Liu *et al.*
Chinese Journal of Mechanical Engineering (2023) 36:136
https://doi.org/10.1186/s10033-023-00965-8

Chinese Journal of Mechanical Engineering

ORIGINAL ARTICLE

Open Access

A 5M Synchronization Mechanism for Digital Twin Shop-Floor

Weiran Liu[1], Jiangfeng Cheng[1*], Zhiwen Wen[2], Xiaofu Zou[3], Zhaozong Wang[1], Hongting Liu[1] and Fei Tao[1,4]

Abstract

In recent years, as a promising way to realize digital transformation, digital twin shop-floor (DTS) plays an important role in smart manufacturing. The core feature of DTS is the synchronization. How to implement and maintain the synchronization is critical for DTS. However, there is still a lack of a common definition for synchronization in DTS. Besides, a systematic synchronization mechanism for DTS is strongly needed. This paper first summarizes the definition and requirements of synchronization in DTS, to clarify the understanding of synchronization in DTS. Then, a 5M synchronization mechanism for DTS is proposed, where 5M refers to multi-system data, multi-fidelity model, multi-resource state, multi-level state, and multi-stage operation. As a bottom-up synchronization mechanism, 5M synchronization mechanism for DTS has the potential to support DTS to achieve and maintain physical-virtual state synchronization, and to realize operation synchronization of DTS. The implementation methods of 5M synchronization mechanism for DTS are also introduced. Finally, the proposed synchronization mechanism is validated in a digital twin satellite assembly shop-floor, which proves the effectiveness and feasibility of the mechanism.

Keywords Digital twin, Digital twin shop-floor, Synchronization in digital twin shop-floor, Synchronization mechanism, Satellite assembly shop-floor

1 Introduction

The global manufacturing industry is paving towards smart manufacturing [1]. The emergence of new information technologies (New-IT) such as Internet of Things (IoT), Big Data, Could Computing, and Artificial Intelligence [2], has effectively boosted the development of smart manufacturing [3]. There is a consensus among smart manufacturing researchers that bridging the physical and digital spaces is essential to achieve smart manufacturing. Therefore, digital twin, as a possible approach to realize the interaction and fusion between physical space and digital space [4] has attracted more and more attention [5]. Generally, digital twin is considered as a physical-virtual integrated system [6]. With the help of high-fidelity virtual models mapping physical entities, and the data connection between physical entities and virtual models, digital twin can depict, simulate, and optimize physical entities [7, 8].

Shop-floor is the core unit of manufacturing. Therefore, in order to accelerate digital transformation of shop-floor, digital twin shop-floor (DTS) has been proposed [9]. Referring to five-dimension digital twin concept [10], DTS contains physical shop-floor, virtual shop-floor, shop-floor service system, shop-floor digital twin data [11], and the connection between each part. The purpose of DTS is to better monitor, control, optimize, and manage shop-floor with the help of data and models. Nowadays, DTS has become one of the hottest research topics in digital twin field [12]. DTS has been successfully applied in various aspects such as shop-floor design

---

*Correspondence:
Jiangfeng Cheng
chengjf1987@126.com
[1] School of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China
[2] Xi'an Precision Machinery Research Institute, Xi'an 710077, China
[3] Institute of Artificial Intelligence, Beihang University, Beijing 100191, China
[4] Digital Twin International Research Center, International Research Institute for Multidisciplinary Science, Beihang University, Beijing 100191, China

[13], scheduling [14], management [15] and control [16]. Many researches on DTS emphasize the importance of high-fidelity model, real-time interaction data, and consistency between the physical and virtual shop-floor. These all point to synchronization in DTS.

Synchronization is critical to DTS. Current research on synchronization in DTS mainly focuses on DTS model synchronization, synchronous operation of DTS, and methods to maintain DTS synchronization under dynamic disturbances. The purpose of model synchronization is to ensure that the model is consistent with physical entities. To realize model synchronization, it is essential to judge the consistency between model and physical entities with physical data and detection methods, and update the inconsistent model. Related research includes model deviation detection methods [17], model update methods [18], and configurable model architecture [19], etc. As for DTS operation synchronization, researchers studied how to synchronize the operation of applications with physical entities in DTS. Research mainly focuses on how to implement online simulation [20] or real-time simulation [21], and how to realize fast decision-making [22] or control under synchronous operation. In terms of DTS synchronization maintenance, the key is to maintain physical-virtual synchronization under various dynamic disturbances. Various dynamic disturbances need to be accurately captured and their negative impact needs to be evaluated [23]. To cope with different degrees of disturbances, methods such as designing adaptive control mechanisms [24], or optimizing and updating parameters of DTS system [25] have been studied.

Although numerous studies have emphasized the significance of synchronization in DTS, and there have been some related studies, several problems persist:

(1) The concept of synchronization in DTS needs to be studied and defined. Some research considered that the synchronization in DTS is to maintain the consistency between model and physical shop-floor. Some studies think that the synchronization in DTS is the simultaneous operation of the simulation and the physical entity. Differences in understanding synchronization in DTS will consequently hamper the development and application of DTS.

(2) There is a lack of a systematic framework or mechanism for DTS to realize and maintain synchronization. DTS is a complex soft-hard coupling system that includes multiple elements, multiple applications and multiple processes. Although relevant research has been carried out on model synchronization, operation synchronization and synchronization maintenance, etc., it is still insufficient to support DTS to realize and maintain synchronization in DTS.

In order to address the aforementioned problems, this paper first summarizes the definition of synchronization in DTS, to clarify the understanding of synchronization in DTS. Subsequently, a 5M synchronization mechanism for DTS is proposed, where 5M refers to multi-system data, multi-fidelity model, multi-resource state, multi-level state, and multi-stage operation. As a bottom-up synchronization mechanism, 5M synchronization mechanism for DTS could support DTS to achieve and maintain physical-virtual state synchronization, and to realize operation synchronization of DTS. The general implementation methods of 5M synchronization mechanism for DTS are also discussed, which contain detailed explanations and procedures of the mechanism. Finally, the proposed synchronization mechanism is validated through its application in a digital twin satellite assembly shop-floor.

The remainder of the paper is organized as follow. Section 2 analyzes the definition and requirements of synchronization in DTS. Then Section 3 proposes a 5M synchronization mechanism for DTS. Section 4 presents the implementation method of 5M synchronization mechanism for DTS. Then, in Section 5, an application case is illustrated to verify the proposed mechanism in a satellite assembly shop-floor. Finally, Section 6 closes with a conclusion and a view for future work.

2 Synchronization in Digital Twin Shop-Floor

2.1 Definition of Synchronization in Digital Twin Shop-Floor

Synchronization is widely observed in nature [26], society [27], and industry [28] and refers to the phenomenon where two or more variables that maintain a certain relative relationship through interaction and coordination for consistency and coordination in the time domain. Synchronization is based on inter-system or intra-system interactions, which may take the form such as physical action or information transmission.

Synchronization can be classified into two types: consistency synchronization and coordination synchronization. Consistency synchronization emphasizes the consistency of events or entities in the time domain. In this type, systems either have the same structure or have parameters that can represent relative relationships. For example, time synchronization emphasizes the need to maintain consistency of time in different hardware and software systems with corresponding mechanisms. Coordination synchronization does not require complete consistency of system states or behaviors, but emphasizes the coordination of system elements or processes to achieve synergy and stability under certain constraints. This kind of synchronization is more often realized by joint decision-making under information-sharing. For example, the synchronization of production logistics in manufacturing emphasizes coordinating various processes to maintain the order of production with low-cost, high-quality, and high-efficiency.

Connection is the key feature of DTS, enabling bi-directional interaction between physical shop-floor, virtual shop-floor, data centers, and service system. Connection is the basis for synchronization in DTS. In DTS, synchronization mainly refers to consistency synchronization. For example, time synchronization is needed to ensure that distributed DTS systems have a consistent system time. In addition, the models and data in the DTS need to have a high level of consistency with the physical shop-floor. Meanwhile, some applications need to run synchronously with the physical shop-floor. Also, DTS needs to maintain physical-virtual state consistency under various dynamics and disturbances. Coordination synchronization also exists in some cases. Process synchronization is required to avoid computing resource competition and conflicts in DTS system.

In summary, the concept of synchronization in DTS is defined as follows.

Synchronization in DTS refers to maintaining the consistency of physical shop-floor and virtual shop-floor in time, data and model with interaction method and synchronization mechanisms, so as to ensure the synchronous operation of DTS system.

More specific, it can be explained from DTS state synchronization and DTS operation synchronization:

(1) DTS state synchronization: based on time synchronization, data synchronization, connection synchronization, model synchronization and service synchronization, DTS realizes physical-virtual state synchronization.

- Time synchronization. Hardware and software in DTS have a uniform system time.
- Data synchronization. Data from different sub-systems and information systems is synchronized and consistent.
- Connection synchronization. Mapping relationships and interfaces of DTS between physical resources, data, models, and services are synchronized.
- Model synchronization. Virtual model in DTS is consistent with the physical shop-floor through model assembly, fusion and update, etc.
- Service synchronization. Services of the DTS are kept coupled and synchronized with the corresponding models and data.

(2) DTS operation synchronization: DTS system can run synchronously with physical shop-floor. DTS needs to maintain consistency of physical and virtual state during actual shop-floor operation, and support the synchronous running of some applications with physical shop-floor.

2.2 Requirements of Synchronization in Digital Twin Shop-Floor

With the research analysis of synchronization in DTS and its definition, the requirements for synchronization in DTS are analyzed as follows:

(1) Requirement for multi-system data synchronization. The synchronization in DTS needs to achieve data synchronization of different subsystems within the system to maintain data consistency. It also needs to realize data interaction with other information systems to support data sharing and collaboration decision-making.

(2) Requirement for heterogeneous resource elements state synchronization. Shop-floor contains numerous heterogeneous resource elements, which need different physical-virtual state synchronization methods. DTS needs to realize the physical-virtual state synchronization of heterogeneous resource elements to support the related applications and DTS physical-virtual state synchronization.

(3) Requirement for multi-level state synchronization. The shop-floor can be categorized into resource level, production unit level, and shop-floor level. Different levels have different characteristics and application requirements. The DTS needs to realize multi-level physical-virtual state synchronization to achieve the whole DTS physical-virtual state synchronization.

(4) Requirement for supporting synchronous running applications. There are different service applications in DTS during production, and some of the applications need to be able to run synchronously with the physical shop-floor and respond in real-time.

(5) Requirement for full lifecycle synchronization. The DTS system needs to achieve and maintain DTS

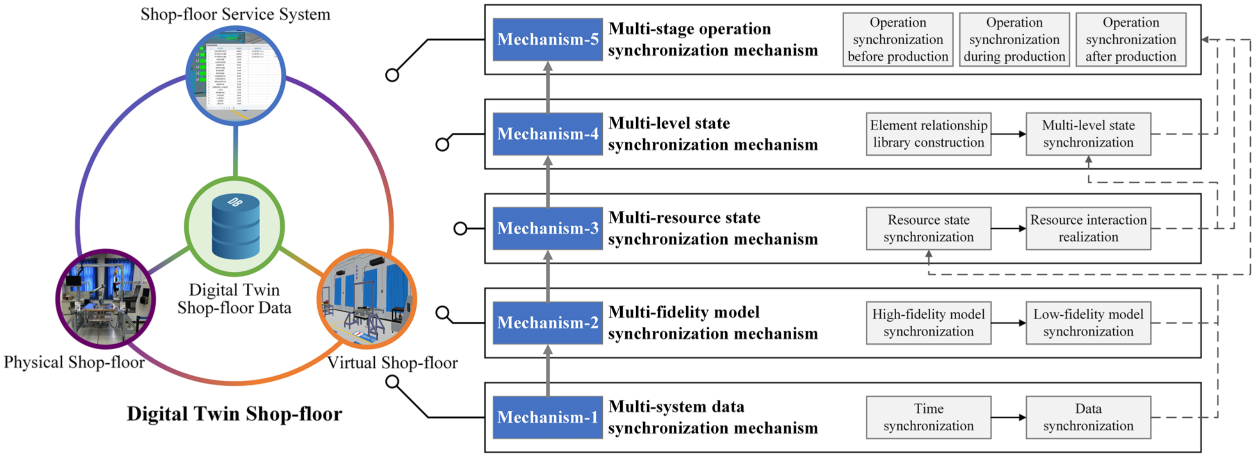

Figure 1 The 5M synchronization mechanism for digital twin shop-floor

synchronization before, during, and after production.

3 The 5M Synchronization Mechanism for Digital Twin Shop-Floor

To meet the requirements of synchronization in DTS, a 5M synchronization mechanism for DTS is proposed, which is intended to ensure physical-virtual state synchronization and operation synchronization. It can be used to guide the DTS construction, and to support achieving and maintaining synchronization in DTS. The 5M synchronization mechanism is a bottom-up synchronization mechanism that includes multi-system data synchronization mechanism, multi-fidelity model synchronization mechanism, multi-resource state synchronization mechanism, multi-level state synchronization mechanism, and multi-stage operation synchronization mechanism, as shown in Figure 1. The former four synchronization mechanisms support DTS to achieve physical-virtual state synchronization, and the multi-stage operation synchronization mechanism supports DTS to achieve operation synchronization. The specific mechanism contents are as follows.

