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VIRTUAL ROBOT CONTROLLERS FOR ENHANCING RELIABILITY IN INDUSTRIAL ROBOT COMMISSIONING

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ABSTRACT

This paper addresses the challenges of inaccuracy in digital twinning and offline programming for industrial robotics. Simulations are conventionally used to design and verify industrial robot systems. These virtual environments are often used as Model-in-the-Loop (MiL) simulations; however, they tend to lack accuracy in joint positioning, trajectory planning, and cycle time estimation. This limitation becomes problematic in assembly operations, where multiple coordinated tasks must be executed accurately and repeatedly. The challenge intensifies further in multi-robot cells, which require coordinated actions. To address this challenge, this article proposes a Software-in-the-Loop (SiL) approach that integrates an external robot emulator with a simulation-based digital twin, enabling robot development within a Software-Defined Manufacturing System (SDMS) architecture. A framework for building an SDMS enables precise modeling of robotic systems. The results indicate that the proposed approach is practical for virtual commissioning during new system development and can be extended to operational stages for system reconfiguration.

1 INTRODUCTION

A system is an organized collection of interconnected resources working together to achieve a specific goal. In manufacturing, factories, also known as manufacturing systems, consist of a variety of resources that collaborate to produce final products (Malik 2023). The process of establishing a new factory or modifying its subsystems is often complex, and similarly, reconfiguring an existing factory can be time-consuming and challenging (Kousi et al. 2021). The rise of Industry 4.0 has added new layers of complexity to manufacturing systems, affecting the way information flows and how predictable these systems are (Striffler and Voigt 2023). While today's manufacturing systems aim to be adaptable, reconfigurable, and resilient in response to market changes (Wang 2022), the demand for rapid, accurate system development and reconfiguration continues to grow (Jeon and Schuesslbauer 2020).

Commissioning is a key step in developing new manufacturing systems, involving the deployment of equipment on-site and the execution of dry runs to ensure operational readiness. Despite its importance, this phase often presents significant challenges that can delay project timelines (Lechler et al. 2019). Empirical data reveals that issues arise during commissioning, such as integration failures, unforeseen logic errors, and hardware-software mismatches. These complications hinder the development of manufacturing infrastructure and contribute to the extended time to market for new products (Konstantinov et al. 2022).

Virtual commissioning (VC) offers a method for testing and validating manufacturing systems early in the design process by creating virtual models of complex systems (Dahl et al. 2016) (Striffler and Voigt 2023). This process involves developing detailed virtual models, such as kinematic simulations, logic control systems, and behavioral models, to replicate the real-world system closely. However, the complex architecture of industrial robots and the diversity in manufacturer-specific designs introduce limitations in the accuracy of virtual models in their simulations. These discrepancies reduce the overall reliability of the virtual commissioning process. Furthermore, the broader goals of virtual commissioning and digital twins to enable offline programming and generate a validated control program are also impacted. The gaps between virtual models and actual robot behavior often necessitate manual adjustments after deployment, thereby diminishing the efficiency and potential of the VC process.

A digital twin (DT) in manufacturing is a digital representation of an Observable Manufacturing Element (OME) that updates in sync with its physical counterpart (ISO 23247 2021). OMEs can encompass a range of components, including equipment, materials, processes, personnel, and environmental factors. A digital twin offers a dynamic, real-time representation of these elements, facilitating better decision-making and improving manufacturing operations (Shao et al. 2024).

Unlike traditional simulations, digital twins incorporate real-time data, lifecycle connectivity, and a certain level of intelligence, which allows them to evolve and adapt in line with the physical system they represent (Shao et al. 2023). These simulations are typically large-scale and polymorphic, providing accurate and realistic representations of systems in real-time. While the benefits of implementing digital twins are considerable, the required resources and investment can vary significantly depending on the DT's intended purpose and scope (Grieves and Hua 2024). These DTs are used along the system development lifecycle of manufacturing systems and automation technologies to address complexity.

Virtual Robot Controllers (VRCs) are vendor-specific robot emulators that accurately simulate robotic systems (Tola et al. 2022). However, they typically do not account for extended peripherals, human interactions, or production estimates, which are key components of a system-level digital twin of a robotic manufacturing system. By interfacing a VRC with a robot digital twin, a dual simulation environment can be created, allowing the digital twin to calibrate itself against the robot emulator for enhanced accuracy continuously.

