Digital Twin Architecture of a Cyber-physical Assembly Transfer System

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Abstract: In recent years, the introduction of Internet of Things ready devices set new standards in the exploitation of Industry 4.0 related concepts. The growing complexity of Cyber-Physical Systems makes industrial machinery to be more connected, interoperable, and controllable. Hereby, topics such as edge/cloud computing, cyber security, and sustainability are gaining considerable importance. In this scenario, the Digital Twin paradigm aims at establishing a safe and seamless integrated data flow from the physical world to the virtual one and vice versa, ensuring a constant optimization of the system and its real-time monitoring. This work aims to design and implement a DT architecture for a cyber-physical intelligent manufacturing line. The implementation of a DT node for a flexible transfer line allows users to simply interface it with other systems, such as collaborative and traditional industrial robots as well as to enable the smart routing and tracing of shuttles. The development of the technological demonstrator has been conducted at the Smart Mini Factory laboratory of the Free University of Bolzano.

1 INTRODUCTION

The rapid advancements of technology make the interconnection and communication of smart devices over the Internet possible. In addition, the storage capabilities and processing power of these devices increased while the size could be reduced. Smart devices have the capabilities of real-time data monitoring, accumulation, saving and processing (Grieves, 2014). Internet of Things (IoT) is a technology which is rapidly growing and offers various functions and applications in many domains and in everyday life. IoT aims at linking the digital to the physical world while letting devices and people connect anywhere, anytime, with anyone and anything (Barricelli et al., 2019) (Negri et al., 2017) IoT and specifically Industrial Internet of Things (IIoT) together with automation and digitalization are seen as enablers of Industry 4.0, the so-called fourth industrial revolution (Grieves, 2014). Industry 4.0 stands for a combination of industrial practices and traditional manufacturing with these new technologies such as the aforementioned IoT (and/or IIoT) and, among others, new machine communications and Cyber-Physical Systems (CPS). CPS are highly integrated and interconnected systems including interacting networks of computational and physical components (Kritzinger et al., 2018). Meaning, a CPS typically consists of a digital part, e.g., data or software, and a physical part, e.g., a machine or device. The state of the physical part is represented by the cyber part which impacts it by automated control (ISO, 2002). Digital Twins (DT) are reciprocally synchronized and connected via actuators and sensors and the term stands (Bellman & Landauer, 2000). The DT of CPS presents a medium

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to manifest, visualize and control a physical twin (Vernadat, 2007) and enables companies to cope with nowadays challenges such as ever more fast-paced complex and uncertain boundary conditions .

After the introduction in the current Section 1, Section 2 focuses on a theoretical background of modularity in DT. Therefore, the DT paradigm and the interoperability and scalability of DT applications are presented. Subsequently, the conceptual framework of standard modules for DTs is presented in Section 3 and exemplary application is shown in Section 4. Following, a discussion is conducted (Section 5) and a conclusion and outlook is presented (Section 6).

2 THEORETICAL BACKGROUND

2.1 The Digital Twin Paradigm

The fourth industrial revolution set new standards for industrial environments thanks to the introduction of innovative technologies including, but not limited to, the Internet of Things (IoT), Cyber Physical Systems (CPS), Big Data analytics, and simulation. Furthermore, thanks to the deployment of AI features, computational systems have gained significant power, being more capable, more robust, and more efficient. The concept of DT rises following the integration of the above-mentioned technological aspects and their coexistence. The first formalization of the term “Digital Twin” has to be attribute to Michael Grieves, who formalized it in 2014 (Grieves, 2014). Even though many different definition has been provided (Barricelli et al., 2019), a generally valid one, applicable to the industrial sector has been provided by (Negri et al., 2017) and defines the DT as “a virtual representation of a production system that is able to run on different simulation disciplines that is characterized by the synchronization between the virtual and real system, thanks to sensed data and connected smart devices, mathematical models and real time data elaboration. The topical role within Industry 4.0 manufacturing systems is to exploit these features to forecast and optimize the behaviour of the production system at each life cycle phase in real-time”. This definition can be further elaborated introducing the concepts of Digital Model (DM) and Digital Shadow (DS) (Kritzinger et al., 2018), that differ from the DT given their level of integration. A DM physical world and its virtual counterpart are not connected, meaning that the information should be collected and transported manually from one world to the other. The DS is characterized by an autonomous data collection feature, but still requires the human presence to transfer the data back, from the virtual environment to the physical world. Finally, the DT is characterized by a fully integrated virtual environment, which enable an autonomous data flow in both directions.