3.1 Mechanism-1: Multi-System Data Synchronization Mechanism

Multi-system data synchronization mechanism achieves data synchronization within DTS system, and data synchronization between DTS system and other information systems. The time synchronization of all systems is required firstly. Then, data synchronization and data consistency maintenance within DTS system need to be realized. In terms of data synchronization between DTS system and other information systems, the DTS system needs to interact and correlate data with other information systems, such as Manufacturing Execution System (MES) [29], Enterprise Resource Planning (ERP), Warehouse Management System (WMS), to realize data sharing and joint decision-making.

3.2 Mechanism-2: Multi-Fidelity Model Synchronization Mechanism

Multi-fidelity model synchronization mechanism enables the DTS with the ability to provide models with different levels of fidelity synchronized with physical entities. There are different types of applications in the DTS that may have different requirements for the digital twin model accuracy and computing efficiency. The multi-fidelity model synchronization mechanism uses the high-fidelity model as the standard model to maintain the model consistency with the physical entities. Low-fidelity models are constructed and modified with the help of high-fidelity model so that the DTS can provide multi-fidelity models to meet different requirements.

3.3 Mechanism-3: Multi-Resource State Synchronization Mechanism

Multi-resource state synchronization mechanism achieves the physical-virtual state synchronization of various heterogeneous resources in DTS, and realizes the resources interaction capabilities. In physical shop-floor, there are many heterogeneous resources such as humans, equipment, materials, and environment. Different resources may need different methods to achieve physical-virtual state synchronization. Simultaneously, different resources need to interact and collaborate with each other in order to realize applications of DTS. The multi-resource state synchronization mechanism proposes corresponding methods to achieve the physical-virtual state synchronization of each resource, and the interaction between different resources in DTS.

3.4 Mechanism-4: Multi-Level State Synchronization Mechanism

Multi-level state synchronization mechanism achieves physical-virtual state synchronization at different levels in DTS. DTS can be divided into different levels such as resource level, production unit level, and shop-floor level. The higher-level elements are composed of lower-level elements according to spatial relationships, interface relationships, logical relationships, and other relationships. Due to production process changes, order adjustments, equipment changes, etc., the structure or parameters of elements at different levels may change during production in physical shop-floor, which ultimately leads to inconsistencies of physical-virtual states in DTS. The multi-level state synchronization mechanism is designed to achieve physical-virtual state synchronization of different level elements in DTS.

3.5 Mechanism-5: Multi-Stage Operation Synchronization Mechanism

Multi-stage operation synchronization mechanism is based on the former four mechanisms to achieve the DTS operation synchronization before, during, and after production. Before production, DTS needs to realize physical-virtual state synchronization. During production, the physical-virtual consistency in DTS needs to be maintained. Simultaneously, how to enable real-time or near real-time synchronous running applications also needs to be concerned. After production, the DTS needs to correct any uncorrected synchronization failure in the production stage and make system backups. In response to the above needs, the multi-stage operation synchronization mechanism proposes methods for each stage to achieve and maintain synchronization and support synchronous operation of certain applications.

4 Implementation Methods of 5M Synchronization Mechanism for Digital Twin Shop-Floor

The 5M synchronization mechanism for DTS is a general mechanism. It should be implemented with appropriate technologies according to the characteristics of different shop-floors, since there are big differences in structure, production process, management, control, and other aspects between different shop-floors. Although there are differences in implementation technologies, the basic procedures of the 5M synchronization mechanism are similar in different DTS. In this section, the general implementation methods of 5M synchronization mechanism for DTS will be discussed.

4.1 Mechanism-1: Multi-System Data Synchronization Mechanism

Data synchronization is the process of achieving time synchronization and data consistency maintenance across multiple systems, which is critical for synchronization in DTS. For DTS, it is essential to maintain data synchronization within the DTS system as well as between DTS system and other information systems. The DTS system may adopt different system architectures, such as centralized or distributed. In the centralized system, data is managed and stored centrally. While in the distributed system, however, data is distributed and stored across different subsystems. Therefore, data consistency must be maintained within distributed system. For analysis and decision-making, the DTS system requires not only the data from its own, but also the production data provided by MES, ERP, WMS, and other information systems. Therefore, data interaction between the DTS system and other information systems also needs to be established.

Mechanism-1: multi-system data synchronization mechanism maintains time and data synchronization of the DTS system together with related information systems. Time synchronization ensures that hardware and software systems have the same system time, which is the basis for data synchronization and shop-floor control. Data synchronization guarantees data consistency within the DTS system and maintains the data interaction between the DTS system and other information systems.

The procedure of multi-system data synchronization mechanism is shown in Figure 2. The specific contents are explained as follows:

Step 1: Multi-system time synchronization. Firstly, determine the appropriate time synchronization protocol, such as Network Time Protocol (NTP) [30], and Precision Time Protocol (PTP) [31], according to the characteristics of the shop-floor. Then select the master clock system, such as Local Time Server, Network Time Server, GPS. Subsequently, the communication between the master and slave clock systems is configured. Finally, errors such as network delays and clock deviations need to be corrected, which is usually achieved by using mechanisms such as timestamping and delay compensation [32].

Step 2: Data synchronization within DTS system. Since the data has been managed centrally in the centralized system, data synchronization within DTS system mainly focuses on distributed system. Firstly, the master and slave nodes within the DTS system need to be determined, and usually, the main shop-floor server is set as the master node. Subsequently, the appropriate master-slave synchronization method needs to be determined according to the data storage service, such as the Semi Sync Replication mechanism in MySQL,

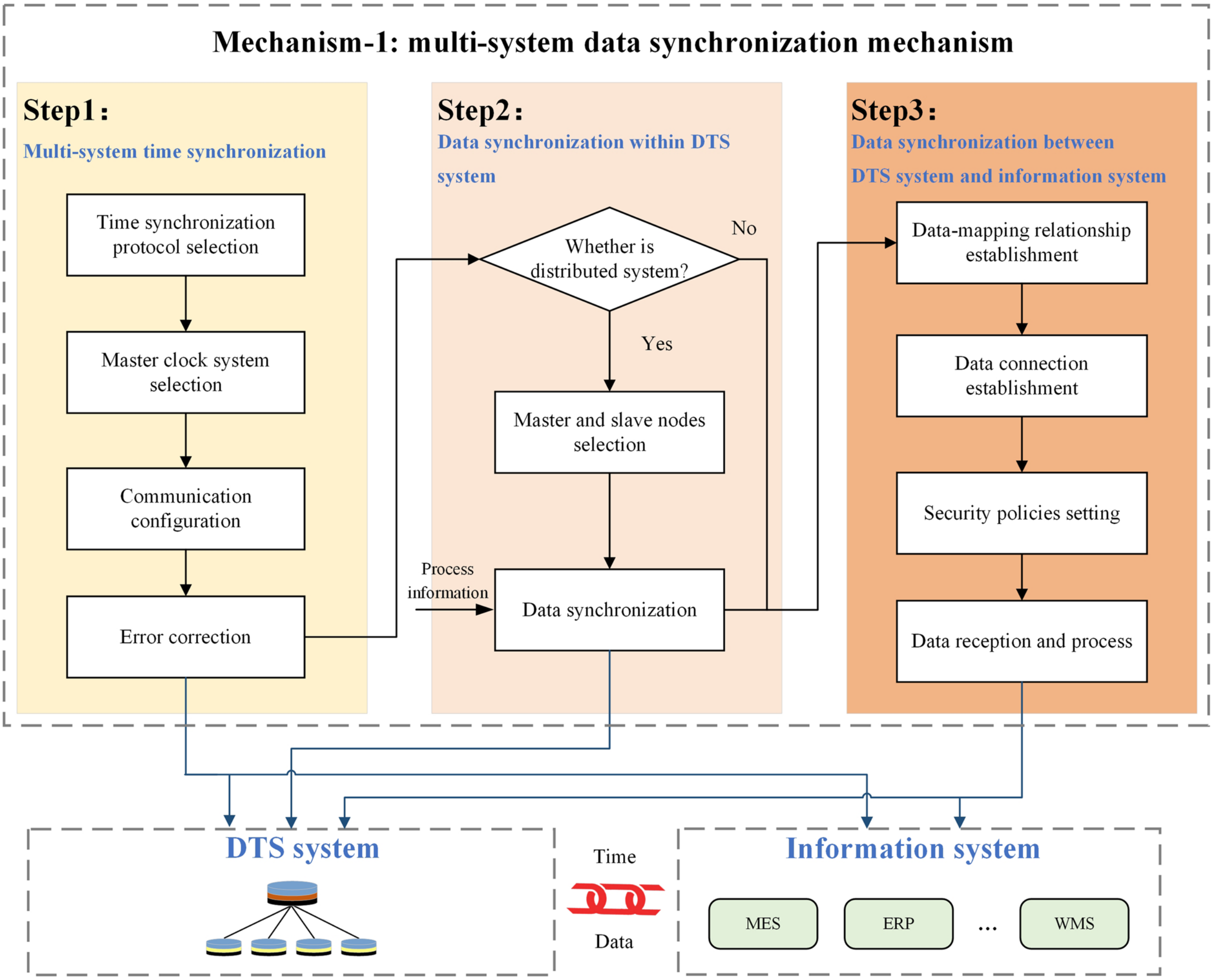

Figure 2 Procedure of multi-system data synchronization mechanism

the In-Sync Replica mechanism in Kafka. Meanwhile, the shop-floor process information can also be used as event logic to assist data synchronization.

Step 3: Data synchronization between DTS system and information systems. Data synchronization in this part primarily focuses on the data interaction between the DTS system and information systems. Firstly, it is crucial to define and maintain the data mapping relationships between different systems. Then, establish data connection between systems, including network address setting, database setting, and data interface development, etc. Meanwhile, it is essential to provide security policies, such as authentication API, token authentication. Then, data communication is established between the DTS system and the information systems, and request data is sent to the target system. Finally, the target system updates and processes the data.

4.2 Mechanism-2: Multi-Fidelity Model Synchronization Mechanism

In DTS, the virtual model needs to be consistent with the state of the physical entity. The virtual models include models with different dimensions such as geometric models, physical models, behavior models, rule-based models, and so on. Virtual models may have different degrees of fidelity. Low-fidelity model, although relatively low in computing accuracy, can be used to achieve fast approximate computing or provide initial feasible solutions due to low computing cost. Therefore, low-fidelity models can be used to realize real-time or near real-time applications in DTS. The high-fidelity model is characterized by high accuracy and high computing cost. High-fidelity model can be used to solve complex problems accurately. Therefore, in DTS, the high-fidelity model can be used for applications that do not require fast response, or that require high accuracy and reliability.

