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A digital-twin visualized architecture for Flexible Manufacturing System

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ABSTRACT

The new generation of industrial 4.0 intelligent manufacturing system consists of Human-Cyber-Physical System (HCPS), integrating human with cyber and physical systems. In manufacturing, a digital-twin visualization architecture is to solve the human-machine interaction problem that concerns digital-twin modeling on the Cyber-Physical (C-P) side and on the Human-Cyber side. Although there are many related research and applications, there lacks attention in terms of full life cycle functional services and lightweight architecture. This paper presents a general architecture of digital-twin visualization for flexible manufacturing systems (FMS). How the digital-twin C-P modeling of multi-source heterogeneous information can be described is investigated and how the 3D visualized human-machine interaction with digital-twin scenario information is explored in the proposed architecture. Besides, the visualization method of high-value information, relating to the life cycle planning, design, debugging and service stages, is studied and discussed thoroughly. Also, a digital-twin modeling concept of "Geometric information (G)-Historical samples (H)-Object attribute (O)-Snapshot collection (S)-Topology constraint (T)" (GHOST) is proposed, and methods for developing virtual digital-twin scenes architecture are presented. Based on the proposed modeling concept of GHOST for digital-twin, prototypes have been developed for the general platform of digital-twin RESTful services and the cross-platform general visual mock-up software. Experimental results show that this method is effective in the FMS lifecycle in various aspects.

1. Introduction

Digital twin, a critical know-how [1] enabling intelligent manufacturing which serves as the main supporting technologies for the fourth industrial revolution [2,3], can map physical information into cyberspace and manipulate physical objects via the study and exploration of information models [4]. It was first stated in the Apollo program of America [5]. Prof. Grieves conceptualized this concept initially in his class on product life cycle management, along with a 3D digital-twin modeling theory of physical entity, information entity and communication [6], establishing mapping relations between physics and information. Over the decades, digital-twin has gained constant attention and progress in both academic circles and on the market [7]. According to the level of data integration of digital-twin, Fraunhofer [8] put forward modeling theories on "Digital Model", "Digital Shadow" and "digital--twin". Tao [9] came up with a 5D digital-twin modeling method, involving physical entity, virtual device, service, digital-twin data and communication, which can be practically applied in multiple fields and industries.

With regard to the research of digital-twin modeling of intelligent manufacturing and production systems, Lee [10] suggested a CPS digital-twin 5C-layered framework for intelligent manufacturing, and the five layers are an intelligent communication layer, a data-information conversion layer, an information layer, a cognitive layer and a configuration layer. Tao [1] discussed a 5D modeling concept, involving physical entity, virtual entity, service, digital-twin data and communication, which is applicable to intelligent workshops. Wu [11] proposed a method for the conceptual modeling of a digital twin based on a 5D digital twin framework to represent the complex relationship between digital twin objects and their attributes. He based on the method, modelled the digital twin of an intelligent vehicle at the concept level. As for the digital-twin application of cyber-machine-tools, Botkina [6] proposed a - method for physical cutters of the machine tool, which accurately characterizes the cutters and can keep upgrading technological processes through precise simulation, control and analysis of the cutting process. Liu [12] brought up a system development method based on information-physical machine tools, and built an MTConnect-based information model to represent the logical structure

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of a machine tool and the real-time status of its component and processing process. Li [13] proposed a framework for manufacturing task (MT) semantic modeling and manufacturing resource (MR) dynamic recommendation for digital twin shop-floor (DTS). The method offerred an effective approach to the description and conception of MTs based on ontology, MT semantic indexing and retrieval, and MR recommendation for DTS. Jumyung [14] proposed an automatic digital-twin environment using universal data models, which is based on AutomationML, and allows multiple load modules to be instantiated via twin modeling of a set of engineering data and relevant models. Jiang [15] proposed modeling methods for rapidly creating a virtual model and the connection implementation mechanism between a physical world production system at a workshop level and its mirrored virtual model. The method and the associated connection mechanism had been applied to a real-world workshop DT to demonstrate its practicality and usefulness. Lu [16] presented a practical method for easy virtualization of manufacturing assets, seeking to simplify the development process of intelligent factories. For the different layers (i.e., component layer, device layer, production line layer and enterprise layer) of intelligent manufacturing system assets, web forms are utilized to construct their digital-twin models. Unfortunately, the above study was still constrained by the boundary between the layers of intelligent manufacturing system assets. Not many all-purpose standard methods or specifications are available, when it comes to the digital-twin modeling of either components or workshops [17]. For human-cyber-physical systems (HCPS) [18], marking the transformation to the new generation of intelligent manufacturing paradigms, research efforts and applications concerning the digital-twin [19] of the whole life cycle of manufacturing systems are still absent. Wang [20] proposed a human-cyber-physical collaboration system as a key means of manufacturing and researched the method of modeling human-cyber-physical collaboration based on the visual question answering (VQA) technology to increase perception efficiency.

In an intelligent manufacturing system, massive digital-twin information described by different modeling methods is being collected and integrated. Digital Mock-up (DMU) can construct the "Physical-Cyber" mapped data of the digital-twin model into virtual 3D scenario motions and state changes. The efficiency and precision of "Cyber-Human" interaction can be improved through data visualization. Moreover, new decision reference information can also be obtained after the "value excavation" of digital-twin information using DMU technology and different analysis and simulation methods. Therefore, human perception to physical space and the target of decision-making level is enhanced. At present, a large number of DMU innovation researches and applications based on digital-twin technology continue to emerge in different stages of intelligent manufacturing.

1.1. Research of DMU in planning and design stage of a manufacturing system

Riascos [21] argued, Digital Mock-up (DMU), as a central verification tool, provides an environment platform of dimensional consistency (e.g., machinery, electricity, and software), a feature that CAD and PDM systems cannot offer. DMU virtualizes the several stages of the product life cycle (e.g., concept planning, mock-up creation, engineering and decision-making, maintenance, and product traceability), and provides a consistent virtualization verification platform for a cross-departmental engagement. Park [22] raised a visual DMU method based on DEVS, which can design and verify virtual production systems. Through concurrent engineering of machine design (device specifications and layout) and electrical design (device behavior and system control), functional tests, the verification of layout scheme and control procedures, and the goal of quickening stability debugging of production systems, before putting the system into service, have been realized. In Tecnomatix's Process Simulation virtual environment, Guerrero [23] realized digital-twin mirroring of manufacturing units, where the motion of virtual mechanisms is PLC-driven. It verifies PLC codes and prevents possible errors when PLC codes are active in the physical manufacturing unit. Leng [24] proposed an Open-architecture Machine Tool (OAMT) to rapidly and flexibly reconfigure the automated manufacturing systems in a novel digital-twin-driven approach. Schleich [25] proposed a comprehensive reference model based on the concept of Skin Model Shapes, serving as a digital-twin of the physical product in design and manufacturing. Guo [26] proposed a modular approach to help to build a flexible digital-twin model of the factory and to conduct corresponding changes of design. Zhang [27] presented a digital-twin-based approach for rapid individualized designing of the hollow glass production line, which generated an authoritative digital design of the system at the pre-production stage. Yi [28] presented a digital twin reference model for smart assembly process design and proposed an application framework for DT-based smart assembly with three layers. He discussed working mechanisms of assembly process planning, simulation, prediction, and control management in the virtual space layer in detail. Liu [29] presented a digital-twin-driven methodology for rapid individualized designing of the automated flow-shop manufacturing system (AFMS) to achieve optimal design performance for required functions of AFMS.

1.2. Research of DMU in use and maintenance stage of a manufacturing system

Alam [30] presented a digital-twin architecture reference model for the cloud-based CPS, C2PS which helped in identifying various degrees of basic and hybrid computation-interaction modes. Tao [31] proposed a new method for product design, manufacturing, and service, driven by digital twin to achieve the interaction and integration of physical space and virtual space in the intelligent manufacturing paradigm. Leng [32] proposed a digital-twin-driven manufacturing cyber-physical system (MCPS) for parallel controlling smart workshops under the mass individualization paradigm. By establishing a cyber-physical connection via decentralized digital-twin models, various manufacturing resources can be formed as a dynamic autonomous system to co-create personalized products. Leng [33] also proposed a novel digital-twin-driven joint optimization approach for warehousing in large-scale automated high-rise warehouse product-service system. Through perceiving online data from the physical warehouse product-service system, periodical optimal decisions can be obtained via the joint optimization model and then feedback is given to the semi-physical simulation engine in the Digital-twin System for verifying the implementation result. Zhuang [34] proposed a architecture of digital-twin-based smart production management and control approach for complex product assembly shop-floors.

1.3. Realization method of DMU architecture and research status of key technology

Yang [35,36] analyzed the overall architecture and logical architecture of DMU systems and created an immersive virtual maintenance environment through a DMU system. Wang [37] presented a smart factory architecture that incorporates industrial network, cloud, and supervisory control terminals with smart shop-floor objects such as machines, conveyors, and products. It can flexibly reconfigure the manufacturing system. Based on the digital-twin technology, Liu [38] presented a quad-play CMCO (i.e., Configuration, design Motion, planning Control, development Optimization decoupling) design architecture to put forward for the design of the flow-type smart manufacturing system in the Industry 4.0 context.

Given all that, the research and application of DMU for manufacturing systems have drawn extensive attention and have been widely used. But there are still deficiencies, requiring further improvement:

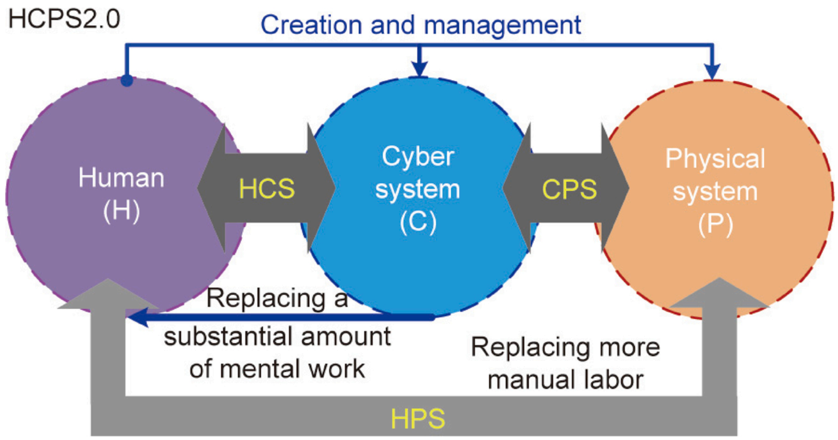

Fig. 1. Human-Cyber-Physical System(HCPS) [18].

1) Although people pay much attention to the digital-twin modeling method for the full life cycle of FMS, there are few researches on the digital-twin general modeling of Digital Mock-up (DMU).
2) Many studies on how to construct visual DMU are limited to specific types of devices, application scenarios, or stages throughout the life cycle of a production system. There is a shortage of related studies and applications of the system architecture of digital-twin visualization for the whole life cycle of a manufacturing system [9].
3) Given that acclaimed virtual DMU industrial software (e.g., Siemens' Process Simulation) must be oriented to various industries, numerous mature software modules exist, leading to very high deployment and learning costs. In this case, ordinary designers cannot be quickly familiar with the techniques, thereby adversely affecting the universalization of visual DMU in practical engineering applications.

To solve these problems, this paper presents a prototyping method for HCPS-oriented digital-twin visualization systems, a concept of digital-twin "Geometry – History – Object – Snapshot - Topology" (GHOST) modeling for the life cycle of FMS, and a cyber-physical multi-source heterogeneous digital-twin RESTful service platform (GHOST Service) for FMS based on the GHOST modeling concept. This visualization architecture, dedicated to FMS and discrete production systems, is lightweight and cross-platform so that it can be flexibly deployed. The FMS-oriented digital-twin visualization method and an interactive app (Visual Field) have been developed and tested. Their application in the planning, design, construction, and service of FMS projects has also been evaluated.

The rest of this paper is organized as follows. Section 2 introduces the concept of GHOST digital-twin modeling in the life cycle of HCPS. Section 3 studies and discusses how to implement the digital-twin visualization architecture for FMS and prototype development. Section 4 presents the application and testing of digital-twin GHOST Service and Visual Field in an FMS project by our lab and discusses the direction of future work. Section 5 is a summary of this paper.

2. Digital-twin model in the life cycle of HCPS

The new generation of intelligent manufacturing systems consists of the collaborative integration of humans, cyber system and physical system [32,33]. Humans are the master, and the creator and user of the physical system. The physical system is the main part, which is the provider of the manufacturing process. The cyber system is the core, it can analyze, calculate, and control the manufacturing process. As shown in Fig.1 [18], Human-Cyber-Physical System(HCPS) represents an innovation archetype brought by the new generation of artificial intelligence technology in the intelligent manufacturing sector. It demonstrates the deep integration and continuous upgrade of the Cyber-Physical System (CPS) and Human-Cyber System.

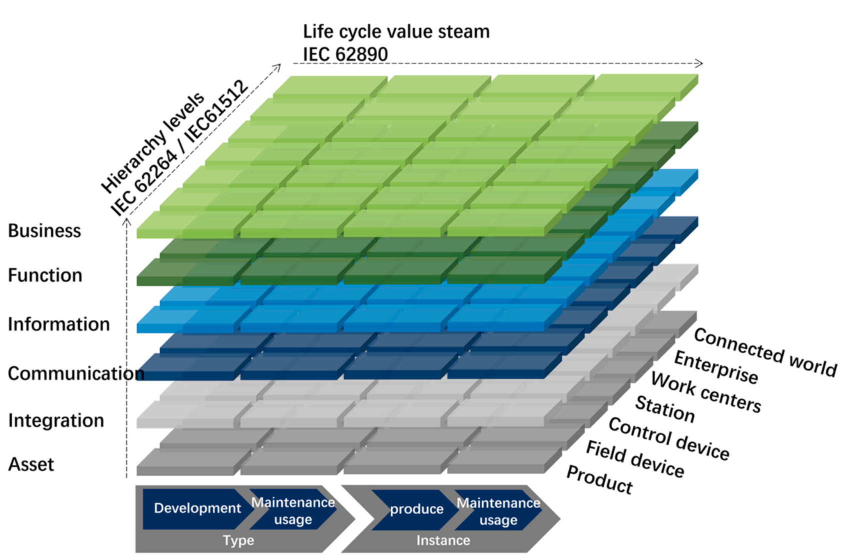

Fig. 2. RAMI4.0 3D Diagram [39].

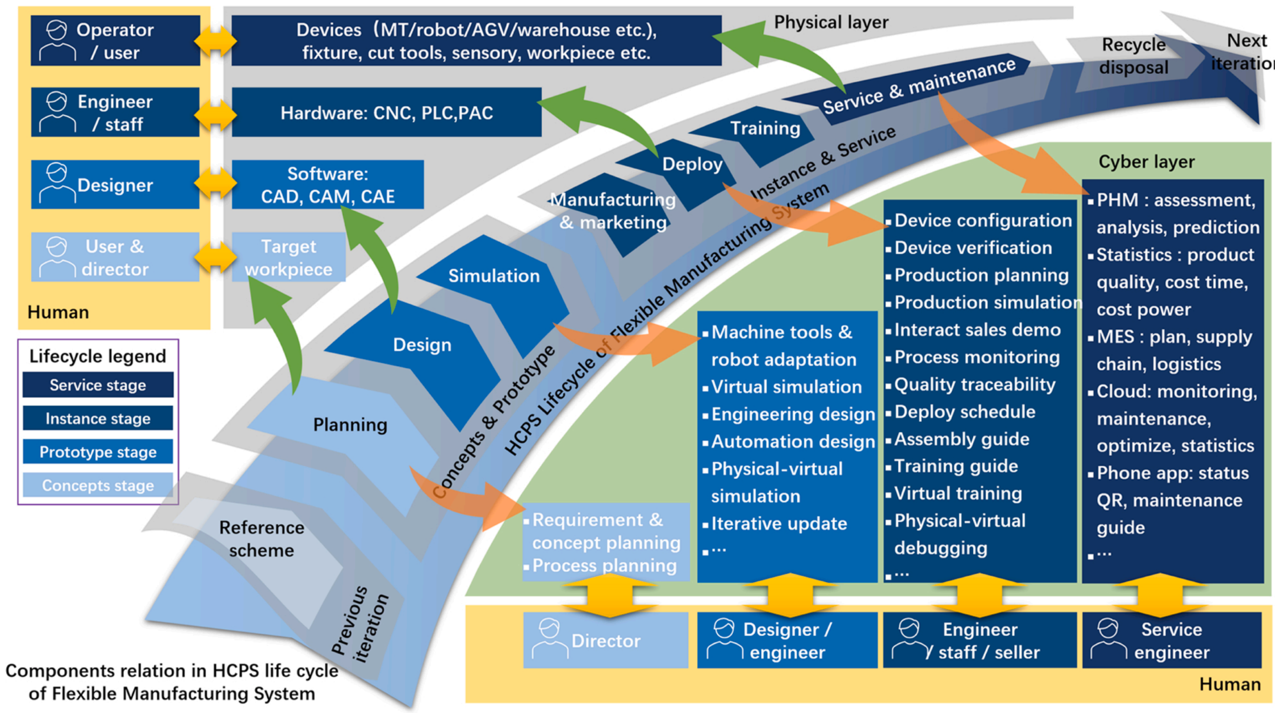

Fig. 3. Relations between FMS life cycle prototypes.