2.2 Interoperability and Scalability of DT Applications

Integration may be understood as the necessary steps that allow a body of disparate systems to be treated as a whole, so that it can be understood, monitored and controlled (ISO, 2002) (Bellman & Landauer, 2000). In what refers to digital systems, where information plays a key role, interoperability is required, intending that each system must be able to use and process the information produced by another system (Vernadat, 2007). This poses several challenges that spans different layers of the digital structure of the system that we desire to integrate (Lin et al., 2015). At its deepest, this involves the nature of the data representation at chip-level and the internal use and meaning that each software gives to data. However, this complex dimension is often simplified by the communication interfaces and protocols that systems expose to successfully communicate. However, these interfaces are rarely homogenous among system types and generations. As a consequence, achieving interoperability poses the challenges of designing a communication solution among disparate systems.

As it is remarked in (Rojas et al., 2017), interoperability needs to be implemented at different layers of the OSI model (Zimmermann, 1980) and can be classified into technical, syntactic and semantic. With technical interoperability, we refer to the capacity of exchanging raw and autonomous sequence of bites. Syntactic interoperability is associated with data formats, i.e., the symbols represented by such sequences of bits. Finally, semantic interoperability is the capacity of exchanging meaning between systems. Semantic interoperability depends on syntactic interoperability that depends on technical interoperability. Among all existing solutions to achieve technical interoperability, Ethernet has become a de-facto choice in industrial systems (Yang et al., 2005) that implement the OSI 1 and 2, 3 and 4 layers. If follows that Interoperability solutions are mainly syntactic and sematic interoperability solutions that depends on the architecture and the intended use of the system as a whole.

We underline that interoperability is a key feature to achieve three key conditions for integrability (Gössler & Sifakis, 2005), as displayed in Figure 1. On the one hand, compositionality, i.e., that the behaviour of the system is predictable from the behaviour of its components. On the other hand, composability, i.e., that the properties of a component do not variate when it is placed inside the system. In fact, interoperability allows exchange the data required to the coordination and orchestration of system components. In addition, this enables system scalability, in the sense that allows adding new components to the system with new functionalities.

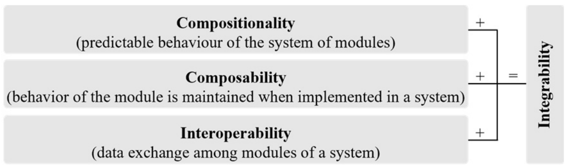

Figure 1: Compositionality, composability, and interoperability as elements of integrability.

3 CONCEPTUAL FRAMEOWORK OF STANDARD MODULES FOR DIGITAL TWIN

In this section the authors aim at proposing an inclusive definition of standard modules for DT application. A number of examples of modular DT application is available in literature, while a clear, shared definition of module is missing yet. The authors of (Guo et al., 2019) suggest that the modular approach must be based on parametrization. Parametrization allow modules that have similar functions and structure to be clustered in larger, functional modules. In this perspective, the final functional modules users will be able to easily replicate the implementation of modules, reducing the programming workload and the effort required for modelling. In (Negri et al., 2019), DT modules are referred to as Functional Mock-up Units (FMUs). FMUs are referred to as black boxes that are capable of interacting with different simulation environment, requiring only little arrangements. FMUs can be instantiated as many times as necessary, allowing users to easily scale their DT applications. (Yun et al., 2017) asses that DT characteristics such as complexity, resolution, programming languages and data formats may represent an issue for DT implementation and its eventual scalability. In addition, the authors of (Yun et al., 2017) underline the fact that centralized DT application may consume too big resources and energies, and therefore suggest the realization of DT applications which are geographically and logically distributed for better addressing data transportation and energy consumption efficiency.