This paper investigates the potential of integrating VRC in a Software-Defined Manufacturing System (SDMS) and enhancing the accuracy of robot behavior. These reliable SDMS or DTs can be utilized for offline programming (OLP), virtual commissioning, process validation, and logic program verification. Through a case study and experimental analysis, the paper illustrates how incorporating VRC into a DT can increase the reliability of robot system design and redesign processes.

The key contributions of this study include:

1. Proposing a structured framework for integrating VRC into robot digital twins.
2. Demonstrating the integration of robot simulation with VRC and event-driven simulation to enable precise robot programming.

2 ROBOT SYSTEM DIGITAL TWIN

This section outlines the primitive building blocks that can constitute a digital twin for industrial robotic systems, as shown in Figure 1. Simulating these components often requires a combination of specialized tools (Malik et al. 2024). Integrated methods now allow for near-synchronous data exchange among these elements, thereby enabling the construction of a trustworthy and resilient DT system.

2.1 3D Modeling and Virtual Layout

Establishing a virtual manufacturing setup begins with developing a three-dimensional model through computer-aided design (CAD) tools. Several software tools can be used for this task. Vendors of specialized equipment, such as robots, grippers, and fixtures, often supply standardized CAD models in STEP (Standard for the Exchange of Product Data) format (Malik et al. 2024). These models may also be available in simulation software libraries that provide both proprietary and generic representations of factory components.

An essential step in this process is to assemble the individual part virtual models into a unified digital assembly that mirrors the physical robot cell. These digital models enable the assignment of material properties, color schemes, and other attributes necessary for subsequent simulation and evaluation stages.

The assembled model may subsequently be transferred into a simulation platform, where motion parameters and dynamic system behavior are specified.

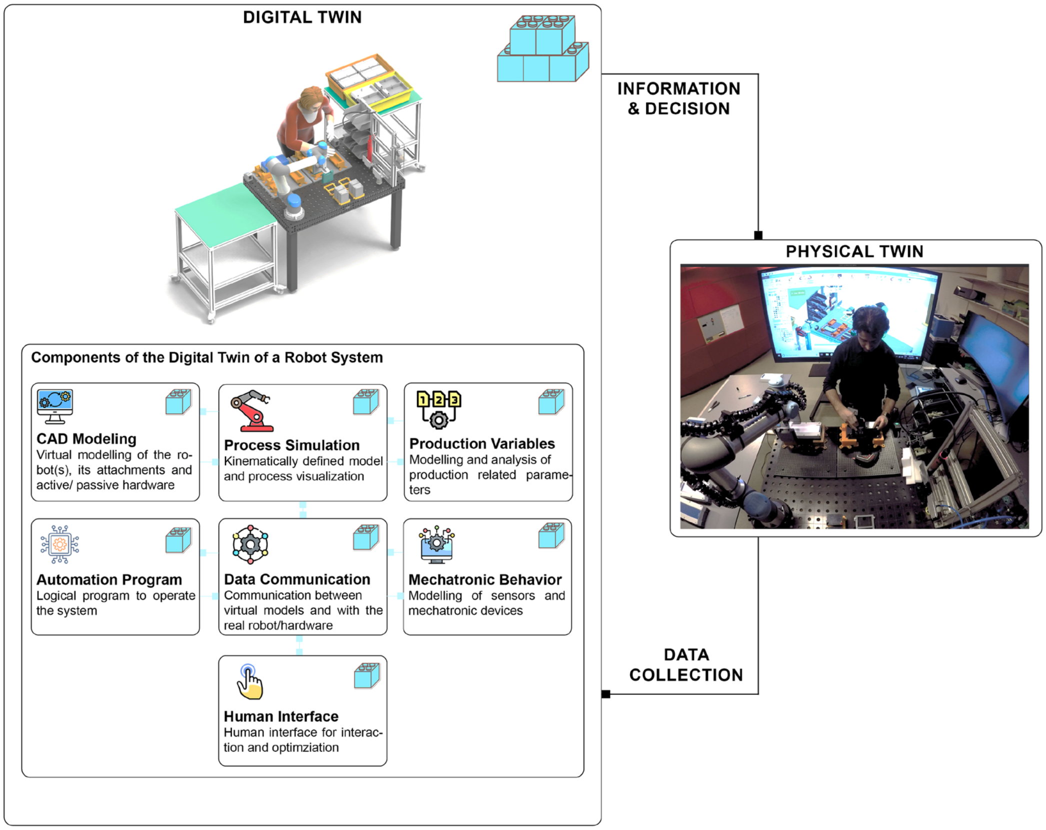

Figure 1: Components of a robot system digital twin (Malik et al. 2024).