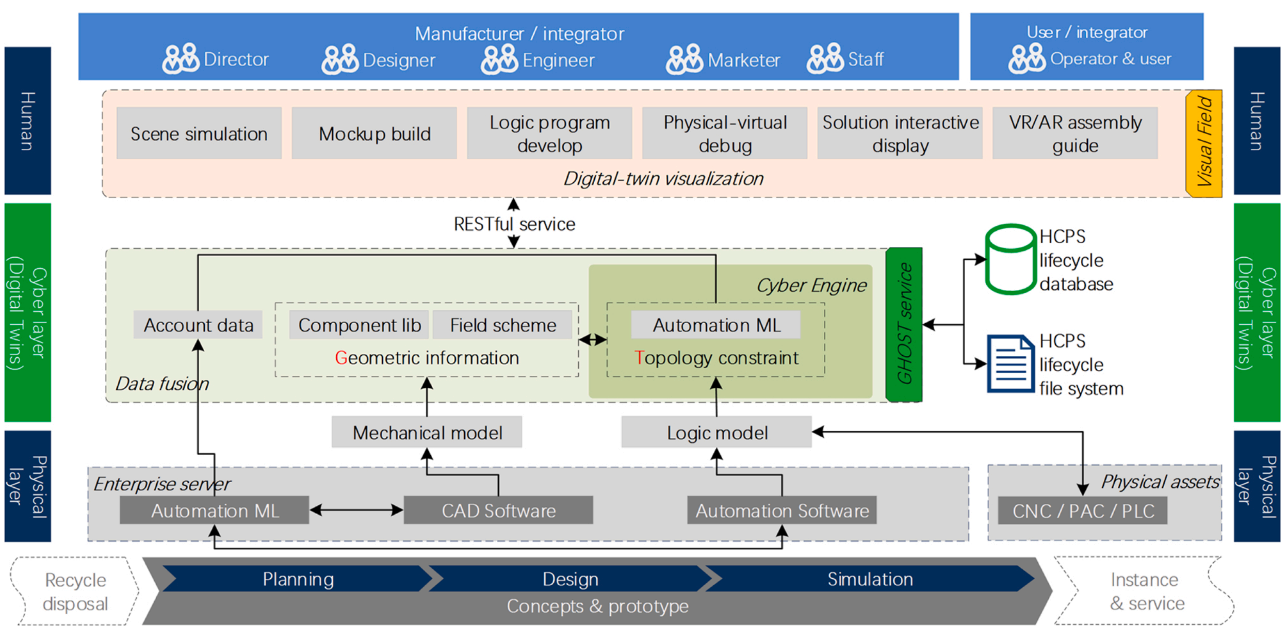

Fig. 4. Relations between prototypes in concepts & prototype stage.

2.1. Digital-twin model and DMU in the life cycle of FCPMS

In the 3D diagram of RAMI4.0 which describes the main elements of Industry 4.0 (Fig. 2), business performance, plant hierarchy, the data model and physical state of the product at different stages of the life cycle are interacted and instantiated in the manufacturing chain.

The new generation of intelligent manufacturing further emphasizes the central role that human beings play [36,37]. Under the HCPS interaction architecture of the new generation of intelligent manufacturing, physical assets are constructed as digital-twin mirror images in cyberspace. Information visualization technologies are leveraged to reconstruct digital-twin as the virtual three-dimensional DMU scene, thereby realizing the paradigm shift of "human-cyber" interaction.

Referring to RAMI4.0, which is required for HCPS information interaction in the new generation of intelligent manufacturing systems, and aiming at the characteristics of digital-twin generated by physical assets in FMS, this paper uncovers the relations between various life cycles of FMS, as shown in Fig. 3.

The life cycle of a device in an FMS can be divided into three stages: concepts & prototype stage, instance & service stage, and recycle & disposal stage.

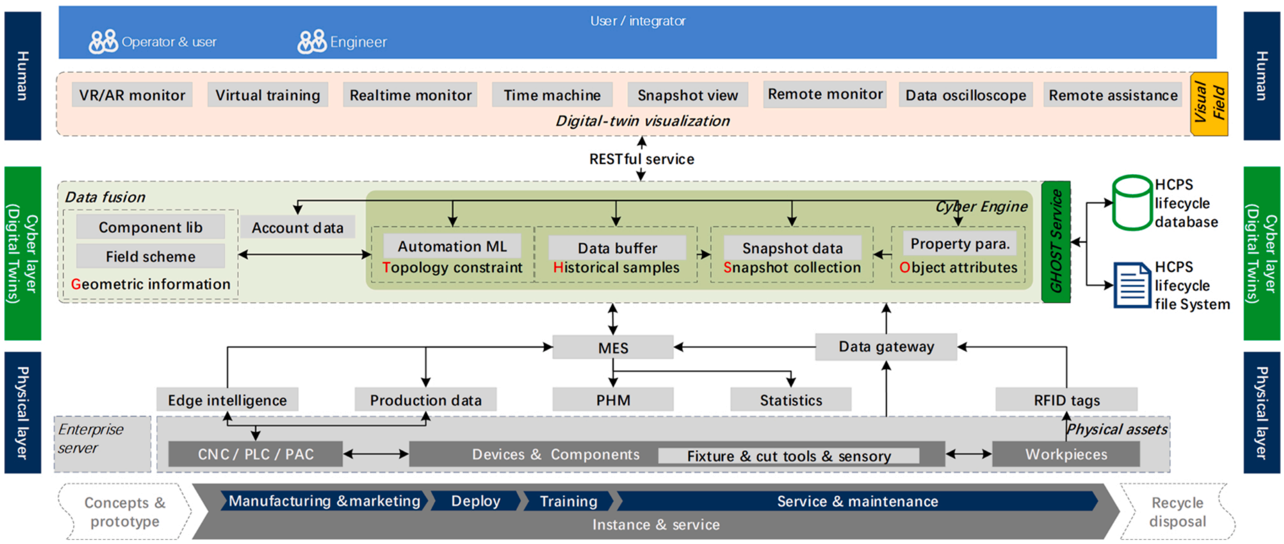

Fig. 5. Relations between instances and the type of service stages.

2.1.1. *Concepts & prototype stage*

As shown in Fig. 4, the concept design and prototype stage of FMS include project planning, scheme design, DMU simulation and virtual debugging.

In the project planning stage, the key information for a manufacturing system (e.g., processing device assets, spatial layout, processing technology and processing time) is tailored to the user's requirements for FMS, and in this paper, software engineering tools (e.g., Automation ML) are used to build the model of descriptions. This model will be an important basis for the design and verification of DMU simulation. In the meantime, as for its initial values, the whole life cycle digital-twin information from other related FMS or the "remanufacturing" data retrieved from the last generation of the FMS project can be referred to.

For scheme design, it's intuitive to construct a virtual FMS scene on a virtual 3D DMU tool platform (e.g., Visual Components or Visual Field built in this paper), and basic verification of the scheme can be verified efficiently by means of parameter configuration, before more detailed design work can be realized on a computer-aided design (CAD, e.g., Solidworks) platform.

In the DMU simulation/virtual debugging stage, FMS manufacturing scenes are simulated and verified in a fully digital manner, through the DMU platform: drive data (for motion control and logic control) from physical controllers (e.g., CNC and PLC) or industrial programming software (e.g., CoDeSys) is used to achieve drive control over the DMU platform (e.g., Siemens virtual debugging automation system, or Visual Field presented in this paper). In this stage, the development, testing and optimization of the project control app can be completed prior to project construction, thereby reducing the time for deploying FMS physical assets on site.

2.1.2. *Instance & service stage*

As shown in Fig. 5, this stage is divided into two segments: deployment and production service of an FMS at the production site.In the instance stage, the physical assets of FMS are deployed to the production site. The DMU platform (assembly demonstration, training instructions and maintenance guidance) can guide employees through asset allocation and delivery training.

In the production service stage, virtual three-dimensional production scenes are constructed with on-site supervisory control and data acquisition (SCADA), FMS digital-twin historical data obtained through the manufacturing execution system (MES) platform, and the snapshot

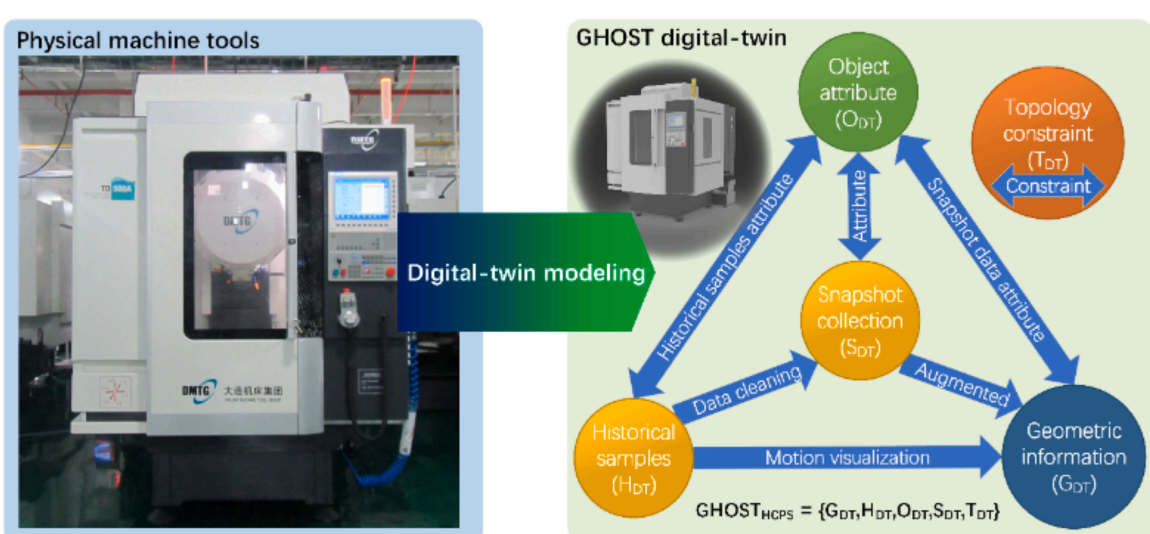

Fig. 6. GHOST digital-twin model for machine tools.

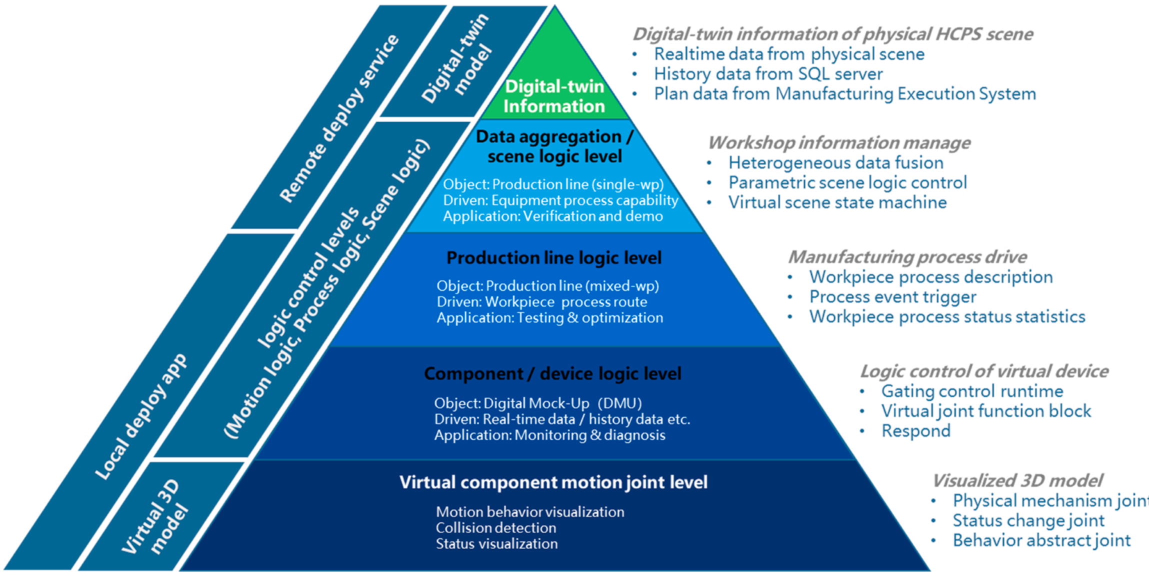

Fig. 7. HCPS digital-twin visualized DMU architecture.

collection driven DMU platform. Virtual reality/augmented reality technology is utilized to enable fast and precise interaction between men and the information layer. It helps users to efficiently and intuitively break up restrictions in space and time dimensions, and changes the plane information interaction paradigm limited by display screens. It also improves users' perception of manufacturing process, makes users' decision-making more accurate, and enhances enterprises' lean production capacity.

2.1.3. *Recycle & disposal stage*

In the final stage of the life cycle of FMS, the physical and cyber assets will enter the remanufacturing stage. Physical assets in FMS may be different from its original modality: re-layout, device upgrade or device scrapping. Digital-twin big data assets, by means of DMU, will present the historical status of each stage of the life cycle of FMS, and provide powerful, intuitive data reference for subsequent FMS projects. Digital-twin DMU intuitively unleashes the residual value of FMS in remanufacturing, and provides key data reference and inheritance for the next generation of FMS, thus realizing the goal of creating, constructing, serving, destroying and inhering HCPS.

2.2. *Digital-twin multi-dimensional information description model for FMS*

In the new era of industrial revolution, FMS are the principal resource for productivity. Despite of the lack of a universal digital-twin modeling method applicable to various fields [17], a universal digital-twin descriptive model must be put forward in the life cycle of FMS, in order to get the expected results of artificial intelligence and cloud computing. In this paper, according to the assets of attributes and data from heterogeneous sensors (position, vibration, stress, temperature, vision, voice and RFID) in the "life cycle value flow" (as shown in Fig. 2) of intelligent manufacturing systems in RAMI4.0, a digital-twin descriptive model for the life cycle of FMS is proposed as follows:

$$GHOST_{HCPS} = \{G_{DT}, H_{DT}, O_{DT}, S_{DT}, T_{DT}\} \quad (1)$$

As shown in Fig. 6, GHOSTHCPS represents the digital-twin information set in the life cycle of FMS. This set of information describes the conceptual planning, design & development, simulation testing, manufacturing & deployment, monitoring & maintenance of production services, and remanufacturing concerning device assets (device, tools, fixtures and workpieces). It also depicts the logic rules (PLC), functional behavior and operating status, digital assets (intelligent analysis data and sample snapshots) in different stages across the life cycle of FMS. Such digital-twin modeling description information can realize 3D DMU visualization in a virtual environment through Visual Field, which is interoperable on different platforms (Windows / Mac OS / iOS / HTML5), thereby achieving an interactive effect of virtual restoration and enhanced display of twin data.

The main elements in GHOST include:

- **Geometric information (G_{DT}).** It refers to the geometric information of physical assets [40]. Data is constituted by FMS device models, mechanical parameters, geometric features and other appearance-related structural elements. Examples also include DMU model libraries (intelligent machine tools, industrial robots, intelligent warehouses and AGV), gripper specifications, parameterized connector information, and CAD models for fixtures.
- **Historical samples (H_{DT}).** They refer to the sample information on the service process of a production system. Data is submitted by the CNC system of an intelligent machine tool, the controller of an industrial robot, and various heterogeneous sensors. It's transmitted to the workshop manufacturing execution system via a data gateway and the digital-twin server in the cloud. In most cases, historical samples include characteristic information on FMS behavior and status (e.g., position, command, status and temperature) and the exact acquisition time, such as the position of an intelligent machine tool, feedback position, motor servo current, cutter information and G code.
- **Object attribute (O_{DT}).** It describes the physical and information attributes of various asset objects in a manufacturing system, including bill of materials (BOM), material attributes, boundary conditions, constants, minimum standards, interlock, rigidity, strength, reliability, maintainability and safety.
- **Snapshot collection (S_{DT})** [3]. During the production of FMS, digital-twin data are being pushed from physical space to cyberspace constantly. In the mining process using an intelligent algorithm, each data makes different contributions. A high-value data set of specific assets, such as the health grade of a machine tool, estimated remaining life of cutters, and iCode instructions for intelligent cutting aid, will be recorded as a snapshot collection. Data sets are closely bound up with the intelligent analysis algorithm used. For one sample, each intelligent analysis algorithm may arrive at totally different conclusions.

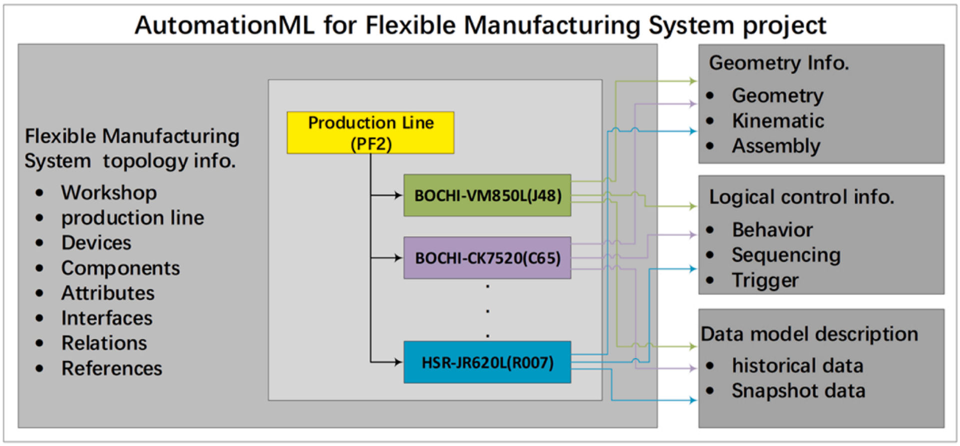

Fig. 8. This paper builds AML models for FMS projects.