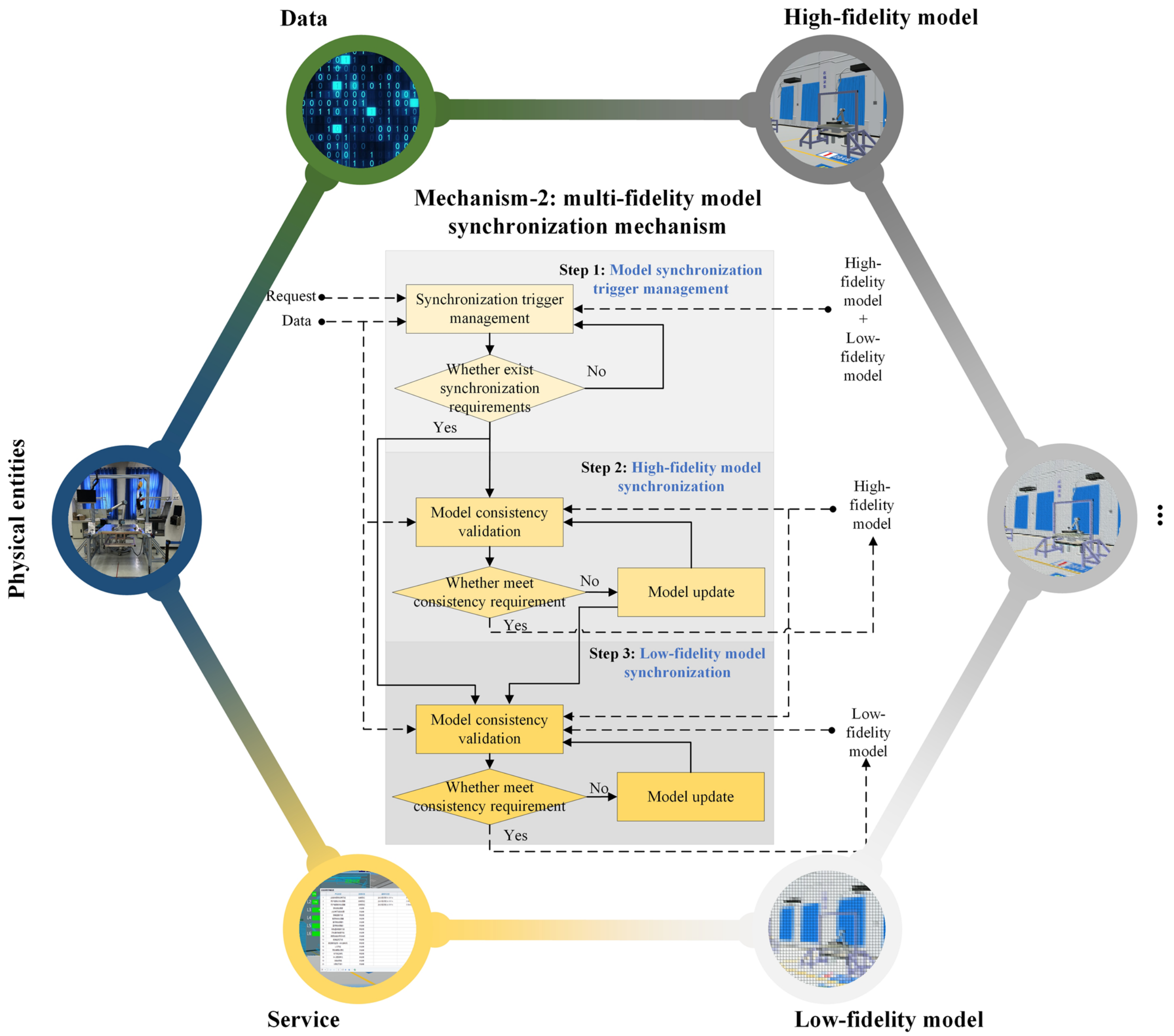

Figure 3 Procedure of multi-fidelity model synchronization mechanism

In some scenarios, high-fidelity model and low-fidelity models can work together to solve the problem, in order to increase the speed of the computing while maintaining accuracy [33].

Mechanism-2: multi-fidelity model synchronization mechanism maintains the consistency between physical entities and virtual models, as well as between different fidelity models. To maintain the consistency between physical entities and virtual models, the high-fidelity model with the finest granularity is regarded as the standard model, and the consistency between high-fidelity model and physical entities is maintained through model updates. The accuracy and credibility of high-fidelity model will increase as the data and knowledge continue to accumulate. Different low-fidelity models are constructed with the help of the high-fidelity model and data to match different DTS application requirements. To maintain the consistency between different fidelity models, the low-fidelity model will update itself due to its own deviation or the high-fidelity model updates.

The procedure of multi-fidelity model synchronization mechanism is shown in Figure 3. The specific contents are explained as follows:

Step 1: Model synchronization trigger management. Model synchronization trigger management is a background process in DTS, which utilizes various mechanisms to trigger high-fidelity or low-fidelity model synchronization. The triggering mechanisms include active triggering, periodic triggering, characterization triggering, task demand triggering, etc. The active triggering mechanism involves manually triggering model synchronization when required. The periodic triggering mechanism automatically triggers model synchronization when the DTS operation reaches a preset moment. The characterization triggering mechanism determines whether model synchronization should be triggered by analyzing characteristic values derived from data analysis. The task demand triggering mechanism refers to triggering model synchronization of model required for specific tasks, when the task demand is predicted or occurs. The selection of the triggering mechanism is based on the specific DTS requirements.

Step 2: High-fidelity model synchronization. After high-fidelity model synchronization is triggered, the consistency of the current high-fidelity model is first validated with data. If the high-fidelity model consistency is not satisfied, choose update methods based on the domain characteristics of the model [34]. If a single-domain model update is triggered, models of other domains should also be validated and updated based on the coupling of multi-domain models [35]. After the high-fidelity model update has been completed and validated for consistency, the original model should be replaced with the updated high-fidelity model, and the original model should be backed up. The high-fidelity model synchronization also triggers the low-fidelity model synchronization.

Step 3: Low-fidelity model synchronization. After low-fidelity model synchronization is triggered, the consistency of the current low-fidelity model is first validated by combining high-fidelity model and data. Similarly, if the consistency of the low-fidelity model does not meet the requirements, the model will be updated with the help of high-fidelity model and data. Since low-fidelity model is usually used for single-domain applications, whether to update the models of other domains should be considered based on the current situation. After the low-fidelity model is updated and validated, the original model should be replaced with the updated low-fidelity model, and the original model should be backed up.

4.3 Mechanism-3: Multi-Resource State Synchronization Mechanism

The physical-virtual state synchronization of resources is the basis for achieving DTS state synchronization. The shop-floor includes heterogeneous resources such as humans, equipment, materials, and environment. Physical-virtual state synchronization of resources is achieved through time, data, connection, model and service synchronization. There are also differences in physical-virtual state synchronization methods for heterogeneous resources.

(1) Humans include operators, managers, technicians, etc. DTS focuses mainly on operators involved in actual production. Since operators have characteristics such as dynamism and uncertainty, it is necessary to realize model synchronization based on the characteristics of operators.

(2) Equipment includes production equipment, logistics equipment, tools, etc. There are various situations such as aging, friction, failures, as well as configuration changes, periodic maintenance, and other external interventions, all of which will trigger equipment model synchronization.

(3) Materials include raw materials, parts, work-in-process (WIP), finished products, etc. In the process manufacturing shop-floor, where material models are difficult to construct, state synchronization and quality analysis are performed with production data. In the discrete manufacturing shop-floor, the state synchronization of materials can be achieved with production data, RFID data, and logistics data, etc., and also can be realized with synchronized model in some cases.

(4) The environment includes factors and entities. The environment is vital to production and safety and should be strictly managed and controlled. The state synchronization of environment can be realized with the support of environmental sensors, cameras, positioning systems, and so on. At the same time, model synchronization is performed only for environment entities that are related to production.

Shop-floor production requires various resources to interact with each other to achieve dynamic collaboration, so resources in DTS should be interactive.

The procedure of the multi-resource state synchronization mechanism is shown in Figure 4. The specific contents are explained as follows:

Step 1: Resources physical-virtual state synchronization. The resource physical-virtual state synchronization needs to achieve time, data, connection, model and service synchronization in turn. Time and data synchronization can be realized based on Mechanism-1. Connection synchronization mainly maintains the mapping relationships and interfaces between physical resources, data, models, and services. Heterogeneous resources can adopt different ways of model synchronization based on their own characteristics.

(1) For humans, the model synchronization method is determined based on their current state and job characteristics. For example, the skeleton-based motion model of an assembler needs to be updated before he/she assembles the product so that it can

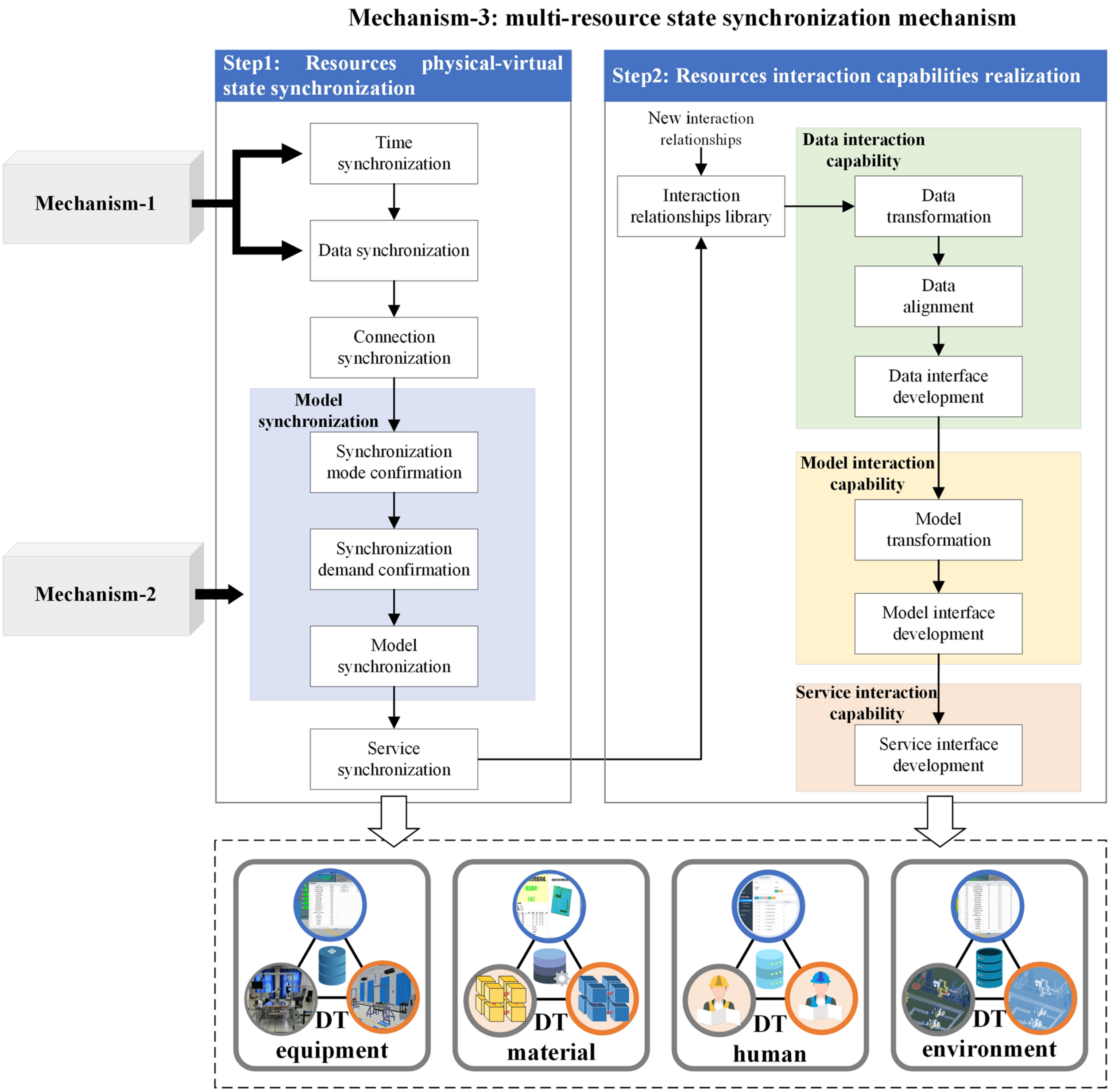

Figure 4 Procedure of multi-resource state synchronization mechanism

be monitored and analyzed during the assembly [36]. Since manual assembly depends on human experience, the assembly time prediction model needs to be updated periodically.

(2) For equipment, model synchronization can be triggered by active triggers, periodic triggers, characterization triggers, and task demand triggers. The trigger mechanisms are similar to the ones in Mechanism-2.

(3) For materials, model synchronization method is selected based on the needs of different shop-floors. In process manufacturing, model synchronization is usually not required. In discrete manufacturing, model synchronization is set according to the production schedule and quality management requirements of the shop-floor. For example, in the complex product assembly, it is necessary to construct the implementation model of the assembled product and analyze the assembly quality with the design model. The model synchronization is implemented with assembly data and inspection data at specific task nodes of shop-floor process.

(4) For environment, whether to perform model synchronization needs to be determined by changes in environmental entities. For example, if the position of entities such as fences and baffles in the shop-floor changes, model synchronization needs to be completed immediately.

The method of model synchronization can be realized based on Mechanism-2. With the synchronized models and data, the associated services are updated to achieve service synchronization.

Step 2: Resources interaction capabilities realization. Firstly, the possible interaction relationships and methods between different resources are defined to form an interaction relationships library, according to the production process and organizational relationships of the shop-floor. The interaction relationships library should be updated when new possible interaction relationships occur. Based on the interaction relationships library, data interaction capability, model interaction capability and service interaction capability are realized respectively for resources with interaction requirements.

(1) Data interaction capabilities are realized through data transformation, data alignment, and data interface development. Data transformation enables data from different resources to be transformed into data in the same data format. Data alignment makes resource data with different sampling frequencies reach spatial and temporal consistency. Spatial alignment guarantees that data from different resources are converted to the same spatial coordinate system. Time alignment guarantees that data from different resources are aligned at partial sampling time points, which can be done by timestamp alignment, interpolation, and other methods. Data interface development enables resource data to be transferred through interfaces.
(2) Model interaction capabilities are realized through model transformation and model interface development. Model transformation can be realized through format transformation, model encapsulation, and construction of surrogate models so that models of different resources can interact with each other through UML, SysML, FMU/FMI, etc. Then the corresponding model interface is developed.
(3) Service interaction capabilities are realized through service interface development, such as developing APIs for services to communicate with each other in the microservice architecture.

