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AML-based web-twin visualization integration framework for DT-enabled and IIoT-driven Manufacturing system under I4.0 workshop

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ABSTRACT

With the development of digital twin technology, the visualization of manufacturing resources through IIoT integration has become an important technical means of Human-Cyber-Physical System. By analyzing the technical bottleneck of realizing digital twin workshop based on Web3D, this paper proposes AML-Based Web-Twin Visualization integration framework for DT-enabled and IIoT-driven manufacturing system under I4.0 Workshop, which aims to provide theoretical and key technical support for the construction of digital twin workshop based on Web3D. (1) Elaboration of web-twin operation mechanism based on I4.0 workshop, the integrated architecture composed of IIoT-Driven Asset Administration Shell modeling and management framework, Automation ML-Based Web-Twin kernel framework and Web-Twin visualization integration framework of manufacturing system is established. (2) Based on the theoretical model of system architecture, a reference technology route based on cloud-edge-browser is proposed. By establishing the management and control model based on AAS and the IIoT-Driven manufacturing system integration model, and introducing the lightweight model and the interest-oriented granular scheduling algorithm, the operation of the system architecture and the development of key technologies are realized. (3) Taking the manufacturing system integration in multiple I4.0 scenarios as an example, the implementation and verification based on the technical framework are illustrated.

1. Introduction

HCPs, which is composed of Human-Cyber-Physical System, focuses on people-centered planning, design and operation of manufacturing systems through human perception, vision, smell, action and other behaviors [1,2]. Its vision is to understand and promote human-technology partnership, enhance human performance, and understand the risks and benefits of new technologies.

1.1. Literature survey

From the perspective of HCPs development, Digital Twin [3] and IIoT [4] are the most important enabling technologies through visualization and digitization in HCPs manufacturing scenarios. Based on the DT technology, people can further realize the upgrading and transformation of intelligent workshop in planning, design, operation, commissioning, operation and maintenance, as well as training. IIoT technology, as a data platform to realize the interconnection of everything, provides an information framework and data-driven source for virtualization sharing. Therefore, under the background of I4.0 technology, how to realize resource virtualization based on I4.0 technology architecture to quickly support the construction of I4.0 workshop has become an important research content; In addition, due to the advantages of Web services in deployment and sharing, it is also an important technical problem to develop Web3D engine to achieve high-speed and stable loading to help build I4.0 ecology [5]. For example, Service-Based MES/MOM architecture in workshop, IIoT-Based data platform, AR/VR guidance and PLC remote-debugging are all based on web to realize service deployment and development. The vision of this paper is to start from Web3D and carry out research on the technical bottleneck of building web3D-Based DT system in the I4.0 manufacturing system. Therefore, relevant literature studies are described from the following two aspects to support the motivation and value of this research: DT-enabled and IIoT-driven I4.0 Workshop and Web-Twin Visualization.

1.1.1. DT-enabled and IIoT-driven I4.0 Workshop

I4.0 Workshop, which is characterized by CPS [6], implements the specific technology on AAS. AAS has a virtual representation as an asset description and technical functionality as a smart manufacturing service [7]. Its purpose is to help workshop solve the problem of creating

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Nomenclature

HCPs Human-Cyber-Physical System.
DT Digital Twin.
AML/Automation ML Automation Markup Language.
Industry 4.0 I4.0.
IIoT Industrial Internet of things.
AAS Asset Administration Shell.
RAMI4.0 Reference Architecture Model Industry 4.0.
MES Manufacturing Execution Systems.
CIF Common Implementation Framework.
BVH-Tree Bounding volume hierarchy tree.
ID Interest degree.
FD Fill degree.
RD Reuse degree.
AD Attention degree.
MOM Manufacturing Operation Management.
PLC programmable logic controller.
AAXS Package File Format for the Asset Administration Shell.
AR/VR Augmented Reality/Virtual Reality.
CAEX Computer Aided Engineering Exchange.
COLLADA™ Collaborative Design Activity.

variable production systems in the production line [8]. The concept of AAS starts with "assets", based on the expansion of AAS sub-model [9], integrate the functions of DT and IIoT, to promote the virtualization construction of physical resources. Park et al. proposed an asset description for the operation procedures of a work-center-level DT application [10]. For the successful application of DT as a smart factory technology, VREDI is designed to meet four core technical requirements: DT definition, AAS property inheritance, improving the existing asset description, and supporting DT-based technical functionalities. Malo et al. proposed NOVAAS [11], a microservices-based implementation of the AAS. Relevant scholars also advocate the use of continuous AAS-integration technology for software development and delivery. Cavalieri et al. presented an AAS model able to represent IEC61131–3 programs and the relevant relationships with Programmable Logic Controllers and each device of the controlled plant [12]. BaSyx-platform also incorporates a Virtual-Automation-Bus built around the networking infrastructure that allows seamless interaction between industrial assets through their corresponding AAS instances [13]. Therefore, from the above technical development, AAS has gradually become the work carrier of I4.0 workshop in the future. There is no doubt that how to realize DT workshop based on AAS has become the technical bases of our research.

In addition, IIoT, as the data platform for the interconnection of all things, and DT, as the key technology to realize resource virtualization, the cutting-edge and maturity of its technology ecology also greatly affect the landing of the I4.0 workshop [14]. It is also the basis for us to study the implementation of DT technology based on Web3D. We have also conducted relevant research on its theory and technology development. Tao et al. proposed the concept of DT workshop and expanded it to five dimensions (physical entities, virtual models, services, DT data, connections) on the basis of the original three-dimensional (physical entities, virtual models, DT data) digital twin architecture [15], to help practitioners provide theoretical reference and guidance in the practice of building DT workshop. Fan et al. presented a general architecture of DT visualization for flexible manufacturing systems and propose a digital-twin modeling concept of "Geometric information-Historical samples-Object attribute-Snapshot collection-Topology constraint" [16],the prototype system is developed and verified based on unity3d. Liu et al. proposed a quad-play Configuration Design-Motion Planning-Control Development-Optimization decoupling(CMCO) design architecture for the design of the flow-type smart manufacturing system based on the DT technology in the I4.0 context [17]. Concetta et al. Comprehensively studied the history, development and technical status of DT in intelligent manufacturing [18]. Bu et al. proposed a three-terminal collaborative platform consisting of cloud servers, embedded controllers and mobile terminals to integrate AI and IIoT-technologies for the autonomous connect manufacturing machines design [19]. Liu [20] and Zhao [21] introduced an IIoT-based edge--cloud-orchestration solution is used for machine design, and a collaborative tracking architecture has been developed to support IIoT-edge computing. Zhang et al. proposed rapid construction method of equipment model for discrete manufacturing DT workshop system, the prototype system is developed based on UE-engine [22].

From the above analysis, under the technical ecology of I4.0 workshop, the work-center based on AAS, the construction of IIoT-based data platform and the theoretical support of DT are important links to realize the integration and symbiosis of CPS system and human behavior activities.

1.1.2. Web-twin visualization

Based on the enabling effect of AAS and IIoT, it has become an indisputable fact that DT can realize multi-dimensional virtual model, virtual-real integration, virtual-real closed loop in interactive mechanism control and virtual-real symbiosis in interactive mechanism. In this paper, it is found in the literature research that the research on the engineering problems of system integration and development in AR/VR, MES/MOM and PLC-debugging of I4.0 DT workshop based on Web3D technology and AAS is very few, so the research direction is analyzed and summarized from the similar studies as far as possible. In Web3D-based AR/VR technology, Sun and Liao et al. proposed A lightweight and cross-platform Web3D system for casting process based on VR using WebGL [23]. Yuan et al. Comprehensively discussed the Implementing WebGL and HTML5 in Macromolecular Visualization and Modern Computer-Aided Drug Design [24], it also points out that all functions of the next generation CADD (computer-aided drug design) based on WEBGL/HTML5 should have the characteristics of plugin fee, online stereo visualization with potential VR-support, interactive design, and real-time data sharing. In Web3D-based framework applications, Jia explored the task of lightweight indoor path planning in complex building information modeling (BIM) buildings, the system is developed and verified based on threejs [25]. Liu et al. presented a Web3D-based light weighting solution for real-time visualization of large-scale BIM scenes, considering the redundancy, semantics, and the parameterization of BIM data under the limited resources of network bandwidth and web browsers [26]. Li and Jia et al. proposed a WebBIM-Based multi--granularity interest loading scheduling algorithm for cloud-edge-page collaboration for large building scenes [27], and conducted a large number of basic experiments, which is worthy of the attention of Web3D researchers.

In general, the basic technologies based on Web3D have made great progress. The 3D-engine represented by open-source threejs gradually supports the new generation of webgl2.0 technology. However, it is undeniable that Web3D is mostly studied in BIM architecture scenarios and single visualization scenarios, and there is no systematic research from the information architecture, algorithm optimization and workshop service integration to explain the visualization integration architecture of manufacturing system under the semantics of I4.0.

1.2. Motivation and contribution

Through the above research and analysis, we have made a complete summary and explanation to further support the research motivation and proposed solutions of this paper: (1)due to the advantages of service-oriented deployment and easy access, it has become an important demand for users to use the web page of PC/mobile to access the large-scale HCPs manufacturing environment, and it is also the key technology of the new generation of intelligent manufacturing; (2)many scholars have discussed the architecture, operation, application scope and enabling tools of DT and IIoT in the manufacturing system theoretically and technically; From the technical development cases taking the I4.0 workshop as the research object, they are all aimed at the development of DT system based on pure hardware resource engines such as unity3d and unreal-engine, which few complete solutions based on Web3D; (3)Mainstream browsers gradually support webgl2.0, which can provide faster real-time rendering. At the same time, the combination of IIoT, 3D lightweight library, HTML5, P2P communication gradually makes it possible to realize large-scale web3D-based I4.0 scenes; (4) the manufacturing system based on AAS with DT-enabled and IIoT-driven has become the key technology mode to realize I4.0 workshop, and it is also the ecological foundation to realize the construction of DT-workshop based on Web3D.

