunity to display its solutions to the exposition visitors. For obvious reasons, the production line could not be dismantled and re-assembled at the exhibition, and it was replaced with cardboard cutouts of each equipment, real-time video feeds from inside the laboratory, and remote monitoring and control of the Automation Manager described in Section 3. This artifice was planned in conjunction with our application to allow our guests to virtually inspect the machines and retrieve their real-time status updates during the live demonstrations.



(a) (b)

(c) (d)

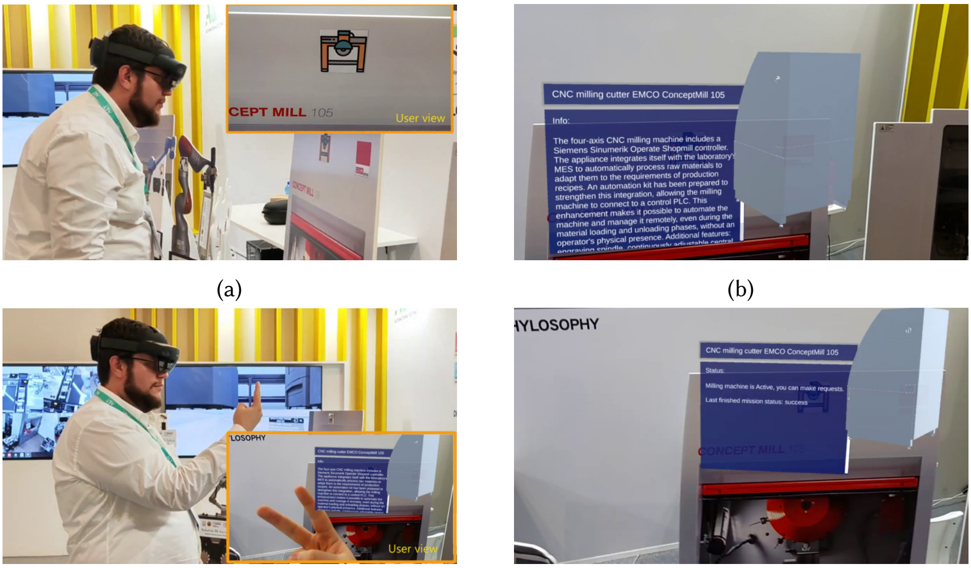
Fig. 7. Demo of the gesture-based production recipes' management. The boxes in the figure show the user view. (a) The worker opens the menu of the active tasks with a menu gesture. (b) They start the transport line operation with a "knob" gesture. (c) With a specific gesture, they call pallet #1 in the local bay for repair. (d) After completing the task, they can see the updated list of available actions.

Specifically, the cardboards were identified by unique image targets (Fig. 8a) and recognized by the Hololens 2 app. By performing distinct gestures in this situation, the users could visualize a 3D model of the machine with associated information (Fig. 8b) and check its real-time status (Fig. 8d). Similarly to the VR Demo described in Subsection 5.2, the live connection was provided by an MQTT module that exchanged messages with the laboratory's broker to command status updates. In the future, we plan to extend these interactions in order to enable a remote operator to be fully engaged with the production activities like an in-place worker, or the same worker to enjoy an enhanced experience.

7 DISCUSSION

Our results demonstrate the readiness of the current technologies for providing support for workers in industrial contexts using eXtended Reality. The integration of industrial software, digital twins, and XR applications allows the creation of specific tools to enhance productivity and safety in the factories. The use cases of our demos can be extended with many other tasks, and the controlled environment of the ICE lab would facilitate the design of specific user tests to evaluate the impact of the technologies and compare different interaction design solutions.

Examples of the tasks we plan to investigate with specific experiments are the use of VR to learn the spatial layout of the environment; the effectiveness of different solutions for immersive digital twin analytics visualization; and specific solutions to synchronize collaborative work of local and remote users based on shared spatial annotations.



CNC milling cutter EMCO ConceptMill 105

Info:

The four-axis CNC milling machine includes a Siemens Sinumerik Operate Shopmill controller. The appliance integrates itself with the laboratory's MES to automatically process raw materials to adapt them to the requirements of production recipes. An automation kit has been prepared to strengthen this integration, allowing the milling machine to connect to a control PLC. This enhancement makes it possible to automate the machine and manage it remotely, even during the material loading and unloading phases, without an operator's physical presence. Additional features: engraving spindle, continuously adjustable central

CNC milling cutter EMCO ConceptMill 105

Status:

Milling machine is Active, you can make requests.

Last finished mission status: success

(c) (d)

Fig. 8. Remote inspection with extended reality. (a) The headset scans an image target. The pane shows the user's view. (b) Subsequent user view where the device's description is displayed together with the 3D representation of the same machine. (c) The user performs a command with a gesture (the pane shows the user's view). (d) Subsequent user view where the status of the machine, updated in real-time, is displayed.

Other tasks to be designed will require further improvements of the system, in particular, related to the accurate simulation of the virtual robotic arms. We plan to introduce their functional models in our graphical twin soon.

Even if the current XR technology is ready for a practical application, there are still some limitations that need to be carefully considered for the interaction design. The first issue is related to potential discomfort due to the use of the headset. Its weight can lead to different issues and limit its "comfortable wear time" [18, 20]. The battery life can be another relevant issue for practical use. In the case of the HoloLens 2, it is limited to 2-3 hours. The limited field of view of the device can be a relevant problem for the effective visualization of augmentations. The next generation of see-trough displays (Apple Vision Pro, Varjo XR3, Meta Quest 3) might remove this issue being based on video see-through technology, but this kind of display has the relevant drawback of excluding the user from the real environment in case of system failure.

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