2.2 Motion and Kinematic Emulation

Kinematic modeling includes configuring each moving element, defining motion paths, constraints, joint types, operational ranges, and velocity parameters. This process can be categorized into three phases. First is process planning, where operations are sequenced in a structured manner, much like constructing a Gantt chart to represent task flow and dependencies. Next is the logical simulation phase, during which the simulation is time-driven and governed by internal logic engines that dictate event progression and system responses. Finally, signal-based control is established by integrating the simulation with virtual programmable logic controllers (PLCs) and other relevant tools, enabling synchronized interaction between system components for realistic emulation of industrial behavior. This digital environment serves as the primary space for DT-driven analysis, encompassing visualization, collision checks, layout studies, and performance forecasting. Both commercial and open-source platforms support such simulations.

2.3 Automation Logic Integration

PLCs are the brains that control an automation system. Logic programs are developed, tested, and refined during the development and commissioning to match the actual robotic cell's operations. Although this programming is often done in the later development stages, virtual integration of control logic with simulations offers greater fidelity to real-world behavior.

PLCs from various manufacturers come with programming environments, although interoperability is generally governed by the IEC 61131-3 standard, which forms the structure and syntax of automation programs. These virtualized controllers can be embedded in the simulation loop, enabling live interaction with process models.

2.4 Behavioral Emulation of Mechatronic Devices

Incorporating accurate responses from physical devices such as actuators, sensors, feeders, or jigs requires behavior modeling. The Functional Mock-up Interface (FMI) standard provides a cross-platform framework for embedding dynamic behavior within simulations. FMI packages include model definitions, executable binaries, and interface protocols in standardized formats, allowing co-simulation across various software environments. Both proprietary and open-source solutions can simulate and link device behavior with broader system simulations.

2.5 Production Parameters

Though not always essential, integrating production metrics into a robotic system DT enhances its usefulness for operational analysis. Stochastic simulations model parameters such as throughput, equipment failure rates, repair times, and human resource shifts in this layer. These require separate toolsets that complement deterministic simulations. Simulations can capture operational and idle times across a multi-station, human-robot collaborative packaging line. Statistical trials using historical datasets can be conducted to evaluate how design and operational choices affect system productivity and resilience.

2.6 Operator Interfaces and Virtual Interaction

Human-Machine Interfaces (HMIs) serve as the interaction point between workers and automated systems. Commonly deployed via touchscreens, HMIs allow personnel to issue commands, receive alerts, and fine-tune parameters. These interfaces should be replicated virtually and linked to the simulated process for digital twin fidelity. A virtual HMI, aligned with ISA-101 guidelines, can be designed to mimic the physical interface and tested for usability and functional correctness. Such interfaces can be deployed on desktop screens or mobile devices and interact with PLCs and simulation environments in real-time. Once validated, the HMI design can be downloaded to actual field devices.

2.7 Data Communication and Information Flow

One of the defining features of a digital twin is the continuous fusion of physical data into the digital model. This capability supports ongoing assessment and model refinement. Robotic systems often use a variety of sensors to collect data on positions, operations, errors, and safety events. For example, a collaborative robot cell using a UR-5 was connected to a cloud platform to log real-time performance, including idle times, collision incidents, and completed cycles. These inputs were then leveraged for layout optimization and motion planning.

Data governance in DTs involves structuring raw data into actionable formats. This includes an acquisition, transmission, storage, processing, fusion, and display lifecycle. Hardware and software components and network infrastructures (wired/wireless) support this flow. Data may be stored using cloud databases, distributed systems, or NoSQL solutions. Final outputs can be visualized through dashboards or immersive technologies, such as augmented or virtual reality.

