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Towards Reconfigurable Cyber-Physical-Human Systems: Leveraging Mixed Reality and Digital Twins to integrate Human Operations

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Abstract

The agility to swiftly and efficiently reconfigure manufacturing systems is crucial in today's rapidly evolving market demands. Traditional reconfiguration operations often fall short, presenting non-intuitive and error-prone tasks for human operators, without the aid of systematic approaches or supportive technologies. This gap not only complicates the reconfiguration process but also significantly increases the risk of errors. In response, we introduce a novel approach that integrates Mixed Reality and Digital Twins within Cyber-Physical Systems to address these challenges. This enhances the human element in manufacturing reconfigurations by facilitating intuitive trajectory planning for robot (re)programming and comprehensive documentation of physical processes, including human operations. The design and implementation of the approach aim to significantly enhance manufacturing reconfigurations by reducing downtime, complexity, and human error. Further, the paper outlines directions for future work, including comprehensive system validation within a Cyber-Physical-Human manufacturing system, emphasizing the critical role of human operators in the reconfiguration process and the potential for technology to address traditional shortcomings.

Keywords: Cyber-Physical-Human Systems; Mixed Reality; Digital Twins; Reconfigurable Manufacturing

1. Introduction

The agility to reconfigure manufacturing systems in response to rapidly evolving market demands is crucial in today's industry. Traditional methods include complex human operations within Cyber-Physical Systems (CPS), which are cognitively demanding to operators and additionally lack systematic approaches [16]. This leads to frequently occurring errors during the reconfiguration process, which adds to the downtime of the manufacturing system. To enhance reconfiguration processes in manufacturing, we introduce a system concept that synergizes Extended Reality (XR) and Digital Twins (DTs) for a more intuitive, effective, and efficient reconfiguration of Cyber-Physical Systems. Our approach evolves around the human operator in manufacturing reconfigurations, enabling intuitive trajectory planning for robotic programming and thorough documentation of spatial actions within the physical space.

We employ the Value Stream Kinematics (VSK) [20], a forward-thinking approach designed for the adaptable production of highly customized products in small batches, as the cyber-physical development and validation environment for our approach. Figure 1 shows the current implementation of the VSK at the wbk Institute for Production Science at Karlsruhe Institute of Technology (KIT). The VSK system exemplifies the integration of high automation and flexibility by using standardized kinematics for various manufacturing tasks. By analyzing the VSK production processes and their reconfiguration, two primary areas for improvement were identified: cognitive trajectory planning during robot (re)programming and the documentation of human operations in the reconfiguration.

Firstly, the integration of DT and XR technologies introduces an intuitive interface for trajectory (re)configuration during robot (re)programming. Traditional methods of robot trajectory programming require operators to engage in cogni-

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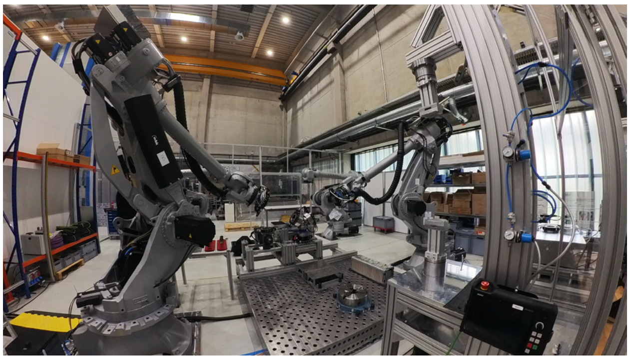

Fig. 1. The Value Stream Kinematic system at the wbk Institute at KIT.

tively demanding mental visualization of the coordinate systems within the robot cell. This often leads to errors and is very time consuming [15, 23]. Our goal is to significantly simplify this task for human operators. Through the use of XR interfaces, operators can intuitively design and adjust robot trajectories with natural hand movements and gestures, visualized in real time within their physical workspace. This not only reduces the cognitive load on the operators, but also accelerates the trajectory design and testing phases, thereby enhancing overall efficiency in system reconfiguration.

