Twins Interoperability through Service Oriented Architecture: A use-case of Industry 4.0.⋆

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Abstract

Since Industry 4.0 technologies were introduced, manufacturing processes have continued to evolve with, for example, Artificial intelligence (AI), the industrial Internet of things (IIoT), robotics, digital twin technology, and other cutting-edge innovations to empower intelligent manufacturing processes. Nonetheless, there remain obstacles to integration within and optimization of systems of systems. An open-source micro-service architecture can alleviate these hurdles. To demonstrate interoperability between technologies, we have chosen to conduct our research using a physical training factory from Fischertechnik with different digital twins (DTs). In this paper, one digital replica of the physical factory is implemented using a three-dimensional CAD tool (Siemens NX-MCD), while the second is an information-centric digital twin created using Eclipse Ditto. The work is focused on creating digital twins of individual sections of the full factory to achieve interoperability, incorporating open-source frameworks to achieve interoperability and systems binding at run-time, and adapting multiple protocol communications in twins. This work is in progress and foresees two scenarios as its further development. The first is the digital twin's ability to facilitate predictive maintenance. Secondly, the use of an information-centric digital twin in the loop to constantly monitor the production process in the event of connectivity issues.

Keywords

Digital Twin (DT), Interoperability, Micro-services, Architecture, Eclipse, Arrowhead, Industrial Revolution (IR), Ditto

1. Introduction

From mechanization (IR1.0) to electrification (IR2.0), digitalization (IR3.0), and IT-driven smart solutions (IR4.0), the industrial revolution (IR) roadmap has witnessed changes drastically [1]. Adding smart technologies, especially during the 4th revolution, is a way to achieve its fundamental design principles, such as decentralization, horizontal and vertical integration, interoperability, smart factory, smart product, product & service individualization, real-time capability, service orientation, and virtualization [2]. Technology like the industrial internet of things (IIoT), big data and artificial intelligence (AI), simulation & modeling (digital twins), additive manufacturing, cloud data & computing, autonomous robotics, augmented & virtual reality (AR/VR), cybersecurity, and so on are all contributing to the increasing intelligence of smart factories [3]. With these technological paradigms and design principles in mind, this study has focused on improving the interoperability challenges by combining the physical and digital twins of a physical training factory.

Digital twin technology was introduced to address industrial asset maintenance issues. Being introduced in the early 2000s and later revisited by NASA in 2012, the term "digital twin" became a staple in industry 4.0 [4]. It is defined as a digital copy of an object, system, or process that communicates with its physical counterpart in real time to serve specific applications [5]. It is a tool to bridge the gap between the physical and digital worlds. Integrating the digital world into the loop of a production line, the need for manual labor goes down, and mobile management becomes possible [6]. A digital twin has several definitions and interpretations, but one thing needs to be consistent, the digital model needs to be integrated. Without integration between the two worlds, what is left, is just a digital model. As digital twin technology grows in popularity, more work must be put into making it flexible and adaptable to meet the needs of different industries. Some of the identified bottlenecks are model creation, interoperability, and data synchronization [7].

Interoperability is one of the important aspects of Industry 4.0. It is the ability of two or more systems or components to exchange information and to use the information that has been exchanged [8]. With the usage of a broad range of protocols and technologies in manufacturing sectors, interoperability between the various industrial components has grown to be a significant challenge [9]. Many industries use the proprietary solution to achieve integration between different components in

TKTP 2023: Annual Symposium for Computer Science 2023, June 13-14, Oulu, Finland
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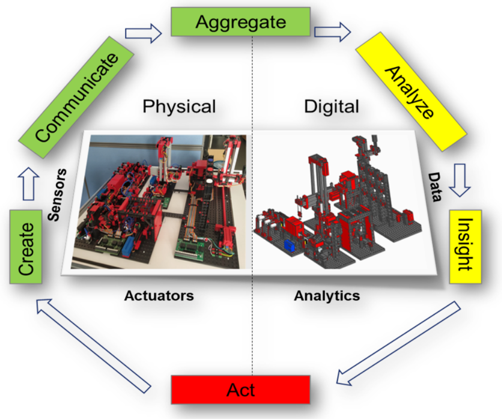

Figure 1: Digital Twin Implementation Architecture (adapted from [5])

the factory. Thus, the requirement for open-source interoperability frameworks and platforms has emerged.

