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Procedia CIRP 120 (2023) 992–997

www.elsevier.com/locate/procedia

56th CIRP Conference on Manufacturing Systems, CIRP CMS '23, South Africa

Implementing transmission of data for digital twins in human-centered cyber-physical systems

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Abstract

This study proposes a model describing the functions and procedures for configuring the transmission of data of Digital Twins (DT) in human-centered Cyber-Physical Systems (CPS). We draw data from two cases including aircraft manufacturing and production logistics and present two contributions. First, we derive a procedure identifying the steps and resources of data processing for DT in human-centered CPS. Second, we propose a systematic procedure for configuring bi-directional data transmission depending on the desired system utilization. These results contribute to realizing data processing activities supporting the implementation of DTs for human-centered CPS in manufacturing.

Keywords: digital twin; human-centered cyber-physical system; production logistics; assembly; industry 5.0

1. Introduction

Recent studies emphasizes the role of humans when applying digital technologies in manufacturing [1, 2]. Human-centered Cyber-Physical Systems (CPS) and Digital Twins (DT) are important examples. Human-centered CPS include physical and software components improving the abilities, skills, and intellectual potential of staff in manufacturing [3]. These systems facilitate the exchange of information between physical systems and staff, and enable intelligent control, decision-making, and sensing in manufacturing [4]. Human-centered CPS and DTs are indispensable for increasing safety, improving training, promoting critical thinking skills, and realizing the collaboration between machines and staff [5, 6]. These benefits are critical for achieving specialization of skills and technical innovation, and promoting the well-being of staff necessary in sustainable and resilient manufacturing [7].

DTs for human-centered CPS are distinct from those previously available in manufacturing [8]. Traditionally, DTs simulate, predict, and optimize behaviors in a bi-directional relation between a manufacturing system and its virtual representation [9]. However, the transmission of data, including the interaction between physical objects and digital ones via staff, differentiates DTs for human-centered CPS [7]. For example, DTs for human-centered CPS require not only uni- and bi-directional transmission of data between machines but also new integration of data about staff (e.g., preferences, skills, or position) [10]. Accordingly, recent studies investigate the transmission of data in DTs for human-centered CPS, and propose heterogeneous architectures including requirements for integrating data from distinct devices and the needs of staff [11, 12]. Yet, the absence of empirical insight describing the functions and procedures for configuring the transmission of data in DTs for human-centered CPS constitutes a critical problem in the literature [10]. Addressing this problem is indispensable for characterizing the interaction of data flows between staff and DTs for human-centered CPS that are necessary for adapting to the needs and diversity of staff in manufacturing and achieving increased competitiveness [18].

Addressing this problem, the purpose of this study is to propose a model describing the functions and procedures for configuring the transmission of data of DT in human-centered CPS. The study answers the following research question: What resources and procedures contribute to configuring the bi-directional transmission of data for DTs in human-centered CPS? The study presents two contributions resulting from the comparison of these cases. First, we derive a procedure identifying the steps and resources of data processing for DTs in human-centered CPS. Second, we propose a systematic proce-

10.1016/j.procir.2023.09.113

dure for configuring bi-directional data transmission depending on the desired system utilization.

The structure of this study is the following. Section 2 presents the method. Section 3 provides empirical results. Section 4 proposes a structured model and its procedure. Section 5 discusses the implications of this study. Section 6 concludes.

2. Method

This study applies a case study method and inductive reasoning to achieve its purpose. This choice is justified by the novelty of research about DTs for human-centered CPS, and the need to develop initial insights from empirical evidence [13]. Accordingly, we give primacy to empirical observations from two cases and analyze the functions and procedures for configuring the necessary data transmission of the DTs involved to answer our research question. The cases include DT-based assistance systems for workers in aircraft assembly and production logistics. We draw data from two distinct industries to observe contrasting patterns for data transmission in DTs for human-centered CPS. A theoretical sampling justifies our choice of cases [14]. Namely, we focus on cases involving a significant change in the role of staff because of the increased use of digital technologies [7, 11]. Accordingly, we find the lowest common denominator for the cases to obtain an abstract model for a data processing platform. Then, we identify the similarities of requirements and approaches for structuring such a platform to enable human-centered assistance via DTs. Finally, we ground our analysis on existing literature about data transmission in DTs for manufacturing [15].

3. Empirical results

This section presents two use cases that utilize DTs for human-centered CPS. The first case presents a digital assistance system for supporting workers in aircraft assembly. The second case consists of a system for supporting production logistics processes.