Based on the vision of Web3D integrated manufacturing system under I4.0 semantics, that is, any user can easily access DT scene through browser mode and realize the integration and interaction of manufacturing system. This paper refines the current technical bottleneck from the aspects of integration architecture, manufacturing semantic interaction and 3D scene processing, and systematically proposes and studies comprehensive solutions. As shown in Table 1.

This paper proposes AML-Based Web-Twin Visualization integration framework for DT-enabled and IIoT-driven manufacturing system under I4.0 Workshop, which aims to provide theoretical and key technical support for the construction of DT workshop based on Web3D:(1) By analyzing the operation mechanism of Web-Twin in I4.0 workshop, the integrated architecture composed of IIoT-Driven AAS modeling and management framework, AML-Based Web-Twin kernel framework and Web-Twin visualization integration framework of manufacturing system is established; (2) Based on the theoretical model of system architecture, a reference technology route based on cloud-edge-browser is established. By establishing the management and control model based on AAS and the IIoT-Driven manufacturing system integration model, and introducing the lightweight model and the interest-oriented granular scheduling algorithm, the operation of the system architecture and the development of key technologies are realized; (3) Taking the manufacturing system integration in multiple I4.0 scenarios as an example, the implementation and verification based on the technical framework are illustrated.

Table 1
Web-Twin Visualization integration Challenges& Solution under I4.0 Workshop.

Classification	Challenges	Solution design
3D scene processing	Complex I4.0 manufacturing scenario model (Tens of megabytes → GB → TB→ 3D big data)	lightweight preprocessing of 3D model/ Lightweight model library
	The granularity of 3D manufacturing scene is too coarse (For engineering modelers, they are based on building or production line modeling, which is very inconvenient to schedule)	Fine-grained preprocessing of 3D scene
	Transmission is too slow/not combined with actual network conditions (Users have low tolerance for network transmission and loading)	Based on network heartbeat detection and fine-grained 3D content progressive transmission scheduling
	Poor rendering (The computational power of web page rendering is weak)	(Hybrid) lightweight Web3D map offline / online light rendering
Integration architecture	Inconvenient access (UE/ unity3d-Based Desktop/Client development and deployment)	Architecture mode based on cloud-edge-browser
	Cloud-only/browser-only rendering mode (Slow response/extremely demanding on hardware)	
Manufacturing semantic interaction	Based on Web-twin system integration is difficult (I4.0 manufacturing semantics)	Modeling based on AAS and AML semantic transformation

1.3. Web-Twin visualization framework supporting manufacturing system integration

Based on the above discussion and analysis, we further elaborate and design the function, integration, operation and related algorithms of the system architecture, the detailed study is as follows: (1)IIoT-driven AAS modeling and management framework for AAS-Based management and control model of I4.0 workshop, and the enabling and integration model of IIoT-driven manufacturing system;(2)AML-Based Web-Twin kernel framework for Data analysis and integration based on AML in I4.0 workshop, Lightweight model library, and Interest-oriented granularity scheduling;(3)Web-Twin visualization integration framework of manufacturing system for IIoT-driven Manufacturing system integration and User-interface control based on Web-Twin. As shown in Fig. 1.

1.4. IIoT-Driven AAS modeling and management framework

The purpose of this framework is to solve the data source based on web-twin for the system integration and management of the equipment layer of I4.0 workshop. In the Reference Architecture Model for Industry 4.0 [28], the concept of AAS is presented as the corner stone of interoperability, which defined as a digital representation of a relevant asset; it provides an interface to an I4.0 network allowing the communication with other assets and the exchange of information. Assets are defined as entities owned by an organization having either a perceived or actual value for the organization itself; for example, physical entities like machines, products or controllers are considered assets, but even software, documents or licenses can be considered assets too. As shown in Fig. 2.

1.4.1. AAS-Based Management and control

In I4.0 semantics, as the core link of workshop equipment layer, AAS plays a role in the management and control of physical entities and virtual resources. (1) Manage the I4.0 workshop design layout (such as workshop size, equipment coordinates, work area division, order resource allocation, etc., which are generally expressed by CAD, CAM, PLM, etc.), asset list (such as equipment, materials, personnel, process, measurement, etc.), operation control (such as equipment status, personnel status, material status, quality inspection qualification rate, etc.), System debugging (such as PLC-debugging, equipment installation debugging, etc.), after-sales maintenance (such as AR-based remote guidance), etc.(2) The core work content of management and control is to dynamically monitor the workshop situation (for example, multi-source and multi-dimensional sensing data acquisition based on IIoT), master the workshop operation dynamics in real time (for example, production planning, production scheduling and work reporting based on MES/MOM), and even reasonably predict the workshop manufacturing trend (for example, equipment fault analysis and workshop capacity analysis), Thus, it can give users a quick response solution.

Generally speaking, the workshop equipment layer information modeling based on AAS refers to RAMI4.0 standard framework, and the asset layer, integration layer, communication layer, information layer, function layer and business layer under the life cycle & value stream framework shall be implemented in accordance with IEC62890 construction standard; And gradually build product, field device, control device, station, work centers, enterprise and connected world under the framework of hierarchy levels, in accordance with IEC 62264/ IEC61512.

1.4.2. IIoT-driven manufacturing system

IIoT is empowering modern-day technologies through expanding the

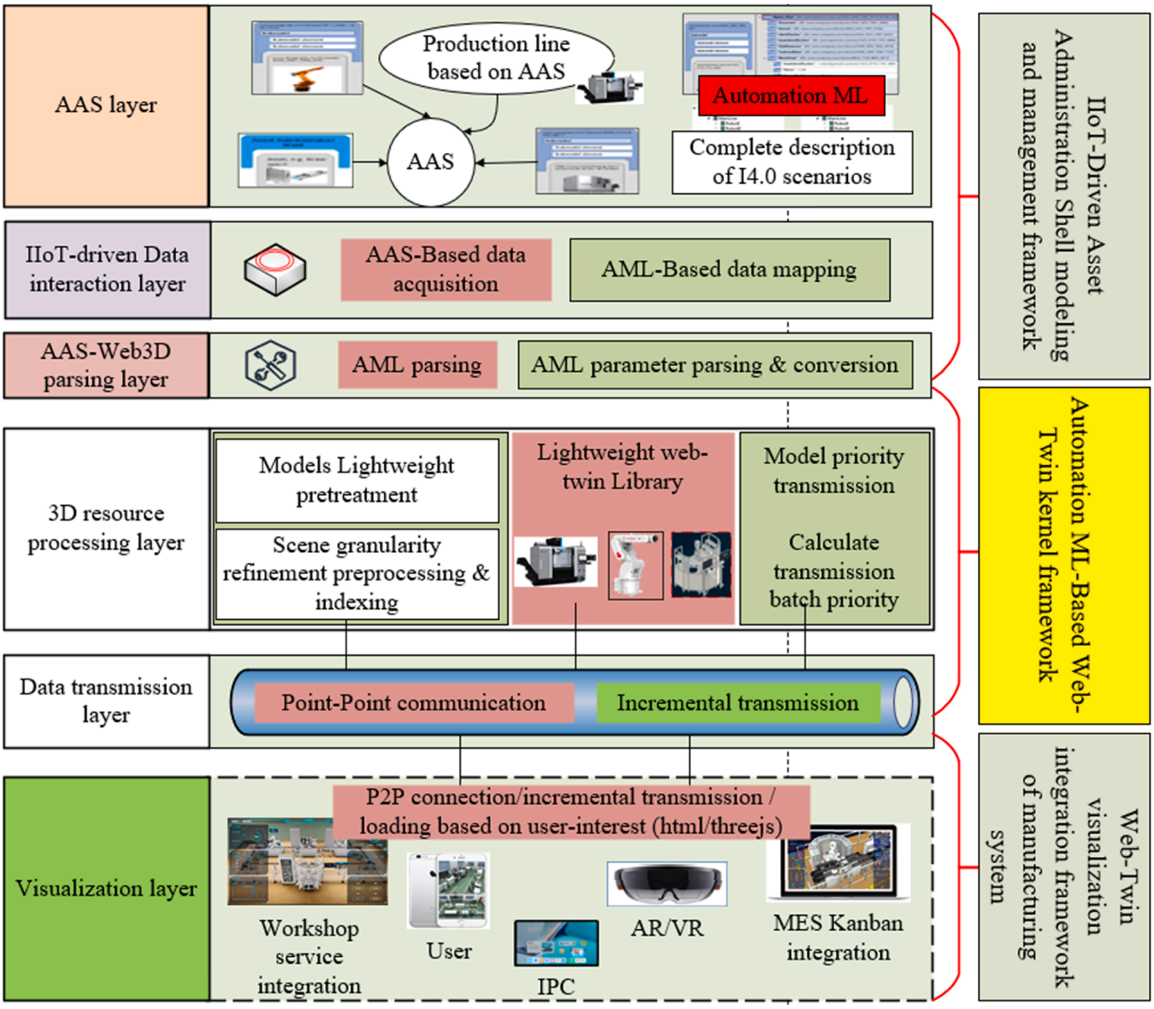


Fig. 1. Automation ML-Based Web-Twin Visualization integration framework.

