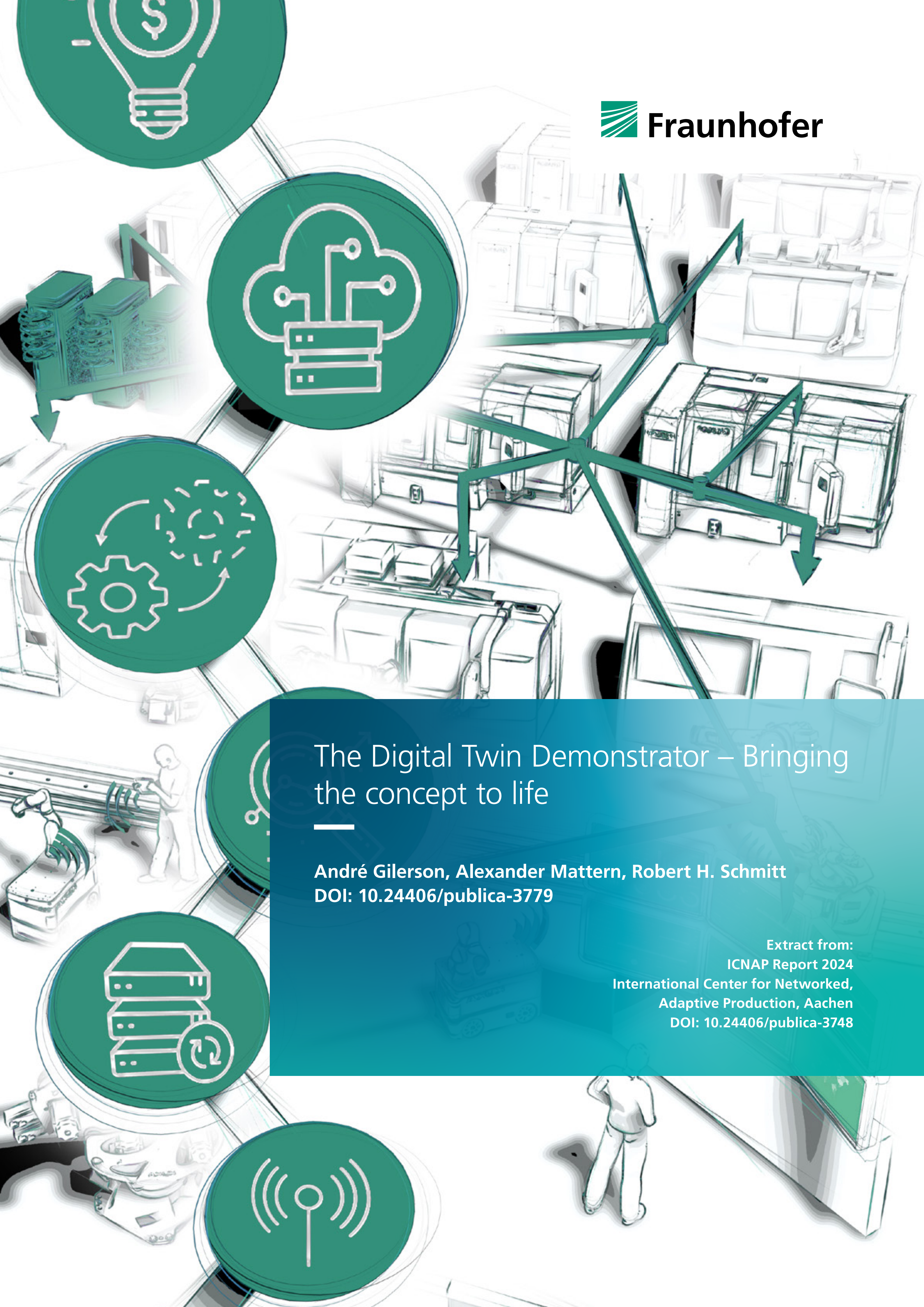

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The Digital Twin Demonstrator – Bringing the concept to life