3.1. Aircraft assembly

Aircraft assembly is characterized by highly complex products and consequently by a high proportion of manual work processes. The responsibility of staff consists of placing components, drilling, and joining parts with rivets or screw connections. In addition to preparatory activities, the scenario under consideration is characterized by a high degree of repetition and high requirements for ensuring compliance with correct process parameters. The DT for human-centered CPS for aircraft assembly supports staff with smart, localized hand tools and digital work documents conceptualized in [16].

To address the described issue under the conditions of the application environment, the smart hand tools are able to send the position of the tooltip with an accuracy of 10 millimeters to match the correct process parameters with the DT based on the position. This allows the tool to be blocked if the parameters are set incorrectly or automatically set to the correct values. For structural mechanics, productivity is increased because there is no longer a need to search for parameters in complex information. Furthermore, quality increases because the tools avoid mishandling. By updating the DT in real-time, the workers can see the progress in the digital work document at any time.

The presented functionality is enabled via a variety of data streams through different clients. For example, the positioning system sends high-frequency data packages with the coordinates of tools, which are processed in the DT to release or lock the tool or to supply it with the correct parameters. For this purpose, the tool must simultaneously send the set parameters as a data package (e.g., entering a joining point). After each tool intervention, the recorded torque curves must be sent to the platform for processing. The different data streams have different requirements in terms of latency, security, stability and other key figures. Figure 1 gives an overview over some of the necessary data streams.

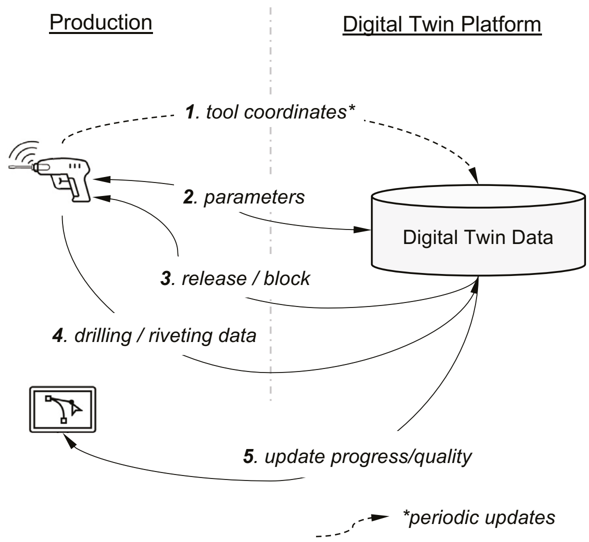

Fig. 1. Data streams in aircraft assembly use case

Due to the different requirements of the data streams, the physical requirements of the deployment scenario and the industrial requirements for scalability of the system in terms of using a variety of tools through the same DT, there are several requirements for the data processing platform. In the sense of a DT and a single source of truth, all data must pass through a central point on the platform, which can be used by microservices to react to these streams and save the data in a central database. In the use case, latency-critical data streams (coordinates, parameters, etc.) are connected via a broker using the MQTT (Message Queuing Telemetry Transport) protocol and data streams with higher safety relevance and standardized data models (drilling and riveting data) via the OPC UA (Open Platform Communications Unified Architecture) protocol. This ensures the scalability of the assistance system through highly modular interfaces.

The interfaces then converge in a central event streaming instance. Apache Kafka was chosen for this, which is connected to a time series database, a non-relational database and all the necessary microservices. The databases can be used for long-term optimizations, dashboards or feeding the digital working document. To be able to deploy, scale and manage each sub-application in a stable format, the system is deployed on the container platform Kubernetes.

One could argue that the need for data transmission in human-centered CPS arises from both the operating environment and desired functionality in the use case. As a result, a data processing platform must have flexible and modular interfaces, as well as the ability to centrally process data streams to meet these dynamic requirements effectively.

3.2. Production logistics

Production logistics includes all activities focusing on the movement of materials and information within the physical boundaries of a manufacturing site. Recently, digital technologies and robotics facilitate the automation of activities involving the movement of materials by autonomous mobile robots (AMRs). However, activities consisting of kitting, picking, placing, delivery or following require staff intervention. Safe navigation around staff and obstacles by AMRs, parallel work, sequential completion of tasks, or immediate reception of orders from staff and their execution by AMR characterize these scenarios. Consequently, DTs for human-centered CPS consisting of AMRs for material handling apply Industrial Internet of Things (IIoT) devices (e.g., radio-frequency identification (RFID), cameras, and laser scanners) for interacting with staff.

Establishing the position of AMRs in a facility is critical for collaborative work involving staff in material handling, especially in automotive manufacturing, which requires a fast production pace to fulfil customer demands. An architecture for IIoT-enabled digital servitization in smart production logistics was proposed in [17]. This describes key components, data streams, and possible applications in smart production logistics. The following use case of material handling for the manufacturing industry is based on this architecture.