Internet competency to the sensing nodes and transmitting to the edge devices. IIoT, as the basic data platform of intelligent workshop, usually has three implementation links to consider. (1) IIoT-device: An IIoT-device is connected to the IIoT-platform and interfaces with the physical process of manufacturing. It retrieves instructions from the IIoT-platform and supplies status information and measurement data, which is undertaken by AAS here;(2)IIoT-Gateway: Furthermore, due to the large amount of data that is created by IIoT-devices, a big data infrastructure may need to be in place to process, store and analyze the data before it can be useful to workshop service(MES/MOM);(3)IIoT-platform: Based on the IIoT-Gateway, the IIoT-platform is responsible for connecting and monitoring a large number of IIoT-devices and playing the role of storage/analysis/mining/prediction. Finally, it realizes interconnection and mutual control with the information system in a unified interface mode. IIoT-platforms such as thing-Worx (developed by American PTC company) or FIWARE (open-source) are expected to replace and enhance some traditional MES/MOM functions. In the process of system implementation, IIoT-platform can be hosted locally or in the cloud. However, we learned from interviews and field studies that most manufacturers prefer to run the IIoT-platform locally because of low latency and avoid interrupting production in the event of Internet connection problems, as well as related data security issues. Much of the manufacturing IT-infrastructure in IIoT-enabled smart factories will be integrated into digital manufacturing platforms, which can be hosted in the cloud and provide the infrastructure needed to support the functionalities of ERP, MOM, etc. in the form of apps.

Therefore, in this demand, AAS as the actual management and control unit of I4.0 workshop, PLC/MES/MOM, etc. need to realize the management and control based on AAS equipment, and adapt and analyze the AAS field information and status obtained based on IIoT-platform. DT needs to be integrated with IIoT-driven manufacturing system from the aspects of AAS-based data acquisition, manufacturing scene visualization and operation interaction, so as to realize the digital twin of workshop intelligent interconnection.

1.5. Automation ML-based web-twin kernel framework

The purpose of this framework design is to realize the granularity division and transmission of 3D manufacturing scene and solve the 3D manufacturing resource scheduling based on Web twin from the analysis of standard AML engineering files to the development of lightweight model library for I4.0 workshop. As shown in the Fig. 3.

This study takes AAS as the delivery core of the turnkey project, solves the equipment layer management and control driven by IIoT, and takes AML as the standard information description document of I4.0 workshop (the final delivery document). After years of technical development, AML standard protocol covers many aspects, such as geometry, logic, sequence, behavior, control, communication, MES/ERP-support. Web-twin framework based on AML is the core of system architecture implementation, which mainly covers three parts: Data analysis and integration based on AML (Analysis of standardized engineering documents), lightweight model library (Lightweight preprocessing of 3D resources based on web-twin) and User-interest-oriented granularity scheduling (User-oriented browser loading).

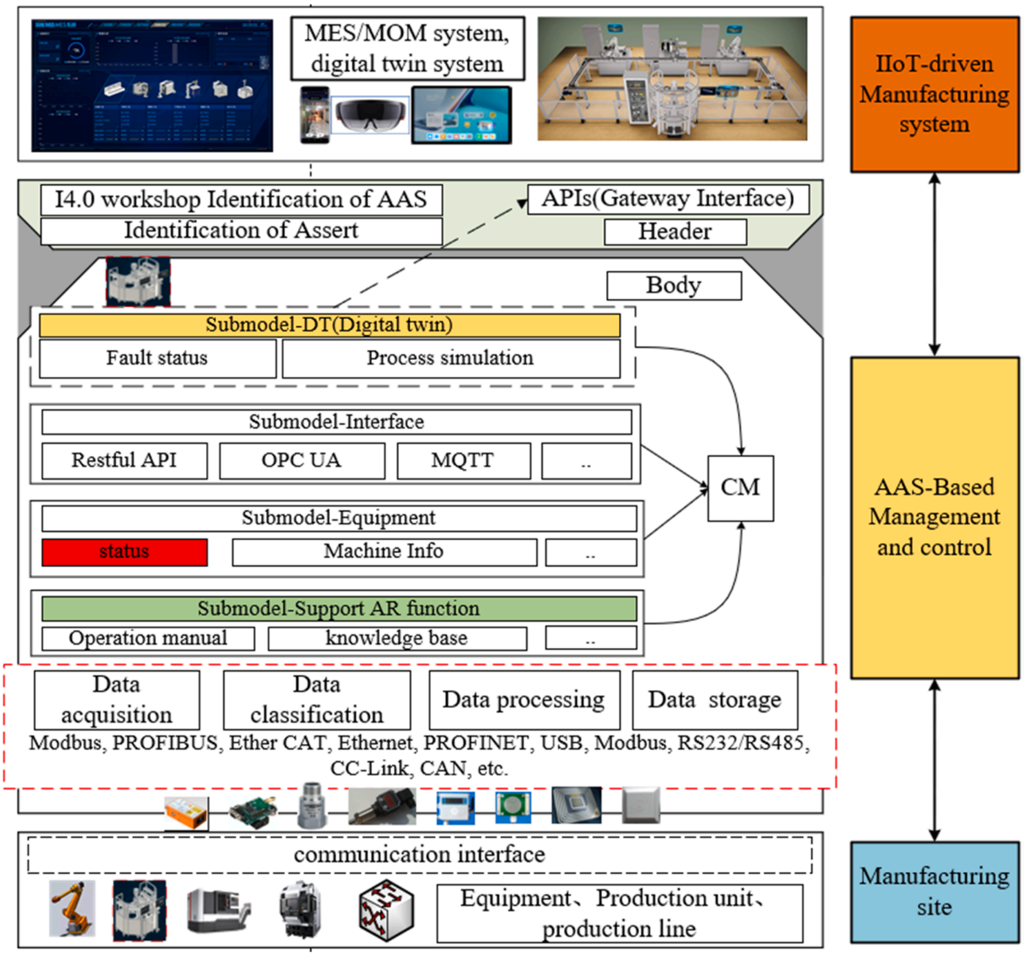


Fig. 2. IIOT-driven AAS modeling and management framework.

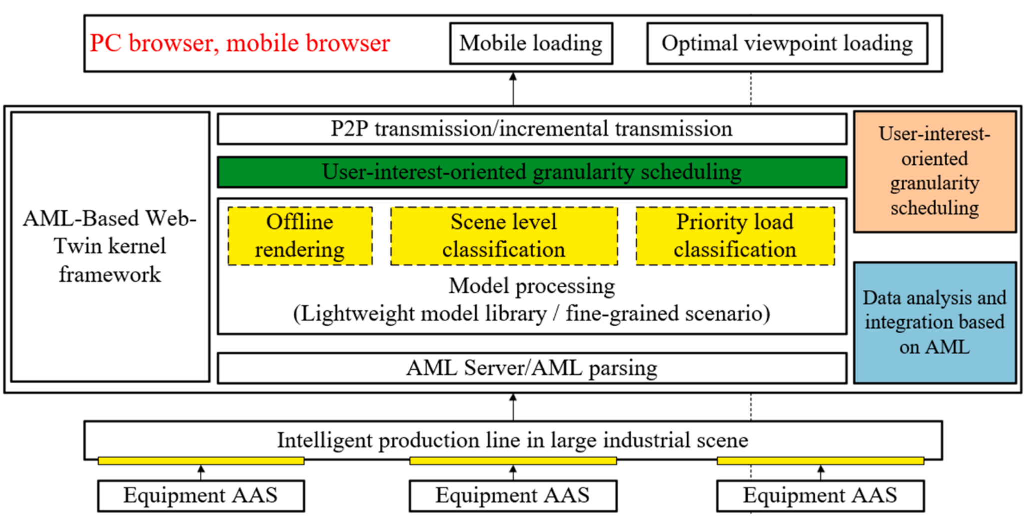


Fig. 3. Automation ML-Based Web-Twin kernel framework.

1.5.1. Data analysis and integration based on AML

It refers to the entity unit manufactured and operated in the whole turnkey process, including unit level, unit level and production line level equipment or equipment combination. Generally, when the manufacturer releases the equipment, it is necessary to model the basic information such as geometric attributes, motion attributes, physical attributes and control attributes of the equipment. At the same time, it supports users to monitor, calculate and analyze the actual evolution process of the equipment in real time. In a word, manufacturing site is the physical resources finally delivered by turnkey project (such as robot, AGV, Stereoscopic Library, machine tool, sensor, RFID, etc.).

In terms of data structure, The AML standard does not define any new file format, instead it defines how the sub-data formats are interconnected, CAEX according to IEC62424 forms the base of Automation

ML [29,30]. Object hierarchies in CAEX form the core of Automation ML. An CAEX object is a data representation of any asset, which can model physical assets, e.g., a motor, a robot; or abstract assets as a function block or a folder. On the one hand, CAEX allows these objects to be combined into systems, because each physical or logical system has the characteristics of internal elements, which may contain more internal elements, and all elements may have interfaces, attributes and connections with each other. On the other hand, CAEX also allows modeling of any plant topology, communication topology, process topology, resource topology, etc., which is compatible with the integration of other standards in the form of open inclusion. AML structure is expressed as follows:

✓ Object topologies: CAEX according to IEC62424
✓ Geometries and kinematics: COLLADA 1.4.1 and 1.5.0 (ISO/PAS 17506:2012)
✓ Discrete behavior: PLCopen XML 2.0 and 2.0.1
✓ Custom extension: Support MES/ERP and other function expansion description

As shown in the Fig. 4, for the I4.0 production line, the workshop information model based on AAS refers to RAMI4.0 implementation, including asset, integration, communication, information, function, business. For example, virtual assets will contain the digital information of equipment (such as FBX, STL, obj and other engineering models, dimensions, file formats, etc.); The communication layer includes the interconnection and interworking communication protocol between the equipment units of the production line (such as OPC UA); The logic control of the production line adopts PLC (e.g. Siemens plc-1200, etc.); For the and upper computer management system, it is necessary to analyze and support PLC/MES/MOM functions (such as station data acquisition, equipment fault alarm, production status, PLC-debugging, etc.).