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Introduction

With the emergence of Industry 4.0 in the 2010s, the idea of digital twins increasingly came into focus. Digital twins were introduced as a concept to create a digital representation of a physical object, machine, or system. The rapid progress of the Internet of Things (IoT) and the availability of powerful cloud computing have further driven the development of digital twins. Even though the first concept of a digital twin has been present for several years, the integration of digital twins in the manufacturing sector still needs to improve. Digital twins are heavily dependent on high-quality and reliable data. If the data used to create and update a digital twin is incomplete or incorrect, this can affect the accuracy and reliability of a digital twin. In addition, not all required data sources may always be available, especially when dealing with older machines or systems that were not designed from the beginning to be integrated into a digital twin. Another challenge is creating an accurate and detailed digital twin. It requires extensive modeling efforts to capture all relevant aspects of the real system. The more complex the real system, the more difficult it can be to include all details in the digital twin, which can lead to modeling simplifications or approximations. Further, scaling a digital twin to large systems or complex production environments can be challenging. Therefore, the scalability of digital twins is an issue that must be considered during implementation.

The Digital Twin Demonstrator – Bringing the Concept to Life study is a follow-up study on the 2023 digital twin study. The 2023 study focused on laying the foundations for digital twins in manufacturing. The Fischertechnik Learning Factory 4.0 was used as simple hardware to demonstrate the concepts and serves as the physical model for the demonstrator. It was selected by the ICNAP community during last year's study based on two main requirements. First, the physical model needed to come preassembled for ease of setup. Second, the actuators must be controlled using industrial-grade hardware to demonstrate the transferability of the digital twin to industrial use cases. In this case, the Learning Factory 4.0 uses a Siemens S7-1500 PLC . Although most of the actuators are not industrial grade, the Siemens PLC allows us to implement the demonstrator using industrial hardware, reducing the gap between the demonstrator and real-world use cases. As a result, the 2023 study implemented a digital twin utilizing the Asset Administration Shell as a data bride and Unity and Realvirtual.io for their visualization and simulation capabilities of the digital twin. However, essential concepts for a digital twin, such as controlling the physical asset through the digital twin, were not completed in the 2023 study. This was the motivation to create a 2024 study.

In the 2024 study, we continue working on the Fischertechnik digital twin demonstrator by expanding last year's study to support new use cases and features. Building upon the foundations laid in 2023, our focus in 2024 is on completing and extending the demonstrator to explore new technological applications within the realm of Industry 4.0. The previous study successfully created a digital twin demonstrator, highlighting key benefits and addressing challenges in integrating digital twins within manufacturing environments. Chapter 4.2 summarizes its content. This year's study aims to go further by implementing a cloud-based control system, introducing a collision warning mechanism, and developing a product defect notification system.

Integrating cloud-based control allows for enhanced remote management capabilities, ensuring greater scalability, flexibility, and real-time oversight of production systems. By leveraging cloud technology, manufacturers can monitor and adjust system parameters from any location. Furthermore, cloud connectivity paves the way for integrating advanced data analytics and artificial intelligence to optimize manufacturing processes.

Another key innovation in this study is developing a collision warning system. This feature is designed to increase safety and reduce risk in the manufacturing process by using data to detect potential hazards in real time. By accurately predicting collisions, the system can provide timely alerts, ensuring that machine operators or automated systems can take preventive action, minimize damage, and maintain production flow.

Additionally, the product defect notification system represents a significant advancement in quality control. This feature enables real-time detection of product anomalies during manufacturing, ensuring defects are identified and addressed early in production. This improves product quality, reduces waste and rework, and contributes to more sustainable manufacturing practices.

This follow-up study evolves last year's demonstrator. We aim to highlight how digital twins can improve production processes, reduce downtime, enhance safety, and improve overall product quality by addressing critical use cases such as cloud-based control, collision detection, and defect notification. The findings from this extended demonstrator will provide valuable insights into the future of digital twin applications in the manufacturing industry, offering practical, scalable solutions to complex industrial challenges.