- **Topological constraint (T_{DT})** [41]. It comprises the system hierarchy and relational tree of each object in a manufacturing system [42]. Regarding the multi-source heterogeneous digital-twin data of objects in FMS, the architecture explained in this paper associates and describes the constraints of various data in the life cycle (genetic data, historical data, object attributes and snapshot data) using Automation ML.

Unlike the 5D digital-twin modeling theory proposed by Tao [9], the GHOST 5D digital-twin modeling description method presented in this paper aims at digital-twin information itself. This translates to a detailed breakdown from the dimension of digital-twin data (DD) in Tao’s [9] 5D theory. In addition, the GHOST method here also focuses on FMS objects, implements the heterogeneous integration and management of digital-twin raw data collections in its life cycle, and utilizes the

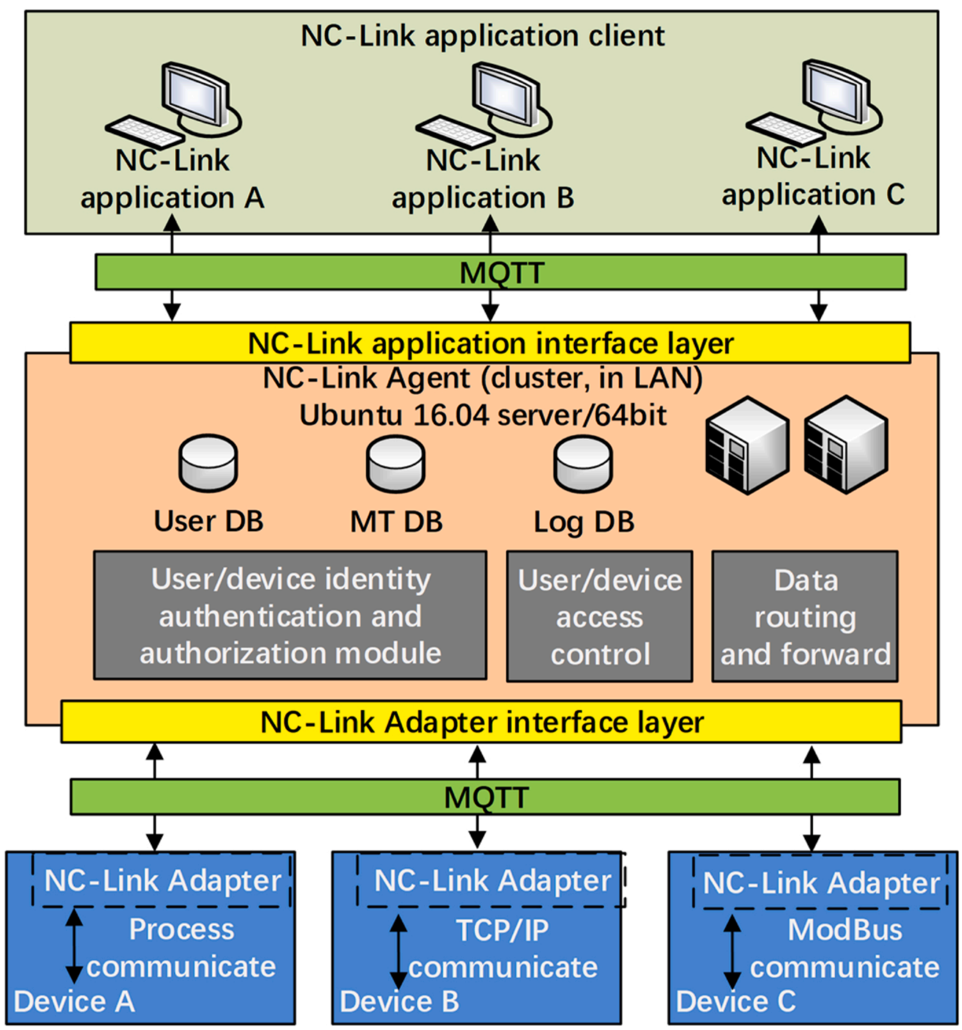

Fig. 9. NC-Link Protocol structure.

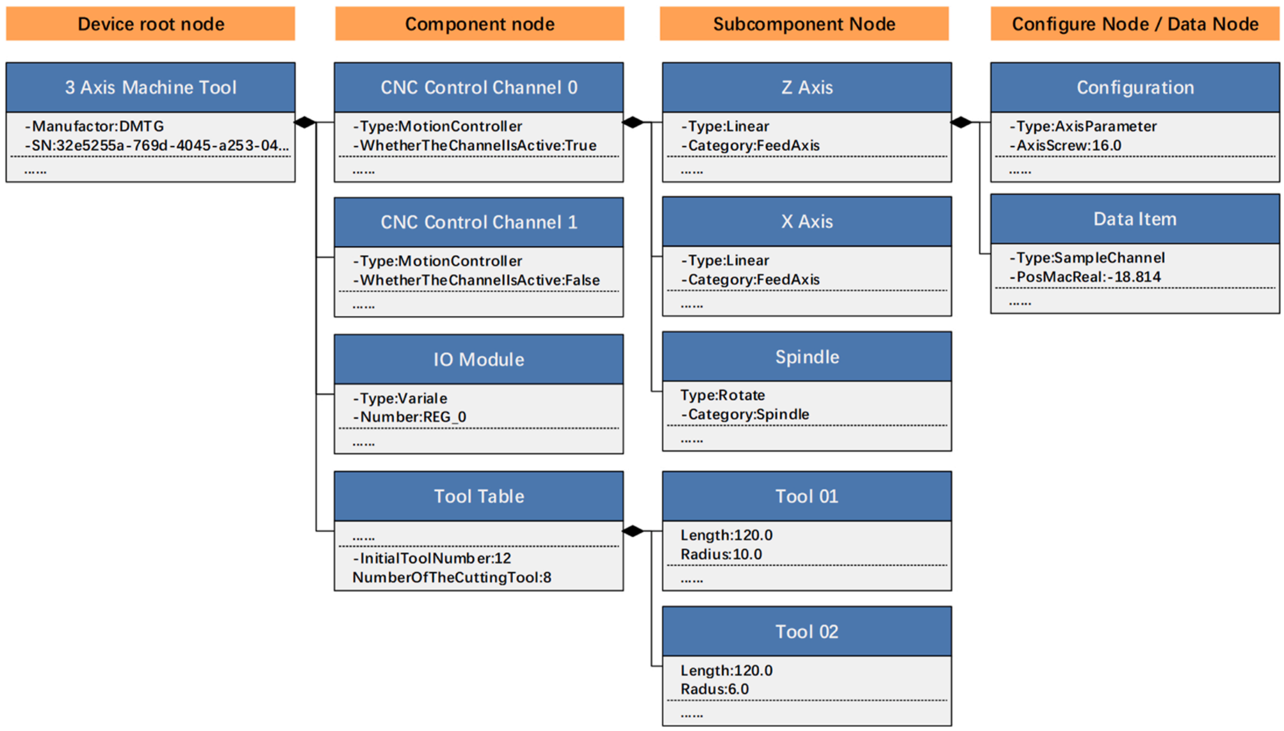

Fig. 10. Descriptive model of machine objects in NC-Link Protocol.

construction, behavior-driven, and performance definition of 3D virtual DMU for the description of behavior experience, alternative technological upgrade and derivative product evolution of physical device.

3. Implementation method for digital-twin visualization

An FMS is a typical human-cyber-physical system. Digital-twin information visualization (3D virtual DMU) is an effective solution that accurately and intuitively presents multi-dimensional digital-twin information during the life cycle of FMS. Visual DMU can display the mechanical characteristics and digital-twin information of an FMS, and can intuitively present data from a corporate information management system (ERP/MES) to users through virtual scenes.

According to characteristics of manufacturing assets described in the "hierarchical structure" of RAMI4.0 (as shown in Fig. 2): based on data management of digital-twin GHOST modeling of HCPS manufacturing systems, the visualization DMU architecture for HCPS consists of 5 instance layers, as shown in Fig. 7.

The top layer is a physical scene-data mapping space using the digital-twin modeling method. Its functionality is implemented by a GHOST server in the remote cloud. The three layers in the middle visualize the logic control layer in a terminal platform, from macro to micro, from abstract to concrete. They implement digital-twin information-driven visualization of workshops, production lines, and device/components in a virtual space, and management of drive triggers of scenes, processes and motions in logic. The lowest layer is the smallest unit-virtual joints and 3D models, for visualizing device/component behavior in the virtual space of a visualized terminal platform. In this layer multiple different virtual joints for a single motion (e.g., linear joints and rotary joints) or state changes (e.g., visibility joints and pallet joints) are combined/used together to make complex behaviors of device/components available.

3.1. Digital-twin information in physical HCPS scenarios

This layer is constituted mainly by digital-twin information, which is mapped from physical scenes to cyberspace, and statistical analysis data from corporate information management systems (ERP/MES). As previously mentioned in the GHOST modeling concept, digital-twin information on the full life cycle of FMS can be classified into five categories: geometric information, historical samples, object attribute, snapshot collection and topological constraint. Geometry information, object attribute and topological constraint can be configured and managed using AML, while historical samples and snapshot collection are collected, transmitted and managed over universal bus protocols (e.g., NC-Link and OPC UA).

3.1.1. Digital-twin modeling of FMS based on AML

AML is an open and neutral XML-based data exchange format that can be used for the descriptions of product, process and resources throughout the life cycle of a production system [42]. It aims to reduce the gap in data exchange in the field of heterogeneous automation engineering tools, and is currently standardized under IEC 62714 [43]. Automation ML fulfills all the requirements under the management framework proposed by Industry 4.0 [44]. Automation ML can be used to implement data exchange between multi-disciplinary tools, including factory plant design and planning, mechanical engineering, electrical design, control engineering, PLC programming and robot programming, etc. [45]. It can also contain typical topology, geometry, kinematics, logic information and other attribute information in an automated factory.

As shown in Fig. 8, in the case of the FMS project presented in this paper, the role category, interface relation and instance level of various FMS resources are included in the AML topology architecture. For instance, the order in which resources are used can be described over interface, and so are the logistics relationship between conveyor belts, robots and machine tools in FMS. It indicates the order in which these resources are used in FMS.

3.1.2. Digital-twin samples of FMS in GHOST

Multi-dimensional digital-twin data in FMS manufacturing processing is collected and backtracked by the universal bus protocols. Currently, the GHOST server supports NC-Link protocols and OPC UA protocols to get physical scene real-time data and history samples.

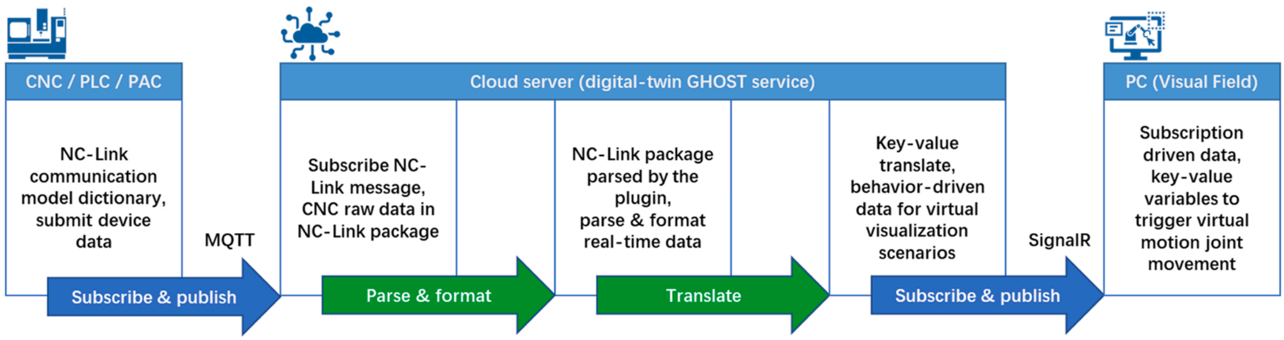

Fig. 11. Transmit CNC real-time data over NC-Link Protocol.

The application case in this paper adopts NC-Link protocol to get physical samples collection of devices in FMS. The architecture of NC-Link is shown in Fig. 9. It combines the advantages of OPC-UA protocol and that of MT-Connect protocol. NC-Link adopts a three-tier architecture that is composed of an Adapter, an Agent, and a Client application. The proxy implements a unified proxy service, which acts as an intermediate layer to transfer data between the Adapter and the application. The MQTT protocol is used for communication between the Client application and the Agent, and the TCP/IP protocol is used for communication between the Agent and the Adapter.

The adapter is divided into three layers: data-driven layer, data dictionary layer and data interface layer. The data dictionary layer uniformly defines the data of CNC machine tools. As shown in Fig. 10, it converts part of the data of smart manufacturing device into component objects, such as channels, axes, and IO modules. The other part of the data is defined as the attributes or variables of the object, such as feed override, actual position, tool length, etc.

As shown in Fig. 11, a NC-Link model dictionary is built in accordance with the characteristics of data information in CNC/PLC/PAC. State information on CNC systems is encapsulated in line with the dictionary structure. For example, in a regular three-axis milling center, an NC-Link message can contain real-time information on 2400 variables. Digital-twin GHOST services subscribe to state information of physical devices by means of MQTT. Variables are distinguished by index number in the original NC-Link message, which is parsed by an analysis plug-in on the cloud server and formatted into a one-dimensional key-value pair format. The data, after being filtered, will be accessed and used by other digital-twin application modules (e.g., modules for visualization, statistics, analysis and scheduling). For a virtual visualization terminal (e.g., Visual Field), configuration parameters in XML format are used to implement the data cleaning function during visualization. They describe the identification information of device in NC-Link services, the IP address and port number of NC-Link agents, and the identification information in virtual scenes. In addition, a variable name dictionary, which filters and screens drive data necessary for the virtual visualization from NC-Link messages, is also contained in these parameters.

Filtering rules for digital-twin data are configured by AML in GHOST. Real-time digital-twin information is cached by Redis SQL and then stored as historical samples in PostgreSQL.

3.2. Data aggregation/logic layer of scenes

In this layer, multi-dimensional physical data is cached, converted and managed by Cyber Engine in real time. Physical components generate multi-dimensional digital-twin information describing their behavior. For example, digital-twin information generated by the motion of a linear axis (driven by the rotating motor) is composed of its target command, actual position, motor angular displacement, motion

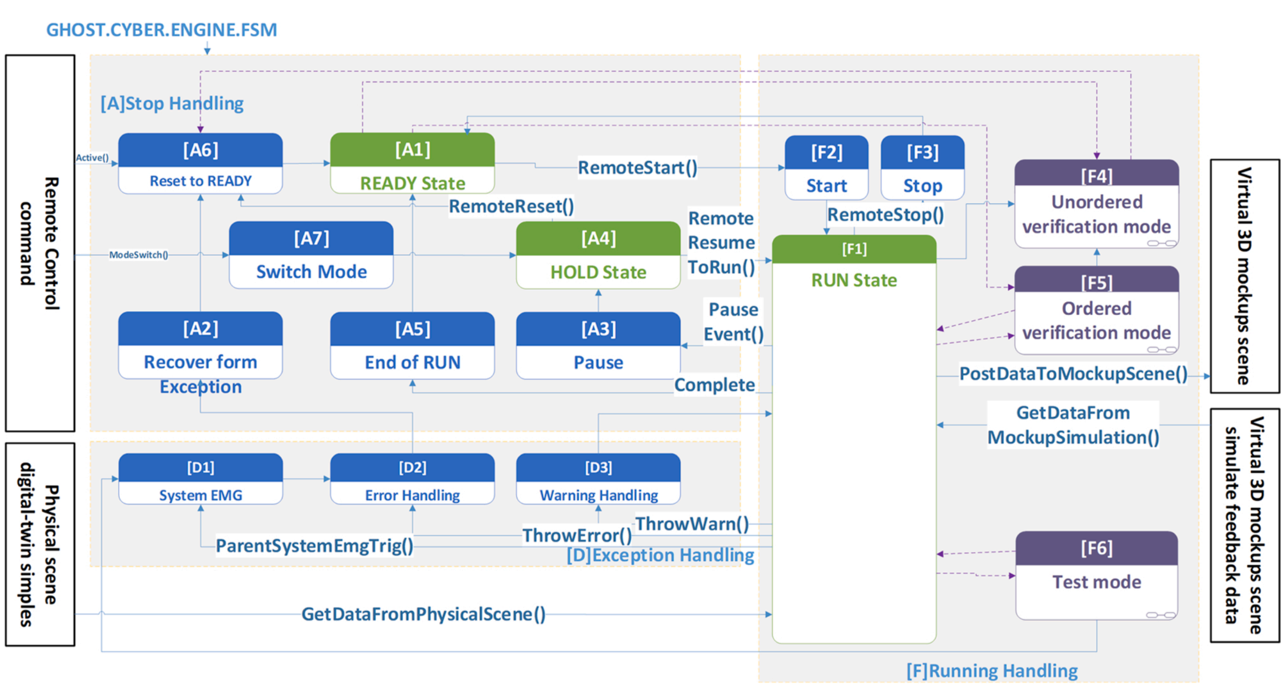

Fig. 12. Cyber Engine based on GEMMA finite-state machine (FSM).