For the clarification of the role of DT in several sectors, profuse consortiums and committees like Industrial Internet Consortium (IIC) [10], Digital Twin Consortium [11], and Platform Industry 4.0 [12] provided a definition. Followed by the definition, several aspects that must be considered are information models, connectivity to the physical twin, data ingestion techniques, APIs, security, and interoperability of DT. Industry 4.0 associated organizations [13, 14] pivoted on industrial entities' adoption of DT technologies based on existing industry 4.0 standards. There is an inexorable need for Open standards and open source implementations as well as the adoption of these standards to expedite DT development within or across different enterprises [14]. Many open-source communities such as Apache Software Foundation, Eclipse IoT, Linux Foundation, and many more have gained the role of a valuable technology supplier to the smart manufacturing and software industry. Present practice in the industry is that DT platforms are built as closed systems (not open source) limiting the overall primacy of smart manufacturing [15]. Therefore, this article steers the discussion of open-source DT solutions to make them more accessible to a broad academic and industrial research community. There are multiple options available to build/deploy DTs as cloud enterprise solutions such as Azure DTs, AWS DTs, and IBM DTs; industrial solutions such as Bosch's DT solution, and GE Predix; and vendor agnostic OSS frameworks such as Eclipse Ditto, Swim OS, iModel JS.

Studies on industry 4.0 practices, existing interoperability scenarios, and the introduction of various open-source platforms, in the context of DTs, have opened various attributes such as DT-modularity, DT-interchangeability, DT-accuracy, DT-interoperability, DT-flexibility, DT-scalability, DT-reusability, and many more [16] are combinedly taken into consideration to find the research gaps related to digital twins. In this article, the main research concern has focused on the interoperability aspects of digital twins. A six-step approach, suggested by Deloitte Insights [5], was followed to deploy the digital twin of the physical factory, also presented in figure 1. The work presented in the paper covers the create, communicate, and aggregate steps (marked green in the figure 1), whereas the other steps are still in progress (marked yellow in the figure 1). However, the complete action of interoperability (Act) is not achieved yet and hence marked as 'red' in the figure. The main highlights of the work are as follows:

- Development & Demonstration of digital twin of a manufacturing unit.
- Incorporation of the open-source digitalizing framework (Eclipse Arrowhead framework) to achieve interoperability and systems binding at run-time.
- Adaptability of multiple protocol communications
- Creating digital twins of individual sections of the entire assembly to demonstrate interoperability among digital twins in the future.

In this paper, the background and motivation for the research work were mentioned in section II. Section III has demonstrated the experimental setup. Results and discussion related to the research work were outlined in section IV. Section V has summarised the work and proposed two scenarios as the extension of this research work.

2. Background

2.1. Creation of Digital Twins

2.1.1. Graphical Type

Digital twins are widely used throughout the industry. However, the meaning of the word varies a lot depending on the context. One rule that applies to all digital twins is the interaction with the physical twin. A graphical digital twin adds, in addition to the aspects of a digital twin of another kind, the visual simulation of its physical twin.

Properties such as gravity, collision, mass, and inertia need to be considered. Depending on the main objective of the digital twin the range of inclusion amongst the physical properties will vary. Having no connection to the real world the model can not be considered a digital twin and will instead exist solely as a virtual model of its physical counterpart [17].

Creating an interchangeability twin requires interoperability between the physical twin and DT with the goal of its scalability and re-usability. Simulating a digital twin in real-time requires a lot of computational power and will hence demand simplifications within the model [18].

There are many different programs suited to creating a digital twin, all with each its own niche [19]. Ansys has properties that benefit computational mechanics while NX and Catia have their main use when working with mechanical construction. NX MCD is a good mechatronics application in NX that allows the model to connect to external signals from varying sources and has therefore been used in this use case [20].

2.1.2. Information-centric Type

Beyond CAD models, digital twins can be created with tools such as NVIDIA Omnipresent, Microsoft Azure, Eclipse Ditto, and many more [21]. Rather than focusing on 3D/2D visualizations, such platforms make information-centric models that mimic the attributes and features of a physical object or process. Such digital twins can also be created using the application programming interfaces (APIs) [22]. Some of the digital twins were built using an open sensor manager (OSEMA) and open platform communication unified architecture (OPC-UA)-GraphQL wrapper [23]. In some cases, document-based digital twins are also created to control smart factories [24]. The advantages of these digital twins over CAD-based twins include their flexibility, modularity, and scalability. In this work, Eclipse Ditto [25], is used to realize the information-centric twin of the factory.