Summary of the 2023 study

The 2023 study concentrated on implementing the backend dataflow of digital twins, aiming to showcase the advantages of open, standardized, and machine-readable digital interfaces. The central element in this setup is the standardized interface, realized through the Asset Administration Shell (AAS) deployed on a BaSyx server, as depicted in Figure 11. This interface centralizes data exchange, making it easily manageable and updateable. The AAS offers several key features:

1. **Asset registration:** The BaSyx Server allows assets to be registered in the AAS, capturing relevant information such as identification, properties, functions, and relationships.

2. **Asset management:** It manages assets throughout their lifecycle, including capturing changes, managing updates and versions, and tracking asset-related events and activities.

3. **Asset provisioning:** It makes assets available for other components within the Industry 4.0 environment, enabling seamless interaction and integration.

4. **Metadata management:** It manages metadata of the assets, including descriptions of attributes, interfaces, states, events, and other relevant information.

5. **Security and access control:** It implements security measures to ensure confidentiality, integrity, and availability of the assets and the AAS, providing access control based on defined permissions and roles.

The standardized interface facilitates modular and independent interaction of software components, simplifying development, maintenance, and integration of new or replacement components. This modularity also allows for the decoupling of data protocols, enabling a centralized data bridge component to dynamically translate between different protocols.

This approach empowers companies to seamlessly leverage software components from various developers, as they can interact without extensive infrastructure adjustments or protocol bridging. The demonstrator illustrates this by using different database technologies tailored to data structure requirements. For static data, such as digital product