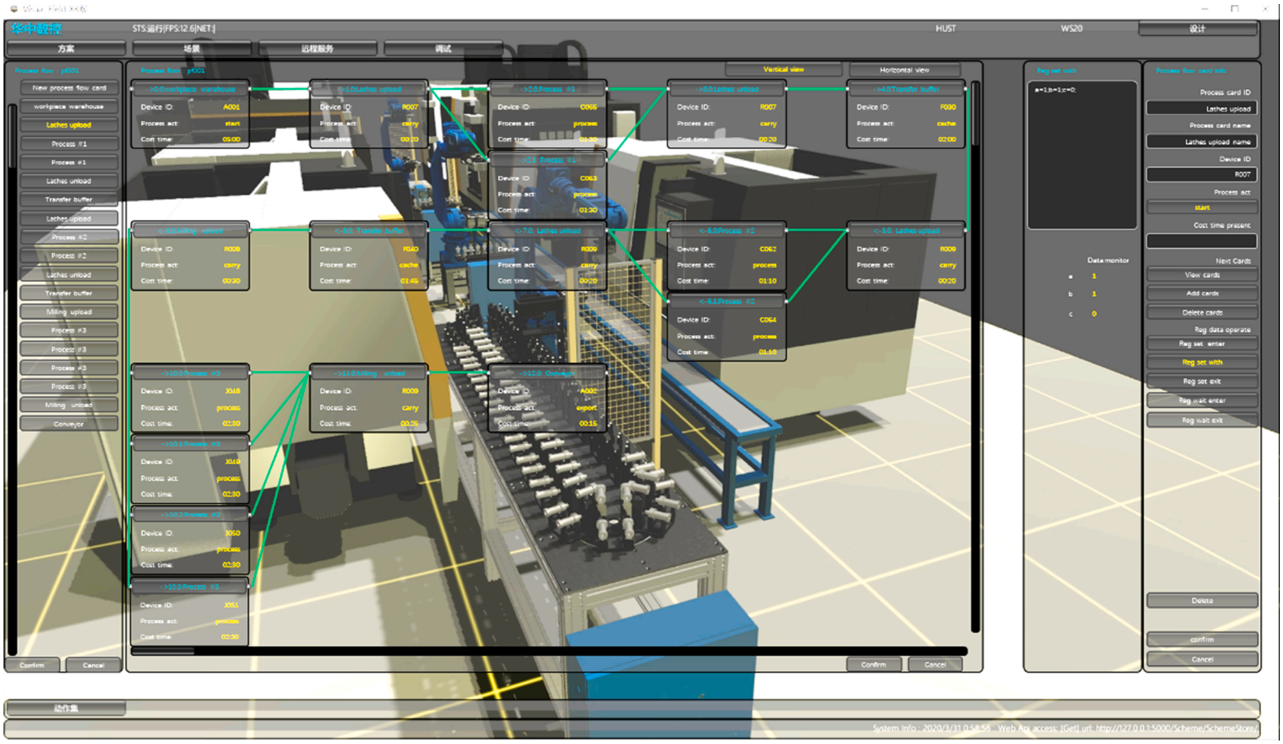

Fig. 13. Workpiece flow editor (UI) in Visual Field.

trigger signal, and position arrival signal. Any information can trigger and describe the visualization of the motion of a linear axis.

According to the different visualization requirements of digital-twin (such as simulation preview, historical replay, real-time monitoring, augmented reality, etc.), Cyber Engine performs logical control and management of the visualization drive data. Cyber Engine is a finite state machine architecture based on the GEMMA model (Fig. 12).

Users can override the class of Cyber Engine API with C# language in

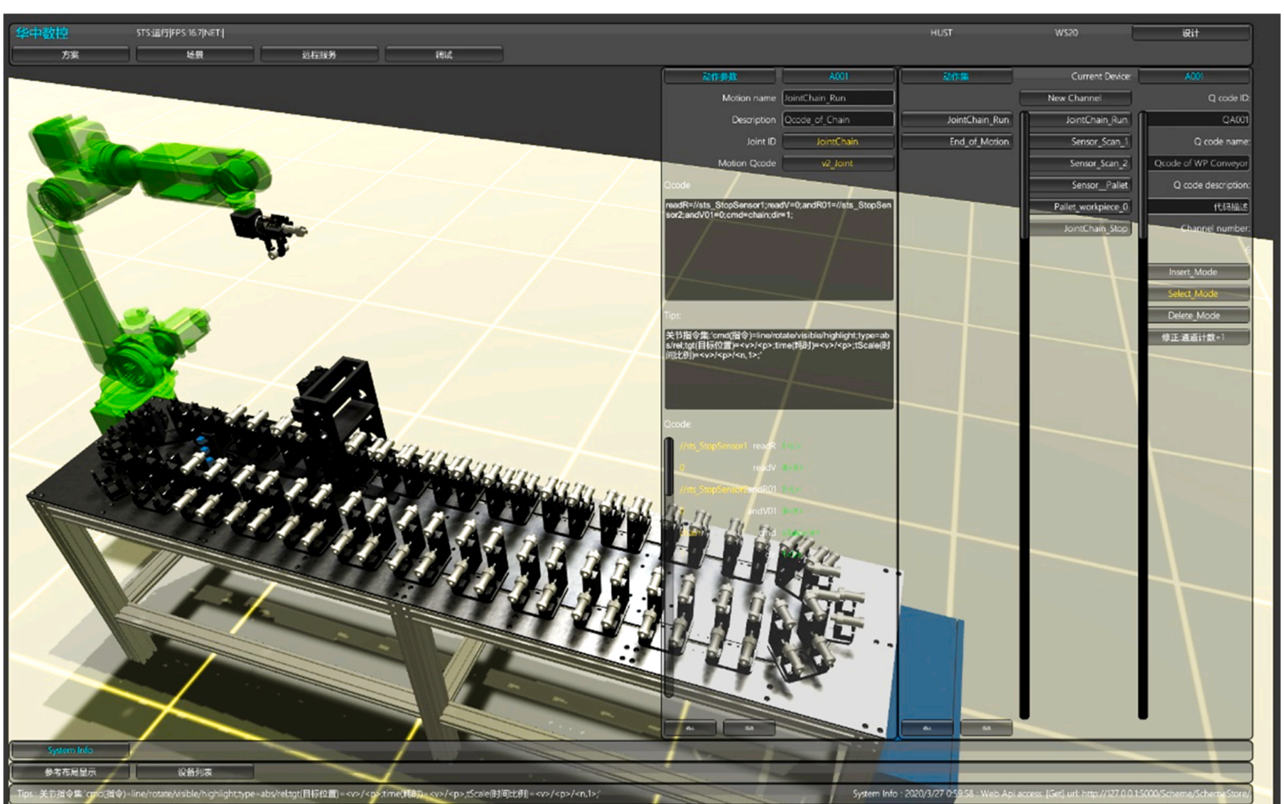

Fig. 14. Q Code editor (UI) in Visual Field.

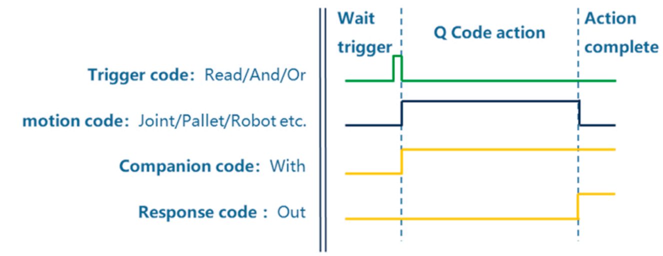

Fig. 15. The sequence in which Q Code commands are executed in Visual Field.

GHOST service or configure parameters in Automation ML to manage and logic control digital-twin information in Cyber Engine for specific workshop scene.

3.3. Logic layer of production lines

FMS is a kind of compounded flexible production line adapting to the processing of multiple workpieces. In the context of intelligent manufacturing, FMS must be able to satisfy the complex production goal covering multiple types and multiple processes. In the FMS digital dual-visualization process, especially in the processing of mixed parts, it's of particular importance to effectively solve logic control issues concerning discrete events of different workpieces in FMS.

Q Process is a digital-twin visual process logic control module for workpieces (as shown in Fig. 13). As an optional lightweight logic module for discrete events in the digital-twin visualized architecture, it's mainly used to simulate simultaneous processing and record processing status statistics of various workpieces. It manages process events of workpieces according to process parameters and routes, records and keeps processing information. In the case of mixed-flow production simulation, Q Process triggers the DMU concerned to execute production behavior in time, according to the process route of each workpiece. Process route simulation and behavior verification under the FMS mixed flow mode are realized.

3.4. Logic layer of components/device

The logic control in this layer is the core module in the digital-twin visualized architecture. For each single device/component, it provides logical judgment and manages the behavior visualization sub-function module. Q Code is the command-control module for the device/component logic in this architecture (as shown in Fig. 14).

According to different behavior characteristics of DMU, Q Code issues different behavior commands to control different virtual joint actions, such as joint movement (e.g., linearity, rotation, visibility, sensors, fixtures, chains and highlight), pallet movement (e.g., creation, release, get and update), and robot movement (e.g., MoveTo and Path). Every Q Code contains a trigger code, a motion code, a companion code and a response code. The motion code is required, while the rest is optional.

Fig. 15 shows the sequence in which Q Code commands are executed in Visual Field, where the Q Code collection adaptive to each DMU is a set of multi-channel, parallel two-dimensional command sequences. Each channel corresponds to a virtual joint, and is composed of multiple Q Code command modules in series, which describes virtual joint behaviors. The behavior of each virtual joint can be described by multiple channel command sequences, and its unique control channel command sequence is determined via triggering and locking. Following the completion of the command sequence, the virtual joint releases the occupation lock on the channel, scans all parallel channel command sequences, and waits for a new trigger signal. 3.5 Virtual component joint layer

DMU is an important part of digital-twin visualization. It is the interactive terminal of the entire architecture, which represents the adaptability and usability of this entire architecture. In the paper, the DMU is constructed based on the Component-Assembly-Part (CAP) component decomposition method. On the basis of analyzing the mechanical characteristics and behavior characteristics of the target device/components, the function decomposition method is adopted on the basis of Function- Motion -Action (FMA) (as shown in Fig. 16) [46], and the behavioral topology model of the DMU is constructed using abstract virtual joints.

In a vertical machining center, potential behaviors and state changes are abstracted into a 3D model of limited virtual joints as shown in Fig. 17.

The virtual joints in Visual Field mainly include: linear joints, rotary joints, visual joints, sensor joints, fixture joints, chain joints, pallet joints, robot TCP joints, and "Label joints" for information interaction. These virtual joints are associated with their matching Q Code commands. When Q Code is triggered, behavior parameters of the virtual

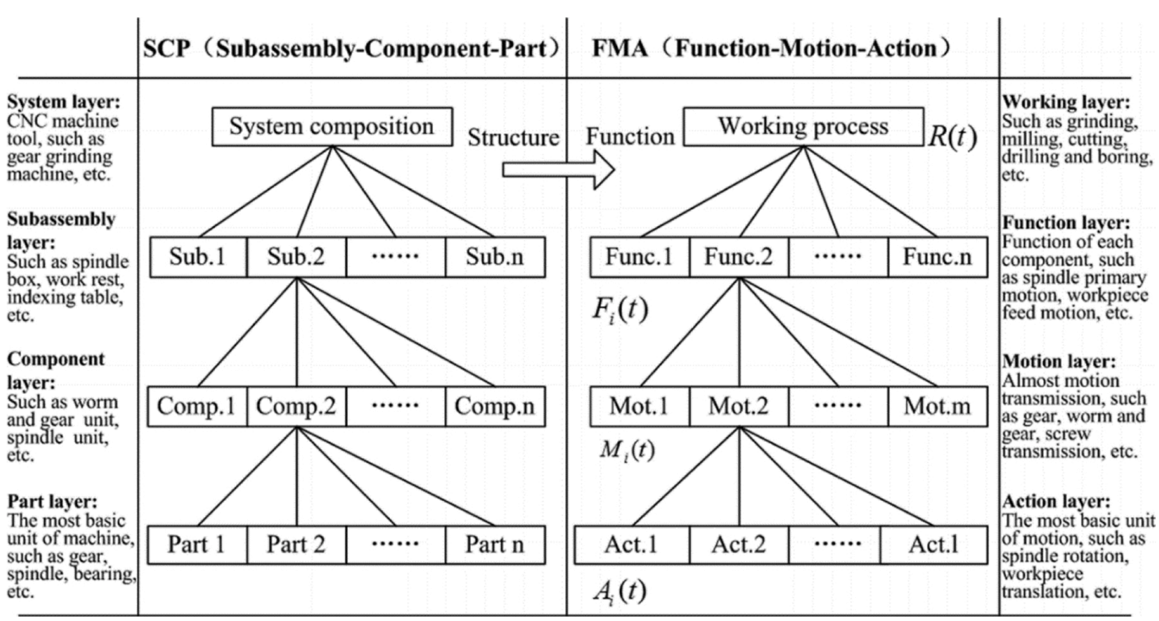

Fig. 16. System decomposition process [46].

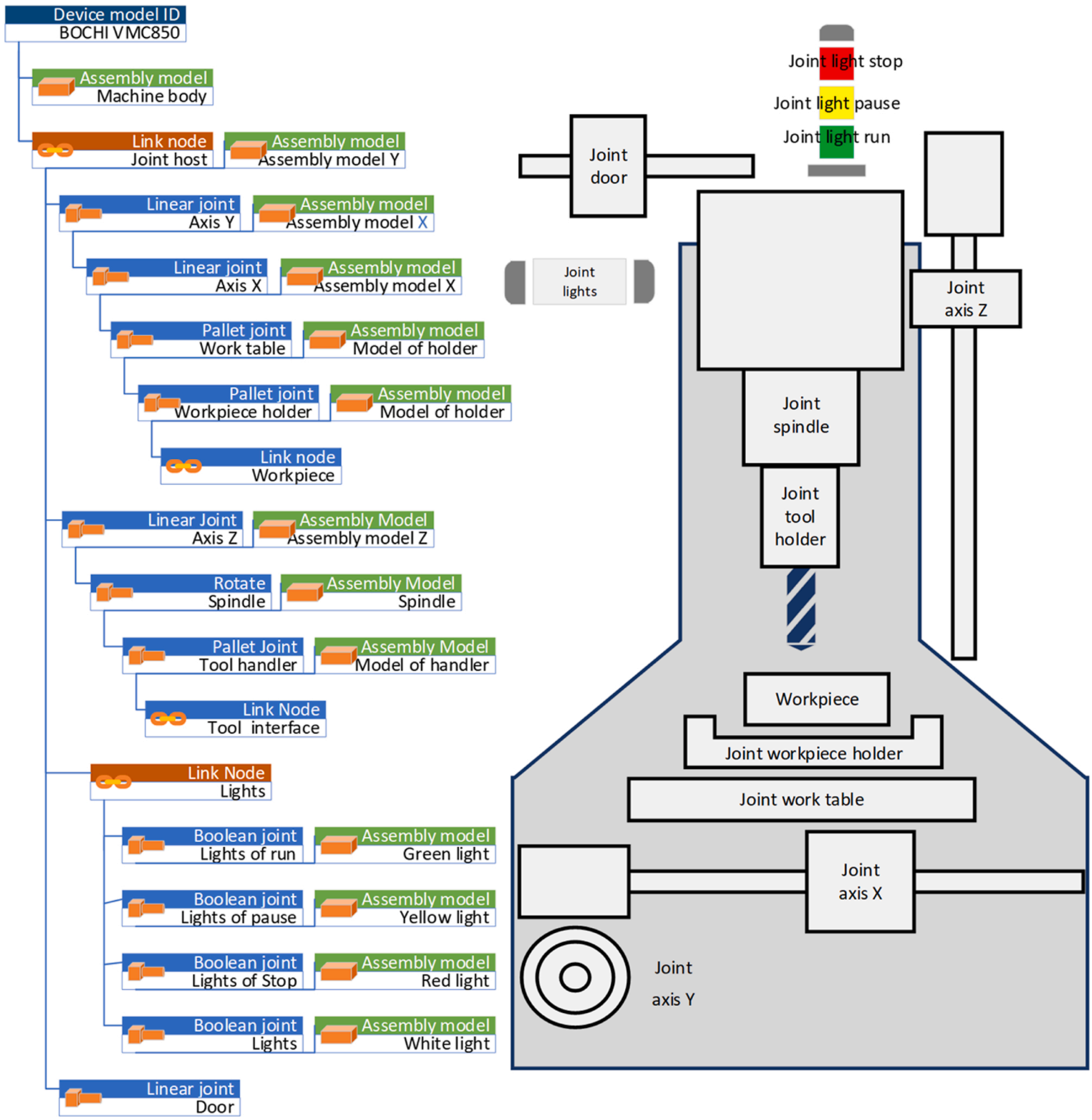

Fig. 17. DMU model architecture.

joint concerned are analyzed, allowing the joint to immediately execute the target motion. The main working states of a virtual joint include: Standby / Ready / Busy / Complete / Error / Reset.

3.5. Deployment and execution sequence of the visualized architecture

The deployment of the digital-twin visualization architecture in this paper is shown in Fig. 18. Devices in FMS are connected to GHOST server in cloud with OPC-UA and NC-Link protocols. Digital-twin GHOST service collects and stores the status and behavior information of the production field in real time. If there is SCADA/MES with information collection and management functions at the production field, the information can also be pushed to GHOST service via HTTP protocol. The information is aggregated and formatted in GHOST service, and the scene logic drive module named Cyber Engine is used to generate a unified digital-twin visualization drive data. The driving data are stored in the RESTful service cache in GHOST.

The DMU tool platform (Visual Field) running on multiple platforms (Windows/Mac OS/iOS/HTML5) can access GHOST's RESTful service. According to the different viewing needs of users, the application obtains the driving data in the cache in GHOST to achieve the visualization of the digital-twin of FMS.