1.5.2. Lightweight model library

Lightweight models have a wide range of requirements in the practical application of 3D models, whether in Web3D or PC loading. (a) Many scenarios do not need the details of the model. Lightweight models can be used to improve the loading speed of the model and reduce the cost of hardware; (b) Especially for the three-dimensional scene based on the Internet, due to the limited memory resources and bandwidth resources, not only loading, but also transmission and operation will bring users a very uncomfortable experience.

For complex manufacturing scenarios, in addition to manufacturing equipment and physical units of operation (such as unit level, unit level and production line level equipment or equipment combination), it also includes architectural scenes (such as office, storage room, floor, support frame, etc.), as well as relevant manufacturing elements (such as personnel, materials, workpieces, etc.). It is necessary to establish corresponding lightweight means and methods for different types. Due to the standardization of manufacturing units in the I4.0 workshop, establishing lightweight model library is a fast-technical means to realize the storage and retrieval of heavyweight models. As shown in the Fig. 5.

Scully and Dabo's et al. presents a novel open-source web-based 3D version control system(3drepo.io) positioned directly within the context of the recent strategic plan for digitizing the construction sector.3D-Repo is a new generation model library for version control, which adopts x3dom technology. And put forward the design idea of BIM (building information modeling) model library 3D-Repo. They use MongoDB as the model access medium to support online modeling and retrieval[31].

Aderhold et al. [32] Presents a technical route from implementation model to virtual display from the perspective of technical architecture, frameworks like the open-source system x3dom provide declarative access to low-level GPU routines along with seamless integration of 3D graphics into HTML5 applications through standardized Web technologies CIF (Common Implementation Framework, CIF). CIF allows the user to upload large 3D models, which are subsequently converted and optimized for web display and embedded in an HTML5 application that can range from simple interactive display of the model to an entire virtual environment like a virtual walk-through.

At present, in the research of lightweight model library, due to the standardization of the mainstream data conversion format IFC (industrial foundation class) as the source data format, many scholars and enterprises are building the process of component redundancy removal,

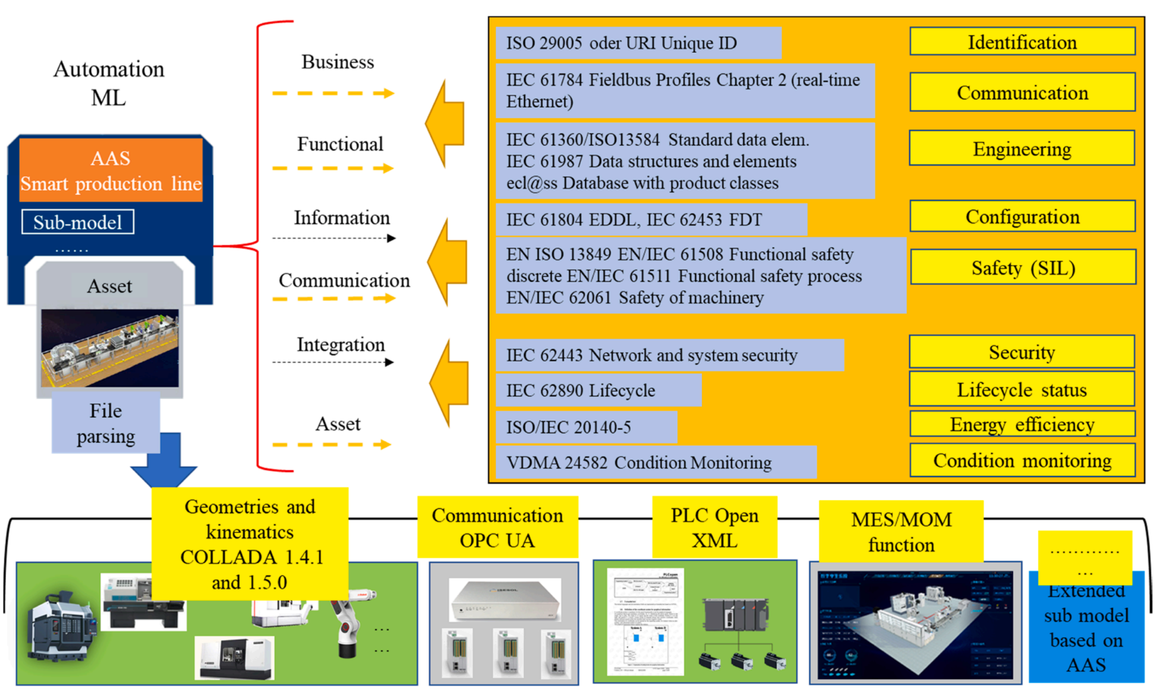


Fig. 4. AML-based modeling in I4.0 Workshop.

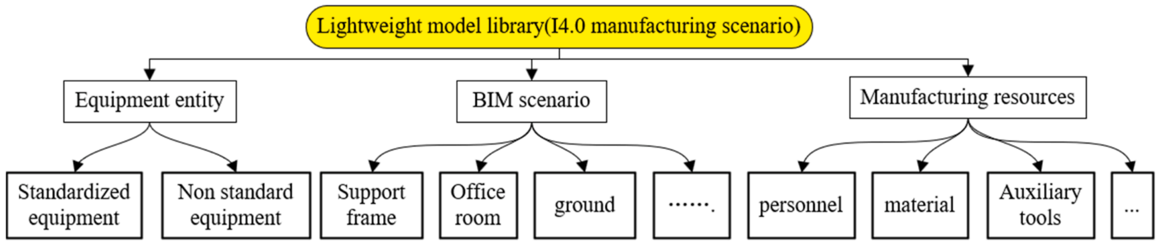


Fig. 5. Classification of lightweight model library based on I4.0 scenario.

aiming at the visual sharing, index construction and multi-granularity dynamic management of large-scale BIM scene under browser platform, which can realize the lightweight real-time roaming of mobile web pages in large-scale BIM scene. The lightweight model plays an important role in the engineering application efficiency of the system. Through the investigation of relevant research results, this paper analyzes the application requirements under the scenario of I4.0 workshop and constructs the lightweight library.

As shown in Fig. 6, by analyzing the application scenario of I4.0 workshop, this study designs the model library from the following points: (1) in the manufacturing workshop, the BIM environment is often not the most important, so it is completely simplified manually or downloaded from 3D-repo and other model libraries, and added to the model library after simple lightweight and rendering (For example, SP is used as an offline rendering tool in the experiment); (2) For the manufacturing scenario, AML describes the layout, 3D assets, unit combination, size, coordinates, PLC control logic, information model and functional model of the whole manufacturing scenario;(3)Refer to RAMI4.0 for I4.0 manufacturing scenarios technical framework, so the model library index is also designed according to the asset layer, integration layer, communication layer, information layer, function layer and business layer;(4)The final storage is based on MongoDB and adopts persistent storage. The browser loading adopts the local storage mechanism on the web side and is realized based on cloud-edge collaboration.

1.5.3. Interest-oriented granularity scheduling

Through the above links, the design scheme of IIoT-Based AAS interactive model and workshop service function integration, as well as the manufacturing scene model base under the I4.0 manufacturing semantics is determined. However, a bottleneck problem is how to transfer the lightweight model to the user browser. For large-scale manufacturing scenes, when actually roaming or displaying, users only observe some components of the scene at any time, that is, selective 3D mode. If all scenes are loaded and rendered according to the user's viewpoint information, it will bring serious waste of resources. Therefore, in the research scheme, we use the method of real-time calculating the priority of the user's visual component set, and only load and render the component model that really affects the user's vision, so as to improve the visualization efficiency from the user's point of view.

1.5.3.1. Bounding volume hierarchy tree. The BVH [33] is constructed for the overall model (In other words, BVH is a method for managing objects in 3D scenes), and the triangular patch of the model can be regarded as its basic unit. In building the index tree, there are two retrieval methods to build the bounding box of the overall model based on the basic unit: top-down and bottom-up. Starting from the components of the model, the bottom-up method first obtains the bounding boxes of all components of the model, and then obtains the large bounding box containing multiple components bounding boxes as the parent node of the above-mentioned multiple components according to