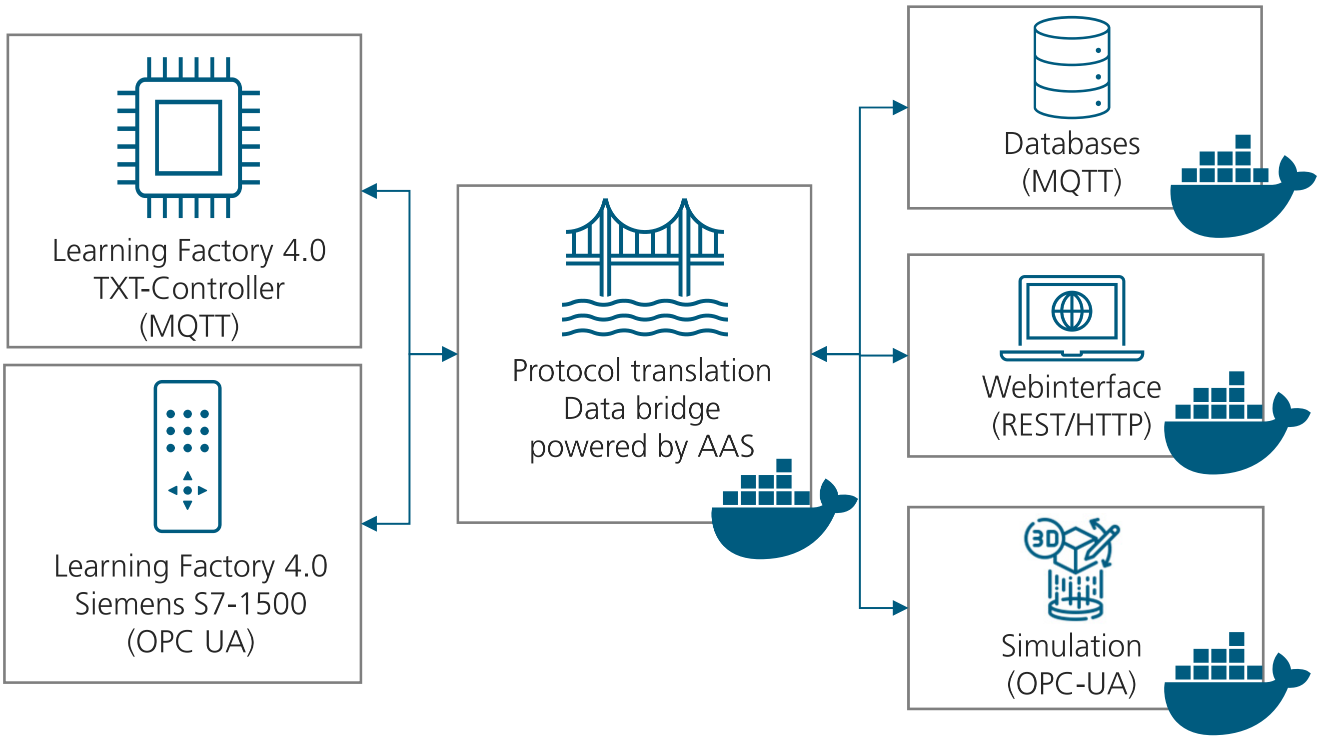

Figure 11: Data flow inside the digital twin demonstrator.

datasheets or production planning, MongoDB is employed, while dynamic, time-series-based data required for simulations is stored in InfluxDB. Both databases are hosted within their own Docker containers, with the AAS registry serving as the sole access point. The semantic description of sensor data from the Fischertechnik Learning Factory 4.0 allows the database to automatically determine the most suitable storage solution.

The results study emphasizes the benefits of a standardized and centralized data interface in creating scalable and adaptable software systems, enabling efficient and seamless integration of diverse components in the digital twin ecosystem.

Motivating the use cases for the digital twin

During this year's study, we extended the functionality of the digital twin. Chapter 4.2.2 discusses the study goals that were planned together with the ICNAP community. Based on the goals, use cases are derived and presented in Chapter 4.2.3.

Goals of the study

Together with the ICNAP community, we defined and prioritized the study's objectives based on their specific interests in digital twin use cases. During the meeting, four main objectives were proposed to guide the development and implementation of the digital twin demonstrator: Complete the 3D visualization of the Learning Factory 4.0 in the Unity framework; Implement a feature displaying machine errors in the digital twin, offering enhanced diagnostic capabilities; Integrate a system to inform users about product defects and improving quality control measures; Achieve full digital control of the hardware through cloud-based systems, allowing remote control and management through the digital twin.

The ICNAP community prioritized finishing the 3D visualization and enabling fully digital control through the digital twin. The third goal, which focused on product defect notifications, was acknowledged as a valuable addition but was marked as a potential option rather than a core priority for this phase. This process of goal setting ensured that the study would focus on the most relevant and impactful developments for the industry partners, with flexibility for future enhancements based on the outcomes of this phase.

In the following chapter, the three use cases are shortly presented.

3D visualization

The 3D visualization of manufacturing processes through digital twins provides an immersive and interactive representation of physical systems, allowing operators to visualize, analyze, and optimize processes in real time. This use case leverages advanced graphics and data integration to enhance decision-making and operational efficiency. The visualization aims to monitor manufacturing operations, including machinery status and production metrics. It seeks to enhance understanding of complex processes through visual representation the operational awareness. Lastly, it facilitates data-driven insights by integrating real-time data from the physical environment, enabling informed decision-making and rapid responses to issues.

The benefits of this 3D visualization approach are significant. By visualizing the entire manufacturing process, operators can identify inefficiencies or bottlenecks that may not be apparent through traditional monitoring methods, facilitating proactive adjustments to enhance productivity. Real time data visualization also allows for immediate insights into system performance, enabling operators to make informed decisions quickly and reducing response times to issues. Furthermore, visualizing machine operations and workflows in a 3D environment helps identify potential hazards, enhancing operator safety protocols and training. Additionally, the immersive nature of 3D visualization fosters better collaboration among team members, as stakeholders can visualize and discuss processes collectively, leading to more effective problem-solving.

Digital cloud-control of hardware
The main objectives of this implementation are to provide remote access to hardware, facilitate real time data exchange, and enable proactive management of manufacturing processes. This digital control system allows operators to adjust machine settings, monitor performance metrics, and respond to issues without being physically present on-site, improving overall productivity.