The execution sequence of each part of the architecture is shown in Fig. 19. The Cyber Engine in GHOST initiates the data sample request (Different FMS has its own corresponding Cyber Engine). The digital-twin mapping module continuously collects the digital-twin information from the FMS. Digital-twin raw information from FMS which is too redundant for visualization data driven is formatted and filtered into Cyber Engine. Cyber Engine processes the raw information logically according to different scene visualization requirements. The driven data is updated in real time into the cache of the RESTful service in GHOST. Visual Field software on different platforms access the RESTful service in

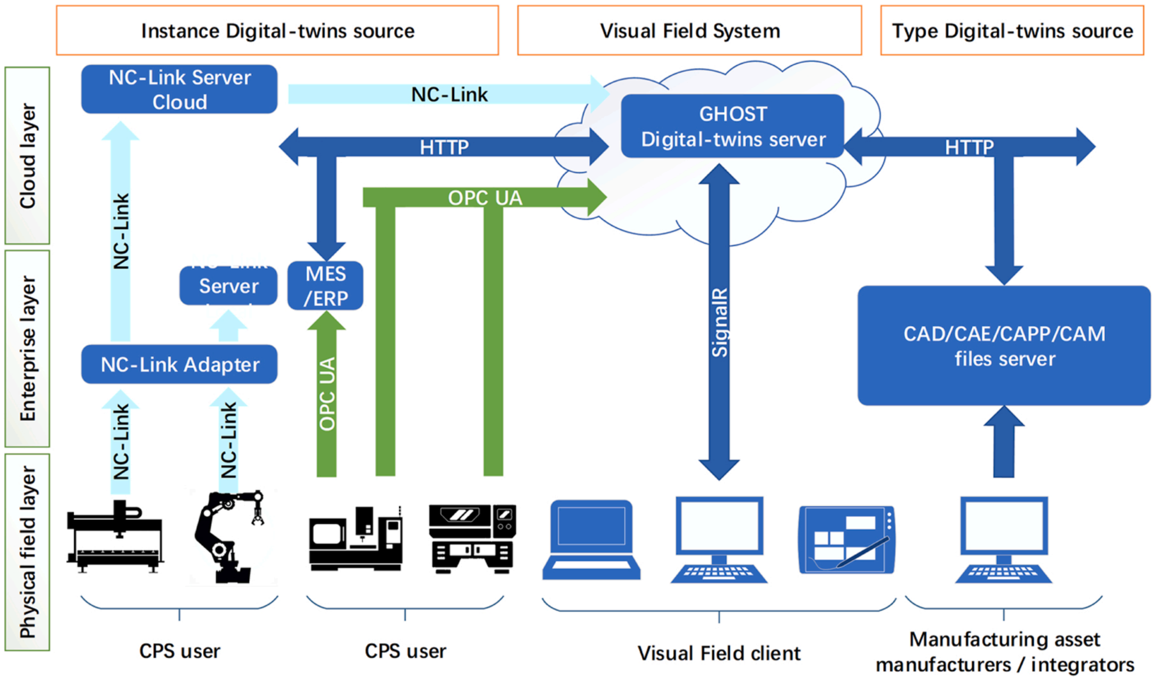

Fig. 18. Deployment of digital-twin visualized architecture.

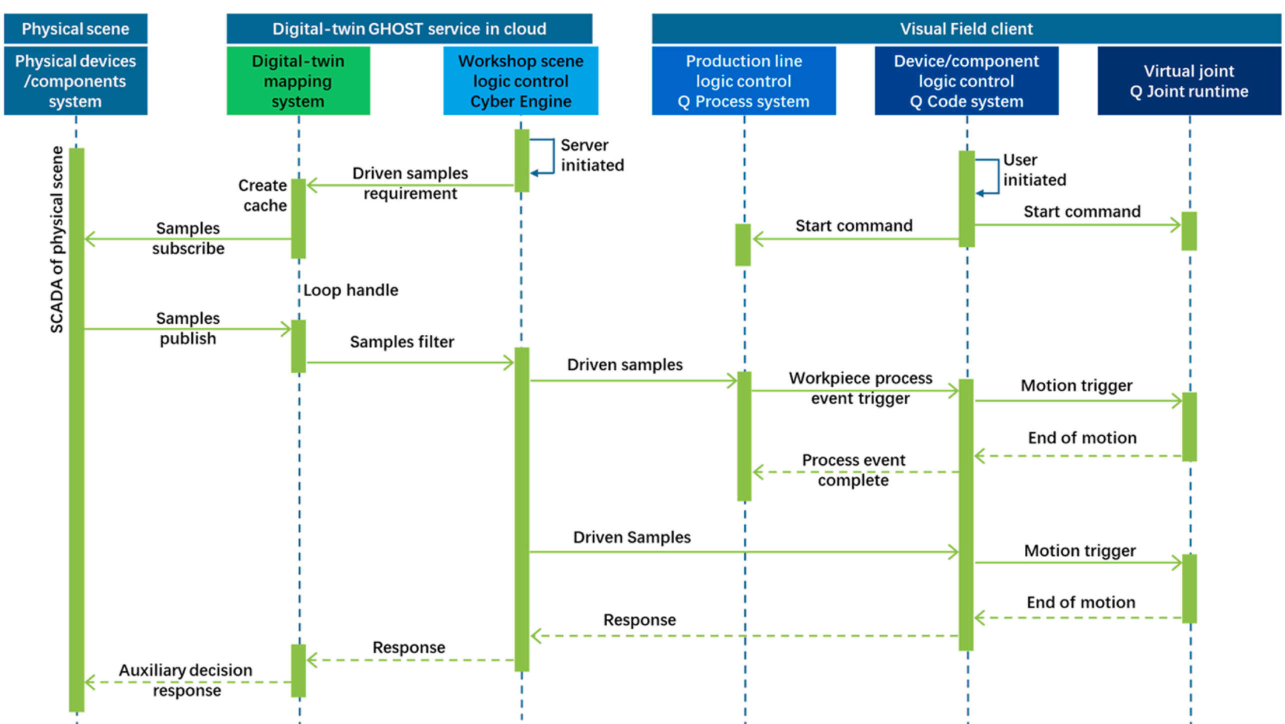

Fig. 19. Execution sequence under the visualized architecture in this paper.

GHOST respectively to obtain the driving data that drives the DMUs actions in the virtual scene. At the same time, interference, collision, behavioral verification, and manual intervention signals that occur in virtual scenes of different clients can cause a "response" from the Cyber Engine in GHOST server. After Cyber Engine comprehensively processes the "response" from multiple clients, it returns the "virtual space" status back to the "physical space". Such feedback information provides additional decision-making reference for the physical space. This architecture fulfills the functional requirements of multi-person remote collaborative operation in digital-twin virtual scenes.

4. Experimental prototypes

Based on the architecture proposed in the paper, we developed a prototype of a digital-twin visualization service platform for Human-Cyber-Physical Manufacturing Systems. The back end of the platform prototype uses GHOST (RESTful Architecture) services, and the front-end is implemented through a multi-platform visual software (Visual

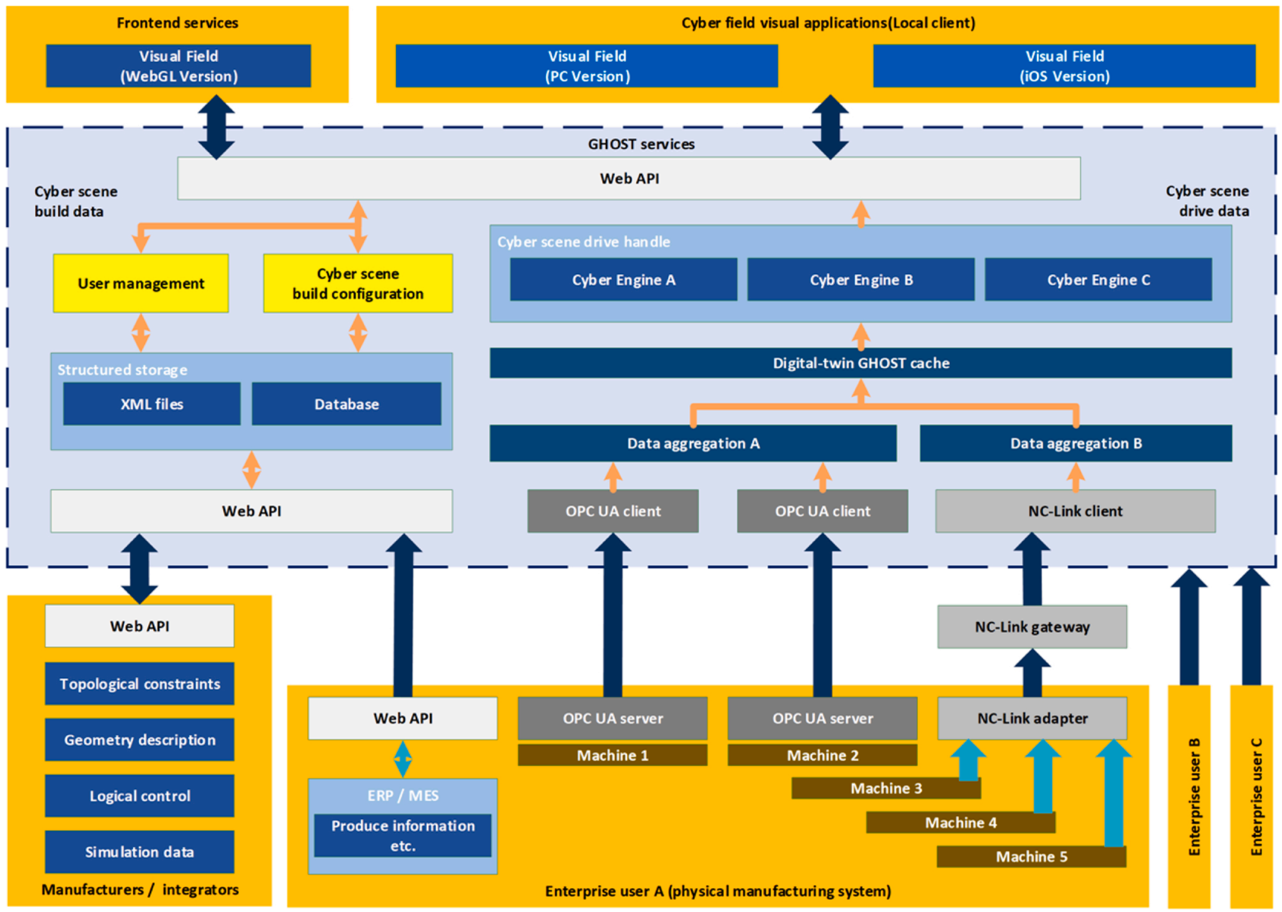

Fig. 20. Digital-twin GHOST services architecture diagram.

Field).

4.1. Digital-twin GHOST Services platform prototype

As shown in Fig. 20, GHOST Service deployed in the cloud is developed and achieved based on. NET CORE 3.1 framework. In GHOST Service, digital-twin information is mainly divided into two categories: descriptive information related to the geometric appearance of the scene and descriptive data related to motions/states. Geometric information of FMS is mostly determined by the device manufacturer/integrator in the manufacturing planning and design stage. Motion/status information is collected and pushed to GHOST Service in real time from the MES or data gateway in the production field with OPC-UA or NC-Link protocol. The multi-source digital-twin data is parsed into sample data sequence (Key-value pair) identified with manufacturing asset URI. Each set of sequences is given a time stamp of collection time. The serialized data is put into a distributed cache. According to different manufacturing scene, there is a different Cyber Engine to convert digital-twin data to drive data of DMUs in virtual scene. Because GHOST Service uses the RESTful architecture, its stateless nature allows different DMUs to obtain driver data on different timelines: it can be real-time status, historical status, and status varian across different timelines.

Benefiting from the cross-platform advantage of. NET CORE 3.1, GHOST Services can be integrated into corporate information system

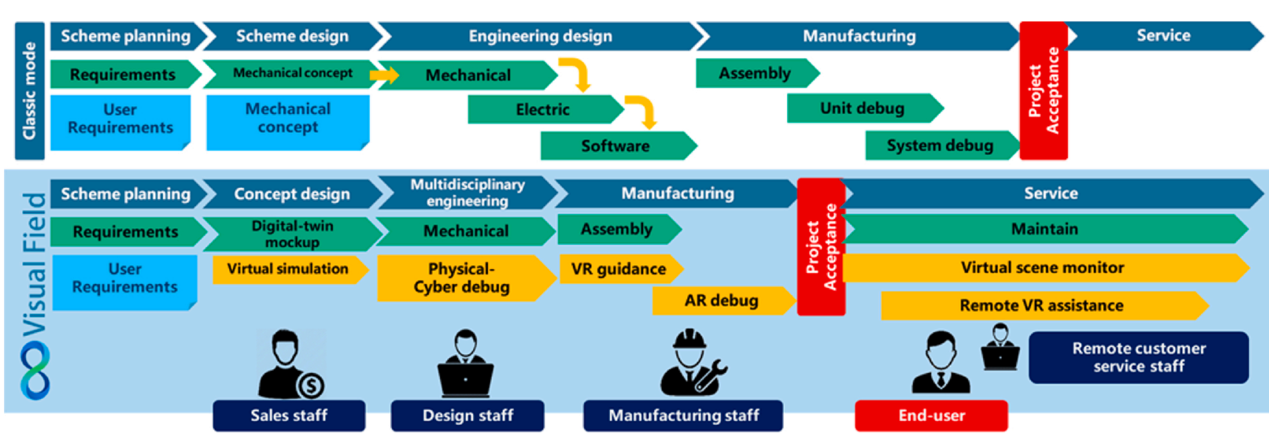

Fig. 21. Service functions of the Visual Field in the life cycle of FMS.

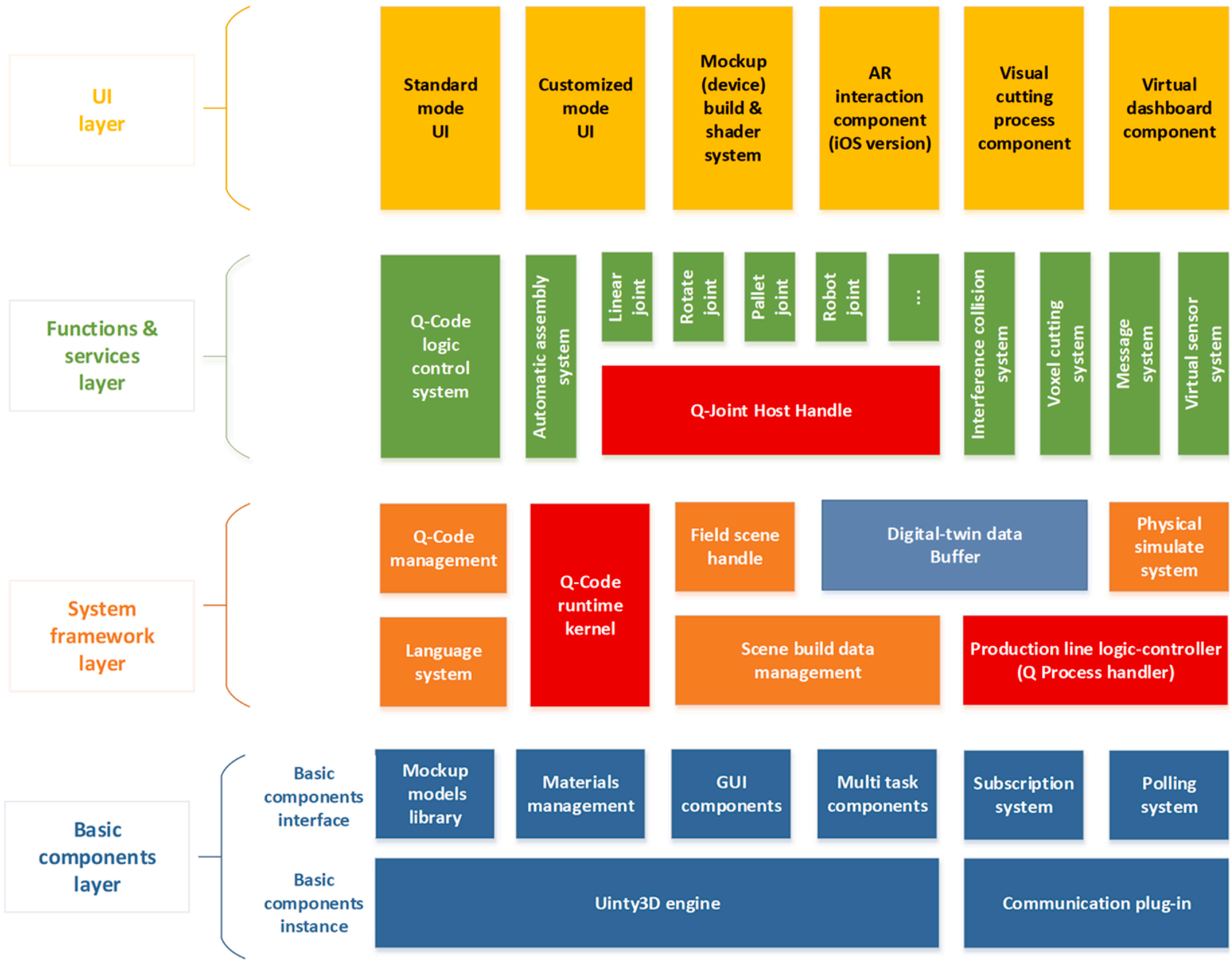

Fig. 22. Diagram of Visual Field architecture.

software platforms covering more dimensions via the support of Docker encapsulation, thereby using GHOST and Visual Field as visual sub-modules for digital-twin management in enterprises.