In our view, it is legit to rise various definitions of DT modules, depending on the desired architectural resolution and the targeted product life cycle phases. Nevertheless, a general definition of DT module, which is not constrained, nor limited, by the architectural resolution focus nor by its peculiar function is proposed next: DT modules are standardized, reconfigurable, parametrized software packages which share similar internal operative structural elements (data collection, data pre-processing, data storage, data exploitation, data visualization and feedback/control) (Rocha et al., 2021) and differ the ones from the others due to the necessary inputs and desired outputs. Standing with this definition, DT modules achieve compositionality thanks to the shared internal architecture, composability due to input-output-bounded design, and interoperability whenever input and output data formats are homogeneous in type and format, enabling system scalability. The synergy of two or more DT modules results in a DT system.

Conceptually, it is possible to subdivide DT modules into five application levels, ranging from the product level, up to the Supply Chain (SC) level, passing through the work cell, system, and factory levels. At the product level, DT modules operate in several product life-cycle phases. In particular, DT modules addressing Product Life-cycle Management (PLM) aim to monitor, simulate and optimize each life-cycle phase of a product (Tao et al., 2018), from the early design up to the retirement. If the benefits of the DT paradigm are trivial for the design, manufacturing and service life-cycle phases of a product, the potential of a DT application for products' retirement phase requires further research (Liu et al., 2020). The product simulation field could be ideally a part of a PLM DT system that serves during the design phase. The implementation of a product simulation DT module ensures a lower time-to-market, reducing the time required for the prototyping phase. In as much, in DT-driven product development, the design is generated by the DT application based on real user experience, thus eliminating (or drastically reducing) the need of design modifications and re-prototyping (Lo et al., 2021). At work cell level, DT modules are employed to manage the work cell as whole. For example, DT modules monitoring and optimizing the performance of robotics systems through real-time robot behaviour adaption features based on adaptive motion planners lead to improvement of motion speed, energy consumption and safety (She, 2021). Safety, in particular, is crucially important for Human-Robot Collaboration (HRC), where human operators and robotic manipulator share the same workspace at the same time. DT modules for HRC enable the dynamic task allocation based on task properties and assembly characteristics, aiming to improve the human-robot workload balance (Bilberg & Malik, 2019). Employed in HRC, but also in quality inspection, autonomous driving or authentication applications, Computer Vision DT modules allow DT system to access data retrieved from 2D, 3D or Infrared (IR) cameras.

Especially in collaborative assembly workstation, to exploit Computer Vision (CV) devices, for predictive maintenance purposes as well as for fault detection and diagnosis. The system level is embodied by the ensemble of work cells and all those entities aimed moving row material, semi-finished products and finished product from one work cell to another. At the system level DT modules can embody virtual representations of transfer lines, Autonomous Guided Vehicles (AGVs) and Autonomous Guided Robots (AGRs) for solving optimal path planning algorithms and to simulate their behaviour in the physical shopfloor (Bottani et al., 2017). DT based Production Management Systems (DTPMS) enable the real-time monitoring of production processes, allowing simulation and forecasting elements of the DTPMS module to efficiently optimize production planning tasks (Ma et al., 2020). In addition, performance prediction (Zhuang et al., 2021) and energy consumption optimization (Zhang et al., 2018) are made possible by the inclusion of forecasting DT modules who rely on the real-time monitoring of the system. On the factory and supply chain levels, DT modules aim at monitoring and optimizing higher level processes. E.g., factory layout planning DT modules allow layout planners to generate a conceptual design of the factory shopfloor before constructing the facility. This ensures resource saving, avoiding the need of reconfiguration. This is also supported by Building Information Modelling (BIM) DT modules, that merges the real-time collected data of a piece of equipment, its static data and its 3D representation to facilitate the access to information when needed (Coupry et al., 2021). Cybersecurity (Saad et al., 2020) is a topic that ideally affects every application level, but can be addressed with dedicated DT modules deployed at factory level, considering the transfer of data between one facility and another more risky than intra-factory data transfer. Supply Chain DT (SCDT) application observe and optimize the behaviour of supply chains (Park et al., 2021).