One of the significant advantages of cloud-based digital control is the scalability it offers. As manufacturing needs grow, additional hardware can be integrated into the cloud system without substantial infrastructure changes. This flexibility allows manufacturers to adapt quickly to changing market demands or production requirements. Furthermore, cloud-based control enhances team collaboration by providing a centralized data-sharing and communication platform. Operators, engineers, and management can access the same information in real time, fostering a culture of transparency and informed decision-making. This collaborative environment also allows for more effective troubleshooting and problem resolution, as stakeholders can quickly identify and address issues.

Machine error notification
The digital twin offers advanced visualization capabilities and can detect machine error states before they happen through simulation technology. This use case lets users test machine programs on the digital twin beforehand. without having to test them on real machines, minimizing the risk of machine failure or damage. During operation, this can also help notify the operator about previous unforeseen error states. This again shows the direct monitoring benefits that digital twins offer the operators.

Product defect notification
The product defect notification system is critical to ensuring quality control within manufacturing processes. By leveraging real-time data analytics and cloud-based communication, this use case enables manufacturers to promptly identify and address product defects, thereby minimizing waste and enhancing customer satisfaction. The primary objectives of this implementation are to provide immediate alerts for product defects and enable data-driven decision-making. By establishing a robust notification system, manufacturers can swiftly react to quality issues, reducing the risk of defective products reaching the market. A significant advantage of the Product Defect Notification system is its capacity for effectively monitoring production quality by combining various data flows within the digital twin. Manufacturers can achieve a holistic view of the production process by integrating data from multiple sources – such as machine performance, environmental conditions, and material specifications. This comprehensive monitoring allows quicker identification of quality issues, as operators can correlate defects with specific machine states or ecological factors.

Technical implementation of the digital twin

3D visualization and digital cloud control of hardware

The technical implementation of the 3D visualization utilizes the CAD files provided by Fischertechnik for the Learning Factory 4.0. While these CAD files contain all components with proper dimensions and placements of the Learning Factory 4.0, they offer no information about the movement capabilities of the components. Instead of creating separate animations for each movement, using regular computer graphics techniques, we implemented a custom movement system based on the established robot joint system, where each separate movement is comprised of six base movement components:

- Rotary joints: Movement around an axis
- Linear joints: Straight-line motions
- Twisting joints: Enabling rotation
- Revolute joints: Single-axis rotation
- Spherical joints: Multi-directional mobility
- Cylindrical joints: Combined movements

This allows us now to actuate each movement via virtual motors, similar to the actuation of the physical counterpart, with the Unity Physics Engine computing the movements of the 3D models inside the digital twin. This approach not only facilitates easier development of the digital twin but also improves the realism of the digital twin by integrating complex motion dynamics simulations without having to incorporate them into 3D animation frameworks. One minor disadvantage of this approach is the visualization's reduced smoothness since all components' positions are recalculated at each time step without blending in between. However, this was regarded as inconsequential as the simulation can still run above 30 fps on a regular desktop PC without high-end graphics hardware, providing the illusion of smooth movement for most components. An example of the UI is shown in Figure 12.

A critical aspect of this implementation is transitioning from a sequential hard-coded PLC code provided by Fischertechnik to a modular code. In the traditional approach, the PLC executes a fixed sequence of operations, which limits flexibility and adaptability. By moving to a modular design, each movement is encapsulated within a separate functional block. This modular approach allows these blocks to be triggered independently through the digital twin interface.