4.2. Visual Field - a terminal software tool for digital-twin visualization

The Visual Field is developed on the Unity3D engine, allowing the software released to run on multiple platforms (Windows, Mac OS, Linux, iOS and WebGL).

As shown in Fig. 21, Visual Field is built to implement different digital-twin visualization service tool platforms at different stages of the FMS life cycle.

During the project start-up stage, the basic user requirements determined in the project planning stage can be quickly verified and displayed by the "Virtual simulation" function of FMS in the conceptual design stage. Sales can use visual virtual scenes to visualize the concept design plan to intuitively provide users with production behaviors such as workpiece logistics paths, station processing beats, and basic device work motions. Sales adopt the method of modifying project parameters to achieve the goal of multiple iterations to upgrade the quality of the concept plan.

In the engineering design stage, based on mechanical design, "Physical-Cyber debug" based on the digital-twin prototype is carried out simultaneously. In this way, the control program of the device or the scheduling control program of the entire system can be developed simultaneously. This is different from the usual engineering design method. Using virtual controllers (such as virtual CNC or CoDeSYS software) or physical controllers (such as numerical control system devices, PLC devices) can control the 3D visualization prototype of the virtual scene. This can verify the accuracy and efficiency of the control program and achieve the goal of optimizing the structure and spatial layout of the mechanical device.

While building up device, virtual 3D construction and testing guidance functions for interactive inspection can be provided for production workers.

In the device service stage, Visual Field can provide users with digital-twin virtual 3D scene reconstruction: rebuilding working state at the scene in real time, back-tracking a historical scene, and previewing the planned production scene. Remote login allows technical experts to grasp historical information, live state information, and planning data in a more intuitive manner, thereby achieving goals like remotely coordinated diagnosis and guidance.

As shown in Fig. 22, Visual Field is mainly composed of 4 layers: Basic Components, System Framework, Functions & Services and UI Layer.

- Basic Components Layer: Based on the Unity 3D engine, instantiate the basic component interface. Basic components include source of device model library, source of material library, GUI interface, task scheduling, communication module, etc.
- System Framework Layer: Include core tasks of app. DMU logic-driven (Q Code) parser, Production line Logic-Controller (Q Process Handler), virtual scene builder, physical micro-engine (collision, gravity, etc.), digital-twin information coupler.

(a) Development mode (UI) (b) Customized mode (UI)

Fig. 23. (a) Development mode (UI) (b) Customized mode (UI).

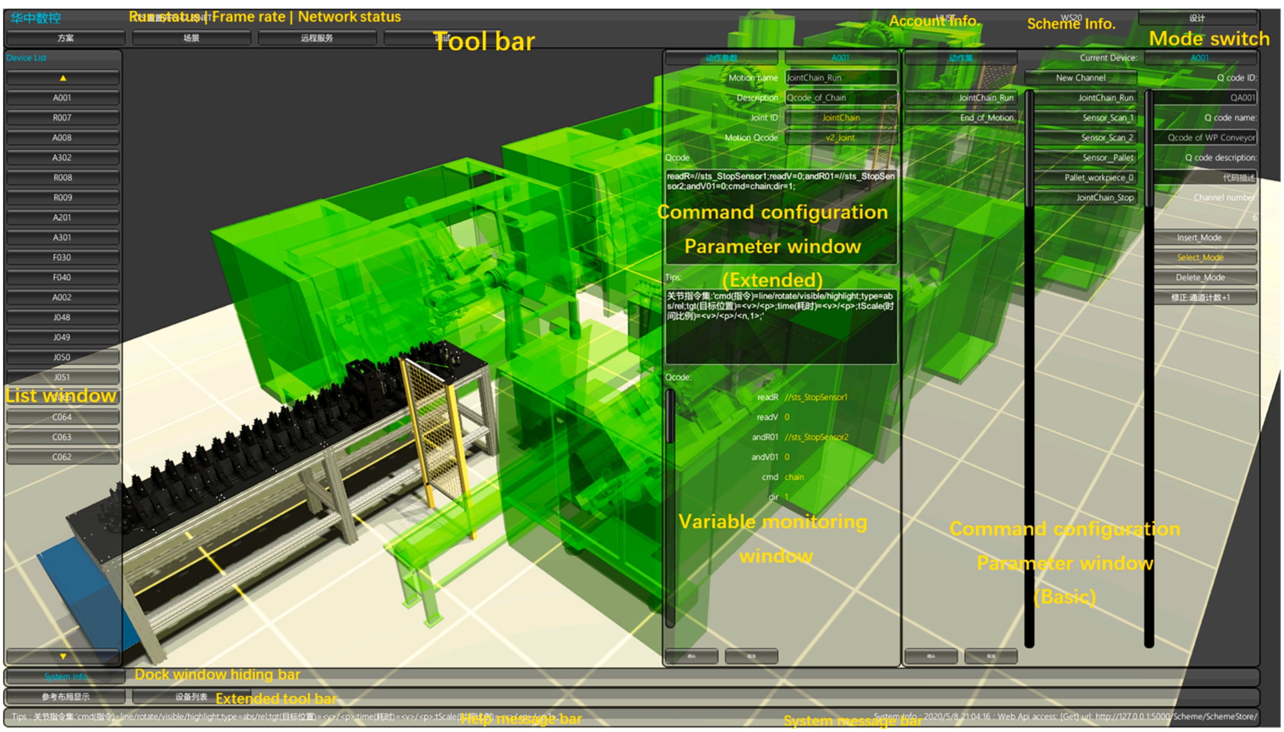

Fig. 24. Virtual scene development/debugging UI in Visual Field.

- Functions & Services layer: Function modules required to achieve full building of the virtual scene logic-driven (Q Code) actuator, automatic assembly systems (building assemblies based on topology relationships), virtual joint modules (linear joints, rotary joints, bool joints, 6-DOF robot joints, pallet joints, etc., message notification system, collision detection system, voxel cutting system, virtual sensor system, workpiece logistics system, etc.).
- UI Layer: Implement different interactive interfaces according to different software services (Fig. 23). By default, the app includes two sets of UIs: development mode and customized mode. In the development mode, users can complete the development and configuration of DMU and virtual scene. In customized mode, users can get better user experience and get more management statistics.

The project operation UI of Visual Field is shown in Fig. 24. Users can manage the device layout in the virtual scene, add digital-twin driver logic control code (Q Code) to the virtual device, and monitor/debug the matching between the behavior of the virtual scene and the driver data.

4.3. Testing the platform prototype in FMS projects

The test platform has been validated in an FMS project for automotive camshaft parts production line. In the project (as shown in Fig. 30), there are 4 lathes (C062, C063, C064, C065), 4 milling centers (J048, J049, J050, J051), 3 robots (R007, R008, R009), 1 loading device (A001), 1 unloading conveyor (A002) and 2 workpiece exchangers (F03, F04). Three kinds of cutting processes were achieved by 4 lathes and 4 milling centers respectively (as shown in Fig. 29) and workpieces were exchanged by 3 robots. The controllers of machine tools and robots in production line all use the NC-Link protocol to submit status information to the NC-Link server. Workshop MES software and digital-twin GHOST service submit subscriptions to the NC-Link server and, use NC-Link to obtain real-time information of FMS devices. At the same time, GHOST service uses RESTful Web to obtain production statistics from the workshop MES software. These statistics can be displayed in the visual monitoring.

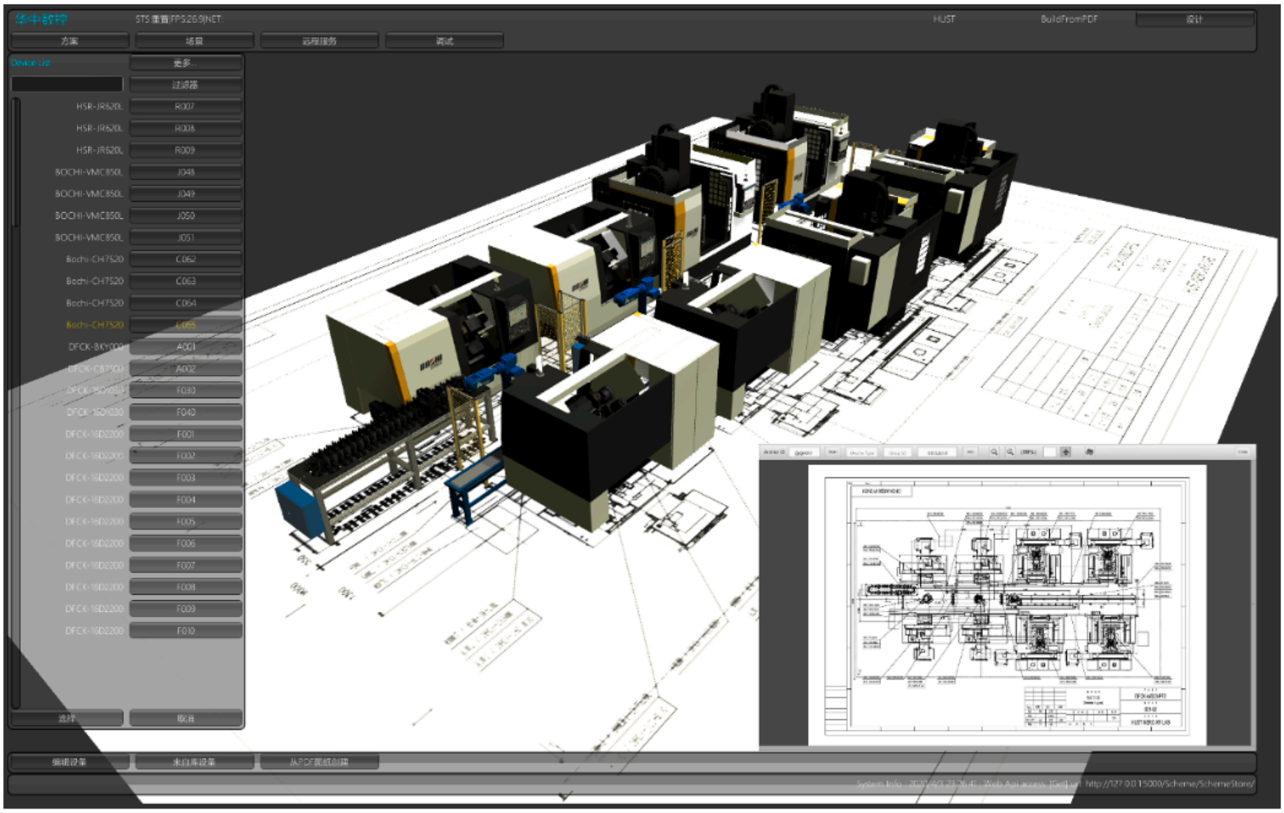

Fig. 25. Generate the layout of FMS from 2D PDF drawing.

Fig. 26. Workpiece warehouse in the production field.

4.3.1. Proof of concept and design stage of FMS

In the stage of project validation, according to the FMS process capability requirements, the device model and layout (Fig. 25) was determined in the Automation ML configuration. Visual Field can import FMS layout from CAD drawings. By scanning the anchor points in the CAD drawing, the DMU layout is automatically generated. The accessibility of the optimized device layout is verified by workpiece logistics simulation and collision detection. By modifying the process parameters of Automation ML, the validity of producing cycle planning is verified. When the scheme verification is completed, the mechanical designer begins to detail the mechanical design.

In the conceptual simulation stage, the construction of a virtual mock-up is a prerequisite for device motion simulation. For general-purpose device (such as machine tools, robots, AGVs, etc.), a single virtual motion pair such as linear mechanisms and rotating mechanisms can be used to construct virtual visual mock-up. For non-standardized device (workpiece warehouse as shown in Fig. 26), different virtual construction methods are needed. Implementation methods vary with the simulation software used. For instance, in the trial version of Siemens Robot Expert (as shown in Fig. 27), motion paths and logical judgment conditions must be set for 28 fixtures. It leads to inefficient development of DMU, and can take about 8–10 h for a postgraduate to construct a usable DMU in a project from the imported the 3D model.

In the Visual Field (as shown in Fig. 28), the feature of the device's motion mechanism is analyzed as a rigid chain structure. Leveraging the chained joint mechanism of the Q joint, the entire structure is decomposed into a set of equally spaced nodes, each consisting of 2 arc paths and 2 straight paths. These nodes, connected end to end, form a closed loop. Setting a fixture model on them, Visual Field can automatically generate the distribution of fixtures that follows a chained layout. The rigid connection ensures that each mode moves at the same speed, and the simulated motion of the real chain mechanism can be driven by a single motion drive parameter. This method effectively makes information on the products' DMU construction more efficient, allowing a postgraduate to construct a usable DMU from the preprocessing of the 3D model within 3–4 h.

DMU can predict and conduct simulation analysis on the Key Performance Indicators (KPIs) such as "Working Time", "Waiting Time" and "Blocking Time" of the machine tools in the FMS [47], to provide decision reference data for FMS planning and production scheduling optimization. As shown in Fig. 29, the processing time of three processes simulated by CAM software is 155 s, 126 s, and 256 s respectively according to the process features of the target workpiece. The process flow

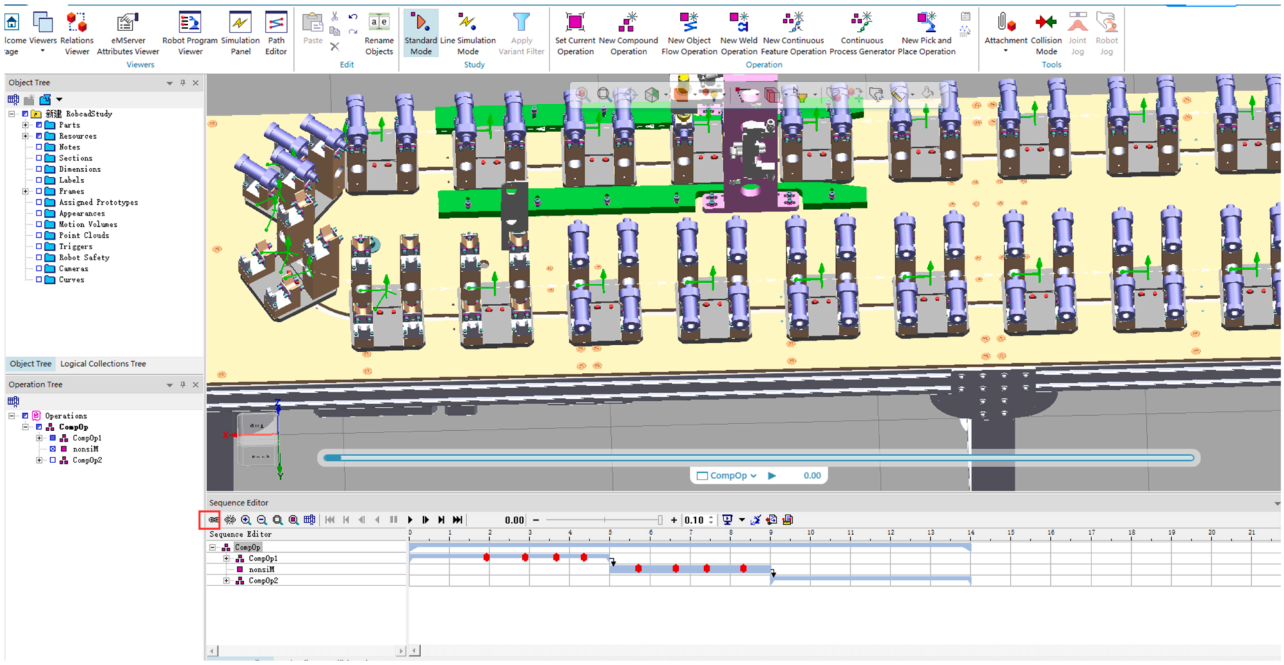

Fig. 27. The DMU of workpiece warehouse in Robot Expert Trial.

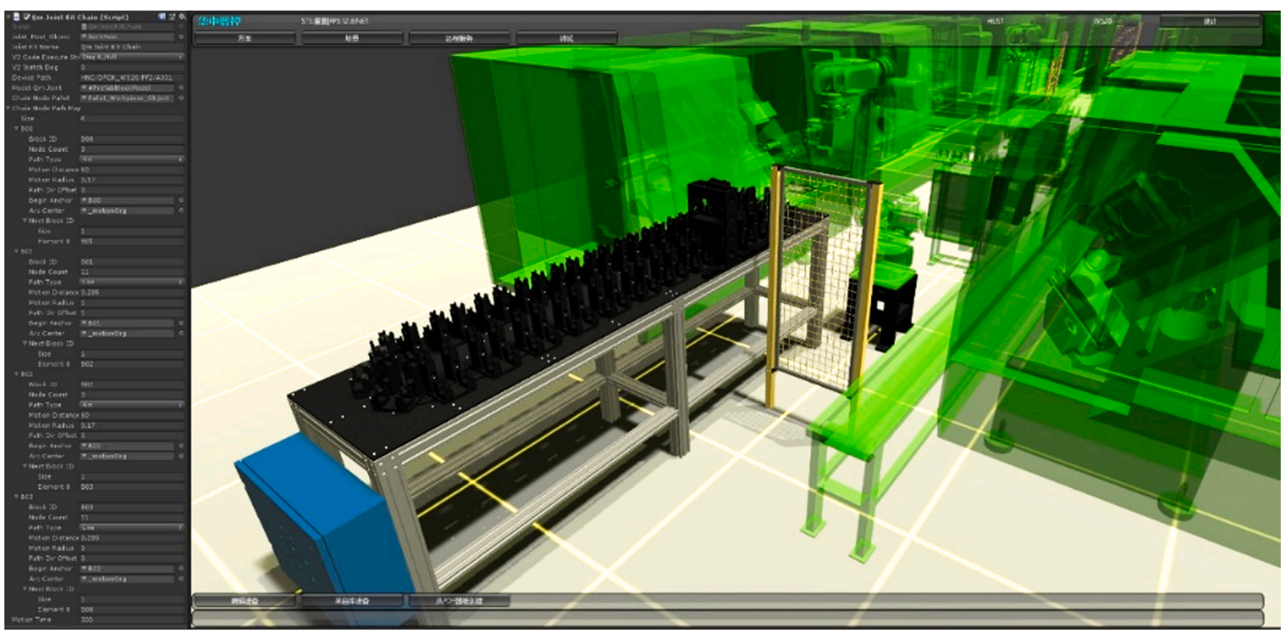

Fig. 28. Workpiece DMU in Visual Field.