4.4 Mechanism-4: Multi-Level State Synchronization Mechanism

DTS can be divided into different levels, such as resource level, production unit level and shop-floor level. Based on spatial, logical and interface relationships, lower-level elements are combined to form higher-level elements with more complex production capabilities. Physical-virtual state synchronization in DTS requires physical-virtual state synchronization and physical-virtual relationship synchronization of elements at all levels. The physical-virtual state synchronization of elements can be realized with the help of Mechanism-3. To realize the physical-virtual relationship synchronization of elements, it is first necessary to monitor and analyze the relationship between the elements in physical shop-floor. Element relationships in physical shop-floor are dynamic, and numerous events can lead to changes in element relationships. Relationship changes are categorized into active and passive relationship changes. Active relationship changes are caused by active behaviors of shop-floor such as production execution, material delivery, shop-floor reconfiguration. Passive relationship changes are usually caused by various disturbances, which need to be analyzed and judged by corresponding monitoring and detect methods and combined with expert knowledge base, knowledge graph and other methods.

The procedure of multi-level state synchronization mechanism is shown in Figure 5. The specific contents are explained as follows:

Step 1: Element relationship library construction. Firstly, the element relationship library is constructed based on the hierarchical relationship, spatial structure, production process, organizational relationship and actual data in physical shop-floor. The element relationship library can be implemented with methods such as graph model, and then maintained by monitoring the element relationships. For active relationship changes, the updates of the element relationship library can be triggered directly by the events. For passive relationship changes, updates are triggered by event monitoring and data analysis. Element relationship changes are verified with process information, monitoring data, and expert knowledge, etc. The validation method is mainly to verify the consistency between relationships in element relationship library and relationships in physical shop-floor. It contains connection attributes consistency validation and parameter attributes consistency validation, which needs to be chosen according to the type of relationship. The connection attributes consistency validation mainly verifies whether there is a connection between physical elements. If there is a connection, the consistency of

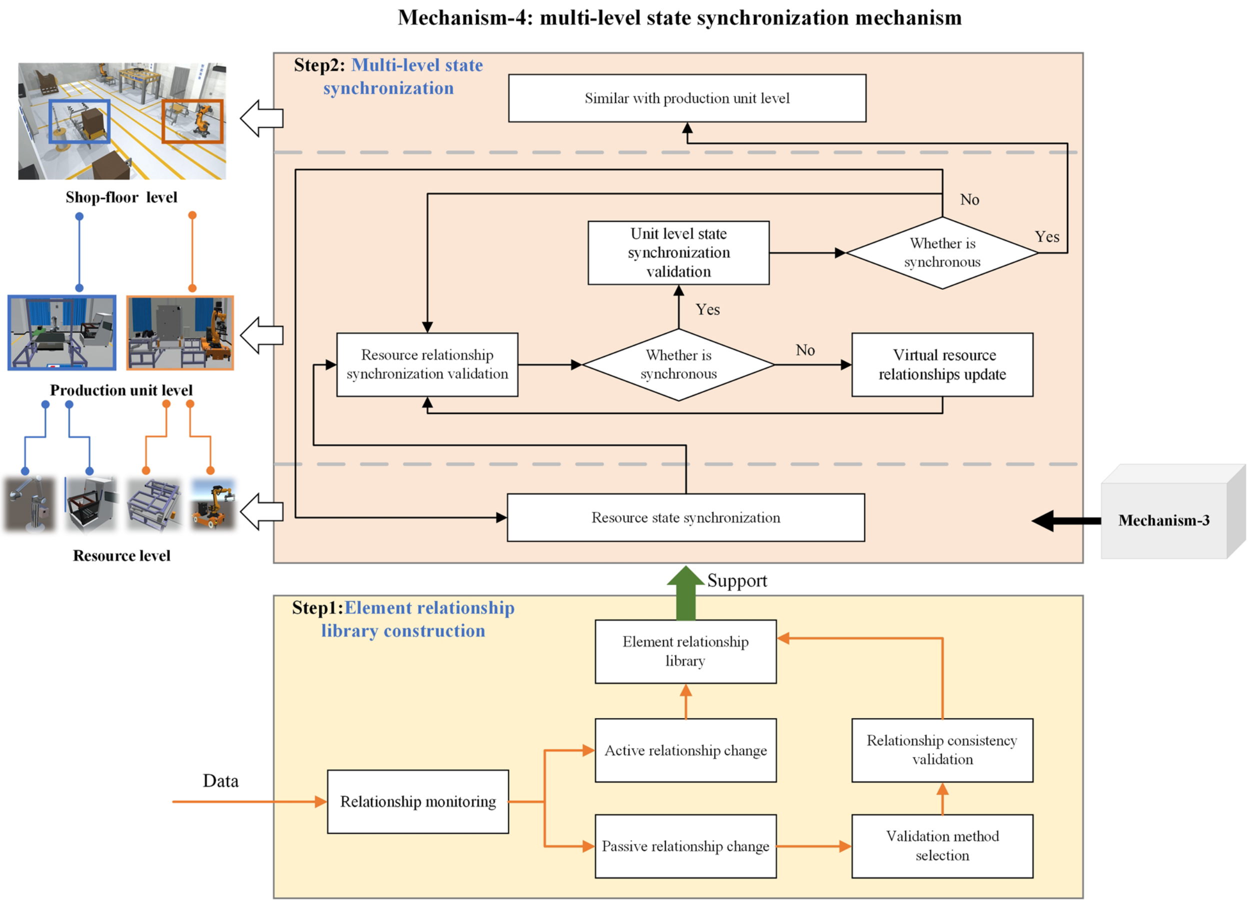

Figure 5 Procedure of multi-level state synchronization mechanism

parameter attributes is verified next. For example, for the spatial relationship between two equipment, it is necessary to detect the spatial relationship and parameters with the help of measuring equipment. If relationships between physical elements are added, deleted, reconstructed, etc., the element relationship library needs to be updated.

Step 2: Multi-level state synchronization. Multi-level state synchronization is used to realize the physical-virtual state synchronization at the resource level, production unit level, and shop-floor level in DTS.

(1) Physical-virtual state synchronization of resource level can be realized with Mechanism-3.

(2) The procedure to realize physical-virtual state synchronization of production unit level contains resource physical-virtual state synchronization, physical-virtual synchronization of resource relationships, and production unit synchronization validation. Physical-virtual state synchronization of resources has been realized with Mechanism-3. Relationships between physical resources are maintained by element relationship library. Therefore, by comparing the relationships in element relationship library and relationships between virtual resources, physical-virtual synchronization of resource relationships can be verified. If not, relationships between virtual elements are updated according to element relationship library. Finally, the physical-virtual state synchronization of production unit level is verified, and the method can be achieved based on Mechanism-3.

(3) The procedure to realize physical-virtual state synchronization of shop-floor level is similar to that at the production unit level.

4.5 Mechanism-5: Multi-Stage Operation Synchronization Mechanism

The DTS can achieve physical-virtual state consistency based on Mechanism-1, Mechanism-2, Mechanism-3 and Mechanism-4. The DTS also needs to maintain physical-virtual state consistency during actual shop-floor operation. Simultaneously, certain applications in DTS require synchronous operation with physical

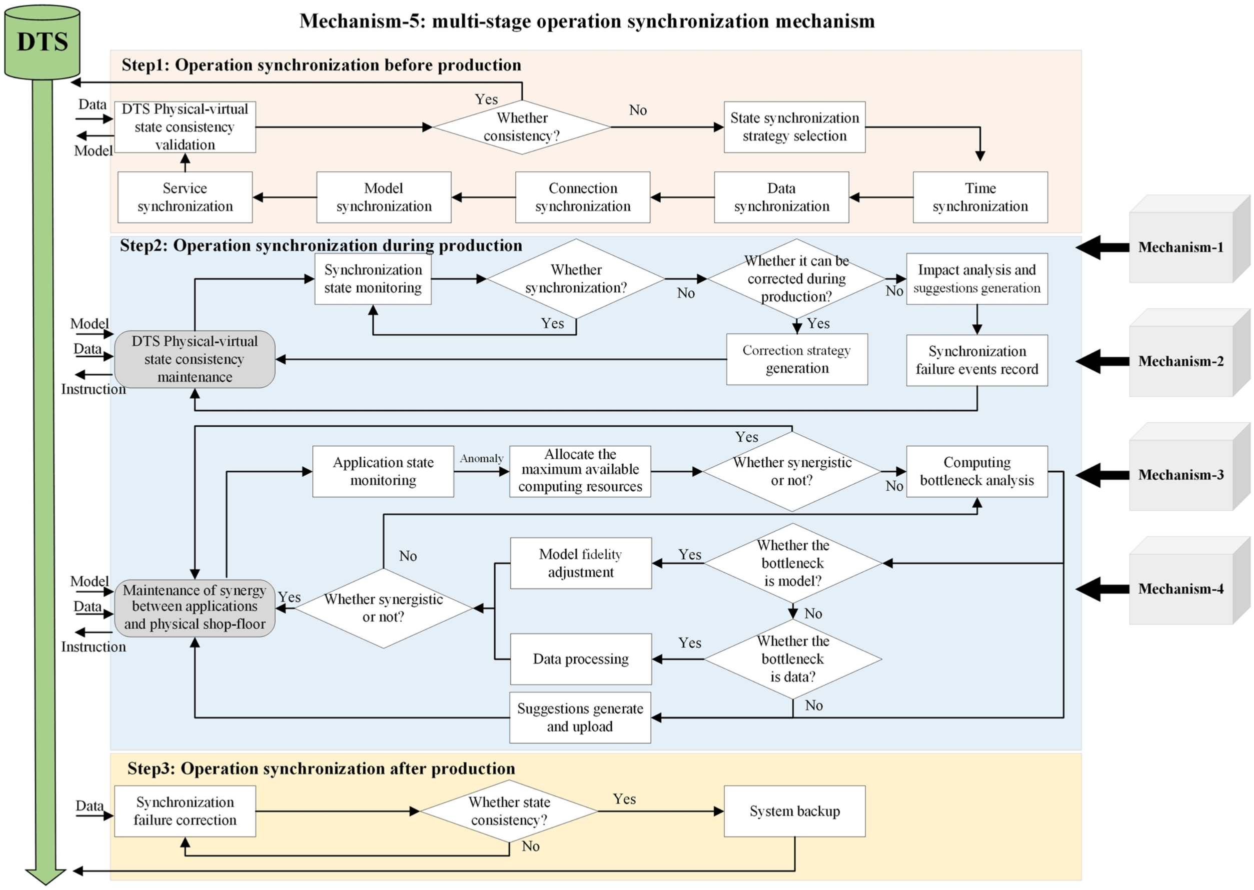

Figure 6 Procedure of multi-stage operation synchronization mechanism

shop-floor, such as real-time monitoring and analysis, real-time simulation. The multi-stage operation synchronization mechanism maintains the DTS operational synchronization from a full lifecycle perspective.

The procedure of the multi-stage operation synchronization mechanism is shown in Figure 6. The specific contents are explained as follows:

Step 1: Operation synchronization before production. Firstly, validate the physical-virtual state consistency of DTS. If inconsistent, select the physical-virtual state synchronization strategy of DTS based on the state of the shop-floor and the DTS system. Then, with the help of Mechanism-1, Mechanism-2, Mechanism-3 and Mechanism-4, time synchronization, data synchronization, connection synchronization, model synchronization and service synchronization of DTS are realized respectively based on the synchronization strategy, and the physical-virtual state consistency of DTS is checked again.

Step 2: Operation synchronization during production. Operation synchronization in production mainly maintains the physical-virtual state consistency and the synergy between applications and the physical shop-floor.