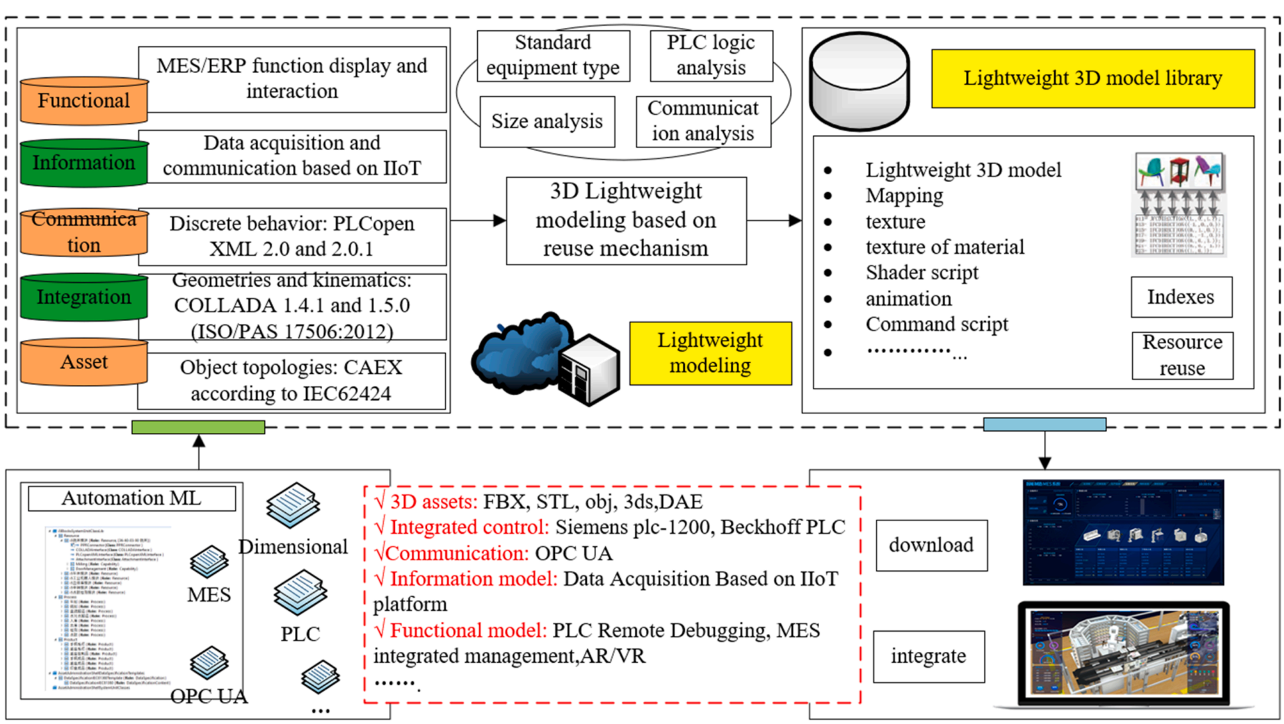


Fig. 6. AML-based model library management process.

the target of generating the smallest new bounding box. This recursion is done until there is only one bounding box left in the scene. This paper adopts the bottom-up method combined with a linear sorting algorithm, which can quickly build the BVH structure of the model at a low cost. After using this method to obtain the structure data, the model is finely segmented according to the leaf node division of BVH tree, which maintains the topology in the tree.

As shown in the Fig. 7. Before selective scheduling, we first need to know the hierarchical relationship and structure of the I4.0 Workshop. The scene segmentation method is based on the application of Web3D. For example, in the global browsing mode, the contour information of the scene needs to be loaded first; In the step-by-step roaming mode, you need to browse station by station, that is, stand in the first-person perspective to let users feel the actual operation of the scene; The specific station viewing mode needs to realize fine loading for any station specified by the user.

This paper generates the BVH for the model and saves its tree structure data. For example:$I4.0workshop_{B2HT} = \{SC_1, SC_i, SC_n\}$;That is, the manufacturing scenario of the entire I4.0 workshop is divided into independent functional sub scenarios, and then each sub scenario is constructed by independent components, for example: $SC_i = \{CM_1, CM_i, CM_n\}$; CM_i needs to be mapped one by one with the specific I4.0 component models in the lightweight model library, including model files, surface mapping files, texture maps, command script, etc. Then, the sub-model is indexed and segmented based on the BVH-tree data, and the local model file corresponding to the BVH-leaf node is generated. After the browser obtains the local model file, it can retrieve the surrounding transmission model according to the viewpoint, and then send the list of retrieval models in order through the following interest calculation.

1.5.3.2. Scheduling mechanism based on granularity. In the manufacturing-scene scheduling, the loading method from inside to outside was initially adopted, that is, starting from the contour and loading the internal scene synchronously, but it was found that the loading effect on the browser side was not ideal. Later, after many experiments, it was found that different component models in the scene have obvious differences in the user's vision, which is generally related to the filling degree of the model envelope, the reuse degree of the instance and the user's attention. For example, components with large volume and more pixels in the depth map occupy a large space on the screen, so these component models should be given higher priority in the transmission process, so as to better quantify the priority of each model in the transmission process; In addition, in the scheduling process, the same type of model only needs to be instantiated once; In addition, it is necessary to consider the number of user interactions with the model and the degree of attention paid to some models or scenes in local prediction.

On this premise, this paper introduces the concept of interest degree (ID) [26], which is related by filling degree (FD), reuse degree (RD) and attention degree (AD). Its purpose is to comprehensively consider the loading priority of any model in the scene, rather than simply using size or internal and external dimensions of space.

$$ID(m_i) = \alpha \times FD(m_i) + \beta \times RD(m_i) + \gamma \times AD(m_i)$$

Among $\alpha + \beta + \gamma = 1$; α, β, γ for each weight. These weights need to be adjusted repeatedly in the experiment, the control variable method is used, and the weight is increased/decreased by 0.1 or 0.05(for example in the experiment, we adjust it according to 0.1 every step, that is, there are ten choices at most for each weight, and there are 10 *10 *10 =1000 choices at most for three weights; If you follow step 0.5 to find, you need to try 2000 choices, but these are not bottlenecks for current computer operations).

Fill degree: FD is the ratio of the bounding box volume (BBV) occupied by the model to its file size, which is defined as:

$$FD(m_i) = \frac{V_b(m_i)}{S(m_i)}$$

Where V is the bounding box volume of the model; S is the file size of the model (Volume size); FD reflects the space occupied in the 3D space

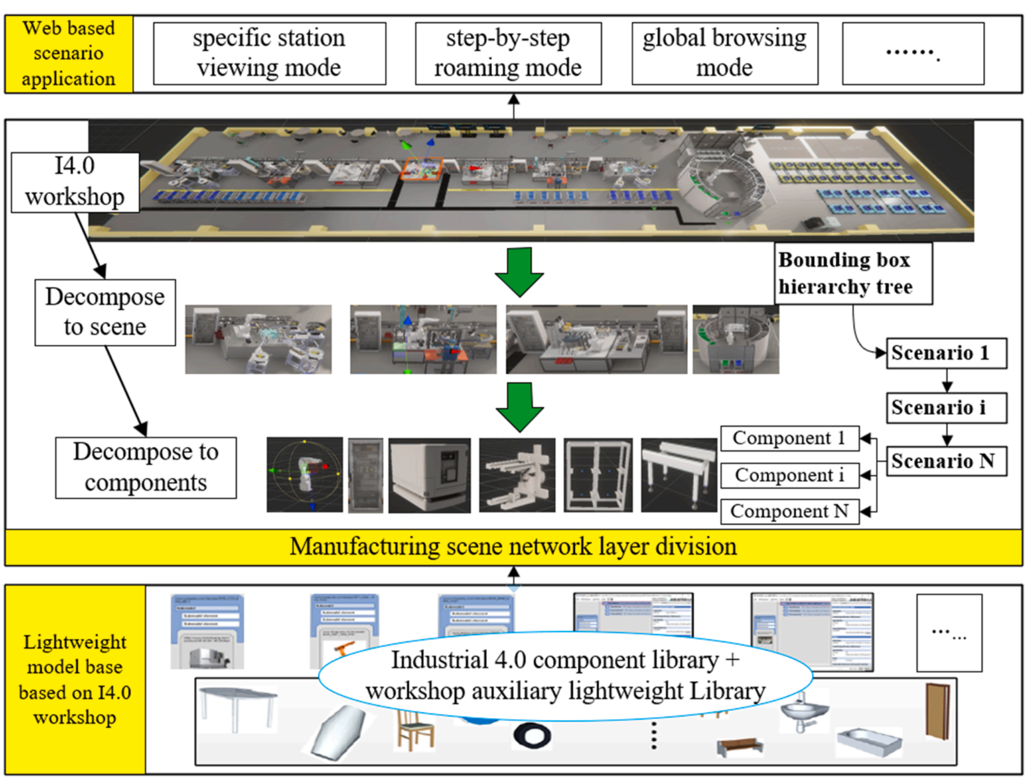


Fig. 7. 3D scheduling mechanism based on granularity in I4.0 workshop.

under the unit transmission consumption of the model. The larger the V and the smaller the S, the greater the impact on the user's vision, and the higher the transmission priority of the model.

Reuse degree: RD is the ratio of the number of instance components of the model to its file size, which is defined as:

$$RD(m_i) = \frac{N_b(m_i)}{S(m_i)}$$

Where N is the number of instances of the model; S is the file size of the model; RD reflects the number of repeated instances of the model in the scene under the unit transmission consumption. In the preprocessing stage of the scene, the instantiation information of the model can be generated by checking the repeatability of the model; In the rendering stage, if you can render all instanced models at once, the rendering efficiency of the model will be greatly improved. Therefore, the greater the number of reused instances, the higher the loading and rendering efficiency, the greater the RD, and the higher the transmission priority. For example, in the I4.0 scenario, each station has the same PLC control cabinet/bench, so the repeatability is very high, and it should be loaded first.

Attention degree: AD reflects the possible attention of users under the unit transmission consumption. The calculation formula is:

$$AD(m_i) = \frac{T(m_i)+N_b(m_i)}{S(m_i)}$$

Where, T is the type coefficient of the model; N is the statistical value of interaction times of the model; S is the file size of the model. AD considers the user's attention to the model in the scene, where T is the priority assigned according to the component type of the model.

Because different types of models have different degrees of impact on users' browsing. For example, in the manufacturing scene, the overall equipment has a great impact on users' intentional observation. Considering the similarity of users' interaction in the scene and browsing models, the impact of some pipes, screws and columns is relatively small. The ID of each specific model is further refined by calculating the interaction times between historical users and each model. The higher the ID, the higher the transmission priority and the better the user experience. Since ID is mainly used to quantify the priority of the model in the transmission process, the selection is based on the rationality of the model transmission sequence, that is, if more models with greater impact on the user's vision are transmitted within a certain time, it can be quantified by calculating the number of screen pixels occupied by all models after rendering in a fixed time. As shown in Fig. 8, relevant scholars [25,27] analyze the loading of interest. When the ID is sorted from high to low, the scene is shown in the overall loading, that is, the user will soon be able to see the overall effect and have a good experience; In other words, ID is the model that is expected to find the optimal loading by comprehensively considering the manufacturing 3D scene.