Secondly, our system can capture human operations around the robot cell, which are digitalized and documented for later review. The VSK is by nature a frequently changing environment that is adapted to the needs of a subset of already existing, but also to new manufacturing requirements. In such flexible, dynamic environments, documenting operations (human or not) is a challenging task. Often, to save time, documentation is skipped. As a consequence, knowledge about the required reconfiguration operations is scattered among many operators. Comprehensive documentation occurs only at the end, when the final configurations and processes are determined. By leveraging XR technology, our system can capture detailed recordings of operator actions during their work (reconfiguration), which are then displayed on virtual avatars for future reference or training purposes. This capability ensures that valuable tacit knowledge is preserved and accessible at any time, streamlining the handover of tasks and facilitating the continuous improvement of reconfiguration practices.

Together, these enhancements not only aim to address the current limitations in reconfigurable manufacturing systems, but also set the stage for a more efficient, effective, and human-centric manufacturing environment.

Following this introduction, Section 2 delves into the related work, highlighting the state of robot trajectory planning and recording of human operations for documentation using XR. Section 3 is dedicated to present our system concept, depicting how DT and XR were integrated into the VSK system. The current state of the implementation is detailed in Section 4, including the preliminary implementation results. Section 5 discusses our lessons learned during conceptualization and implementation, and Section 6 reflects on our contribution and outlines future research directions.

2. Related work

To the best of our knowledge, there are currently no support systems that integrate DT and XR technologies to enhance the efficiency of physical processes during the reconfiguration of CPS. While our project is pioneering in its approach, there exists a body of related work that addresses aspects of robot trajectory (re)configuration and the documentation of human operations using DT and XR technologies, which is presented in this section.

2.1. Robot trajectory configuration using XR and DT

Currently, there are various methods for planning robot trajectories, including lead-through programming, offline programming or walk-through programming, and programming by demonstration, to name a few [24, 21]. Gianni et al. developed an Augmented Reality-based system to plan and control the trajectories of tracked vehicles in complex rescue operations[9]. Their system utilizes Augmented Reality for interactive trajectory design directly in the operation field and integrates real-time localization to ensure that the robots accurately follow the designed paths. Similarly, Cai et al. explored the use of Augmented Reality to improve tool path planning in reconfigurable additive manufacturing systems employing multiple robotic arms [3]. Their methodology supports the rapid deployment of robot configurations according to the optimized layouts determined in a DT, showcasing the potential of DTs to facilitate flexible and efficient manufacturing processes. An Augmented Reality interface that significantly enhances human-robot interactions during the task planning phase has been developed by Fang et al. [7]. Their system allows for the real-time modification of robot paths and end-effector orientations, providing interactive visual feedback that simplifies complex task setups.

The objective of all methods is to determine the optimal path for the movement of the robot within its working area, considering its range of motion from the initial point to the destination point [10, 13]. The configuration of robot cells is a challenging, time consuming and critical task [23]. The need for rapidly reconfigurable systems is underlined by the high manual effort that can be involved in reworking individual points. Ostanin et al. demonstrate their approach to programming industrial robots, which allows users to view holographic visualizations of robot movements in the real world [21]. This method offers a more intuitive alternative to traditional programming techniques.

Once the optimal trajectory has been identified, it can be transferred directly to the reconfigurable Cyber-Physical-Human System using the corresponding DT. This ensures that the physical system executes the planned motion accurately and efficiently. Direct transfer of information eliminates the need for manual intervention and reduces the risk of errors, thereby demonstrating immense potential to support trajectory planning in various industrial applications [15, 27, 1]. By extending this approach with a conceptual architecture as described by Häußermann et al. [14], a generic unitwin with flexible reconfiguration design can be achieved, further enhancing its applicability and scalability.