Most industries and component suppliers use proprietary engineering tools and information processing systems for product development in IIoT systems. Intercommunication or interoperability among different systems or applications is thus required to exchange mutual information. So far, only a few works of literature addressing interoperability issues have been discovered. In literature [26], a customized mapping model is proposed, which translates the proprietary ABB Ability digital twins to the Asset Administration format. It targeted to enable interoperable digital twins by transforming the information models. It demonstrated a real-world application using ABB devices as a use-case with some facets of interoperability achieved through files and APIs using model transformation. The implementation, however, still needs to achieve complete digital twin interoperability. Recently, literature [27] has proposed twins interoperability artifacts to establish communication between products and production systems. Nevertheless, the question remains: 'How to represent products, components, production resources, and relevant infrastructures virtually by their digital twins and make them inter-operate.'

Because of technological advancements, manufacturers are no longer limited by the physical design of the machines. Instead, hybrid simulation environments give an advantage in visualizing overall processes and end products before production. Cost-cutting and efficiency-boosting strategies are crucial for businesses of all stripes in today's highly competitive global market. DTs, or High-Fidelity virtual protocols, are gaining popularity due to the following aspects:

1. Real-time monitoring enables quick task planning & building accurate testing environments.
2. Predictive Maintenance of the real assets.
3. Allow the operators to get hand-in-experience on virtual machines before handling the real machines.
4. Pre-diagnosis and fault detection of goods before their production.
5. Optimization of the performances of physical assets.

The real challenge for an original equipment manufacturer (OEM) is to find a standardized method for assembling various physical components from multiple vendors. If digital twins of each part can interact the same way they do in the real world, the existing manufacturing system will be much more robust, advanced, time-consuming, and error-prone. As a result, the interoperability of DTs is critical for developing such multidisciplinary engineering competence. Interoperability here means that data and information can be transferred from the physical twin to the digital twin, from the digital twin to another digital twin, and from the digital twin to the real assets, as depicted in the figure 2. PT, in figure 2, is the Physical Twin.

2.2. Need of DT Interoperability

2.3. Eclipse Arrowhead Framework

The Eclipse Arrowhead Framework is an open-source, local cloud-based industrial framework that provides interoperability solutions in Industry 4.0.[28]. This is built on SOA (Service Oriented Architecture) and promotes late binding, loose coupling, cyber security, and multi-stakeholder integration. The framework allows run-time communication between systems within a local cloud or between systems registered in different local clouds. To facilitate interaction between systems, it provides three mandatory core systems. The mandatory core systems are:

1. the *Service Registry* which records the services currently being offered,
2. the *Authorization* system that controls system-to-system authorization at a detailed level for secure service exchange,

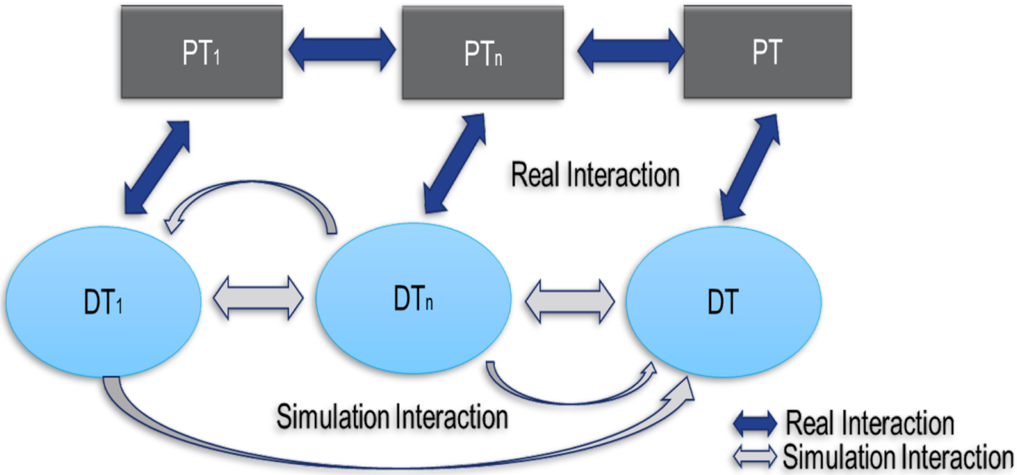

Figure 2: System-of-Interest Interoperability Scenario using DTs

3. the *Orchestrator* that enables the consumer application to discover the required service endpoint at run time.