From the above analysis, it is not difficult to see that the ID based multi-granularity transmission scheduling mechanism used in this paper is based on S. in fact, ID represents the comprehensive loading index.

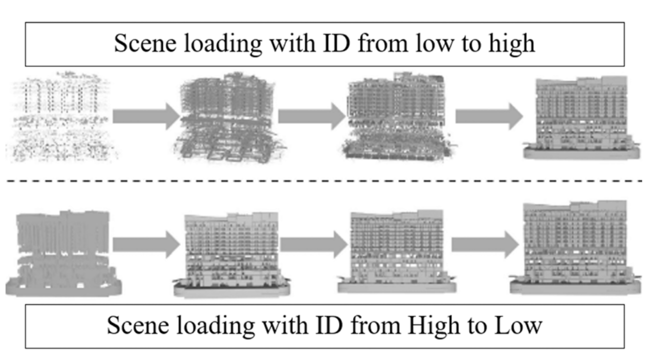


Fig. 8. Scene loading test effect under different ID.

The larger the ID, the higher the loading priority and the better the user experience. In fact, it is to divide the manufacturing scene into fine granularity in advance, and form an incremental form by calculating the value of ID. Then, through the calculation of the following links, the current bandwidth mode is detected based on the heartbeat service of the client and server, and the packaging size is calculated. Taking the complete loading process of the scene in a viewpoint update as an example, As shown in the Table 2, the specific process is as follows:

1.5.3.3. Transmission based on network adaptation. After establishing a reasonable resource scheduling strategy, we also need to consider the problem of network changes in practical application scenarios. Because each network Request/Response will consume certain network resources, if only one scene file is sent for each network Request/ Response, the front and rear ends need to interact frequently, which will bring a lot of additional network resource consumption to the file transmission of the whole scene. In order to minimize the waiting time of users, it is expected to transfer the most packaged model to the web browser in the shortest time in the low bandwidth network environment. Therefore, this paper uses heartbeat detection to judge the transmission speed to adjust the packaging strategy.

Transferring files by adapting to the network bandwidth is a widely used method to solve the problem of networking, especially to adapt to the mobile terminal. It can ensure the best experience of viewing viewpoint files from the perspective of users. As shown in the Table 3, Specific measures are as follows:

1.6. Web-Twin visualization integration framework of manufacturing system

Through two links IIOT-Driven AAS modeling and management framework and Automation ML-Based Web-Twin kernel framework, the conversion and integration of manufacturing scene and Web3D-based digital twin, as well as the lightweight of 3D resources, scene granularity refinement and classification, transmission compression are realized based on AAS as the work core in the I4.0 workshop. Finally, the user can quickly realize web twin in the dynamic manufacturing scene and access the scene through the browser mode. As shown in Fig. 9**.** This research is realized by studying two key technologies: IIoT-driven Manufacturing system integration, User interface control based on Web-Twin.

Table 2
Scheduling mechanism based on granularity in I4.0 workshop.

Num.	Specific process
1	The core of cloud work is to analyze the AML scene, lighten the model, map, material, bake to form a lightweight model library.
2	The edge layer is mostly the actual application site, and the model list (including model ID number, color number, map number, etc.) is obtained from the cloud lightweight model library.
3	The client side, that is, the browser side. When the user opens the browser, the web side and the edge side establish a data connection through WebSocket to realize two-way communication.
4	The edge terminal obtains the user's viewpoint information (camera position, orientation, etc.) in real time, which is used to synchronize the user's viewpoint at the edge-terminal.
5	The method of loading the current scene from the user's viewpoint is adopted, that is, the list of real and visible models under the current viewpoint is extracted according to the model comparison table, and the difference value from the list of visual models of the previous viewpoint is taken to the list of visual incremental models, which is the minimum set of models to be transmitted under the current viewpoint.
6	Calculate the ID of all models in the visual incremental model list, and then package it adaptively according to the user's bandwidth.
7	The web side loads the model data package transmitted by the edge side, parses and renders the corresponding scene through the above steps.

Table 3
Transmission based on network adaptation.

Num.	Specific process
1	The browser side of the user adopts the full duplex communication protocol of WebSocket. The client and server can carry out two-way message transmission, and then detect the current network speed of the user side by regularly sending heartbeat.
2	send a file packet of a certain size after establishing the connection between the server and the web browser, and calculate the bandwidth WB according to the transmission time.
3	By adjusting and setting the maximum packet transmission time T, the packet transmission size SP = WB * T under this heartbeat can be calculated.
4	The components in the previously obtained visual increment list are sorted according to ID, and then packaged and merged in turn.
5	Transfer the obtained packages in order.

Specifically, in the transmission link, for the server to maintain the resource index interface, provide the list of download URL and compressed file MD5 value. When receiving the resource request sent by the browser, parse the request URL and verify the file MD5 value. The browser adopts multi-threaded download to provide links, so as to speed up the download speed.

1.6.1. IIoT-driven manufacturing integration

Workshop manufacturing service is a collection of a series of service activities for workshop system management and decision-making. Including: workshop manufacturing execution system (MES/MOM), PLC control system, Workshop Kanban (Oder, equipment, production, etc.), AR/VR, PLC virtual real mutual control, IIoT-based data acquisition, etc. (1)Integrated with service system (such as MES/MOM system), the executive layer can realize 3D workshop digital roaming, production execution plan, equipment operation status and fault through web-twin based manufacturing system; The management truly shares the 3D scene through the browser to realize the order plan, equipment capacity, cost statistics, etc.(2) The workshop service integration scenario based on Web twin needs to be associated with the equipment layer (or AAS-layer) in real time, and the data of various types of sensors (such as Modbus, PROFIBUS, Ether CAT, Ethernet, PROFINET, USB, MODBUS, RS232/RS485, CC-Link, can, etc.) can be collected in real time through IIoT-data gateway.(3) Seamless integration with the manufacturing system mainly focuses on the application requirements of users. Configurable interfaces or functional modules can be provided for users to quickly build I4.0 virtual manufacturing scenarios.

1.6.2. User-interface control based on web-twin

For web-twin users, the rapid loading of lightweight scenes greatly improves the application experience. On the one hand, from the user's point of view, it can see as many scenes and models as possible within the viewpoint range, all users expect to select the initial loading position of the scene, that is, through the selection of the best initial viewpoint position and observation angle, so as to load as few data as possible and as many models as possible, and users can observe as many scene details as possible under this viewpoint; On the other hand, it can facilitate users to quickly operate and load views. Because 3D scenes can truly map the layout, running state and equipment parameters of physical manufacturing scenes, users often need to realize virtual roaming of Web scenes and virtual control of real operations.

Therefore, based on the above series of studies, in this link, as long as we maximize the loading field of view of the client, we can meet the final use needs, using the interest degree method for reference, visual viewpoint priority P, the visualization scale (S_v), scene reuse (R_v) and scene filling (F_v) are introduced here.

$$P = \rho \times S_v + \sigma \times R_v + \varphi \times F_v$$

among $\rho + \sigma + \varphi = 1$; ρ, σ, φ for each weight. These weights need to be adjusted repeatedly in the experiment, the control variable method is used, and the weight is increased/decreased by 0.1. That is to say, in the process of loading 3D scenes on the client side, according to the size of P, switch to the viewpoint of the browser through the camera, traverse the maximum P value, that is, the best viewpoint, and load the rest in turn. As shown in Fig 10 and Table 4. The steps of the optimal initial viewpoint search algorithm in this paper are as follows.

The visual scale (S_v) is the ratio of the data volume of all model files of the scene to the data volume of all visual models under this viewpoint. The calculation formula is:

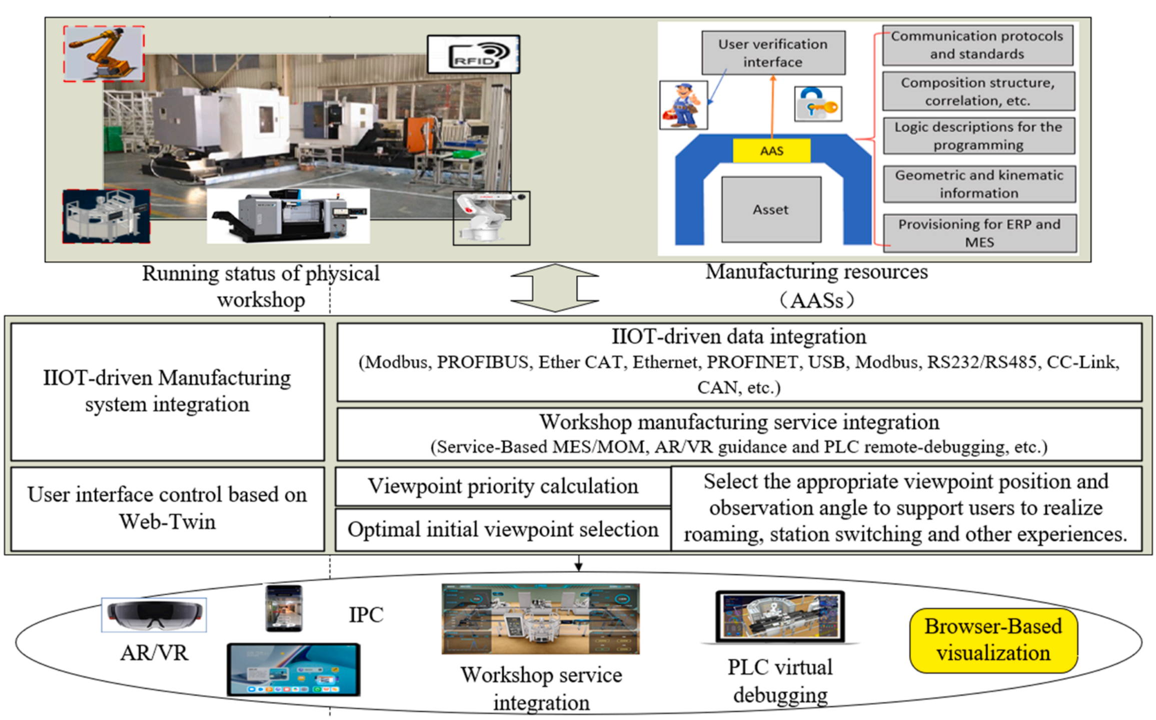


Fig. 9. Web-Twin visualization integration framework of manufacturing system.