Process index	Cutting Type	Time of processing	Time of reloading
010	Lathe turning	155(s)	10(s)
020	Lathe turning	126(s)	15(s)
030	Milling	256(s)	10(s)

Fig. 29. Processing times and reloading time of the individual machine tools.

planning of the device in Fig. 30 is adopted based onthe layout plan. The reloading time for different machine tools can be obtained by simulation in Visual Field. Afterward, the production process of 1000 workpieces is simulated and calculated in the Cyber Engine of GHOST. Fig. 31 is the simulated result of total time for the 1000 workpieces production on the interaction between different buffer sizes of workpiece logistics and the number of the workpiece in the milling machine each time. When the "workpiece buffer" is 4 pcs, and there are 4 workpieces in a milling center each time, the KPI of FMS would be the best (as shown in Fig. 32).

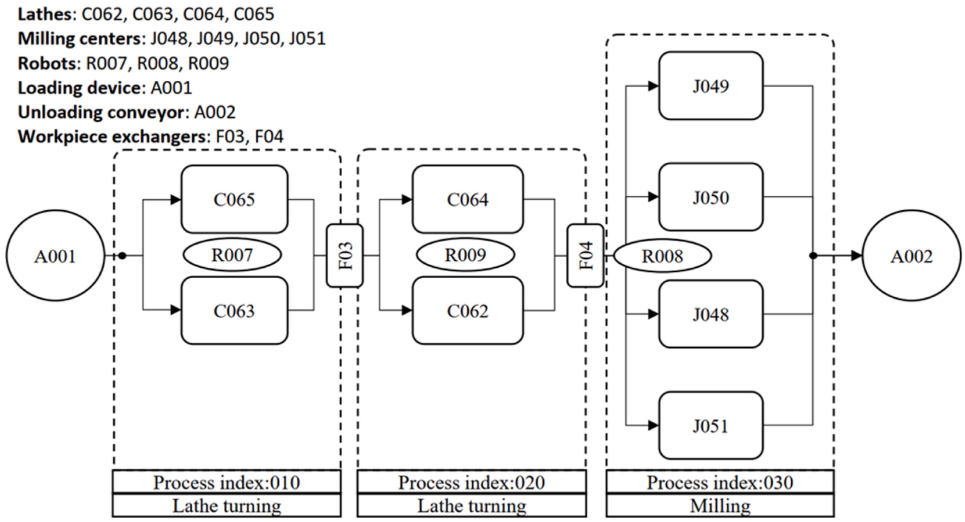

Fig. 30. Process workflow diagram.

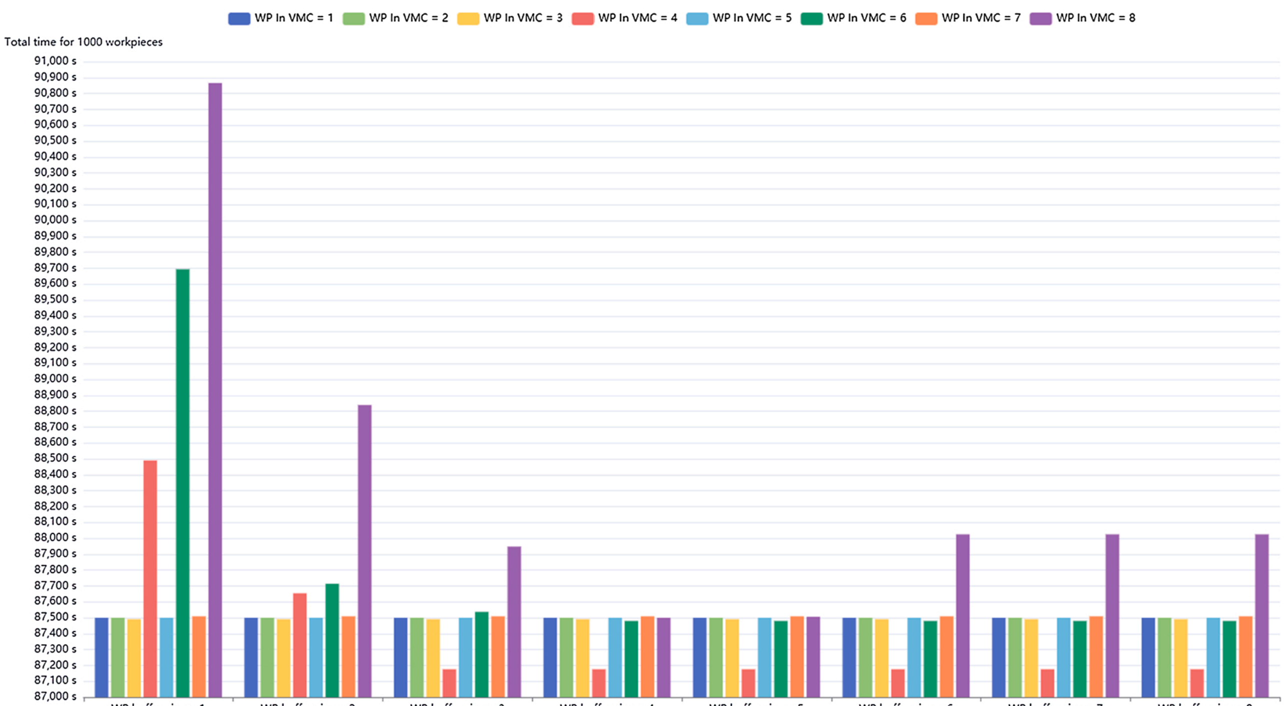

Fig. 31. The simulated result of 1000 workpiece production.

Machine Tool	WORKING	WAITING	BLOCKED
C065	88.56%	0.00%	11.44%
C063	88.57%	0.00%	11.43%
C064	71.99%	10.85%	17.16%
C062	71.98%	10.88%	17.14%
J049	79.88%	13.88%	6.24%
J050	79.88%	13.88%	6.24%
J048	79.86%	13.89%	6.24%
J051	53.27%	42.52%	4.21%

Fig. 32. KPI of the individual machine tools simulated in prototype.

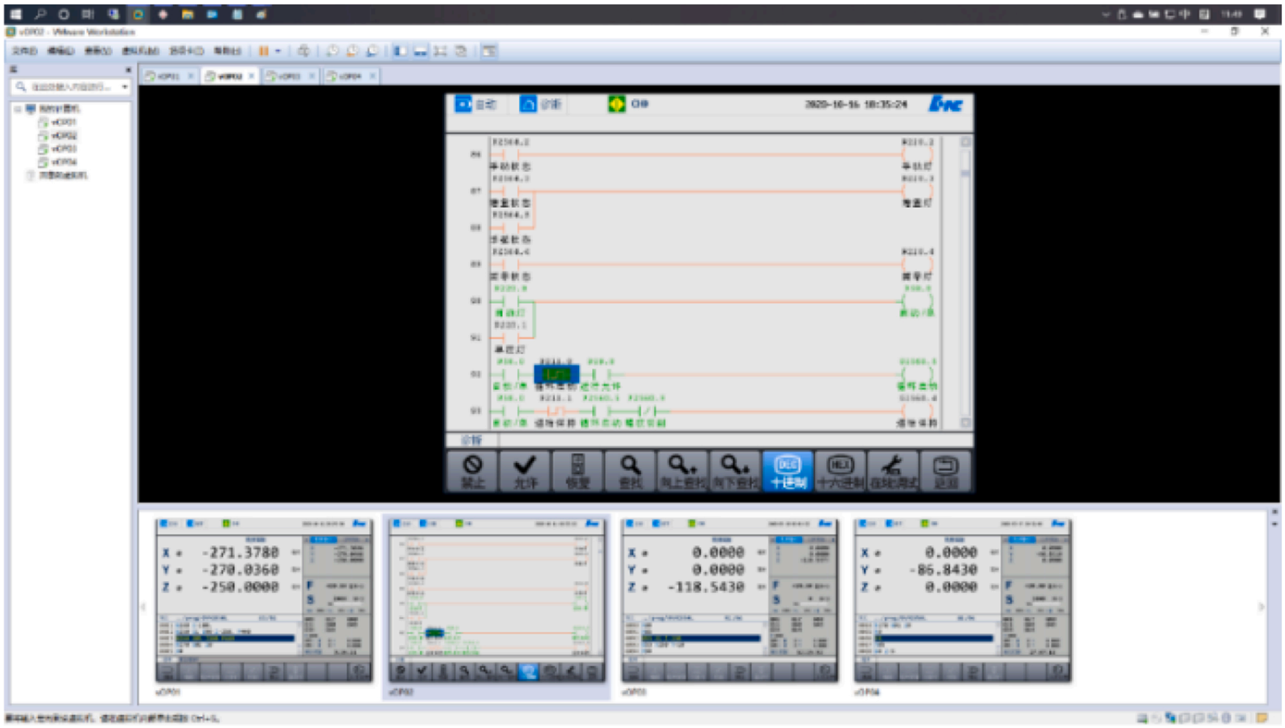

Fig. 33. Four CNCs simulated in the virtual machine.

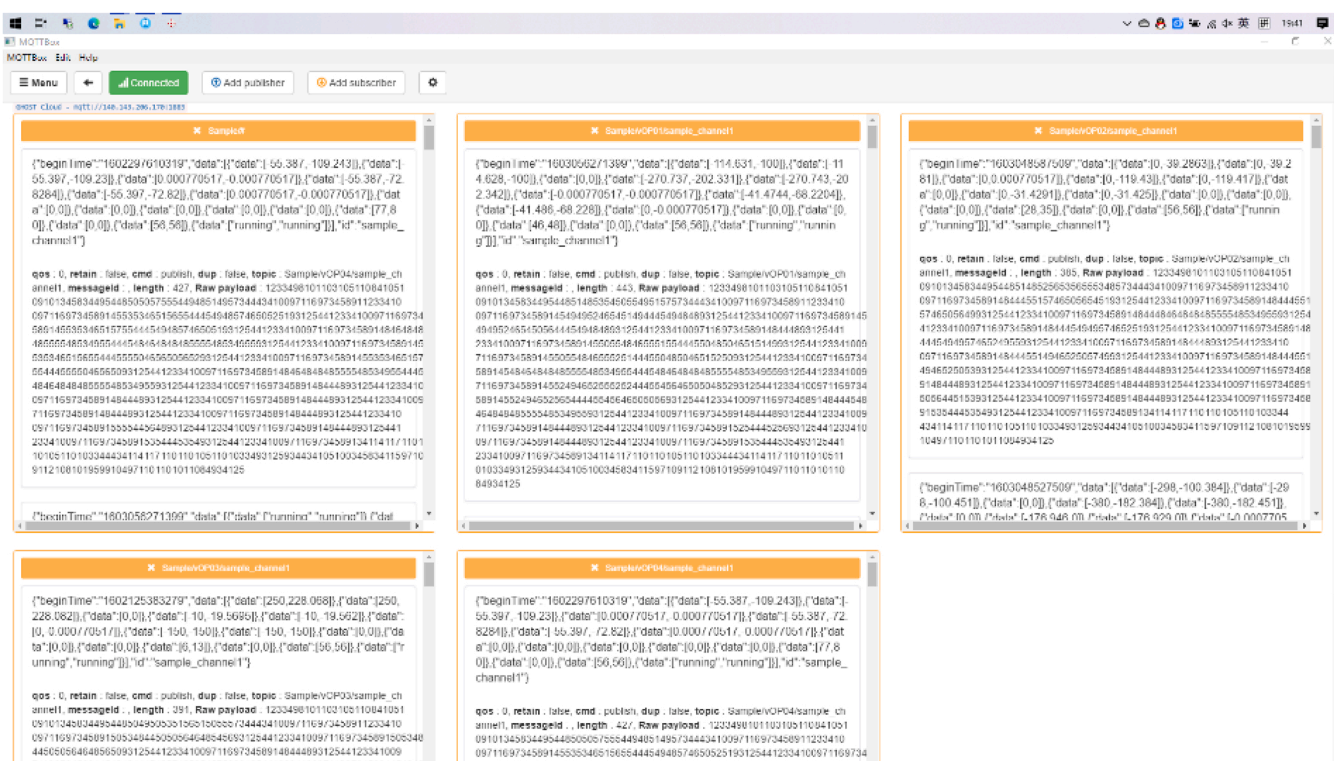

Fig. 34. NC-Link data samples monitored and controlled digitally by MQTT Box.

4.3.2. Information-physical development and debugging methods of FMS

As for the development and debugging of PLC programs for machine tools, robots and controllers, as well as for industrial software (e.g., CoDeSys)/virtual CNC, these programs are connected to GHOST Service via OPC-UA/NC-Link to debug and control the logical and timing relationships between motions of program devices using the virtual machine in Visual Field, thus testing and optimizing the control program.

In the FMS project discussed in this paper, the CNC systems of four machining centers use virtual machines (as shown in Figs. 33 and 34) to simulate and drive the motion of machine tool DMU in virtual spaces. Engineers use DMU and achieve the information-physical debugging goal of the PLC and CNC machining programs for machine tools (as

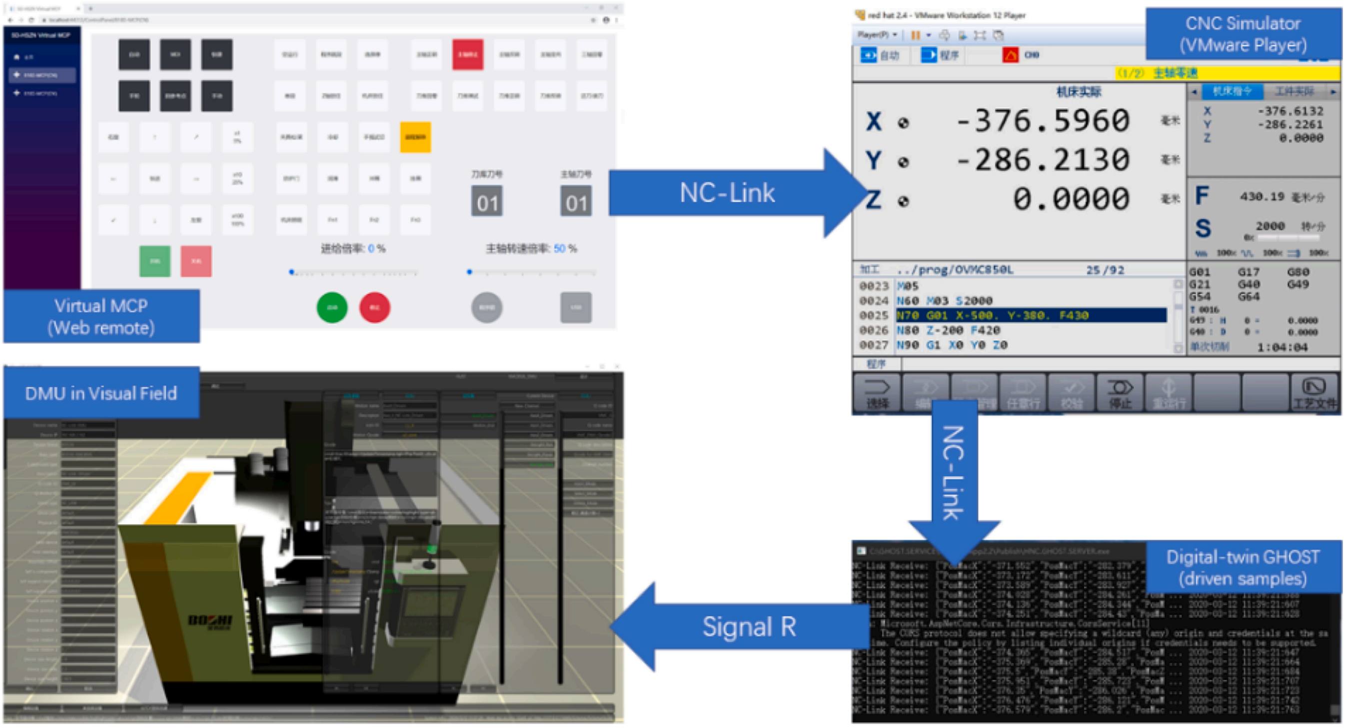

Fig. 35. Information-physical development method in Visual Field.

shown in Fig. 35). In this connection, the development and testing time of the physical CNC system and machine tool can be reduced directly. For the program development of disc tool warehouse PLC control process of general vertical milling center in Fig. 36, the development time of an electric engineer in classic mode and DMU simulation mode is shown in Fig. 37. With the help of DMU, programming and logic verification can be carried out simultaneously under off-sit. The accuracy and integrity debugging and test of PLC program logic can be finished with DMU before on-set, thus saving the site programming and debugging time of PLC by 30 %.