In order to facilitate inter-cloud communication, the framework also offers supporting core systems, such as the *Gateway* and *Gatekeeper* systems.

3. Experimental Setup

The prototype factory, procured from Fischertechnik Gmbh [29], includes four stations, the high-bay warehouse, the sorting line, a vacuum gripper robot, and a multi-process station. Parts of the physical factory have been disassembled to allow measurements to be taken. The measurements are brought into the NX modeling application and applied to sketches. 3D models are extruded and generated from the sketches, this way the digital model will hold the same proportions as the physical counterpart [6].

The individual parts created in the modeling application are brought together with the help of the NX assembly application. By creating an assembly the parts can be copied and constrained together. The assembly is divided into four sub-assemblies representing the four stations in the physical factory. By dividing the main assembly it is easier to maintain the safety of the assembly and not constrain it in a wrong fashion [6].

By bringing the assembly to NX MCD, NX allows the user to assign communication with external sources of communication. To assign physical aspects to the model rigid bodies and collision bodies are defined and constrained by joints created by the user. Creating internal signals and mapping these to the external sources of signals the digital twin is bound to work like the physical counterpart [6].

3.1. About the Factory

An important aspect to take into consideration is the presence of objects and/or functionalities that are harder to determine than simple movements. The factory includes both sensors and actuators that somehow need to be represented in the digital twin [29].

3.1.1. Sensors

The factory holds two different kinds of sensors, color sensors, and light barrier sensors. The color sensor that this particular factory holds is located in the Sorting Line section of the factory [10]. The goal of the sensor is to determine in which pocket the product should end up. The light barrier sensors act as position sensors to update the position of the product and make sure that there still is a product in play.

3.1.2. Actuators

Actuators in the factory are used to mark certain positions of the machines. An example of the use of actuators is to home a machine. There is a certain position that is always marked with actuators [10]. The machine moves until it notices an actuator being pushed, it then knows that the machine in question is home and does now contain a sort of reference point. There are actuators on every axis for every moving machine in the factory.

Each station in the factory will be connected with a ribbon cable to a programmable logic controller (PLC) that handles the logic operating the factory. With the use of Siemens's totally integrated automation (TIA) or other Structure Language Text program, the logic is compiled and downloaded to the PLC. In this case, to compile and run codes, TIA Portal is used. However, the logic and interfaces used to program the PLC may vary since many companies use their proprietary software.

4. Results and Discussions

4.1. Digital Twin Modelling

4.1.1. Graphical View

The complete digital model of the digital twin is illustrated in figure 3. As mentioned in section *Experimental Setup* the factory consists of four stations, and like so, the digital visualization is also put together. The model receives signals from a simulated PLC which runs the same code as the physical twin.

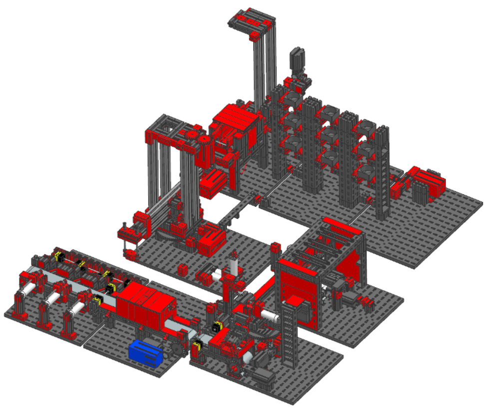

Figure 3: Illustration of the full assembly model in NX-MCD tool.

This use-case covers the possibilities of real-time applications, and it is, therefore, crucial to making the simulation as fast as possible to reduce the amount of delay. As a result, the conveyor belt is heavily simplified. Figure 4 illustrates accepted simplifications for the application.