2.2. XR documentation of human operations

XR is the umbrella term that encompasses all immersive technologies, including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). These technologies can be differentiated by their degree of immersion and interaction with the virtual and real worlds. AR enhances the real environment with digital overlays, MR allows virtual objects to coexist within and interact with the real world, and VR offers a completely immersive virtual experience that disconnects the user from the physical environment [19].

For the documentation of human operations, especially those involving 3D or spatial operations within physical spaces, such as during manufacturing reconfiguration, immersive technologies are very suitable. Considering the XR continuum, most related work utilizes VR, such as Wang et al. who present a system that captures collaborative VR sessions where users are represented by abstract full-body avatars [25]. This opens the possibility to relive the VR group experience anytime. They find that users experience a higher level of immersion and social presence compared to 360° video playback, both on VR or on 2D display. However, the playback of the experience is not interactable and users cannot act when watching the playback.

Chow et al. [5] explore a multimodal recording of VR users. Their avatars are simple, consisting of an abstract head, upper body, and hands. In addition to avatars, verbal speech, user interactions with the VR environment, such as object manipulations and teleportation, and annotations are also recorded. During playback, users can still interact with their environment and control playback with functions such as pause and rewind.

In XR-Live, Thanyadit et al. playback a recorded chemistry instructor to students within a user study [22]. They experiment with several visualizations, a duplicate of the workbench with the upper-body avatar demonstrating the experiment, as well as a shadow of the instructor's hands and tools superimposed on the student's workspace. Furthermore, they replaced teleportation of the avatar by a walking animation (although their avatars do not have legs), to make following the instructor easier, and added temporal tools like auto-pause function to create a step-by-step learning as well as a checklist for the tasks. In their validation study, they could reduce the workload and increase the learning performance compared to the avatar-only condition. In the work of Bruza et al. abstract upper-body avatars are also utilized for content creation in education [2]. The avatars can be recorded and replayed, including their interactions with a simple VR environment. Furthermore, they present a feature to create educational 2D videos in the VR environment by defining trajectories for a virtual camera.

Complementary to VR, some works enable user capture and avatar playback in AR and MR. Wang et al. present CAPturAR, which facilitates upper-body avatar capture and a feature of linking recordings to context in AR [26]. For instance, the user can select detected objects and link them with specific recordings. This method can be used to detect user actions and trigger linked events in AR, e.g., start a digital timer. They emphasize that their system can be used for creating demonstrations and tutorials by the avatar. A drawback is the hardware that the user has to carry in a backpack to use the system. Fender et al. present a stationary system within a work space, consisting of volumetric cameras that capture a physical work space and a VR headset to visualize and playback the captures [8]. The volumetric recordings of users can be linked to virtual objects as triggers, as soon as a trigger is touched by the VR user, the corresponding volumetric capture is replayed.

In the work of Cho et al. [4], a social presence user study is presented that compares avatar playback with 2d video and 180°volumetric playback of users. They find that volumetric user representation is best with respect to social presence in dynamic spaces and, together with video, also best for static tasks, where users do not leave their workbench. In their work, they scanned an actor to create a photorealistic avatar, which did not pass through the uncanny valley. Furthermore, the replayed user recording was stationary and not moving through the 3D space, which limits the eligibility of their results regarding dynamic use cases.

Using XR technologies to capture and digitalize humans and their operations adds the human component towards holistic DTs of processes and not just machines or systems. Furthermore, the preservation of these captures opens the possibility of reliving the operations at any time and adds a new possibility to document human work more easily and quickly. In this work, our process towards creating an XR prototype to capture and document human work within spatial physical tasks is presented. Our prototype represents the users by full-body avatars in MR environments. Thus, the virtual objects are visualized within the real environment, and the user can see and interact with both, the physical environment and with the virtual avatars.

3. System concept

With the goal of enhancing reconfiguration processes within CPS, particularly in manufacturing, this work introduces a novel approach, leveraging DT and XR technologies to support human operators. The envisioned support is promising to reduce reconfiguration downtime and initially focusses the two enhancements:

1. Cognitive trajectory (re)configuration assistance to speed up robot programming.
2. Digital documentation of human operations within a physical environment.