4.3.3. *Visual monitoring and maintenance*

During FMS production (as shown in Fig. 38), users can view the real-time working state of a production line via the virtual 3D device in the virtual scene simulated in Visual Field (as shown in Fig. 39), or trace the production process by rebuilding the scene with historical digital-twin information.

4.3.4. *Remote assistance*

When users on the production site need technical assistance from engineers, multiple engineers can remotely access the digital-twin GHOST data through the Visual Field simultaneously (as shown in Fig. 40). In the FMS digital-twin data visualization app, engineers can see devices motion and status changes in virtual scene with DMUs, remote desktop information of the controller, etc. On the production site, users obtain remote technical guidance from engineers by using the Visual Field program on the iOS platform (augmented reality mode, as shown in Fig. 41).

4.4. *Future work*

The current theory and prototype in the paper are still constrained in several aspects. The first issue is the massive amount of digital-twin information generated by physical assets during filtering and management. For different purposes, the source of digital-twin information driving from virtual scenes may vary a lot. Further studies on developing a more effective integration method are required. Second, while modeling Digital Mock-ups (DMU) of devices/components, the hierarchical division of virtual transmission pairs also requires to be investigated from theoretical perspectives. For physical devices/components, their power sources, transmission, and drives can all produce digital-twin information. More studies and verification tests should be conducted before digital-twin information can be accurately selected from DMU drivers. Third, the platform prototype does not provide a universal digital-twin visualization method about the temperature, vibration, lifetime, and other data of device/components. At last, given that the FMS project in this paper is still in the production service stage, the performance of the platform prototype in the remanufacturing stage needs to be further explored and verified.

The scope of future work is summarized as follows. Above all, more attention will be put into the efficient construction of DMU efficiently. The realization of rapid modeling of DMU in an intelligent manufacturing system satisfies the need for visualization of the motion and state of physical assets. Second, this is to make the multi-dimensional heterogeneous integration of digital-twin GHOST information more universal and optimize the AML topological structure. Third, with standardized modules for drive data conversion in Cyber Engine virtual scenes based on FSM, and optimized logical relations between script configured digital-twin information and virtual scene reconstruction, the configuration efficiency of Cyber Engine will be further enhanced. Besides, it also aims at reducing the delay time of DMU motion playback in virtual 3D scenes, and improving the synchronization rate of heterogeneous digital-twin information during visualization (e.g., the synchronization rate between the remote desktop of the controller and the motion of DMU). In conclusion, the visualization of geometric changes in the workpiece cutting process within a manufacturing system will be implemented by the "voxel method". Regarding the concepts and methods presented in this paper, which might be specific to FMS, but their basic implementation methods can apply to the digital-twin visualization requirements of other intelligent manufacturing devices as well (e.g., five-axis machine tools and intelligent warehouses). Besides that, the software tools implemented in this paper can also be used for the visualized simulation and monitoring of other types of digital-twin information from the manufacturing process.

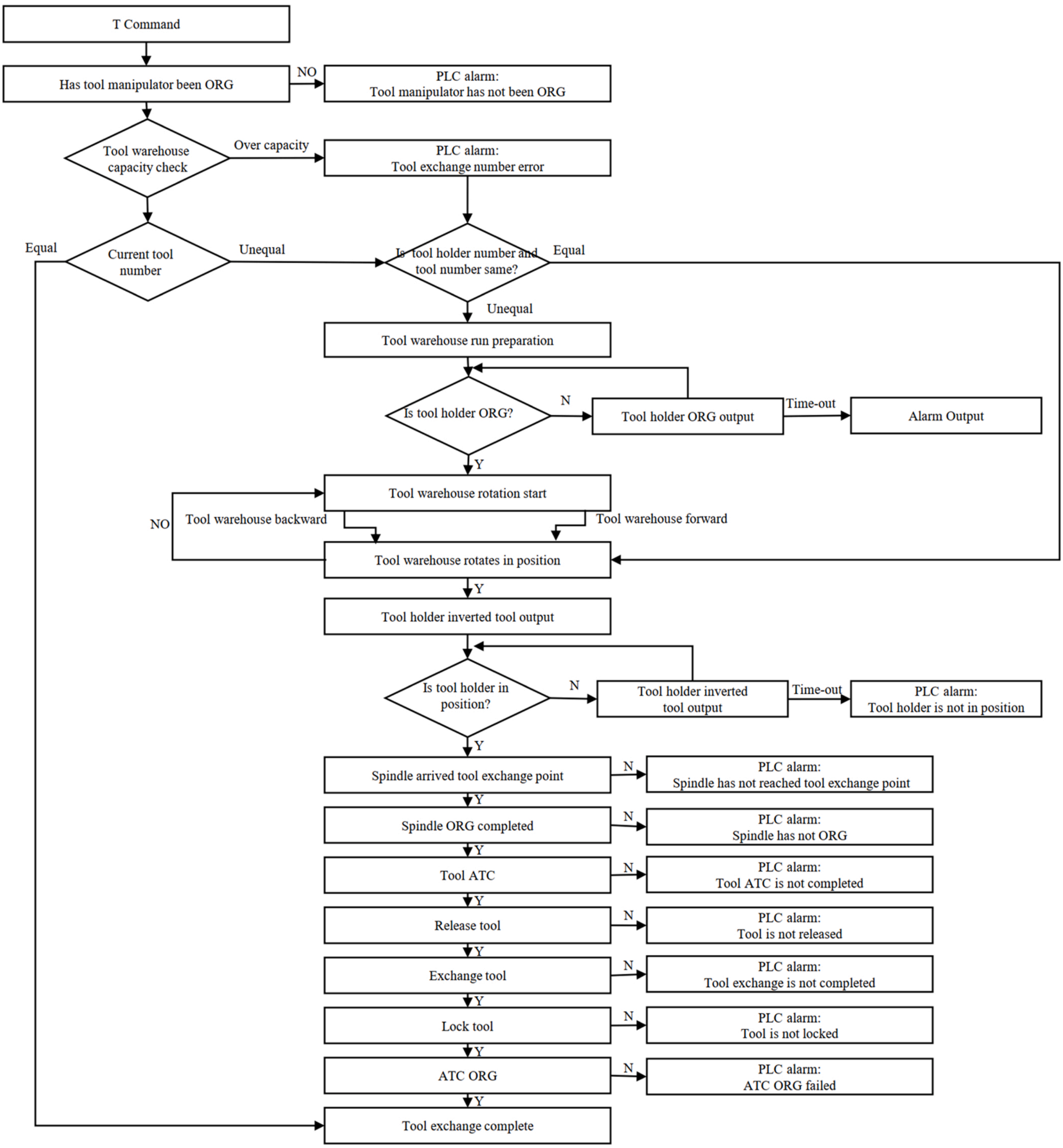

Fig. 36. Flow diagram of PLC for the disc tool warehouse in the vertical machining center.

As shown in Fig. 42, in the project where an enterprise uses machine tools for production, order quality inspection data in its ERP system can be utilized to make the progress and process of machine tool manufacturing transparent and virtually visible.

Since the digital-twin visualized architecture must be subject to the industrial Internet platform, Decentralized Multi-agent System [48] (e.g., blockchain and smart contract) and Industrial Internet Identification and Resolution [49] will be more and more focused during intelligent manufacturing. In the future, key enabling technology of them will be used appropriately as the upgrading of architecture in the paper.

5. Conclusion

This paper proposes a digital-twin “Geometry – History – Object – Snapshot - Topology” (GHOST) concept for human-cyber-physical manufacturing systems (HCPS), discusses the digital-twin modeling of the life cycle of HCPS, and develops a general visualization architecture. According to the architecture, digital-twin information on solution design, simulation, debugging, production service and remanufacturing in intelligent manufacturing systems has been described.

In line with the concept of HCPS-oriented digital-twin virtual mock-ups, a virtual mock-up service platform prototype for FMS has been

Motion description		Classic development (Hrs)		Development with DMU (Hrs)		
		Off-site	On-site	Off-site		On-site
Motion	Sub-motion	Programming	Debugging	Programming	DMU simulation	Debugging
Tool warehouse rotation	Manual control tool warehouse forward and backward T code to select tool Tool warehouse ORG	6	8	2.5	3	5
Tool holder moves up and down	M code control tool holder T code control tool holder	1	0.5	1	-	0.5
Tool hold & release	M code control tool hold & release Manual control tool hold & release	1	0.5	1	-	0.5
Manipulator	ATC catch tool ATC exchange tool ATC ORG	4	5	2	2	3
Spindle positioning	Manual control positioning M code control positioning	1	0.5	1	-	0.5
Subtotal		13	14.5	7.5	5	9.5
Total		27.5		22		

Fig. 37. Time cost of PLC development for the disc tool warehouse in the vertical machining center.

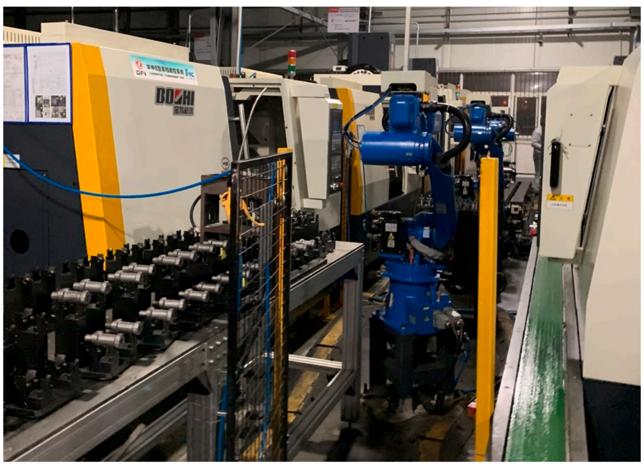

Fig. 38. The FMS project discussed in the paper.

developed, verifying the feasibility of the conceptual architecture and development method. Digital information management in the design, optimization and production stages of the production line project of automobile camshaft parts has been realized. Through the Cyber engine provided in GHOST, the digital-twin information on the production line is converted into data that drives visual DMU motion. Considering the particularity of digital-twin models of the life cycle of human-computer interaction systems, an application named "Visual Field" has been developed, which can be used in virtual 3D scenes to reproduce the digital-twin data on the motion/state of device/components. In Visual Field, users can verify the FMS layout scheme and production efficiency. PLC programs for FMS can be optimized using virtual debugging and development. The motion and state of production lines can be monitored in real-time. Historical digital-twin information on production lines is replayed as virtual 3D scenes. During the application verification process based on the platform prototype, a universal information-physical modeling method for the life cycle of manufacturing systems has been investigated, and a universal realization method for the human-information digital-twin visualization DMU has been tested. It demonstrates digital-twin information of FMS to users completely and

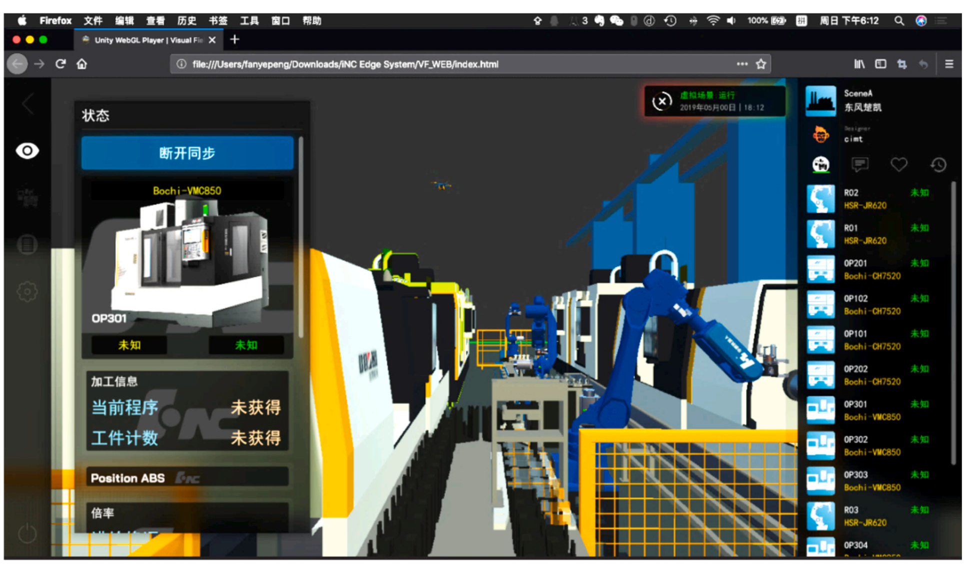

Fig. 39. The FMS project scene simulated in Visual Field.

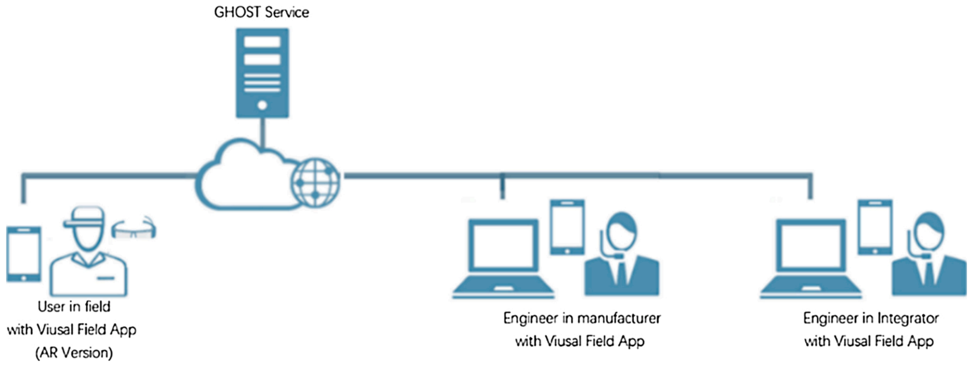

Fig. 40. Remote assistance architecture.

Fig. 41. AR function of Visual Field on iOS platform.

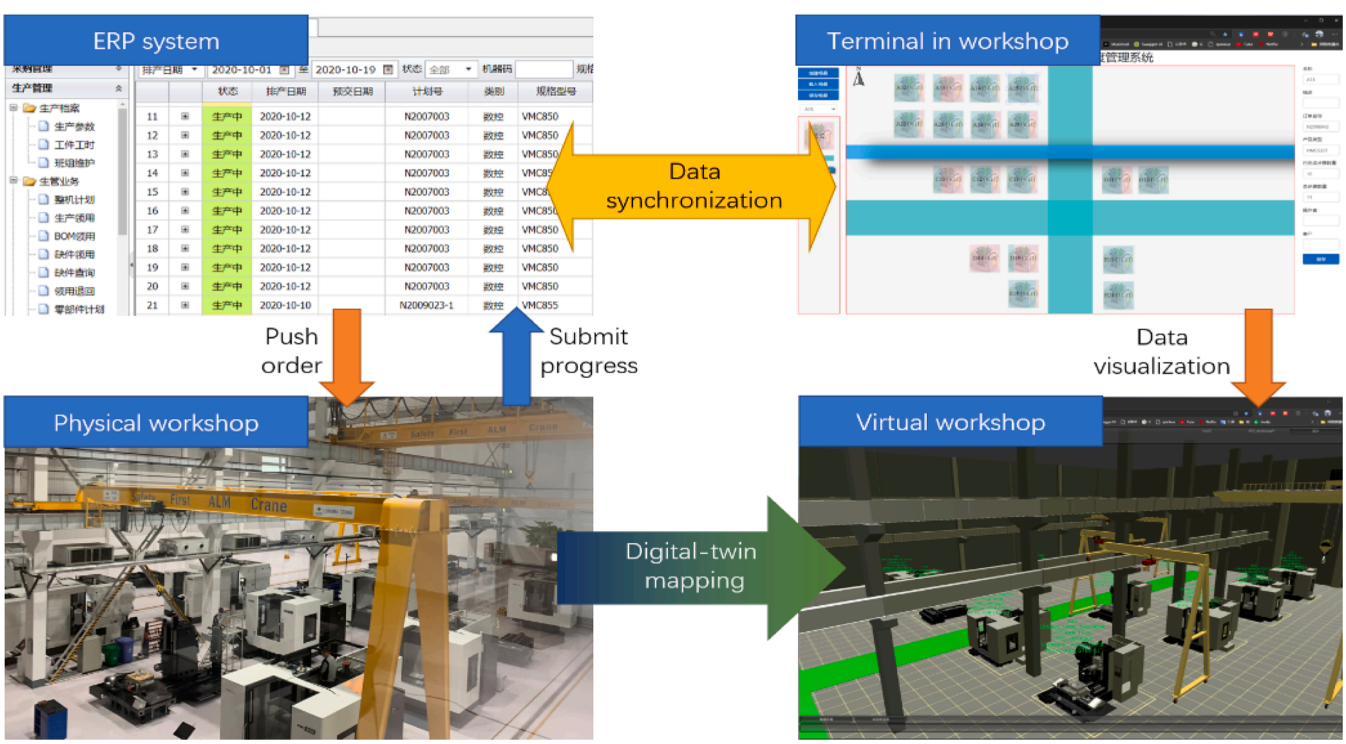

Fig. 42. Visually reproduce the product assembly progress in the EPR system in a virtual scene.

intuitively, and improves the interaction efficiency between the digital-twin network layer and humans, thus further enhancing human decision-making levels at the physical layer.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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