4.1.2. Information-centric View

Eclipse Ditto is used to create the factory's information-centric digital twin. The only part of the assembly that has been worked on so far is the high-bay warehouse. The steps for making the digital twin are shown in the architectural diagram in figure 5. The data models for the factory parts were written in javascript object notation

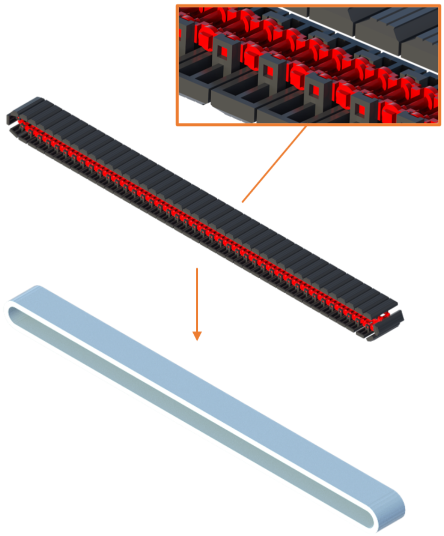

Figure 4: Simplification made to a conveyor belt in NX-MCD tool[6].

(.json) files and are stored as "things." Similarly, JSON files were created for policies and connectivity; an example is shown in figure 5. This research is ongoing, and a full-fledged digital twin of the factory is being developed.

4.2. Multi-protocol communication

After creating the 3D model of the factory, the goal was to simulate the digital twin with respect to the physical factory. This was achieved through the external signal configuration feature in NX MCD. There are multiple technologies like OPC UA, OPC Data Access (OPC DA), Shared Memory network (SHM), Matlab, PLC Simulation (PLCSIM) Advanced, Transmission Control Protocol (TCP), UDP, Profinet, Functional mock-up Unit (FMU), and Virtual Machine (CMVM) that can be used to map signals to the DT. In our experiment, we used protocols like OPC UA, TCP, and PLCSIM Advance to simulate the DT as shown in figure 6.

4.2.1. OPC UA

OPC UA is a standard for the exchange of data or communication between different devices in the industrial sector and IoT applications [30]. The high-bay warehouse part of the factory was connected to a Siemens Simatic ET 200SP PLC with an OPC UA server in it. The sensor and actuator signals from the PLC were mapped to individual nodes of the OPC UA server. Once the OPC UA server is added to the signal configuration and the input-output nodes are mapped to the sensors and actuators in the 3D