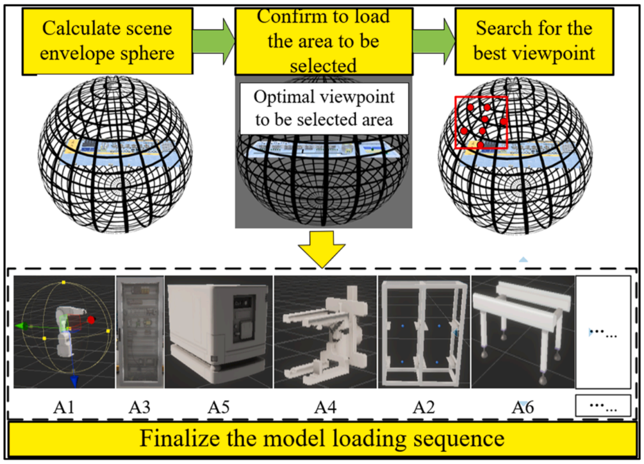


Fig. 10. Viewpoint calculation loading sequence.

Table 4
User-viewpoint control based on Web-Twin.

Num.	Specific process
1	Calculate the axis aligned bounding box (AABB) of the scene, and take the center of the bounding box as the ball center to calculate the circumscribed ball of the bounding box.
2	This paper takes the front of the scene as the priority display area, and further refines the area to be selected by dividing the quadrant area of the envelope sphere.
3	The optimal initial viewpoint search algorithm is used to calculate the optimal initial viewpoint of the scene.
3.1.	Calculate the priority of the points to be selected in the quadrant area in turn.
3.2.	If the priority of the next adjacent point > the priority of the current viewpoint, set the next adjacent point as the current viewpoint and continue polling.
4	According to the optimal initial viewpoint, the list of visual models under this viewpoint is calculated, and then the models in the list are sorted from high to low according to the degree of interest of the model, and finally the initial loading model sequence of the scene is obtained.

$$S_v = \frac{\sum_{i=1}^{N_v} S_i + \sum_{i=1}^{N-N_v} S_i^{'}}{\sum_{i=1}^{N_v} S_i}$$

Where, S_i is the data volume of visual model file; $S_i^{'}$ is the data volume of invisible model file; N is the total number of models in the scene; N_v is the number of visual models under this viewpoint; S_v reflects the proportion of the data volume of the visual model file under the current viewpoint. The smaller S_i, the greater S_v, the smaller the amount of data to be loaded by the viewpoint, and the higher the priority of the viewpoint.

The reuse degree (R_v) of the scene considers the ratio of the file size of the visual model under non-reuse (instantiation) and reuse under this viewpoint. The calculation formula is:

$$R_v = \frac{\sum_{i=1}^{N_v} U_i}{\sum_{i=1}^{m} U_i^{'} + \sum_{i=1}^{N_v-m} U_i}$$

Where, U_i is the original file size of each model; $U_i^{'}$ is the instantiation file size of the reuse model; M is the number of reused visual models under this viewpoint The instantiated model is de reprocessed in the preprocessing stage, and its instantiated file is relatively small. The higher the proportion of reused models in the current viewpoint, the lower the cost of model loading and rendering in the viewpoint, and the higher the priority of the viewpoint.

The scene filling degree (F_v) considers the size of screen space occupied by all visual models under this viewpoint, which affects the user's viewing details of the scene. The greater the scene filling degree, the more user's observable details and the more fully utilized screen space the calculation formula of scene filling degree is:

$$F_v = \frac{V + V^{'}}{V}$$

Where, $V^{'}$ is the space occupied by the model on the screen; V is the total screen space.

In the actual case application, this paper introduces three common application modes in scenarios, which is based on Web twin: Global browsing mode, step-by-step roaming mode and specific site viewing mode. According to the subsequent experiments, the core work of loading is to realize progressive loading of fine-grained scenes. Due to the different size of the scene, the visual range for users is different. As long as we can maximize the progressive loading of the first concerned scene and adjust the weight, we can meet the reasonable use requirements.

1.7. Operation, integration and implementation of system architecture

As shown in Fig. 11 and Fig. 12. Based on the design and development of the above series of system architectures, the Web3D digital twin application of manufacturing scenes under the I4.0 semantics is realized. The overall integration and implementation process is divided into the following three stages:

In the first stage, users will submit physical workshop engineering files based on AML document description. They need to go to the cloud-platform served by Web-Twin for file analysis, find and replace from the lightweight material library or carry out lightweight processing for specific model scenes, determine different accuracy and levels, and then generate BVH-tree to save its tree structure data. Then, the sub-model is indexed and segmented based on the BVH-tree data, and the local model file corresponding to the BVH leaf node is generated to form an incremental index file.

In the second stage, it is necessary to discuss the integration mode of workshop service system with the manufacturing workshop, access to the actual production line through AAS-based management and control mode, as well as the data acquisition, IIoT-Based interface interaction and mutual operation control mode, such as DT workshop Kanban through scene switching, or Service-Based MES/MOM, AR/VR guidance and PLC remote-debugging.

In the third stage, integrate the web twin service with the framework manufacturing service, and then publish the DT scenario through the service container. Users access it through the browser URL address. In the front-end loading process, the heartbeat packet is used to detect the user's optimal viewpoint range and current network speed in real time, so as to realize 3D scene priority incremental and network adaptive loading, and present the most manufacturing scenes to the user to the greatest extent.

1.7.1. Cloud platform Layer

The most important features of Web3D based on cloud platform technology are rich computing resources (accelerating rendering and distributed storage of 3D resources through software and hardware cooperation modes such as multi-CPU, GPU, ram and database) and service-oriented component capability (realizing service-oriented access to Web3D algorithms, models and materials, and realizing the value of Web-Twin as a service). (a) Automation ML Server: Analyze the AML standardized engineering documents provided by users to obtain 3D model information, PLC control logic, station position information, communication interface, etc.; (b) Model lightweight & Offline

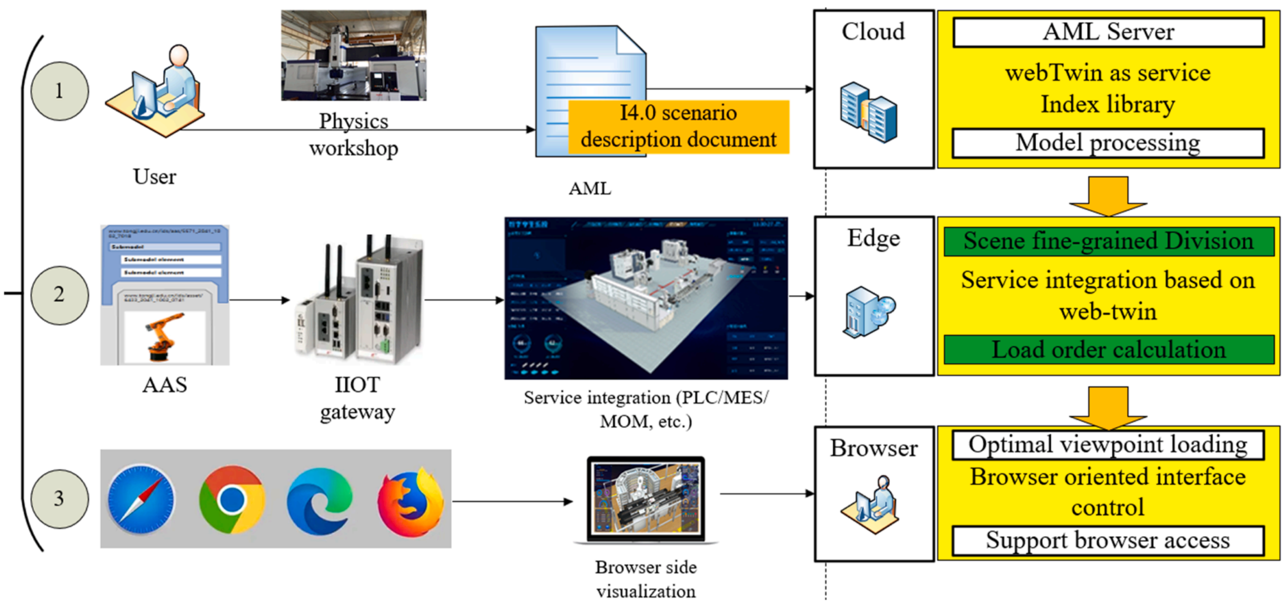


Fig. 11. Cloud-edge-browser I4.0 integration process based on web-twin.