Production logistics support production by minimizing disruptions to the production flow. Therefore, it is important to operate according to the production plan, reduce interference in the production flow, and respond rapidly to unexpected situations. These characteristics require information about the surrounding environment, planning, product, and material handling devices. In general, IIoT devices such as cameras, location tracking sensors, and RFID devices are used to collect environmental data, and AMRs, collaborative robots, conveyor belts, and cranes are used as material handling devices.

In many production logistics environments, data is collected sufficiently. Still, there is a problem connecting or communicating with different devices and objects because each device comes from different suppliers with different interfaces, data formats, and protocols. To solve and supplement this problem, a flexible DT platform offers significant potential.

Fig. 2 presents data streams between the AMR device and the DT platform in production logistics. These communicate with each other with two types of data: task and status. Task-type data can be delivery order information from the production management system that can drive to move of the AMR devices from the pick-up point to the delivery point. It is not a recursive data stream but a single data stream at the beginning of each delivery mission. The AMR device receives data from the DT platform in this case. However, there is another type of data which is status-type data. It can be divided again into the device status data and the environment status data. Device status can include the current location, speed, battery percentage, etc., representing the status of the device. This data can be transferred from the production logistics side to the DT platform in near real-time with high frequencies. On the other hand, the environment data includes real-time information from the other components of the AMR device in the DT platform. This data can help the AMR to avoid obstacles and update the route in real-time.

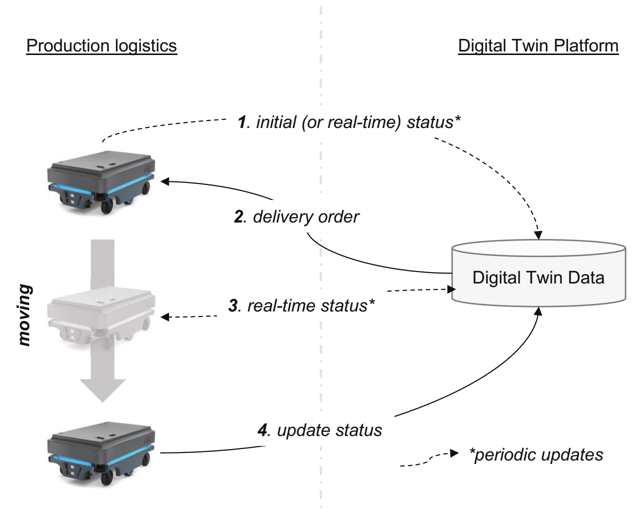

Fig. 2. Data streams in production logistics use case

As in the aircraft assembly case, latency-critical data streams (status data) are connected via a broker using the MQTT protocol. Apache Kafka was chosen to connect the AMR device and the DT platform since it is easy to scale up to other devices in the production logistics environment. It also requires a middleware layer to connect the data stream, database, digital services, and virtual/physical assets.

Production logistics involves the movement of materials and information within a manufacturing site. Recent digital technology and robotics advancements allow AMRs to automate material handling. However, safe navigation around staff and obstacles requires human intervention. A human-centered CPS for production logistics can use IIoT devices to interact with staff, automate material handling involving AMRs, and solve connectivity issues. By establishing the position of AMRs and using IIoT devices and robotics, a human-centered CPS can enhance collaboration, increase productivity, and reduce disruptions to the production flow.

4. Concept for Human-centered Cyber-Physical Systems

Human needs and interests supported by digital technologies characterize the human-centered approach in manufacturing. Accordingly, machines and automation are subservient to staff, and digital technologies facilitate their diverse needs [1]. Human-centered CPS require the seamless integration of digital technologies, protocols, and modular functionalities supporting the needs of staff [18]. The analysis in this section includes the structure of data processing platforms for human-centered CPS and the associated systematic procedure for configuring bi-directional data transmission.

4.1. Structure of data processing platforms for human-centered cyber-physical systems

Two cases of the use of DTs in human-centered CPS from different industries and environments were introduced in the previous section. Empirical data suggests common resources, components, and structure of data processing platforms in such DTs. For example, the data platform should have modular interfaces for connecting highly diverse devices, improving efficiency, and helping staff. Hence, this platform should be open to different types of application protocols and standards to have better scalability, flexibility, and functionality.

These requirements drive the structure of the platform with five key elements. First, the physical assets include edge connections to the DT platform. Nowadays, there are many devices, components, and products with internet connections such as IIoT devices. However, network connections are absent in machines, infrastructure, and systems in manufacturing. Therefore, an edge device is required to connect them to the platform. When the physical asset is ready to connect to the DT platform, the platform also needs to be ready to be connected.