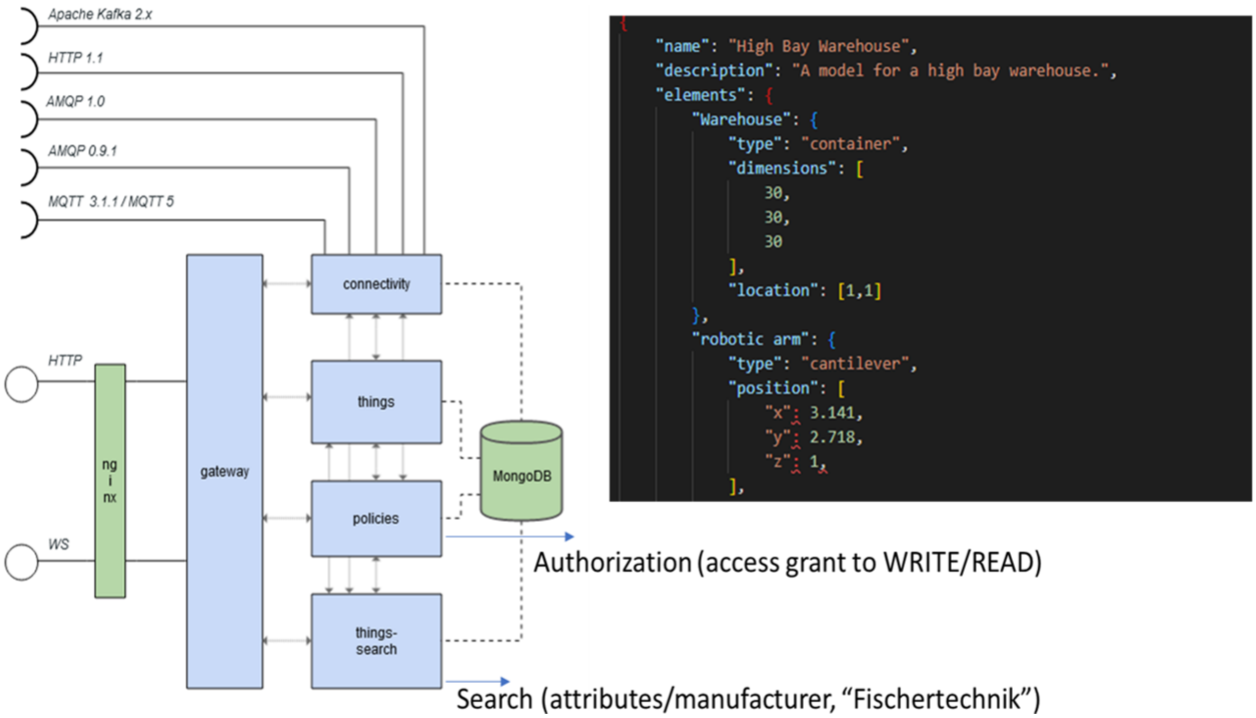

Figure 5: Illustration of the creation of Ditto model along with its Architecture [25]

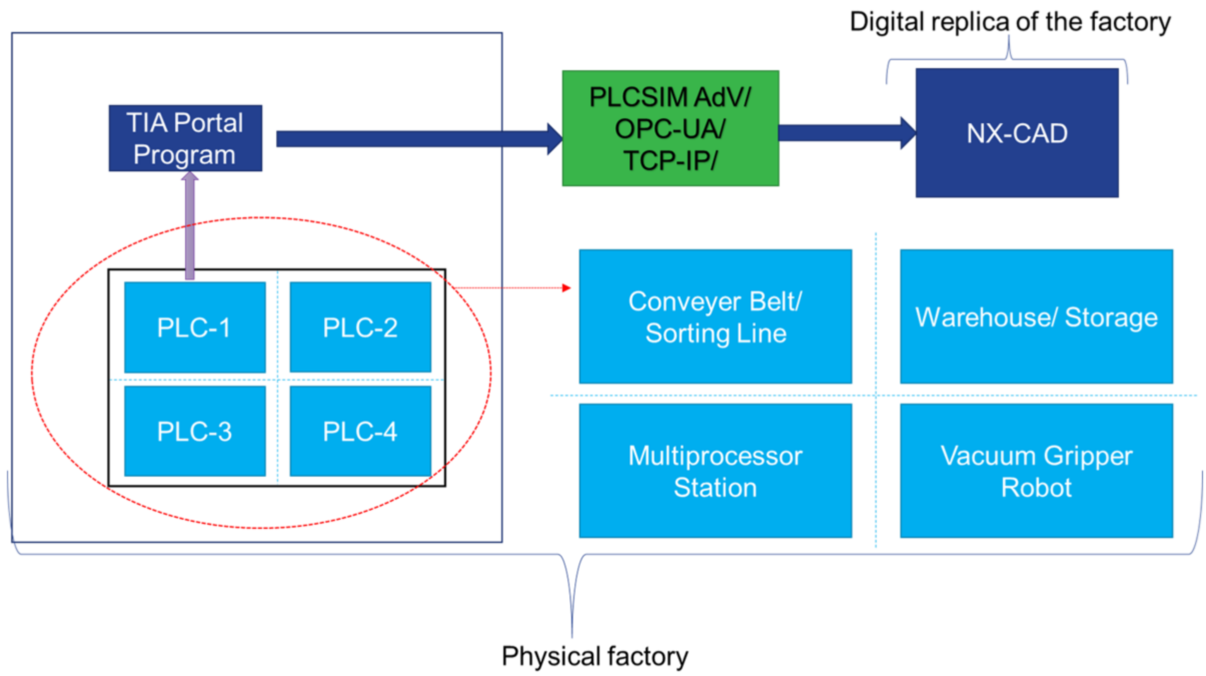

Figure 6: Communication Architecture Diagram

model, the DT components are machined concurrently with the operation of the actual factory as a result.

4.2.2. TCP

Transmission Control Protocol, or TCP, is a communications standard that enables computer hardware and software to exchange messages over a network. It is meant to transfer packets across the internet and make sure that data and messages are successfully sent through networks. The digital model of the factory is able to communicate through TCP. Once a TCP server is created the model is able to act as a TCP client and connect to the data. The structure of the data sent through the TCP protocol is handled as a byte array where each byte is related to a specific I/O. By mimicking the logic created in structured language the digital model operates in a similar fashion.