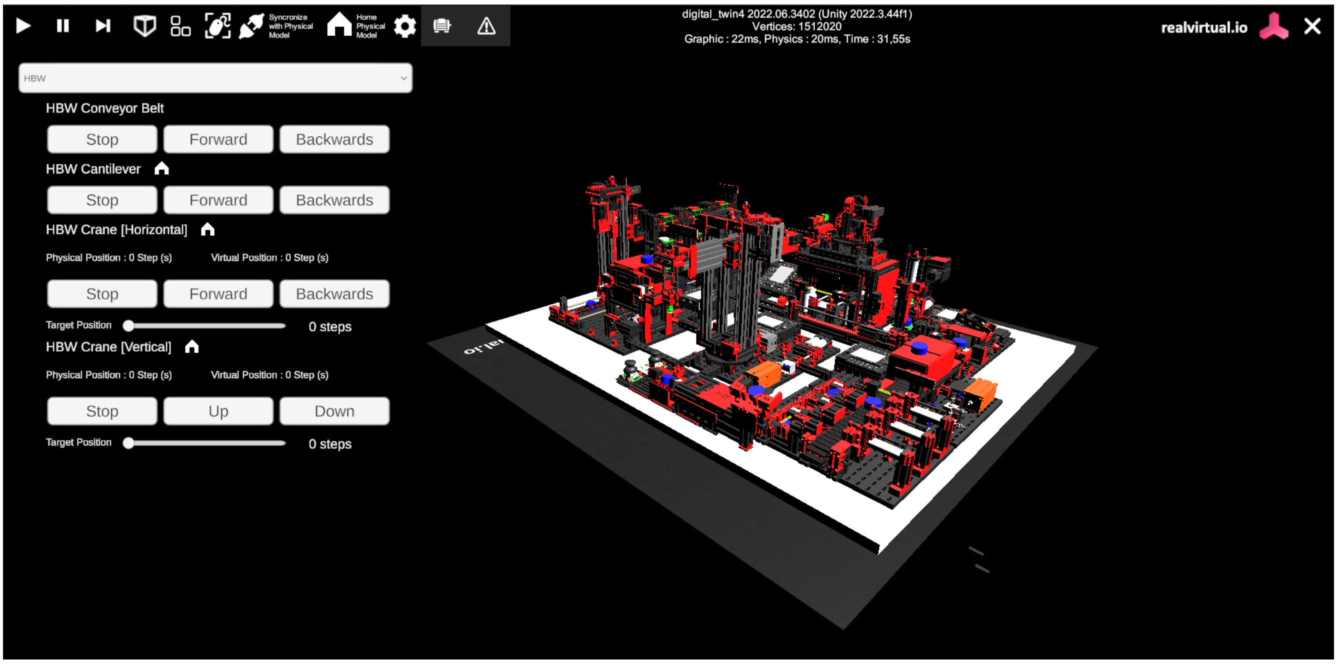

Figure 12: User interface of the digital twin of the Fischertechnik hardware.

The benefits of this modular structure are substantial. Firstly, it enhances flexibility, enabling operators to adjust individual movements without rewriting the entire control program. This adaptability is particularly useful in dynamic manufacturing environments where processes must be altered frequently. Secondly, it simplifies debugging and maintenance, as developers can isolate issues within specific functional blocks rather than navigating through a complex, interconnected sequence. Lastly, this approach promotes reusability, allowing the same movement blocks to be employed in different processes or setups, ultimately speeding up the development cycle. However, limitations are associated with the S7-1500 PLC used in the Learning Factory 4.0, particularly concerning its OPC UA server. The minimal update time for the OPC UA subscription mechanism is set at 0.5 seconds, which introduces significant latency into the system. This delay can hinder real-time responsiveness, making achieving the desired interactivity and fluidity in the 3D simulation challenging. We propose moving from the subscription mechanism to a busy polling system to address this issue. In this configuration, the Unity application will actively poll the appropriate OPC UA variables for each movement at a much higher frequency. By employing separate threads for each movement, the system can independently query the PLC for updates without introducing excessive latency. This design allows for more immediate feedback in the 3D simulation, enhancing the overall user experience and ensuring operators can interact with machinery in real time.

Machine error notification

The machine error notification system is a crucial component of the digital twin that enhances the safety and reliability of manufacturing processes. This system is demonstrated by predicting potential collisions among components in the Learning Factory 4.0 setup.