An overview of our system is depicted in Figure 2, which includes the Human Operator, CPS, XR, and DT components.

3.1. Cyber-physical system

The *CPS* consists of digital and physical components within an operating environment. Within the VSK use case, the *CPS* is the robotic manufacturing system in the robot cell. For direct

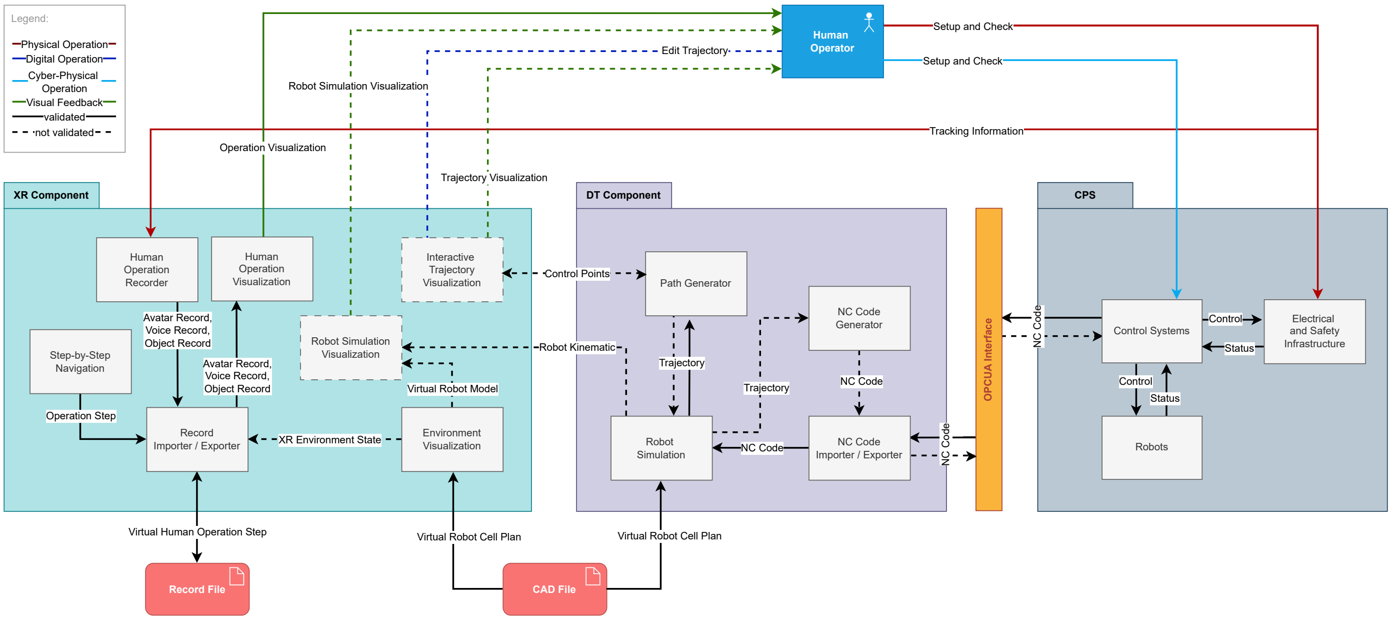

Fig. 2. System overview of the integrated Cyber-Physical manufacturing environment with Extended Reality (XR) and Digital Twin (DT) components. Components that were not validated at the time of this publication are represented by dashed lines.

control, the *Robots* are connected to different *Control Systems*, like the robot control panel, through which human operators can interact with the robots. Operators can also observe the status of the robots via the *Control Systems*, like monitoring software running on a desktop PC. Furthermore, the VSK contains the *Electronic and Safety Infrastructure*, including safety switches, laser barriers, and control displays, with which a human can operate directly.