4.2.3. PLCSIM Advanced

PLCSIM Advanced is Siemens's own simulation of a PLC. The virtual simulation acts identically to a real PLC and can connect to a digital model just as a physical machine can connect to a PLC. Taking advantage of PLCSIM Advanced it is possible to make sure that the two twins operate identically.

4.3. Incorporating Open source IoT Platform

To achieve interoperability among twins (both physical and digital twins), our solution is to extract microservices out of the digital twins into a common IoT platform. We aim to use the Eclipse Arrowhead Framework as the IoT platform that enables interoperability between systems operating on different technologies and protocols. In our use case, each twin will be an Arrowhead complaint application system, that offers micro-services to read the status of all sensors and actuators. Now, with the Arrowhead service exchange architecture, the Arrowhead complaint application systems of the twins can exchange information irrespective of the protocols they are using.

An inter-cloud communication between the Arrowhead systems is demonstrated in figure 7. In both local clouds, the mandatory core systems such as the *ServiceRegistry*, the *Authorization System*, and the *Orchestrator* are running along with the supporting core systems *Gatekeeper* and *Gateway*. DT Cloud 1 has an application provider system for the document-based DT as a proxy from Eclipse Ditto, that keeps track of the historical data for the factory's sensors and actuators. DT Cloud 2 has 3 application systems, including one for the physical twin, one for the graphical DT, and a consumer SCADA system to monitor the factory. Both the physical twin system and the graphical DT system can provide microservices to read the status of sensors and actuators and write values to the actuators. The SCADA system can communicate with all 3 provider application systems and keep track of all twins and make decisions based on the status of the factory and DT.

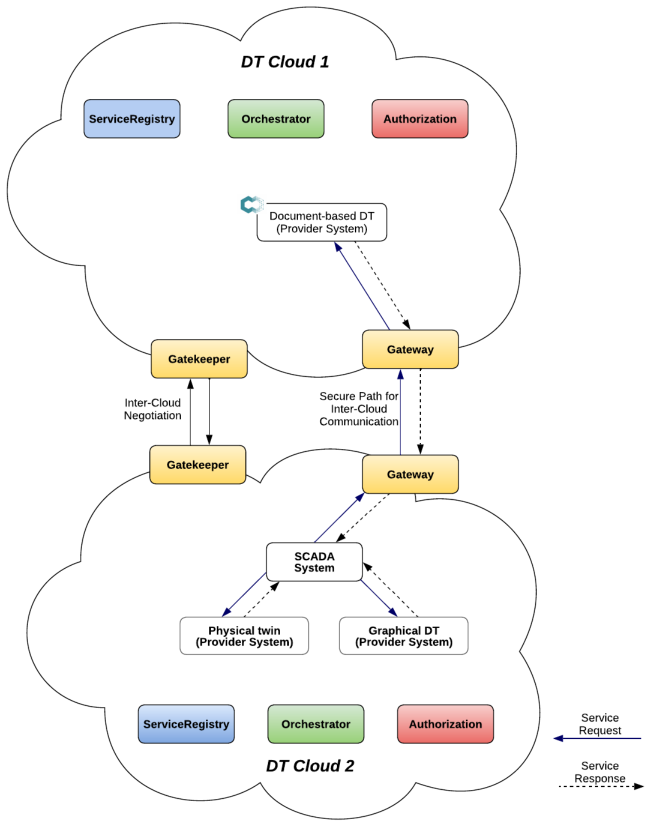

Figure 7: Arrowhead Inter-cloud Communication Scenario for Interoperability.