(1) Physical-virtual state consistency maintenance. Firstly, monitor the synchronization state. If out of sync, validate whether it can be corrected during the DTS operation. If possible, generate the correction strategy, and correct the synchronization failure based on the relevant mechanisms. If not, analyze the impact of synchronization failure on the DTS system and generate handling suggestions. Then, the synchronization failure events are recorded.
(2) Maintenance of synergy between applications and the physical shop-floor. Firstly, monitor the state of applications. If applications do not run synchronously with physical shop-floor, allocate the maximum available computing resources to the application without affecting the normal operation of DTS system. If still unsatisfied, analyze the computing bottleneck of applications. Adjust model fidelity based on Mechanism-2 if the bottleneck is model,

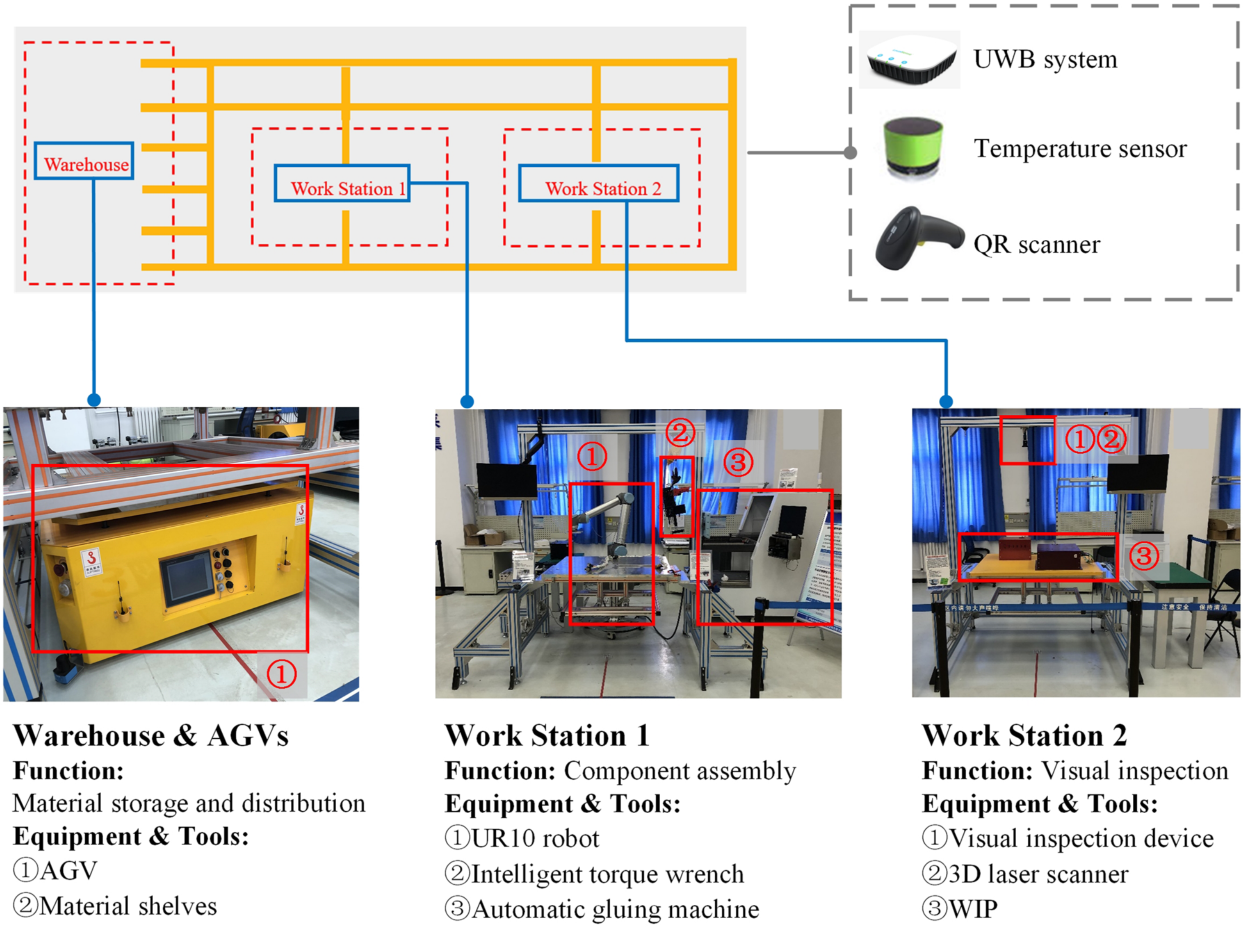

Figure 7 Scenario of satellite assembly shop-floor

or reduce data frequency or dimension based on data processing methods if the bottleneck is data. If still unsatisfied, handling suggestions are generated and uploaded to the system.

Step 3: Operation synchronization after production. Firstly, synchronization failures that are not corrected during production need to be corrected after production. Then, a backup of the DTS system state is made and will be used to support the next DTS operation synchronization.

5 Application Case in a Digital Twin Satellite Assembly Shop-Floor

5.1 Case Description

This case study is conducted in a satellite assembly shop-floor, as shown in Figure 7. The satellite assembly shop-floor realizes the assembly of satellite structural slab, which contains two work station and a warehouse. Materials are transported by automatic guided vehicle (AGV). The resources in satellite mobile assembly shop-floor is shown in Table 1.

Specifically, the assembly process in the satellite assembly shop-floor is as follows:

- Work station 1: AGV transports materials to work station 1. The components are coated with heat-conducting silicone grease by the automatic gluing machine. Then the components are automatically moved to the assembly position on the satellite structural slab by robot arm UR10. The assembler fastens components to the satellite structural slab with the intelligent torque wrench, which can also collect torque data automatically. Finally, the assembler connects cables.
- Work station 2: AGV transport WIP to work station 2. Visual inspection device and 3D laser scanner are used to collect visual data of WIP. Industrial PC (IPC) of work station 2 uses data to analyze assembly status and generate test reports.

Table 1 Resources in satellite assembly shop-floor

Name	Assignment	Communication method	Time frame
UR10 robot	Grab material and place it on the satellite structural slab	Ethernet	500 Hz
Automatic gluing machine	Coat material with heat-conducting silicone grease	Ethernet	10 Hz
Intelligent torque wrench	Fasten material to the satellite structural slab	Bluetooth/RS-232	Event trigger
Visual inspection device	Check cables installation status	Ethernet	Event trigger
3D laser scanner	Generate cloud point data of WIP	Ethernet	Event trigger
AGV	Transport materials	Wi-Fi	10 Hz
Material	Components, satellite structural slab, screws, cables	RFID	860–960 MHz
Assembler	Fasten material using intelligent torque wrench, connect cables	RFID	860–960 MHz

5.2 *Implementation of Digital Twin Satellite Assembly Shop-Floor System*

Digital twin satellite assembly shop-floor system (DT-SASS) includes physical layer, connection layer, virtual layer, data layer, and service layer, as shown in Figure 8. The physical layer includes the assemblers, equipment, materials, and environment of the physical shop-floor. With the help of Ethernet, Wi-Fi, RS-232, Bluetooth, etc., the connection layer realizes real-time transmission of shop-floor data, control instructions, work order, etc. to the shop-floor server via the shop-floor network. After the transmission, data is extracted with protocol parsing. The virtual layer includes virtual models of the physical shop-floor. The data layer stores all the DT-SASS data. The service layer includes various services provided by DT-SASS, such as product quality management, assembler management, equipment management, assembly task control.

The architecture of DT-SASS is shown in Figure 9, which adopts the master-slave distributed system architecture. The shop-floor server is set as the master system to realize the management of the whole shop-floor models, data and services, providing overall monitoring, analysis, simulation, decision-making, control and other applications. The IPC of each work station is set as the slave system to realize the management of work station, providing state monitoring, assembly quality analysis, equipment control and management and other applications.

5.3 Validation of the 5M Synchronization Mechanism for Digital Twin Shop-Floor

5.3.1 *Validation of Multi-System Data Synchronization Mechanism*

In DT-SASS, NTP protocol is utilized to achieve system time synchronization, as shown in Figure 10. The shop-floor server realizes time synchronization with an authoritative clock source. The shop-floor is set as the master time server as Stratum 1. The work station IPCs, AGVs, Ultra-Wideband (UWB) stations, etc. in Stratum 2 get the system time from Stratum 1. Stratum 3 gets the system time from Stratum 2.

Data synchronization of DT-SASS is shown in Figure 11. For data synchronization within DT-SASS, it mainly refers to data synchronization between the shop floor server and the work station IPC, which can be divided into real-time data synchronization and event-driven data synchronization. Real-time data synchronization refers to the real-time transmission of work station IPC data such as real-time equipment state data, material state data, assembler state data, assembly execution data, to the shop-floor server. Some of the data need to be preprocessed before transmission to reduce the amount of transmitted data. Due to the low transmission latency in satellite assembly shop-floor, the Semi Sync Replication mechanism of MySQL is used to achieve data synchronization. Event-driven data synchronization refers to data synchronization triggered by events. For example, after completing the preliminary quality analysis of WIP, the work station will synchronize the quality data and analysis results to the shop-floor server. The shop-floor server will send the assembly work order data to the work station IPC according to the task assignment of the shop-floor at the specific time.

For data synchronization between DT-SASS and other information systems, DT-SASS will synchronize data with the logistics management system of the satellite assembly shop-floor. DT-SASS will synchronize the material demand data to the logistics management system. The logistics management system will synchronize the material inventory state data with DT-SASS in real time. It will also synchronize the material distribution data to DT-SASS according to the material demand.

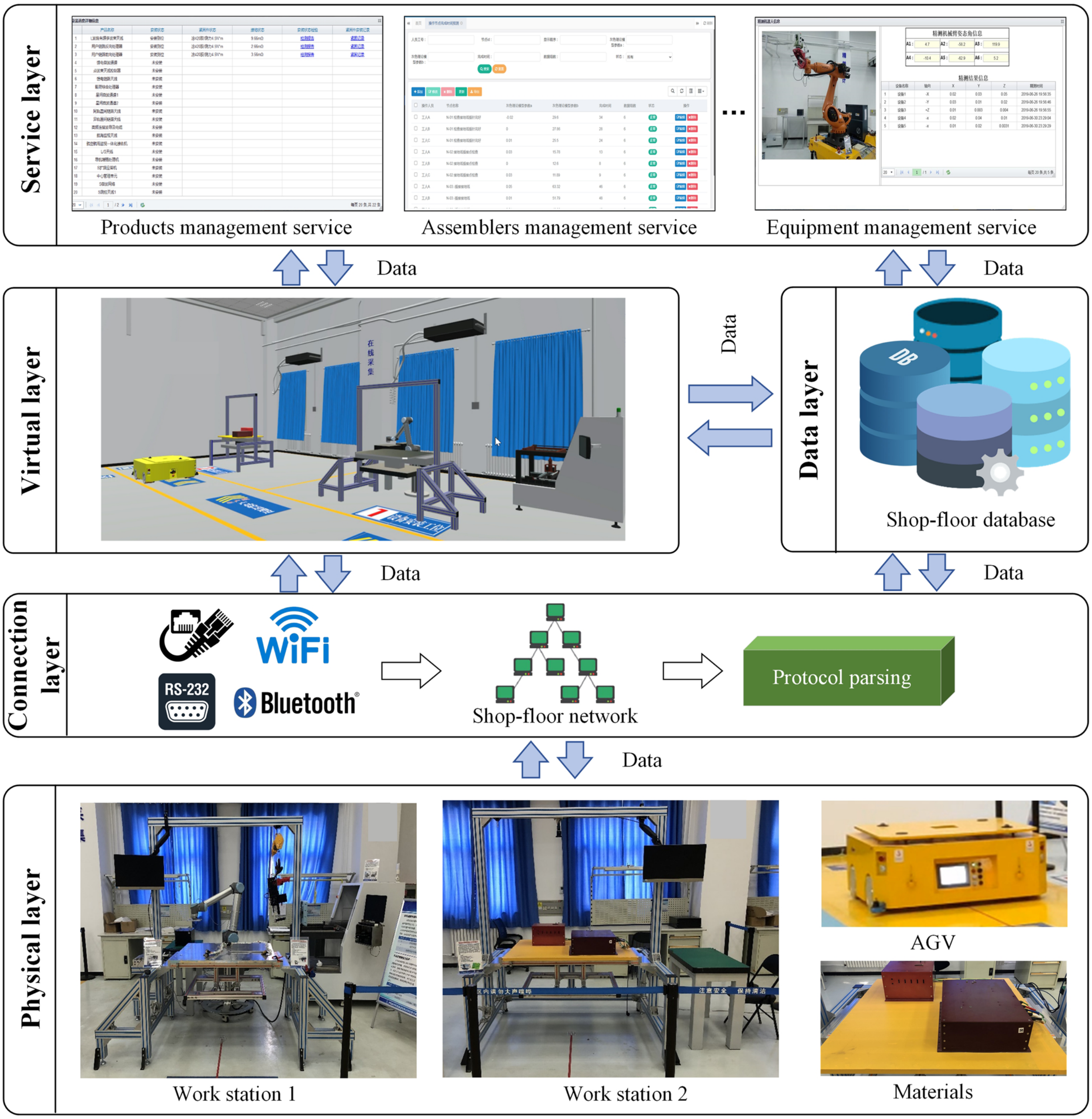

Figure 8 Digital twin satellite assembly shop-floor

5.3.2 *Validation of Multi-Fidelity Model Synchronization*

In DT-SASS, WIP realizes real-time monitoring with low-fidelity geometric models and quality analysis with high-fidelity geometric models, as shown in Figure 12. With the real-time positioning data, real-time 3D monitoring of WIP can be realized. With the real-time assembly data, the low-fidelity model of the WIP can be preliminarily updated, so as to monitor the current assembly state of WIP with the help of the model. The high-fidelity model can be updated with the point cloud data after the 3D scanning is completed at station 2. The updated high-fidelity model of the WIP will be compared with the design model to determine whether the assembly quality meets the design requirements. The low-fidelity model will be updated after the high-fidelity model has been updated.