4 EXEMPLARY APPLICATION

The idea of treating DT applications as a body of interoperable and replicable modules that have been explained in Section 3 has been put into practice at the Smart Mini Factory laboratory for Industry 4.0 of the Free University of Bozen-Bolzano, which has the objective of replicating an industrial environment, both from manufacturing and logistics perspectives, to allow undergraduate students as well as practitioners from industry to learn Industry 4.0 related concepts through hands-on experiences.

In this case a technological demonstrator has been set up to explain the benefits and potential of a modular DT application. In particular, the demonstrator consists of the assembly of a product that requires the orchestration of several entities in order to be successfully manufactured. For this purpose, a “gopher holes” puzzle will be employed. The puzzle is made out of a bottom plate, by six laths (four unique parts and two equal parts), and a top plate. The assembly of the product is carried on autonomously by a smart assembly line. The components of the puzzle are randomly scattered on a conveyor belt. A DT module of the conveyor belt is deployed and is in charge of dynamically adjusting the speed of the belt conveyor based on the future requirements of the production line. The conveyor belt brings the components under a CV system that recognizes the Reference Frame (RF) and the identity of each part. The CV system also features its own DT module, which is in charge of creating a virtual representation of the components sparse on the conveyor belt and to produce actual and future (simulated) data to be shared with a delta robot. The robotic system picks the puzzle elements through suction caps and placing them on a shuttle, that runs on an intelligent monorail transfer line. Each shuttle can host one base of the puzzle or three laths. The DT module of the delta robot receives information about the actual and future (simulated) position of puzzle’s elements on the conveyor belt. Thanks to this synergy, the delta robot is capable of continuously replanning its trajectories, preventing the arrival of components, thus optimizing speed performance. Moreover, the delta robot DT module is informed by the CV DT module about the identity of the arriving component. This information is required by the delta

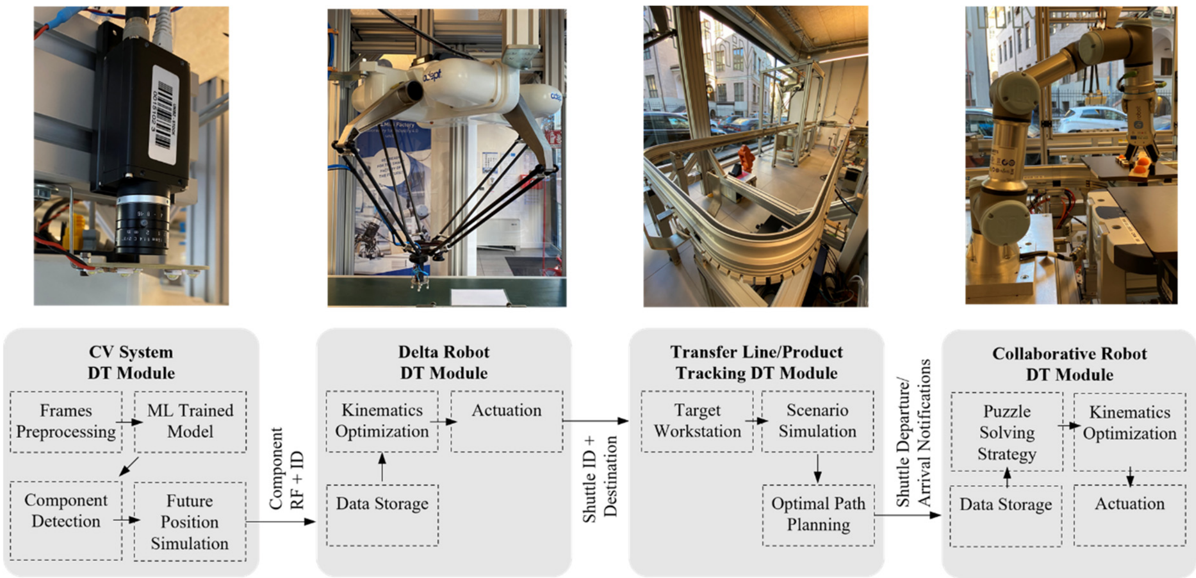

Figure 2: DT modules arrangement.