3 VIRTUAL ROBOT CONTROLLERS

A VRC is a software-based emulation of a physical robot. It emulates the behavior, control logic, and communication interfaces of an actual industrial robot, without requiring any hardware. This enables engineers to test robot programs, motion planning, and system integration in a virtual environment before deploying them on the factory floor (Noga et al. 2022). A VRC executes the same programming languages used on real robots, such as RAPID for ABB, KRL for KUKA, or TP programs for FANUC, allowing developers to validate robot logic in a virtual environment.

A VRC also supports interaction with virtual I/O and communicates with emulated PLCs using standard industrial protocols like OPC UA or PROFINET. This capability enables system-level integration and testing. Additionally, a VRC integrates with simulation platforms such as Siemens Process Simulate, ABB RobotStudio, or FANUC ROBOGUIDE, enabling the performance of collision detection, cycle time analysis, and safety validation. By facilitating early-stage debugging and process verification, VRCs help reduce commissioning time, lower costs, and minimize the risks associated with on-site deployment.

4 INTEGRATING VRC IN A ROBOT SYSTEM DIGITAL TWIN

This section presents the application of VRCs within the DT of a robotic system (Figure 2). The DT architecture includes several components as outlined in Chapter 3. In this setup, each robot within the simulation environment is linked to a corresponding emulator through a VRC server. A key challenge in this implementation is that every robot requires a dedicated VRC instance. For example, four separate VRC instances must run simultaneously in a robotic cell with four robots, each configured with a unique IP address. This requirement increases computational complexity and demands high-performance computing resources, particularly machines with powerful GPUs.

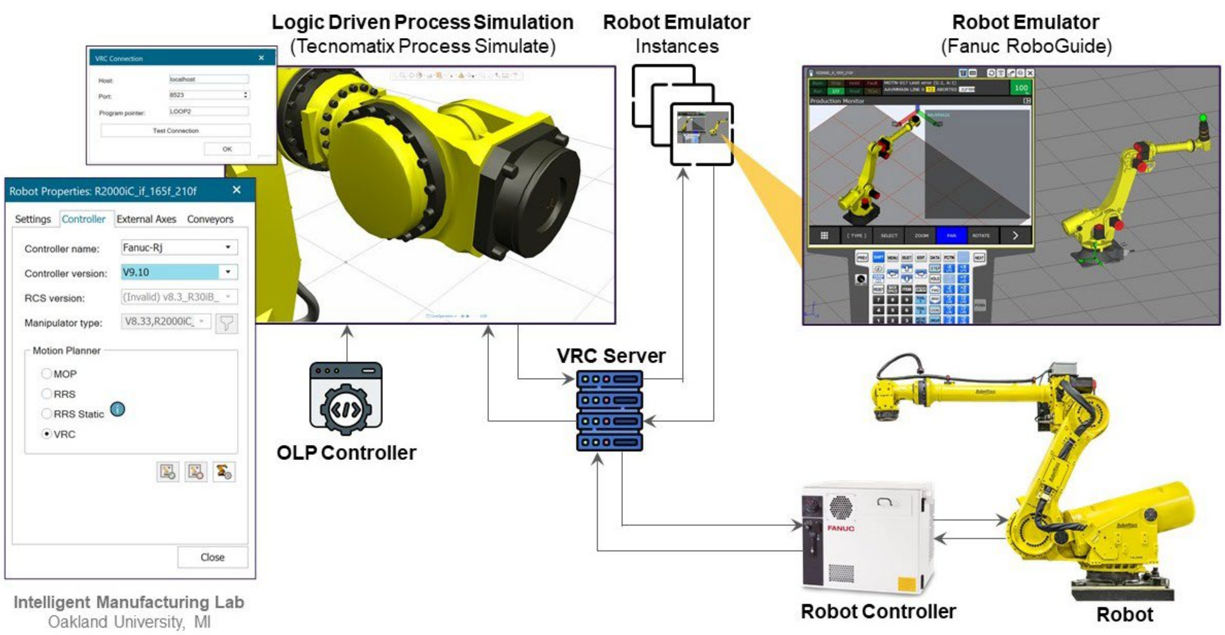

Figure 2: VRC in robot digital twin.