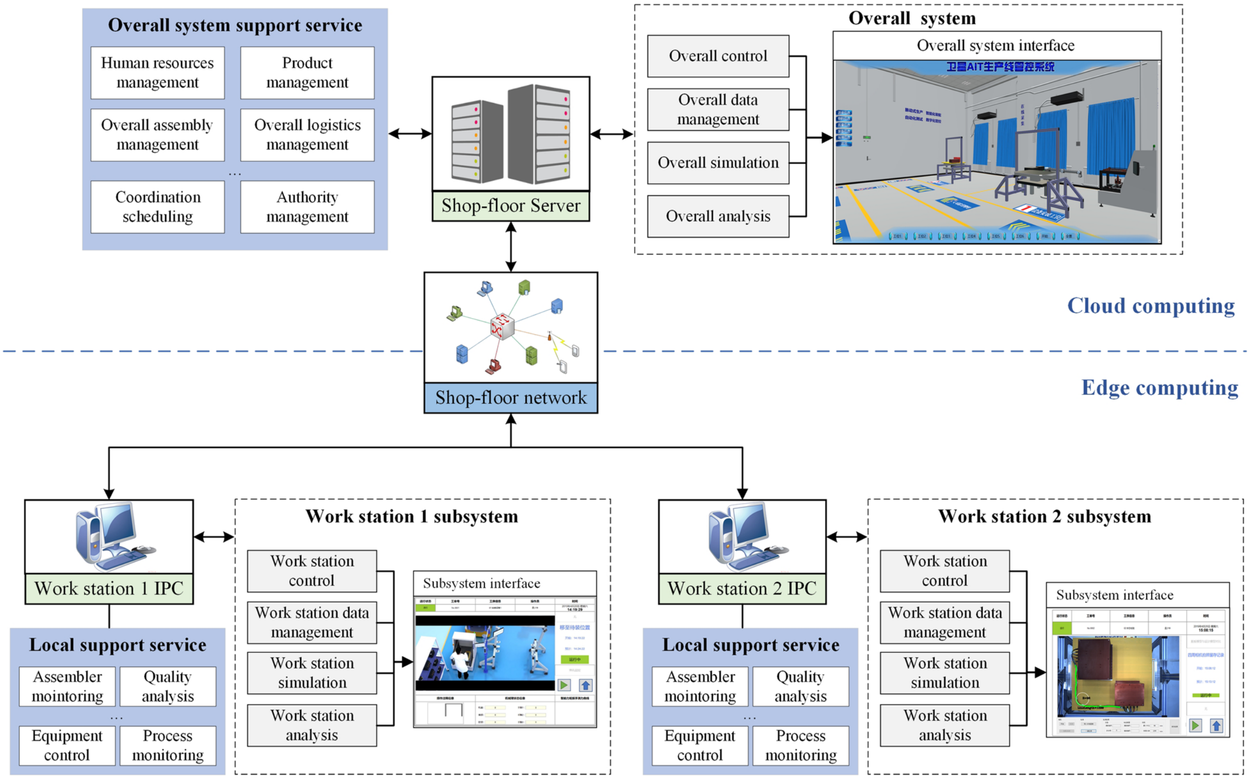

Figure 9 System architecture of digital twin satellite assembly shop-floor

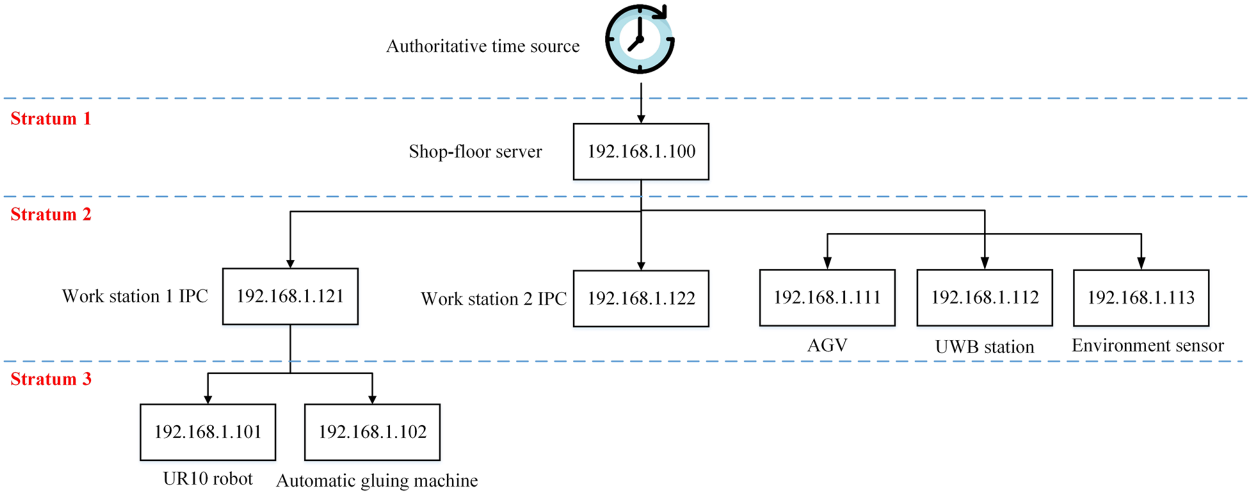

Figure 10 Time synchronization of digital twin satellite assembly shop-floor system based on NTP

5.3.3 Validation of Multi-Resource State Synchronization Mechanism

In DT-SASS, the physical-virtual state synchronization of assembler, equipment, material, and environment are achieved with different methods respectively.

(1) Physical-virtual state synchronization of assembler. In this shop-floor, the assembly tasks of assembler are mainly performed with the help of tools. And since there are no complex assembly movements, it is not necessary to construct a skeleton-based motion model of the assembler. Physical-

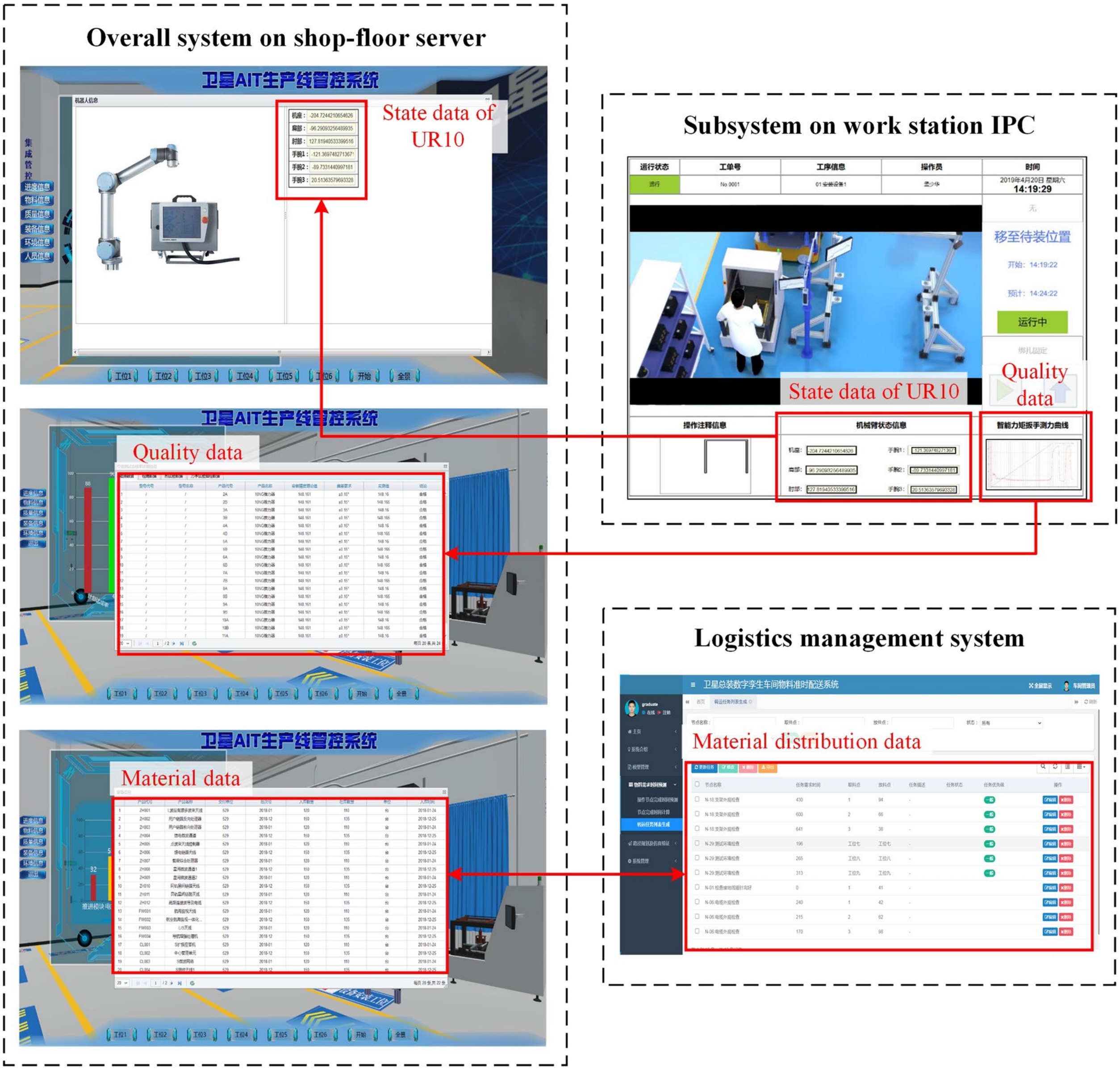

Figure 11 Data synchronization of digital twin satellite assembly shop-floor system

virtual state synchronization of assembler is mainly achieved with the help of data. The real-time positioning data of the assembler is generated by the fusion of the data from RFID and UWB system. The operation states of assembler are tracked by the data of intelligent torque wrench and assembly execution records.

(2) Physical-virtual state synchronization of equipment. The physical-virtual state synchronization of equipment is realized with the help of virtual model consistent with the physical equipment and real-time collected data. The following takes AGV as an example to introduce. In the satellite assembly shop-floor, the real-time states and material transfer capability of AGV need to be concerned. The real-time positioning data of AGV is generated by the fusion of the data from RFID and acceleration sensor of AGV. Meanwhile, the real-time state data are collected with the help of the on-board system of AGV. The geometric model and kinematic model of AGV are constructed in DT-SASS. Based on the geometric model of AGV and positioning data, the position of the AGV can be monitored in virtual shop-floor. The kinematic model of AGV, control

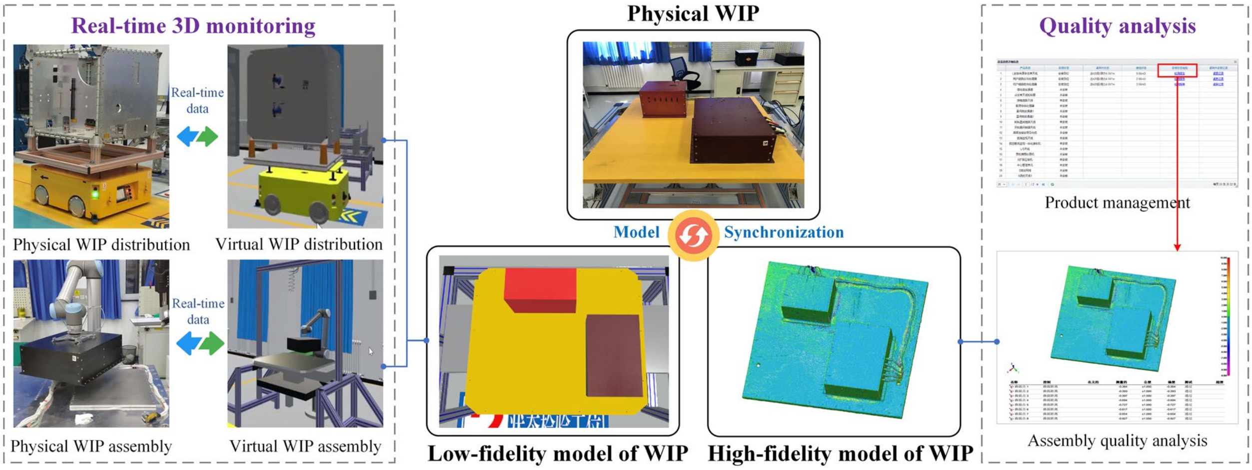

Figure 12 Multi-fidelity model synchronization of WIP

commands, actuator data, etc. are used to analyze whether the actual motion state of the AGV is consistent with the model simulation results. If there is any deviation, it is necessary to modify the kinematic model of AGV, and then evaluate the material transfer capability of AGV.

(3) Physical-virtual state synchronization of material. The physical-virtual state synchronization of material is mainly realized by data, while the synchronization of WIP is realized by data and model. The real-time positioning data of material is collected by RFID, and the assembly quality data is collected by intelligent torque wrench, visual inspection device, 3D laser scanner, etc. The method of model synchronization of WIP is described in Section 5.3.2.