3.2. Human operator

The *Human Operator* is at the center of our system, operating with the physical and digital environments. Despite a high degree of automation in future CPS, it is unlikely that no human operations will remain, particularly during reconfiguration processes. The more important it is to facilitate intuitive and quick operations with highly complex environments such as CPS, to minimize occurring reconfiguration errors and required time.

As illustrated in Figure 2, the operator can interact directly with the CPS or indirectly through the XR and DT components. In current VSK processes, human operators use the direct CPS interaction to adapt and reconfigure it. With our system, the user instead interacts mainly with the *XR Component* for digital reconfiguration and with the *Electrical and Safety Infrastructure* to perform physical adjustments. By directing the interactions of the operator with the robots through the XR and DT components, we can add support functionalities to simplify and accelerate the reconfiguration process of the CPS.

3.3. DT component

The idea of the *DT Component* is to represent digital information, for instance, robot programs, in a more comprehensive and tangible way for humans. Instead of analyzing the numerical code of a manufacturing program, the DT can simply execute it and show a virtual preview of what will happen. By definition, the state of a CPS and its DT are mirrored. Changes to the CPS occur to the DT, and changes to the DT also affect the CPS in real-time. DT with bidirectional characteristics are also referred to as Hybrid Twins. However, in our context, it is essential to allow digital previews of the changes before they are applied to the CPS. Thus, the DT component will be able to load manufacturing programs and preview them using the DT of the CPS. This allows operators to interact with the visual representation of the DT, and, for instance, visually manipulate programmed trajectories. Without the DT, operators can only use the robot control panel to enter the numerical coordinates of the trajectories point by point, which is a long and error-prone process. With the DT and XR components, trajectories can be visualized in the robot space and manipulated by hand gestures. After virtual validation, the operator can confirm the changes and apply the adapted program to the CPS.

3.4. XR component

XR synergizes perfectly with DT and humans. The idea of the *XR Component* is to enable natural user interaction with DT representations. For example, an operator would use hands to interact with physical objects within the manufacturing environment. However, to interact with digital information, such as trajectories, the operators perform numerical input into the robot subroutine. Operators have to keep track of the CPS coordinate systems and try each coordinate with the robots before finalizing the program. Using the XR component with the DT, operators can see the geometrical virtual representation of the trajectories right inside the CPS space, instead of their numerical representation. Since they do not need to translate into coordinates any more, this frees up cognitive resources that can be useful for preventing errors. In addition, operators can intuitively grab and manipulate trajectories with their hands enabled by the XR system.

Implementation of XR brings another significant addition, the possibility to track and document human operations that are happening inside the physical space. Cyber-physical operations and processes are continuously monitored and can simply be documented within the CPS. However, this is usually only one side of the reconfiguration, as the processes also include adaptation of the physical space, tools, and resources, often done by human operators. Usually, comprehensive documentation of human operations is not easy to implement and is left out or extremely abstract. Our XR component perceives human motions within the physical space and allows them to be captured and reproduced, visualizing virtual replicas of human operators — their avatars — performing the physical operations.

4. Implementation

This section describes the implementation of the DT and XR components, as well as how they interact to facilitate the XR robot trajectory (re)configuration and XR documentation of human operations.

4.1. DT component development

The *DT Component* is implemented in the PolyVR Virtual Reality authoring tool [12]. PolyVR already ships an extendable *OPC UA Interface*, which is used in our implementation to receive Numerical Control (NC) code of the VSK. The NC code is imported and handled by PolyVR's *NC Code Importer/Exporter*, which was extended to be able to parse unique commands in the VSK context. For instance, the importer could already handle standard NC commands such as *F6000* to set the feed rate, *M0* and *M30* for program control, as well as standard operations such as dwell (e.g. *G4 F0.5*). The VSK context adds custom commands, e.g. *TRAORI* to set the tool orientation, *SWS_ZU_OFFEN(1)* to open the clamping device, *Anfahrposi(Roboter_Nummer)* to move a robot to its starting position, *kontaktfahrt(ROBOTER_NUMMER)* to initialize contact drive for the alignment. PolyVR's NC Code importer was extended to parse custom operations needed in our use case. The imported NC program is then passed to the *Robot Simulation*, which creates virtual previews of the robot execution. The *Robot Simulation* includes a 3D representation of the VSK cell, including the robots, and is created from an import of the Computer Aided Design (CAD) model of the cell. PolyVR has a general robot kinematic module that can be added to the most common industrial robots and co-bots. For the Comau robots, an offset had to be added for the joint 1 (connected to the base), to resemble the Comau kinematics.