4.4. Full Assembly of the Factory

In this work, the 3D model of the factory has been built. The full assembly can be divided into four parts: conveyer belt, multi-processing station, vacuum gripper robot, and high bay warehouse. Each piece has its replica, as shown in figure 8. Each part can be communicated with its physical twin using the earlier protocols. The further target is to incorporate different communication protocols for each piece and achieve interoperability among the digital twins. The document-based twin (ditto model)

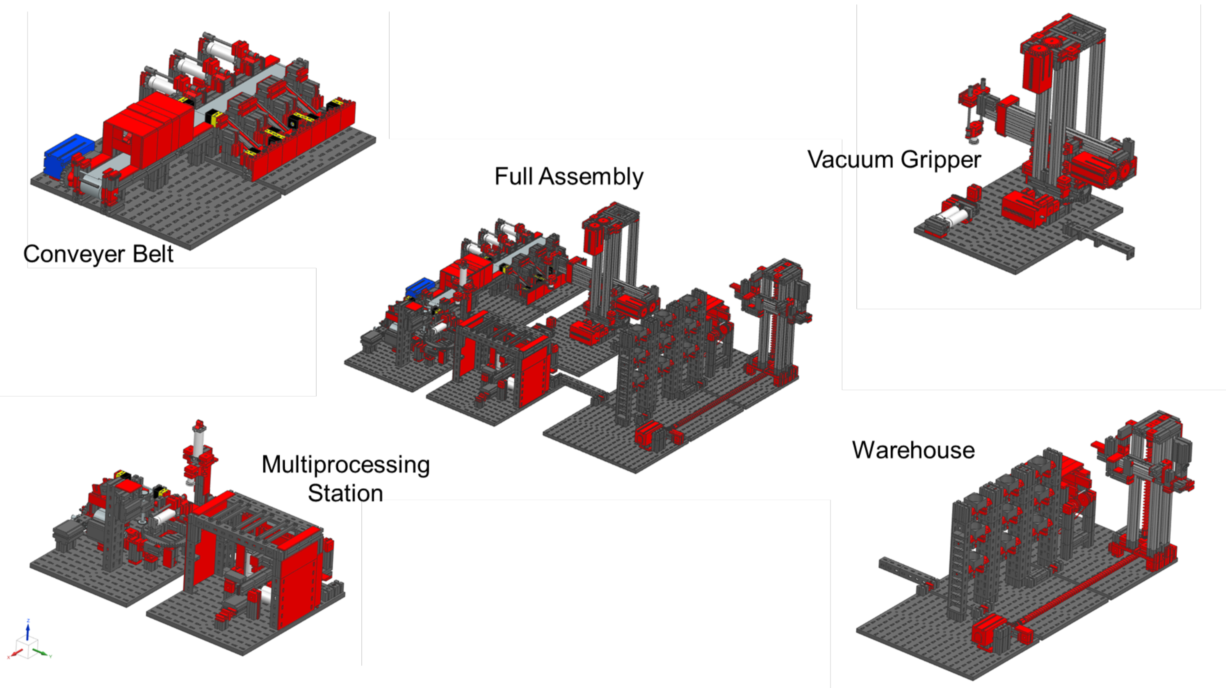

Figure 8: Four Individual Digital Twins of the Fully Factory Assembly

of each component will also be in-loop to demonstrate interoperability between different types of DTs.

5. Conclusion and Future Work

In this article, we have presented the initial results of building a digital twin of a physical training factory. A six-step approach is adapted to accomplish the use-case scenario, as shown in figure 1. The digital replica of the physical factory is created using two open-source tools, one with three-dimensional CAD (Siemens NX-MCD), which is of graphical type. We also created an information-centric view or document-based digital twin of the same factory using Eclipse Ditto. The communication in the digital twin framework has been established by incorporating open-source frameworks, system binding at run-time, and adaptability of multiple protocol communication. Digital twins and predictive maintenance are the perfect pair as DT technology ushers the exact replica in the digital format of a process, product, or service. As a further extension of this work, we propose two use-case scenarios. With the emergence of IoT and DTs, there is a need for a predictive maintenance model that optimizes the maintenance cycle and balances between a corrective and preventive maintenance approach. Another use-case scenario of the information-centric DT is to constantly monitor different processes, especially the production process in the event of connectivity issues i.e. with minimal connectivity it can propagate the message across and the system will have an updated information-centric view of the actual physical system at all times.

Acknowledgments

The research work is carried out under the project 'Operational eXcellence by Integrating Learned information into the AcTionable Expertise (OXILATE) sponsored by ITEA 3.0. This is a collaborative work between the University of Oulu, Finland, and LuleåUniversity of Technology (LUT), Sweden. The authors would like to express their gratitude to Prof. Jerker Delsing for using the Laboratory and resources at LUT. The authors would like to thank Fischetechnik Gmbh for providing the training factory.

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