(4) Physical-virtual state synchronization of environment. The physical-virtual state synchronization of environment is mainly realized by monitoring the environmental factors. The building and workbench of the satellite assembly shop-floor are fixed, so there is no need for monitoring and synchronization. The monitoring of environmental factors is realized with the help of environment sensors in the shop-floor.

The realization of physical-virtual state synchronization of resources in DT-SASS is shown in Figure 13. The interaction between resources in DT-SASS is realized using data association, data interface, model interface, and model interaction rules, etc.

5.3.4 *Validation of Multi-Level State Synchronization Mechanism*

DT-SASS is divided into resource level, work station level, and shop-floor level. The resource level consists of assemblers, equipment, materials, and environment. The work station level consists of assemblers, equipment, materials, and environment entities in each work station. The shop-floor level consists of work stations, warehouses, AGVs, and environment entities, etc.

The construction of the multi-level DT-SASS has been completed in this case, as shown in Figure 14. The multi-level state synchronization mainly focuses on the physical-virtual relationship synchronization in the DT-SASS. The element relationships in DT-SASS are mapped with the help of graph models, and the relationship graph models are updated mainly based on the execution state of the assembly process. For example, while the assembly is executed at work station 1, relationships between WIP and assembler, UR10, intelligent torque wrench, and automatic gluing machine in work station 1 are established, then data associations and model associations are established. After completing the assembly task at work station 1, the AGV transfers the WIP to work station 2. While the assembly is executed at work station 2, relationships between the WIP and the assembler, visual inspection device and 3D laser scanner in work station 2 are established, then data associations and model associations are established. The above process is shown in Figure 15.

5.3.5 *Validation of Multi-Stage Operation Synchronization Mechanism*

Before production, the state of hardware and software in DT-SASS needs to be checked, including the state of sensors, interface, data transmission, and shop-floor

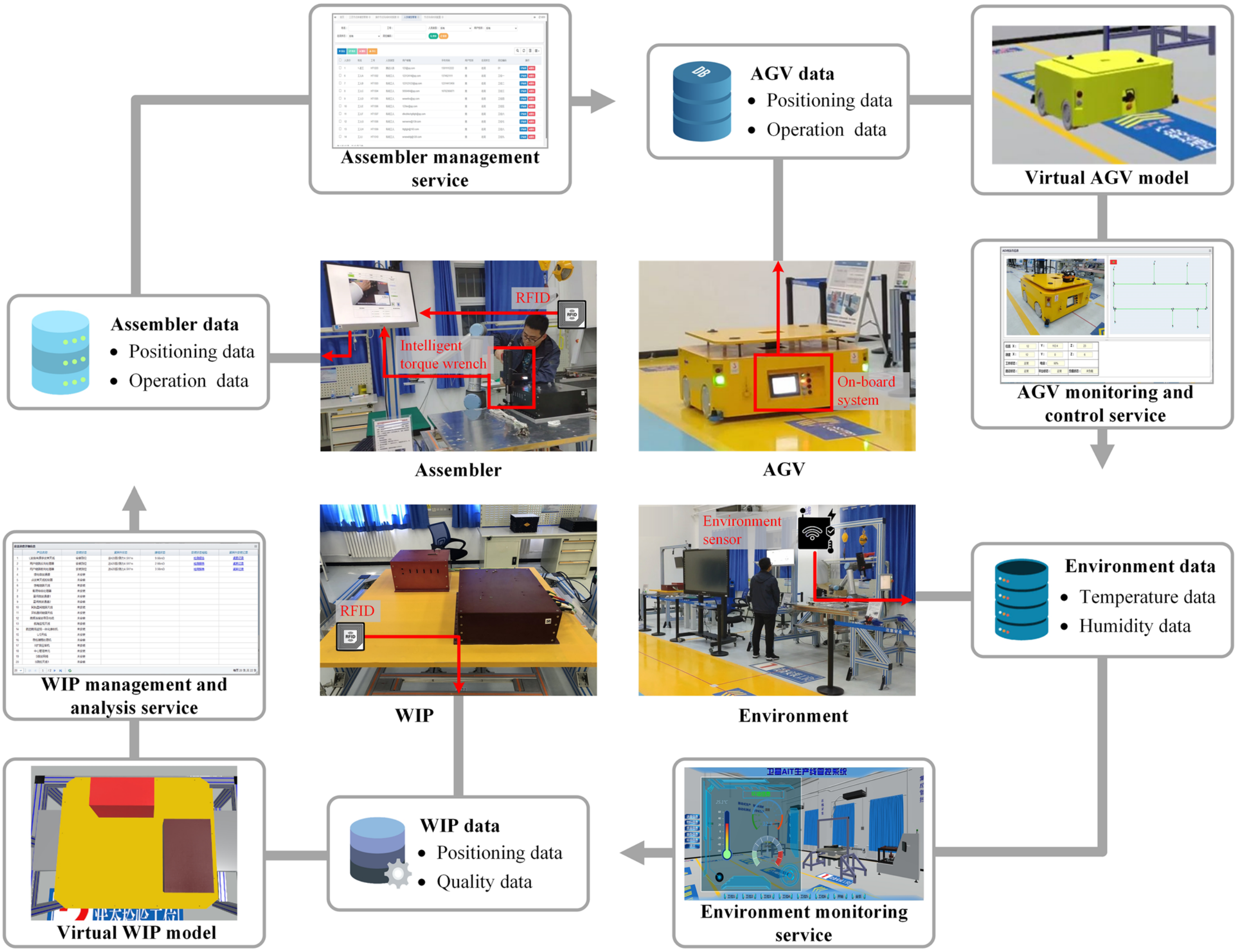

Figure 13 Physical-virtual state synchronization of resources

network connection, etc. Then the material information is obtained from the logistics management system. The shop-floor model is updated according to the physical data.

During production, the physical-virtual state consistency of DT-SASS is maintained. Based on the methods from Sections 5.3.1 to 5.3.4, DT-SASS can achieve time, data, connection, model, and service synchronization from the resource level to the shop-floor level, and update the data, models, and services of DT-SASS according to the execution state of the assembly tasks. Meanwhile, the model consistency of key equipment is monitored. If inconsistent, the problems will be reported to the system and the model will be updated by the technicians. In DT-SASS, the application that operates parallelly with physical shop-floor is real-time monitoring, which is mainly realized by using low-fidelity geometric models and real-time data of shop-floor. If the device can hardly support monitoring application using geometric model at current fidelity, methods such as mesh optimization based on reduction, Level of Detail (LOD) can be used.

After production, the models of satellite assembly shop-floor are checked and updated, and the state of DT-SASS is backed up.

6 Conclusions and Future Works

Synchronization is critical to DTS. What is synchronization in DTS, and how to achieve and maintain synchronization in DTS are topics worthy of attention in the field of DTS. This paper first analyzes the general characteristics of synchronization in different fields, and then summarizes the definition of synchronization in DTS considering the features of DTS. The requirements of synchronization in DTS are also presented. Then, based on the requirements, a 5M synchronization mechanism for DTS is introduced, where 5M refers to multi-system data, multi-fidelity model, multi-resource state, multi-level state, and multi-stage operation. The multi-system data synchronization mechanism realizes data

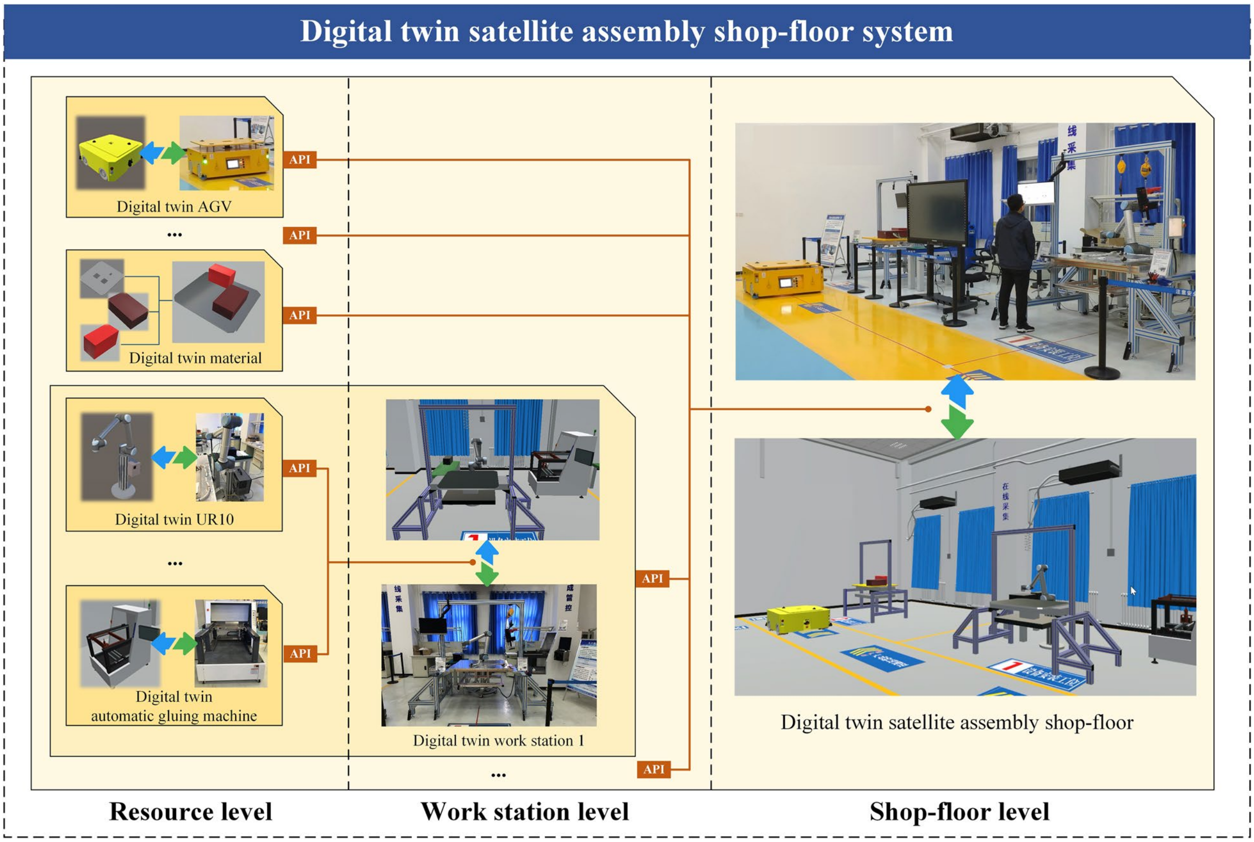

Figure 14 Three-level of digital twin satellite assembly shop-floor system

synchronization within the DTS system and between the DTS system and information systems. The multi-fidelity model synchronization mechanism enables DTS to provide multi-fidelity models that are synchronized with physical entities. According to the characteristics of heterogeneous resources, the multi-resource state synchronization mechanism achieves the physical-virtual state synchronization of various heterogeneous resources in DTS and enables resources to interact in DTS. By maintaining the physical-virtual synchronization of relationships, the multi-level state synchronization mechanism achieves physical-virtual state synchronization at different levels in DTS. And the multi-stage operation synchronization mechanism achieves and maintains physical-virtual state synchronization of DTS before, during, and after production, then supports running applications synchronously. The general implementation methods of the 5M synchronization mechanism are introduced in detail. Finally, the proposed 5M synchronization mechanism for DTS is validated in a digital twin satellite assembly shop-floor system, which has been used in practice.

This research summarizes a comprehensive definition of synchronization in DTS, to clarify the understanding of synchronization in DTS. According to the definition, a 5M synchronization mechanism for DTS, a systematic and practical synchronization mechanism that supports DTS to implement and maintain synchronization, is proposed. The general implementation methods of 5M synchronization mechanism for DTS are introduced, including detailed explanations and procedures. The practical implementation of the mechanism in a digital twin satellite assembly shop-floor also has a certain reference value for the development of DTS and the deployment of the mechanism.

Future works are as follows:

(1) The implementation methods of 5M synchronization mechanism for DTS need to be further studied, such as the multi-fidelity model synchronization method for multi-field models, general multi-resource interaction framework to support multi-resource and multi-level state synchronization, synchronous operation architecture for various applications.