The implementation begins with creating custom collision boxes for each component within Learning Factory 4.0. These collision boxes are designed to encapsulate various physical dimensions and operational boundaries, such as robotic arms, conveyor belts, and other machinery. By accurately modeling these components, we ensure the collision detection system can effectively simulate real-world interactions. Once the collision boxes are established, the Unity Physics Engine handles

real time collision detection. The engine continuously monitors the positions and movements of the components, checking for intersections between the collision boxes. When a potential collision is detected, the system triggers predefined responses, including notifications to operators, alerts to halt operations, or visual cues in the 3D simulation indicating the impending collision.

Implementing a collision detection system offers several potential benefits for actual industrial processes.

1. **Enhanced safety:** By predicting collisions before they occur, manufacturers can significantly reduce the risk of accidents and injuries in the workplace. This proactive approach to safety creates a more secure environment for operators and machinery alike.

2. **Reduced downtime:** Early detection of potential collisions allows for timely interventions, preventing equipment damage and subsequent downtime. In a manufacturing context, unplanned stoppages can be costly in terms of lost productivity and repair expenses. By minimizing the likelihood of collisions, manufacturers can maintain smoother operations.

3. **Improved efficiency:** With collision detection systems in place, operators can optimize their workflows without fear of unintended interactions between components. This increased confidence can lead to more efficient use of machinery and resources, ultimately driving higher productivity.

4. **Training and simulation:** The collision detection mechanism can also serve as a valuable training tool for new operators. Trainees can gain hands-on experience in managing machinery safely and effectively by simulating potential collision scenarios within the digital twin. This educational aspect enhances skill development while reducing the risk of real-world incidents.

The collision detection system seamlessly integrates into the digital twin framework, allowing real-time monitoring and control. Operators can visualize the current state of the manufacturing process, including any detected collisions, within the 3D simulation. This integration provides a comprehensive view of operations, enabling informed decision-making and quick responses to potential issues. The machine error notification system is designed to be highly customizable, allowing manufacturers to tailor the parameters and thresholds for collision detection based on their specific operational needs. This flexibility ensures that the system remains relevant and practical across various manufacturing.

Product defect notification

An initial challenge we faced was that the Learning Factory 4.0 does not come equipped with sensors that could be directly utilized for detecting product errors. To address this limitation, we adopted the approach of creating simulated virtual sensors. These virtual sensors are programmed to simulate the behavior and data output of real-world sensors that would typically monitor various aspects of the manufacturing process, such as dimensional accuracy, surface quality, and assembly precision. The virtual sensors generate data based on predefined error conditions and scenarios that mimic potential real-world defects.

The AAS framework provides a standardized, centralized interface for managing and exchanging data among various components of the digital twin ecosystem. In this setup, the simulated virtual sensors generate data captured and registered within the AAS. The AAS framework enables real-time monitoring and management of this data by storing detailed metadata about each virtual sensor, including identification, properties, and error conditions. When an error is detected, the AAS triggers an immediate notification, leveraging its robust security and access control mechanisms to alert the right personnel promptly. This integration ensures that all data exchange and error notifications are handled in a modular, scalable, and secure manner, facilitating efficient interoperability among the digital twin components and enhancing the overall reliability of the manufacturing process.

Conclusion

In conclusion, this study builds upon the foundations established in the previous year's digital twin demonstrator study, significantly expanding its capabilities to address critical Industry 4.0 use cases. By integrating cloud-based control, a collision warning mechanism, and a product defect notification system, the digital twin is now more versatile and relevant to modern manufacturing environments. Implementing 3D visualization through advanced modeling and data integration enhances operational efficiency by allowing real-time monitoring and optimization of production processes.

The introduction of cloud-based control adds flexibility, scalability, and real-time data exchange, enabling remote management of manufacturing systems. This promotes enhanced collaboration and faster response times. The collision warning system improves safety and operational flow by detecting potential hazards before they occur, while the product defect notification system supports quality control through early detection of anomalies, reducing waste and rework.

Through these innovations, the study not only extends the functionality of the Fischertechnik demonstrator but also provides valuable insights into the future of digital twin applications. The findings illustrate how digital twins can improve productivity, enhance safety, reduce downtime, and ensure better product quality, offering practical solutions to meet the evolving needs of the manufacturing industry.