4.1 Primary Robot Simulation

Establishing a digital twin begins with constructing detailed virtual representations of physical equipment used in manufacturing. These digital counterparts must replicate not only the geometry but also the physical characteristics—such as mass, joint configurations, motion constraints, and velocity boundaries—of the real machines. Typically built using continuous simulations grounded in agent-based modeling, these models offer precise movement dynamics. Upon completion, the result is a mechanically accurate, kinematically active digital model of the system. Key evaluations such as collision risks, spatial layout, and timing analysis can be performed at this phase. Numerous commercial platforms support such modeling, while game engines like Unity or Unreal Engine also offer open-source alternatives for creating interactive environments.

Creating this type of simulation involves a three-stage progression. First, a foundational model is developed, along with its task execution order, which is typically managed in a timeline similar to a Gantt chart. The second phase transforms this setup into a continuously looping process where the model runs autonomously as long as predefined logic conditions are met. Finally, the model reaches an advanced fidelity by integrating with virtual or physical PLCs, enabling near-real-time decision-making through signal-based interactions.

4.2 Simulated Industrial Controller

Programmable Logic Controllers (PLCs) are central to executing automation programs within industrial systems. Traditionally, programming these controllers takes place after the physical equipment has been assembled and is ready for commissioning. However, under the digital twin paradigm, automation logic is developed and tested with system design. This pre-validated code can be deployed in real PLCs later, significantly reducing commissioning time and minimizing errors during deployment.

4.3 Operator Interaction Interface

To facilitate interaction between human operators and manufacturing systems, Human-Machine Interfaces (HMIs) are employed. These features enable users to issue commands, monitor performance, or adjust parameters such as operational speed. In this digital twin framework, HMIs are recreated virtually, allowing users to interact directly with the simulated model. These can mimic touchscreen panels in industrial settings or take more advanced forms such as augmented reality overlays, mobile apps, or wearable tech. Importantly, the virtual HMI developed here can be later implemented in the plant environment without redesign.

4.4 Emulated PLC

Once the control logic has been configured and tested within the virtual PLC, it is loaded into a digital controller that emulates the real-time execution of that program. This controller manages communication with the virtual mechanical setup without physical connections. It relies on a digital processing core and simulated communication protocols, such as virtual Ethernet. Interfaces like PLCSIM Advanced facilitate interaction across different software platforms, while standards like OPC UA and MQTT enable seamless data exchange between digital assets and control units. The culmination of this integration is a synchronized simulation of mechanical operations and logical control processes, effectively mimicking real-world production behavior in a virtual space.

5 CASE STUDY

This case illustrates the implementation of a VRC-enabled DT for a human-robot collaborative (HRC) assembly cell in an industrial environment. The selected system produces battery modules for actuator mechanisms that enable adjustable positioning in hospital beds. Each product unit integrates 15 components across 21 operations, including alignment, quality inspection, orientation, and fastening.

5.1 Virtual Cell Design and Simulation

A digital model of the collaborative cell was created and simulated using virtual commissioning tools. The robot selected for the cell was a Universal Robots UR-5e model, featuring six degrees of freedom, an 850 mm reach, and a 5 kg payload capacity. A SCHUNK EGP 64-N-N-B parallel gripper was modeled for part manipulation, originally equipped with 40 mm fingers. However, due to some components exceeding 120 mm in size, the gripper's capabilities were virtually augmented through custom-designed end effectors, later manufactured using additive manufacturing.