For virtual representations of the trajectories extracted from the NC code, the *Path Generator* is implemented, which uses PolyVR's path tool. The path tool can be used to define control points and generate and visualize curves through them. On the one hand, the *Path Generator* receives control points of the robot trajectories from the *Robot Simulation* to generate their visualization. On the other hand, it can also receive updated control points by user manipulation of the XR component, to provide visual feedback for the *Interactive Trajectory Visualization*.

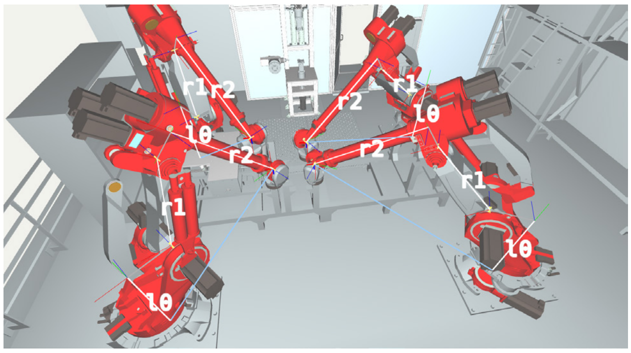

Fig. 3. Digital Twin of the VSK robots with visualization of the adapted kinematics model.

To bring user-adapted trajectories back to the CPS, new NC code, representing the program changes, has to be generated. Therefore, the *NC Code Generator* receives new or adapted trajectories (PolyVR paths) and generates NC executable code. The *NC Code Importer/Exporter* is then used along with the *OPC UA interface* to export the code back to the CPS context.

4.1.1. Preliminary results

Initial testing of the *DT Component* has provided valuable insights into its functionality within the VSK, demonstrating its promising integration potential. Each subcomponent was manually tested to confirm functionality. The system overview diagram (Figure 2) marks incomplete and unvalidated components with dashed lines to distinguish them from fully tested ones.

The CAD model of the VSK was imported into PolyVR, and the adjusted kinematics was added manually to the robots. These adjustments were crucial for the realistic visualization of the robot movements. Additional kinematic meta-information can be visualized, including the joints and end-effector vectors. The results are shown in Figure 3.

For visual testing of the virtual robot movements, mouse interaction was added in the desktop PC mode. Target coordinates for robot end-effectors can be set via mouse click into the virtual 3D environment, starting a robot to move towards the target respecting its kinematics. The target definition will be replaced by control point sequences of the trajectory paths imported from the NC programs.

The NC code interpreter now includes custom VSK operations, which improves the parsing and visualization of trajectories for robot cooperation. This capability is crucial to verify the accuracy of the path planning and to facilitate further integration with the XR component.

The preliminary validation confirms the functionality of the implemented *DT Component*, which adds to the foundation for full integration testing in future work.

4.2. XR component development

The development of the *XR Component* started with the XR capture of human operations, which will be detailed in this section. The implementation of XR trajectory reconfiguration, including the *Interactive Trajectory Visualization* and *Robot Simulation Visualization*, will be added in future work.

In our previous work [17, 18], a basic capture and replay approach of human operations using XR systems was developed, where head and hand poses are captured, as well as interactions of users with virtual and physical objects, and the operations reproduced by replaying these captures using avatars as virtual representations of the user and 3D geometry as representation of the objects. In this work, the previous implementation is ported from Unreal Engine (UE) 4.7 to the newer UE 5.3. In addition, avatars were extended to capture and replay full-body motions. Support for the Meta Quest Pro Head Mounted Display (HMD) was added, enabling both VR and AR representations, registration of the virtual objects in physical space, as well as finger, eye, and facial expression tracking.