Inside the DT platform, an event-distribution-broker controls the event messages from the different devices, components, and systems. This broker can have multiple connections to different digital services, potential services, databases, and back-end systems. The main goal of the human-centered CPS is to help human staff in the production environment. Therefore, a user-friendly interface (web application etc.) is required to close the loop. Figure 3 presents the data processing resources in DTs human-centered CPS.

4.2. Systematic procedure for configuring bi-directional data transmission

The proposed structure of the data processing platform allows for the implementation of various data transmission protocols and interfaces. This makes it generally applicable for a multitude of use cases at this level of abstraction. However, to achieve the desired functionality for a specific data transmission, more detailed development is required. It is important to design the function-critical elements of the data transmission protocols and technologies based on the individual use case. This involves considering the requirements of the physical environment for the transmission technologies, as well as the requirements of the data streams necessary for the desired functionality in the transmission protocols.

We propose a seven-step systematic procedure for configuring bi-directional data transmission. The first step is to analyze the application of the DT and the planned physical environment. Next, the resulting data streams and their transmission requirements must be defined. To cluster data streams according to quantitative requirements, a detailed analysis of the individual data packets and their frequency, size, scalability, and maximum permitted latency is necessary. Once data streams are clustered, a separate transmission configuration can be implemented for each cluster. Hard criteria such as latency or transmission rate can exclude certain protocols and technologies, while soft criteria such as range or energy consumption may also lead to exclusions. However, it is important to assess beforehand whether an increase in the number of routers or acceptance of higher energy costs is possible to accommodate soft criteria exclusions. After narrowing down the available protocols and technologies, a value-benefit analysis can be conducted for each data stream cluster. Table 1 provides an overview of the proposed procedure and the necessary considerations.

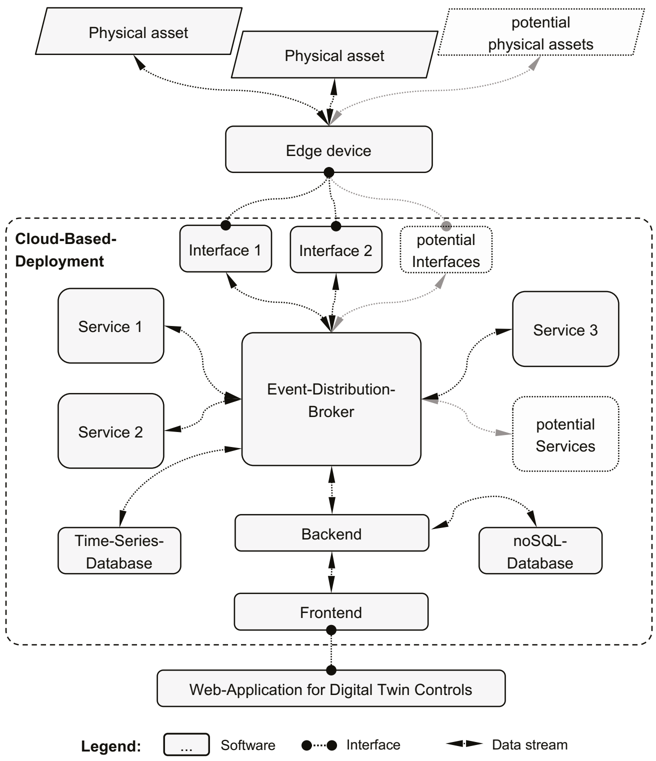

Fig. 3. Data processing resources in digital twins human-centered cyber-physical systems

5. Discussion

This section discusses the implications of the proposed structure of data processing, and the procedure for configuring bi-directional data transmission for DTs in human-centered CPS. First, it describes the facilitation of human-centered use cases through modular bi-directional data transmission. Second, it presents its benefits for human-centered CPS. Third, it explains the implications of additional industry types.

5.1. Facilitation through modular interfaces

DTs for human-centered CPS pose a number of requirements. The inherent flexibility of humans means that a wide range of different work tasks can be performed. Different work equipment, machines and environments are used for this purpose, which results in high flexibility of the technologies to be integrated. Furthermore, people can adapt their actions to new situations or improve their handling of known situations. The DT and structure of the data processing resources should meet these requirements and be able to integrate new technologies smoothly as well as create new logic and functions for existing systems. Besides this scalability of functionality, the CPS must be scalable in the sense of easily integrating new workers. The described modular and bi-directional structure of data transmission and processing enables the addition of new physical assets via existing or novel interfaces and the development of new functionalities via the decoupling of interfaces and services into individual software modules. The platform can therefore be adapted to new use cases and ideas at will. The systematic approach ensures that the data transfer is configured according to the purpose, resulting in a user-friendly system. The necessary flexibility, scalability and usability of human-centered CPS are therefore met by the proposed data processing structure.