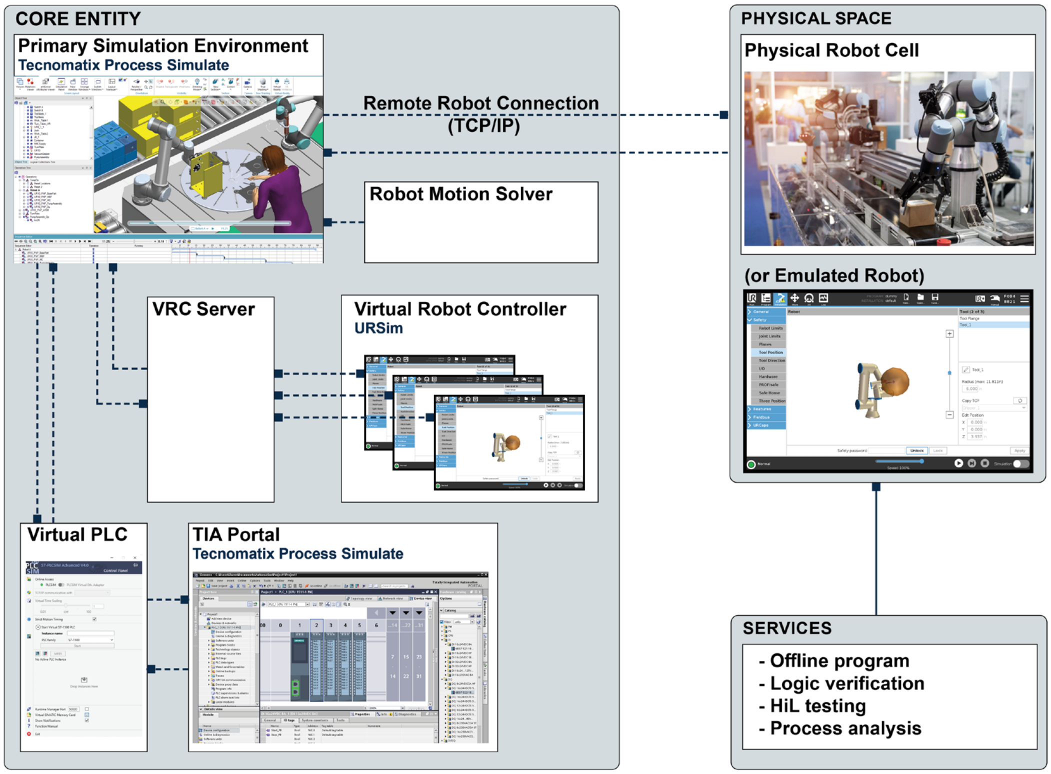

Figure 3: URSim interfaced with robot simulation and TIA Portal.

The VRC provided by Universal Robots, called URSim, was utilized for this study (Figure 3). The simulation model was developed using Tecnomatix Process Simulate, a continuous, event-driven simulation platform. Integration between the virtual robot in Process Simulate and the URSim environment was established through a VRC Server using an IP-based connection (see Figure 4). In this configuration, the simulated robot continuously synchronizes its joint positions and motion trajectories with the emulated controller, allowing for real-time calibration and correction of movements.

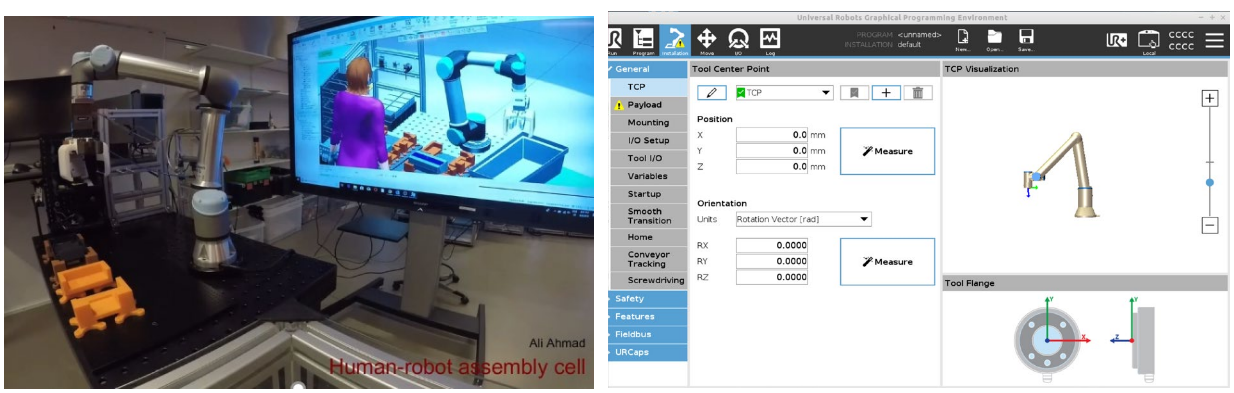

Figure 4 URSim interfaced with robot simulation.