For the VSK use case, a passthrough layer was added to enable AR and allow the user to move and interact within the physical environment. The pass-through layer can simply be disabled to switch back to a full VR application. This may be useful in future remote collaboration use cases, where remote operators will see the DT of the manufacturing environment in VR and on-site operators will continue using AR.

To be able to interact with the XR system, a simple menu, containing four 3D buttons, was implemented and added to the user's left hand. When the menu gesture — left hand palm facing up — is performed, the menu is visualized inside the palm. The menu consists of four interactive 3D buttons, which can be pushed with the right hand. While the *Record Button* activates and deactivates spatial body capture, the *Play Button* activates and deactivates the playback of spatial capture visualizing the avatar. With the *Next Button* and *Previous Button*, the user can navigate through the documentation steps. The *Step-by-Step Navigation* is used during the creation of step-by-step recordings to document spatial operations, as well as to replay the documentation.

Since our earlier implementations did not support verbal speech, voice capture, export, import, and replay were added utilizing the Runtime Audio Importer UE Plugin. During the recording, *Human Operation Recorder* captures direct data from the user's XR system, as well as the full-body movement approximation. Once the recording is finished, the motion information is exported to a text file and the voice recording to a .wav file using the *Record Importer/Exporter*. The file naming is constructed from the user's ID and the step number to find corresponding pairs. The files can then be shared with remote users, although the transmission is not handled in this work. The import of the recordings is also handled by the *Record Importer/Exporter* and replayed in the *Human Operation Visualization*, which maps the recorded skeletal joint poses onto the avatar. This enables to see the human operation within physical spaces.

Fig. 4. Human operation documentation with the XR component using the Meta Quest Pro Head Mounted Display. Left: XR view of the user demonstrating a human operation. Right: XR view of a user viewing the human operation performed by a virtual avatar.

The XR component also includes *Interactive Trajectory Visualization* and *Robot simulation Visualization*. However, the implementation of these components is not finished yet and will be published in a later development state.

4.2.1. Preliminary results

During the development of the *XR Component*, the *Human Operations Recorder* and *Human Operations Visualizer* were used to document several critical quality assurance operations within the VSK environment. These operations included the startup of electric cabinets, computers, robots, network systems, and the laser safety barrier, as well as the inspection of safety switches.

The recording process was conducted by a user wearing the Meta Quest Pro HMD while interacting with various controls such as switches, panels, and the verification of LEDs and cables. Each operation was treated as an individual step, resulting in separate recorded files for tracking information and voice recordings, ensuring detailed documentation of each task.

The playback of these operations was similarly tested; a user, equipped with the HMD, viewed the instructions through the device. An avatar representing the user who previously demonstrated the operations was visualized performing the operations within the VSK, allowing the viewing user to simultaneously operate without waiting for the playback to end. The HMD view during the recording of an operation and its playback with the avatar is depicted in Figure 4.

5. Discussion

In this section, we highlight the most significant issues encountered during preliminary testing of our system and provide an overview of key findings. These insights are instrumental in guiding the ongoing development and refinement of the integrated DT and XR components within the CPS.

5.1. Virtual replica of the robots

Our method to create a digital representation of manufacturing robots is fast and straightforward, although there are some limitations. The animation of the model is not perfect. Some parts of the model are not animated, which is most obvious in the gray back part. This issue does not limit the robot simulation, but is an aesthetic concern. Furthermore, the process is not yet fully automated and requires manual preprocessing steps for the virtual replica creation. Depending on the model's complexity, some geometry must be separated for animation, and the kinematic mapping onto the geometry must be adjusted manually. Regarding the Comau robots, as used in the VSK, there is a gray back part that would require additional effort to adapt the model for perfect animation. As the implementation matures, it will be necessary to test how accurately the kinematics-driven animations depict the real robots.