5.2. Benefits for existing digital twin concepts

The structure of data processing platforms and procedures for configuring bi-directional data transmission has important implications for realizing modular designs of DTs for human-centered CPS. Recent studies identify that data transmission is decisive for achieving the modular design of a DT and reducing its development costs, reusing already existing information, and extending its use in manufacturing [19]. DTs in human-centered CPS require the extensive transmission of data between machines and diverse inputs not previously taken into account originating from staff [1]. For example, direct communication recognises the intent of staff (e.g., human speech or biological signals) or indirect observation (e.g., inferring intent by observing the actions and gestures of staff). This study provides insight into the characterization of data transmission including its platforms and procedure for configuration. This contributes to developing modules of data transmission that are reusable and contain identical or comparable functions, which may reduce the effort and cost of developing DTs for human-centered CPS.

Furthermore, the results of this study have significant implications for the scalability of both current and future DTs, particularly in the context of human-centered CPS in manufacturing. DTs play a crucial role in enabling bi-directional communication between physical and virtual resources throughout their lifecycles. Therefore, DTs require rapid configuration and scalability to adapt to changes in manufacturing systems and the needs of personnel [20]. The findings of this study offer a blueprint for the structure of data processing platforms, which is essential for managing changes in the data requirements of resources within DTs.

Table 1. Systematic procedure for configuring bi-directional data transmission

Nr.	Step	Considerations
1.	Analysis of the proposed digital twin (application)	Targeted functionality Physical asset to mirror Real-time operations Scale
2.	Analysis of physical environment (requirements)	Current infrastructure Spatial requirement Physical obstacles Frequency bands Number of modular DT
3.	Analysis of data streams (qualitative)	Data streams necessary Functionality of data Security relevance Reliability relevance Latency relevance
4.	Clustering of data streams (quantitative)	Data model and size Frequency of transmission Number of transmissions
5.	Exclusion of transmission protocols	Strong criteria (latency, bandwidth usage) Soft criteria (flexibility, reliability, ...)
6.	Exclusion of transmission technologies	Strong criteria (latency, transmission rate) Soft criteria (range, energy use, ...)
7.	Value-benefit analysis per data stream cluster	Pairwise comparison Ranking by benefit Including potential values for changing soft criteria

5.3. Benefits and transfer to further industries

The concept of DT and CPS plays a fundamental role in the context of Industry 4.0. While there are numerous Industry 4.0 applications focused on technological advancements, recent studies have highlighted the importance of placing the well-being of personnel at the center of manufacturing and utilizing digital technologies to achieve sustainable prosperity [21, 22].

The importance of staff as center of manufacturing does not limit to specific industries. On the one hand, digital technologies constitute enablers of increasing automation in manufacturing. On the other hand, the involvement of staff remains essential for manufacturing. Because staff and machines have different capabilities, it is better to find a way to emphasize their strengths. Therefore, exploring implications to staff in DTs for human-centered CPS is indispensable for manufacturing. The findings of this study constitute a first step for realizing the multi-directional relation including the production process and its virtual representation while placing the well-being of staff at the center of manufacturing.

6. Conclusion

This study proposed a structure describing the functions and procedures for configuring data transmission of DTs in human-centered CPS. The study presented two contributions based on two cases consisting of assembly in aircraft manufacturing and production logistics in the manufacturing industry. The study contributed to existing understanding in two ways. It proposed a procedure identifying the steps and resources of data processing for DTs in human-centered CPS. Additionally, it presented a systematic procedure for configuring bi-directional data transmission depending on the desired system utilization.

We also found the proposed structure facilitates human-centered CPS through modular bi-directional data transmission and benefits for existing DT concepts as well as transferring to other industries. However, our study includes a limitation that future research could address. There were only two use cases even though it was enough to analyze and drive the proposed structure. To overcome this limitation, it would be better to apply and compare the proposed structure to the existing CPS applications with human actors from various industries.

Acknowledgements

The authors would like to acknowledge the support of Swedish Innovation Agency (VINNOVA), and its funding program Produktion2030. This study is part of the Explainable and Learning Production Logistics by Artificial Intelligence (EXPLAIN) project.

The authors would further like to thank Bundes-Ministerium für Wirtschaft und Klimaschutz (BMWK) for funding the research. (Project No. 20W1922E).

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