robot to easily plan the picking of the incoming component, as components show varying surfaces. This same information is then forwarded to the product tracking DT module, which is in charge of virtualizing the logical location of products along the production line, together with the address of the shuttle that is carrying the component(s). The intelligent transfer line DT module solves an optimal path planning problem to ensure the optimization of one or more Key Performance Indicators (KPIs) (e.g., speed, idle time, path length, energy consumption, jerk avoidance) for moving the shuttle from the delta robot workstation towards the collaborative robot workstation. Here, a lightweight collaborative robot is notified about the arrival of a loaded shuttle by the transfer line DT module, and immediately retrieves the information about component ID and position on the shuttle by the product tracking module. The collaborative robot must unload the components from the incoming shuttle. Given the unpredictable components arrival order, the collaborative robot workstation features a rack onto which components that cannot be immediately assembled are temporarily stored. The collaborative robot is driven by a DT module similar to the one driving the delta robot, with additional features for human-robot collaboration. Even though in this peculiar application a collaborative robot is employed on its own (without the constant presence of a human operator), the robotic arm is not fenced, hence, the eventuality of a collision with a human operator cannot be excluded. In addition, the collaborative robot DT module simulates the cinematics of the collaborative manipulator aiming at finding the best set of joints motion for flexibly assembling the puzzle. Completed puzzles are loaded on a shuttle which will move to a representative warehouse. Figure 2 graphically reports the arrangement of DT modules that concur to the successful assembly of the product. Only the most important parts of the DT system have been reported in Figure 2 for space saving reasons.

5 DISCUSSION

The union of the DT modules gives life to a DT application which is finally capable of managing the assembly of a product, whose components supply does not attend the Just in Time (JIT) nor the Just In Sequence (JIS) principles. This introduces unpredictability and randomness in the system, which would be impossible to tackle with traditional assembly lines, that require long reconfiguration times and costs and provide low flexibility during the assembly phases. These issues are easily tackled by the introduction of decentralized control of machines provided by DT modules. All the items composing the presented case study (conveyor belt, CV system, delta robot, intelligent transfer line, and collaborative robot) have been programmed in such a way that it is possible for them to exchange information with external DT modules through XMLRPC calls over the local Ethernet Infrastructure. Practitioners from industry as well as students can consider this work as a starting point for learning the features and the potential of DT application, together with the concept of modular DT implementation. The work, in its current form, is structured in such a way that each DT module can be teared apart and presented in detail, both from an architectural perspective and from an informatic point of view. The strength of the presented work resides in the facilitated combination of several DT modules, which are capable to construct a large-scale DT application for an entire production line. In addition, the modularity of the proposed architecture enables system reconfigurability, flexibility and scalability.

Two major issues can be met during the development and deployment of a modular DT application:

(1) Systems integrability is not always easy to realize. For example, great effort has been spent to create an external controller for the delta robot, which is originally driven by proprietary programming language, that strongly limits system's integrability.

(2) Cybersecurity plays a major role in DT applications since they strongly rely on data transportation over the Internet. In this sense, dedicated research should be carried on for ensuring the security of data transportation in the DT era.

6 CONCLUSIONS AND OUTLOOK

This paper presents the design and implementation of a DT architecture for a cyber-physical assembly transfer line. The implementation of a DT node enables an easy-to-implement connection with other systems. The authors give a definition of DT module and describe their internal structure. In addition, the authors list and describe a list of possible DT modules application in industry. For validating the novel definition, a practical case study is presented. Here, a demonstrative assembly line composed by a conveyor belt, a delta robot equipped with a CV system, an intelligent transfer line, and a collaborative robot are in charge of assembling a logically difficult to assemble product, a puzzle, for this demonstrative case study. The implementation of DT modules remarks existing challenges in Industry 4.0 environment such as cybersecurity and the need of integrable systems and opens new horizons such as the fine granularity and level of detail that is possible to obtain through the adoption of modular DT applications. In the future, more research is needed on cyber-security, as this will play an increasingly important role in DT applications. In the next future, the authors aim at developing the case study, including more DT modules in the production line, as well as more equipment. Moreover, the objective is to demonstrate the potential flexibility of such a production line assembling more than one product at the same time on the same line. In addition, ways and possibilities should be elaborated to simplify the integration process.

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