5.2. Registration

Registration in XR refers to the process of aligning virtual objects with the physical world so that they appear in a fixed position in space relative to the user's view. The current system does not provide the possibility to detect physical markers of objects, restricting access to the video stream of the passthrough AR. Typically, specific objects or markers are used in AR to register and align digital elements with the real world [3, 7]. For instance, a physical robot could be superimposed on the virtual robot to show a preview of how it will operate running a specific program. However, the Meta Quest HMD offers a workaround, where the room (walls) and specific objects like tables can be outlined by dummy objects which are fixed to the physical location. This 3D room model can be used as a reference to place virtual replicas. Alternatively, external cameras could be mounted within the CPS, and object positions detected using markers and object detection algorithms. Since the HMD used was capable of recognizing the same room defined by the user, this characteristic was sufficient for the initial tests, but registration should be implemented for future tests.

5.3. Passthrough augmented reality

CPS operations involve interaction not only with physical objects such as valves and switches, but also with cyber-physical elements such as 2D displays and LEDs. In this context, significant passthrough AR limitations of the Meta Quest Pro device were noticed. Analog and digital displays are hard to read through the HMD screens, making it difficult to determine the states and signals of the CPS. On desktops, the mouse cursor and icons are difficult to see, and text cannot be read. Although the used HMD provides color passthrough AR, the color sometimes appears to be offset from the actual object [11], making it impossible to recognize the color of small objects, such as LEDs. For use in the industry, either better passthrough AR hardware should be utilized, or digital replicas of the cyber-physical elements and displays should be superimposed onto their physical counterparts to ensure visibility and readability.

5.4. Human operation capture and replay

Overall, the capture and replay of human operations during the quality assurance process worked successfully, although several issues should be addressed in future work. For instance, the avatar and audio playback are not synchronized at this point, resulting in audio playback outrunning avatar playback. This should be fixed by a synchronization mechanism using timestamps for both streams. However, we encourage recording step-by-step instructions, as proposed in [22]. In particular, many short step recordings are to be preferred over a few long recordings, since they are easier to replace and coordinate. Additionally, in short recordings, the deviation of the streams is insignificant.

5.5. User interface and interaction

The developed hand menu, which contains the function buttons, has advantages but also disadvantages. The strengths are that the menu is always at hand when needed but hidden when the menu gesture is not performed to avoid accidental button presses. In addition, the menu provides self-haptic feedback, as suggested by [6]. However, the interaction with single buttons is not easy and not satisfying fur the users. Furthermore, on the standalone HMD, the buttons' visibility should be improved, as they appear too translucent.

5.6. Avatar

Since we are using a standalone HMD, which provides only 3-point tracking for the head and hands, full-body posture has to be estimated using inverse kinematics and pre-trained posture estimation models. Initially, the UBIKSolver plugin, available on GitHub, was used for upper-body animation, although after switching to a newer development framework (UE 5.3), it stopped working properly and instead the MetaXR v60.0 plugin for the Meta Quest HMD was used for full-body movement. The new plugin also includes an estimate of leg movements. When the user is crouching down, jumping or walking, the corresponding leg animations are triggered. This should not be confused with foot tracking and should not be used to demonstrate accurate foot operations or specific leg movements. In our case, exact leg movements are not important, and the addition of lower-body animations makes the avatar appear more natural.

The presented insights gained from the preliminary tests are foundational for further improvement of the functionality and usability of our integrated system.

6. Conclusion and future work

This paper presented a novel approach that integrates Digital Twins and Extended Reality within Cyber-Physical Systems to improve manufacturing reconfiguration processes. Our system facilitates intuitive trajectory planning and detailed documentation of human operations, effectively reducing downtime and easing the cognitive load on operators.

Preliminary tests have identified critical areas for improvement, particularly in system integration and user interaction enhancement. Future efforts will focus on refining these elements and completing the implementation of the concept presented. Furthermore, we plan to expand the validation of the system in various industrial settings to fully assess its effectiveness.

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