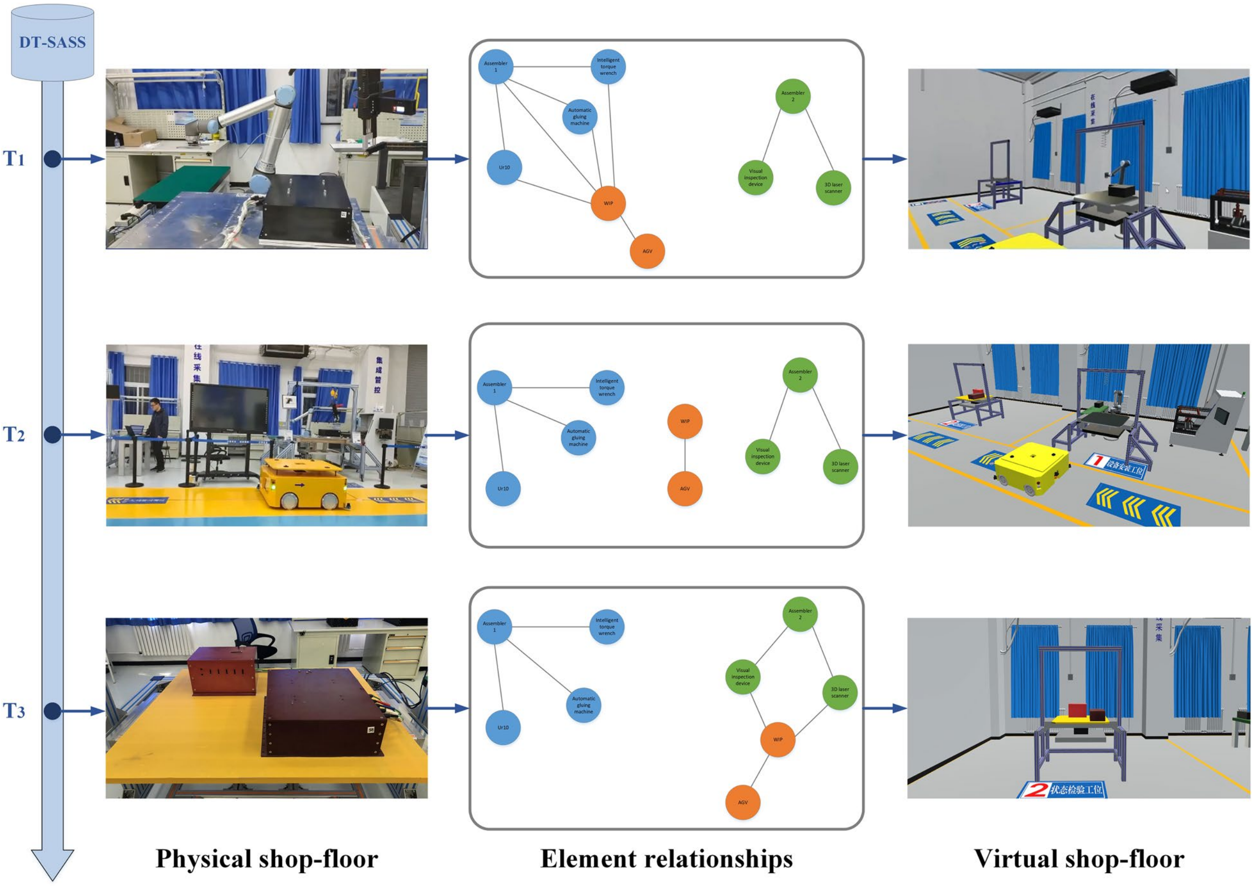

Figure 15 Physical-virtual relationship synchronization in the digital twin satellite assembly shop-floor system

(2) The quantitative methods and evaluation methods of 5M synchronization mechanism for DTS need to be researched.
(3) The definition and mechanism of synchronization in general digital twin systems should be studied.

Acknowledgments
Not applicable.

Authors' Contributions
WL was in charge of the theoretical research, application case development, and wrote the manuscript. JC assisted with the theoretical research and manuscript writing. ZW and XZ reviewed the manuscript and provided suggestion. ZW and HL assisted with case development and format modification. FT provided theoretical guidance and guided journal submissions. All authors read and approved the final manuscript.

Authors' Information
Weiran Liu, Born in 1991, is currently working toward the PhD degree at *School of Automation Science and Electrical Engineering, Beihang University, China*. He received his B.S. degree from *School of Automation Science and Electrical Engineering, Beihang University, China*, in 2014. His current research interests include digital twin technology, theory and application technology of digital twin satellite and digital twin shop-floor system.
Jiangfeng Cheng, Born in 1987, is currently an associate professor at *School of Automation Science and Electrical Engineering, Beihang University, China*. He received the Ph.D. degree from *School of Automation Science and Electrical Engineering, Beihang University, China*, in 2019. His research interests include digital twin, smart manufacturing, complex equipment PHM.
Zhiwen Wen, Born in 1992, is currently an engineer at *Xi'an Precision Machinery Research Institute, China*. He received the M.S. degree from *Xi'an Precision Machinery Research Institute, China*, in 2017. His current research interests include overall performance design and digital twin technology.
Xiaofu Zou, Born in 1987, is currently an associate professor at *Institute of Artificial Intelligence, Beihang University, China*. He received the Ph.D. degree from *School of Automation Science and Electrical Engineering, Beihang University, China*, in 2019. His current research interests include data-driven intelligent manufacturing and digital twin technology.
Zhaozong Wang, Born in 1999, is currently working toward M.S. degree at *School of Automation Science and Electrical Engineering, Beihang University, China*. He received the B.S. degree from *University of Science and Technology Beijing, China*, in 2021. His current research interests include fault diagnosis and remaining useful life prediction.
Hongting Liu, Born in 1998, is currently working toward the M.S. degree at *School of Automation Science and Electrical Engineering, Beihang University, China*. She received the B.S. degree from *School of Automation Science and Electrical Engineering, Beihang University, China*, in 2021. Her current research interests include platform-aggregated manufacturing service collaboration and operation optimization and complex system-oriented digital twin shop-floor modeling construction and operation optimization.
Fei Tao, Born in 1981, is currently a professor at *School of Automation Science and Electrical Engineering, Beihang University, China*. He received the B.S. and Ph.D. degrees in Mechanical Engineering from *Wuhan University of Technology, China*, in 2003 and 2008, respectively. His current research interests include service-oriented smart manufacturing, manufacturing service management,

sustainable manufacturing, and digital twin driven product design/manufacturing/service. He has authored four monographs and over 100 journal papers in the above areas. He is currently an Editor of the International Journal of *Service and Computing-Oriented Manufacturing* and the Associate Editor of *Robotic and Computer Integrated Manufacturing*.

Funding
Supported by National Natural Science Foundation of China (NSFC) (Grant Nos. 52120105008, 52005026, 52005025).

Declarations

Competing Interests

The authors declare no competing financial interests.

Received: 1 August 2023 Revised: 23 September 2023 Accepted: 19 October 2023

References

[1] H S Kang, J Y Lee, S Choi, et al. Smart manufacturing: Past research, present findings, and future directions. *International Journal of Precision Engineering and Manufacturing-Green Technology*, 2016, 3(1): 111–128.
[2] Z Lv, S Xie. Artificial intelligence in the digital twins: State of the art, challenges, and future research topics. *Digital Twin*, 2022, 1: 12.
[3] F Tao, Q Qi, A Liu, et al. Data-driven smart manufacturing. *Journal of Manufacturing Systems*, 2018, 48: 157–169.
[4] M Grieves. Intelligent digital twins and the development and management of complex systems. *Digital Twin*, 2022, 2: 8.
[5] F Tao, Q Qi. Make more digital twins. *Nature*, 2019, 573(7775): 490–491.
[6] K Wang, Y Wang, Y Li, et al. A review of the technology standards for enabling digital twin. *Digital Twin*, 2022, 2: 4.
[7] Q Qi, F Tao, T Hu, et al. Enabling technologies and tools for digital twin. *Journal of Manufacturing Systems*, 2021, 58: 3–21.
[8] Y Wang, X Wang, F Tao, et al. Digital twin-driven complexity management in intelligent manufacturing. *Digital Twin*, 2021, 1: 9.
[9] F Tao, M Zhang. Digital twin shop-floor: A new shop-floor paradigm towards smart manufacturing. *IEEE Access*, 2017, 5: 20418–27.
[10] F Tao, M Zhang, Y Liu, et al. Digital twin driven prognostics and health management for complex equipment. *CIRP Annals*, 2018, 67(1): 169–172.
[11] M Zhang, F Tao, B Huang, et al. Digital twin data: methods and key technologies. *Digital Twin*, 2022, 1: 2.
[12] F Tao, H Zhang, A Liu, et al. Digital Twin in Industry: State-of-the-Art. *IEEE Transactions on Industrial Informatics*, 2019, 15(4): 2405–2415.
[13] J Leng, Q Liu, S Ye, et al. Digital twin-driven rapid reconfiguration of the automated manufacturing system via an open architecture model. *Robotics and Computer-Integrated Manufacturing*, 2020, 63: 101895.
[14] M Zhang, F Tao, A Y C Nee. Digital twin enhanced dynamic job-shop scheduling. *Journal of Manufacturing Systems*, 2021, 58: 146–156.
[15] C Zhuang, J Liu, H Xiong. Digital twin-based smart production management and control framework for the complex product assembly shop-floor. *International Journal of Advanced Manufacturing Technology*, 2018, 96(1): 1149–1163.
[16] K Zhang, T Qu, D Zhou, et al. Digital twin-based opti-state control method for a synchronized production operation system. *Robotics and Computer-Integrated Manufacturing*, 2020, 63: 101892.
[17] B A Talkhestani, N Jazdi, W Schloegl, et al. Consistency check to synchronize the Digital Twin of manufacturing automation based on anchor points. *Procedia CIRP*, 2018, 72: 159–164.
[18] E Negri, S Berardi, L Fumagalli, et al. MES-integrated digital twin frameworks. *Journal of Manufacturing Systems*, 2020, 56: 58–71.
[19] C Liu, P Jiang, W Jiang. Web-based digital twin modeling and remote control of cyber-physical production systems. *Robotics and Computer-Integrated Manufacturing*, 2020, 64: 101956.
[20] H Zipper. Real-time-capable synchronization of digital twins. *IFAC-PapersOnLine*, 2021, 54(4): 147–152.
[21] P Wu, M Qi, L Gao, et al. Research on the virtual reality synchronization of workshop digital twin. *2019 IEEE 8th Joint International Information Technology and Artificial Intelligence Conference (ITAIC)*, 2019: 875–879.
[22] D Guo, R Y Zhong, Y Rong, et al. Synchronization of shop-floor logistics and manufacturing under IIoT and digital twin-enabled graduation intelligent manufacturing system. *IEEE Transactions on Cybernetics*, 2023, 53(3): 2005–2016.
[23] Y H Pan, T Qu, N Q Wu, et al. Digital twin based real-time production logistics synchronization system in a multi-level computing architecture. *Journal of Manufacturing Systems*, 2021, 58: 246–260.
[24] Y H Pan, N Q Wu, T Qu, et al. Digital-twin-driven production logistics synchronization system for vehicle routing problems with pick-up and delivery in industrial park. *International Journal of Computer Integrated Manufacturing*, 2020, 34(7–8): 814–828.
[25] H Zipper, C Diedrich. Synchronization of industrial plant and digital twin. *2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, Zaragoza, Spain: IEEE, 2019: 1678–1681.
[26] S H Strogatz. Spontaneous synchronization in nature. *Proceedings of International Frequency Control Symposium*, 1997: 2–4.
[27] S H Strogatz, D M Abrams, A McRobie, et al. Crowd synchrony on the Millennium Bridge. *Nature*, 2005, 438(7064): 43–44.
[28] D Harding, A Pagan. Synchronization of cycles. *Journal of Econometrics*, 2006, 132(1): 59–79.
[29] P D U Coronado, R Lynn, W Louhichi, et al. Part data integration in the Shop Floor Digital Twin: Mobile and cloud technologies to enable a manufacturing execution system. *Journal of Manufacturing Systems*, 2018, 48: 25–33.
[30] D Chefrour. Evolution of network time synchronization towards nanoseconds accuracy: A survey. *Computer Communications*, 2022, 191: 26–35.
[31] M Aslam, W Liu, X Jiao, et al. Hardware efficient clock synchronization across Wi-Fi and Ethernet-based network using PTP. *IEEE Transactions on Industrial Informatics*, 2022, 18(6): 3808–3819.
[32] H Li, G Shou, Y Hu, et al. SDN/NFV enhanced time synchronization in packet networks. *IEEE Systems Journal*, 2021, 15(4): 5634–5645.
[33] Z Zhang, Z Guan, Y Gong, et al. Improved multi-fidelity simulation-based optimisation: application in a digital twin shop floor. *International Journal of Production Research*, 2022, 60(3): 1016–1035.
[34] H Zhang, Q Qi, W Ji, et al. An update method for digital twin multi-dimension models. *Robotics and Computer-Integrated Manufacturing*, 2023, 80: 102481.
[35] B A Talkhestani, T Jung, B Lindemann, et al. An architecture of an intelligent digital twin in a cyber-physical production system. *at - Automatisierungstechnik*, 2019, 67(9): 762–782.
[36] Q Hong, Y Sun, T Liu, et al. TAD-Net: An approach for real-time action detection based on temporal convolution network and graph convolution network in digital twin shop-floor. *Digital Twin*, 2021, 1: 10.