Upon successfully validating the virtual model, the physical cell was constructed to mirror the digital configuration (Figure 5). This physical twin included a modular fixture table housing the UR-5e robot and the upgraded SCHUNK gripper, now fitted with 100 mm fingers and 3D-printed extensions. Fixtures for both robot and human tasks were produced using additive manufacturing, offering flexibility and precision. Additional components, such as a vacuum-based part-handling system and screwdriver tool holders, were developed and integrated, with actuation managed through a FESTO control interface.

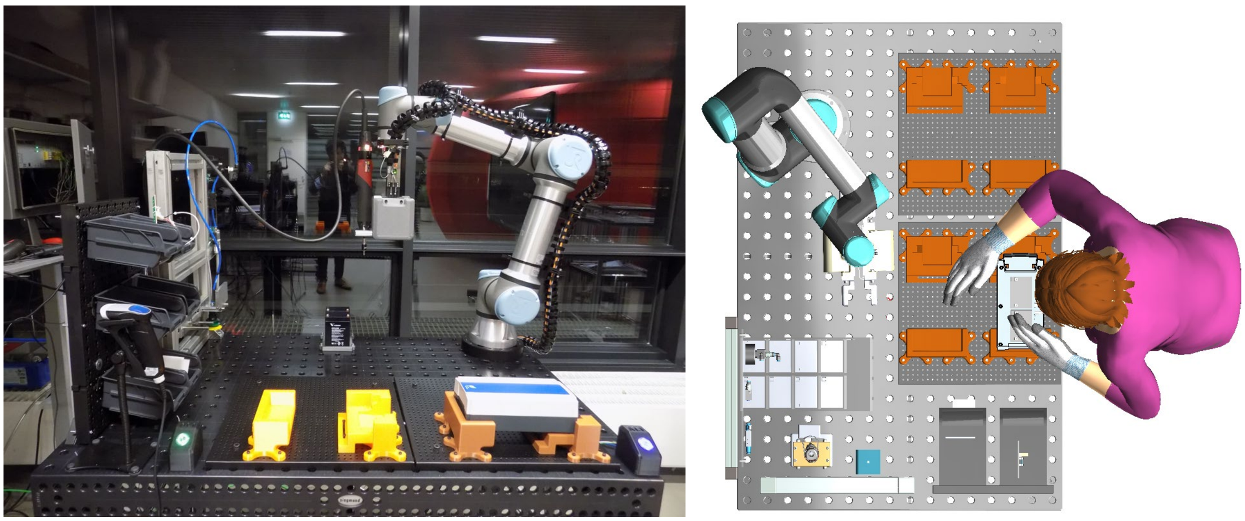

Figure 5: The developed robot system and its simulation.

The deployed HRC cell was conceptualized as a distributed production network where robots and humans operate in close coordination. Advances in computational infrastructure, connectivity, and robot programming environments facilitated real-time task execution and decision-making. The digital twin was continuously updated with live data from the physical twin, creating a bidirectional feedback loop that supported dynamic task assignments within a family of product variants.

This case study represents a single deployment based on specific selection criteria and manufacturing context. While the outcomes are promising, broader generalization requires further experimentation across diverse use cases. In particular, integrating digital twins into collaborative systems must account for cultural factors, such as region-specific interpretations of gestures or social cues, which can influence safety and collaboration efficiency.

6 CONCLUSION

Integrating Virtual Robot Controllers into digital twin systems enables reliable commissioning of robotic systems in an SDMS. This study demonstrated how VRCs act as fully functional software replicas of physical robot controllers, enabling early validation of robot programming, motion planning, and system-level integration without requiring physical hardware. When combined with virtual PLCs, HMIs, and mechanical simulations, VRCs enable a high-fidelity representation of real-world operations. It can be used for collision checks, timing analyses, and interaction validations in a virtual space. The case study presented a VRC-enabled simulation environment in Tecnomatix Process Simulate and URSim. This reduced commissioning time and de-risked the deployment process. The modular structure of the DT also allowed for flexible integration of HMIs and control systems. The limitations have been noted that multiple VRC instances are needed in multi-robot environments. Future research should continue to focus on optimizing computational performance, expanding multi-agent synchronization capabilities, and leveraging AI to enable adaptive, learning-based behaviors in virtual environments.

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