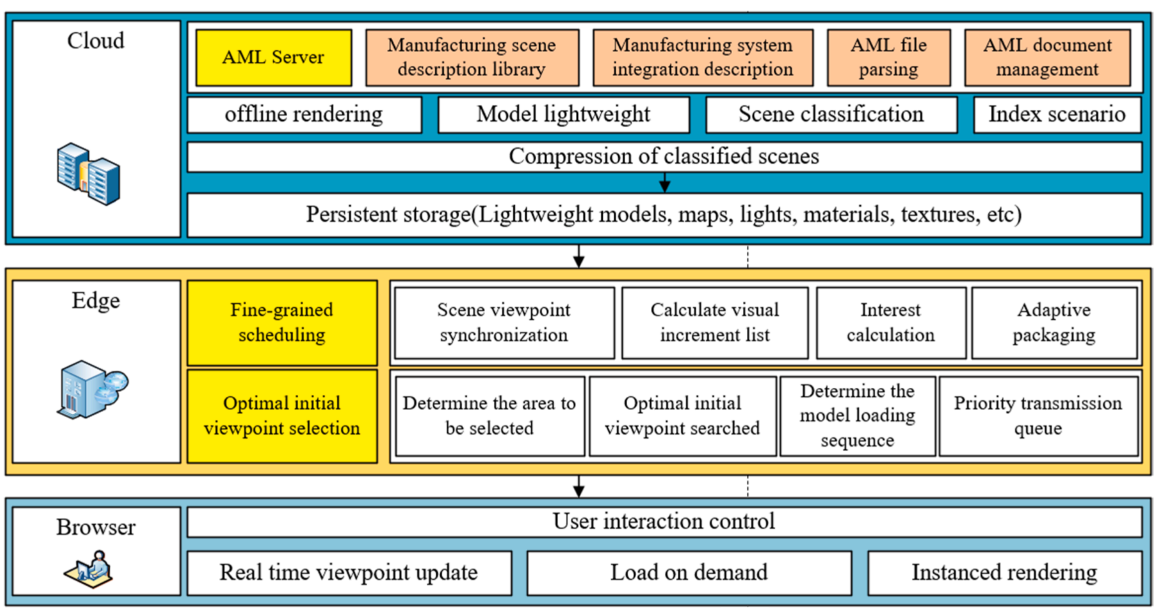


Fig. 12. Cloud-edge-browser application framework based on web-twin.

rendering: Lightweight the 3D model and add it to the lightweight model library. In the light processing stage, you also need to make maps and light rendering to realize the beautification of the 3D scene;(c) Build scene index: it provides a configuration interface, which allows users to package according to the importance of the scene through the arrangement of ID values;(d) Storage & Interface: provide persistent storage of interface calls and scenarios for workstations actually used at the edge. When you get an AML document describing a complex manufacturing scene, you first need to analyze the original scene based on AML semantics (including scene scale, scene space, unit relationship, component size, color, PLC logical relationship, etc.); Then analyze the model file (such as STL file of SolidWorks), and carry out lightweight preprocessing to reduce the amount of scene data in this paper, the model-based processing process is as follows: firstly, semantic and geometric repeatability are detected to remove redundant data; Then the scene is indexed by sparse voxelization, for example, the BIM-scene is divided into indoor and outdoor parts by using the inclusion relationship of voxels; Then, for the lightweight type that cannot be realized by the algorithm, conduct manual inspection. Because the workload is very small at this time, most of them can be obtained from the lightweight model library, and then the scene is segmented by using the adjacency relationship of each component in the voxel block, so as to establish the BVH index structure tree; Finally, the data of the model is compressed to further reduce the transmission volume (For example, compressed into RAR packets for transmission).

1.7.2. Edge layer

The edge end and the actual manufacturing workshop realize interconnection and interaction based on IIoT, so users need to realize function integration for the manufacturing scene based on DT, such as PLC virtual debugging, integrated MES management, IIoT-based data acquisition, etc.

The edge layer is the user's actual workshop service operation environment, which is generally inside the manufacturing workshop or can be extended to the IIoT-based cloud platform to realize the web-based access mode of engineers, managers and users. The edge layer needs to integrate the model resources processed by Web3D cloud platform into workshop services (such as PLC/MES/MOM), and collect data from the equipment layer through IIoT-based communication gateway or sensor, so as to realize the real-time mapping between Web3D and physical workshop; The web-twin server or workstation at the edge needs to realize multi-granularity scheduling and initial loading optimization Multi granularity scheduling processing is a real-time processing process. By synchronizing the user's viewpoint information, the user's real-visual model set is calculated and transmitted, which greatly reduces the amount of data to be loaded in real time. The multi-granularity scheduling processing process includes scene viewpoint synchronization, calculation of visual increment list, calculation of interest, adaptive packaging and transmission according to priority the optimal initial viewpoint selection is the optimization for the initial loading. By selecting the optimal initial viewpoint of the scene, the amount of loading data required for the initial visualization of the scene is reduced, and a good initial observation viewpoint is provided to improve the user experience of the initial loading of the scene the optimal initial viewpoint selection process includes calculating the scene surrounding sphere, determining the viewpoint to be selected area, searching the optimal viewpoint and determining the model loading sequence.

The addition of edge layer aims at the disadvantages of pure cloud visualization mode and pure browser visualization mode, in order to realize the requirements of functional collaboration, virtual real interaction, immersive inspection, 3D roaming and so on in large-scale manufacturing scenes. Pure-cloud mode puts all computing, rendering and other tasks in the cloud, and sends the rendering results to the web for display. Its rendering quality is excellent and is not affected by the hardware of the web, However, this mode has very high requirements for cloud hardware performance and bandwidth. It completely ignores the computing and rendering capabilities of web devices, resulting in a great waste of resources. In addition, providing real-time rendering by the cloud will inevitably bring serious rendering and transmission delay; Pure-web side mode puts all the calculation and rendering tasks into the browser side, and the browser side completes all the calculation, scheduling, loading and rendering. It has high requirements for the hardware performance of the browser side, especially for the mobile end equipment. Through experiments, it is found that the lightweight details of the model need to be handled very carefully, and there is no design of data compression, point-to-point transmission and other mechanisms at the edge end. When the scene is relatively large, Very Caton.

1.7.3. Web browser layer

Finally, through the above series of operations, the browser is responsible for the lightweight online visualization of scenes on Web pages, including real-time viewpoint update and user interaction control. For users, they need to use mainstream webgl2.0 browsers (such as Google, Firefox, etc.).

2. Case study

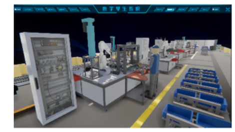
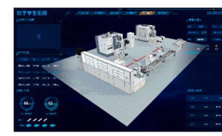
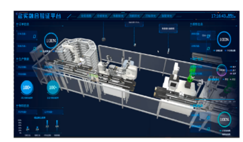
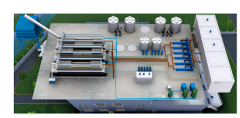
2.1. Case description

Since the system architecture studied in this paper is aimed at the Web-Twin mode in the I4.0 workshop, it is analyzed and illustrated by selecting multiple laboratories and practical industrial scenario applications.

2.1.1. Test scenario description

As shown in Table 5, workshop equipment (For example: manipulator, high-precision lathe, high-precision engraving and milling machine, mirror machining center, spraying machine, etc.) in the case are modeled according to AAS standard; AAS are interconnected and communicated through OPC UA. During project delivery, it is necessary to deliver the user's hardware list and AAS control software package (AAXS) at the same time.

Table 5
Web-Twin Visualization integration Test scenario.

Case	Scene description	Scene map
Case1	There are 15 stations in the manufacturing unit alone. The sum of all models is > 1.5 GB, and the total number of patches is > 8 million; In addition, there are BIM models such as architecture, which are almost impossible to load and roam on the web. Realize linkage control with PLC, virtual and real mutual control.	
Case2	The production line includes 11 stations: angle steel cutting machine, plate sticking welding, drilling machine, cooling, angle steel conveying, single limb handling and team formation, step welding, fishplate welding, single limb buffer grinding, assembly welding and discharge conveying, and is under the scenario of multi production line. The sum of all models is > 1.2 GB.	
Case3	The production line has 7–8 core stations, and the total volume of the model is about 500–600 megabytes. However, it needs very high rendering requirements and needs to be able to show the operation details of the station in the teaching and training. Therefore, it needs a large number of high-definition rendering scene diagrams to realize the virtual and real animation of the production line.	
Case4	Similar to case 3, it is a display production line with 7–8 core stations, and the total capacity of the model is about 1 GB. Need to be able to display the operation details of the site in teaching and training. Therefore, a large number of high-definition rendering scene maps are needed to realize the virtual and real animation of the production line.	
Case5	It belongs to the flow operation of different plant production lines, so there are many building models, which mainly display the information of key equipment. The total capacity of the model is about 300 M.	

2.1.2. Test environment construction

For the proposed architecture and technical path, in the selection of test environment construction, we select very mainstream software and hardware to ensure that this experiment can be adapted to all users based on Web3D to build DT workshop.

1) The edge end and browser end adopt PC configuration of conventional industrial application environment, w10 operating system, intel(R) Corei7–9750 H CPU@ 2.60 GHz, RAM 16 GB, NVIDIA GeForce GTX 1050.
2) The network bandwidth configuration is slightly lower than the actual application scenario, with a bandwidth of 100MB/s, and the client uses 4 G network.

3) Workshop-AAS is developed by Basyx open-source component library (AASX-Package-Explorer/AASX Server library) (https://github.com/admin-shell-io) [34].

4) On the software development platform, we use unity3d and 3DMAX engines as the real-time rendering engine of cloud back-end lighting map, and threejs based on webGL graphics library as the main Web3D rendering engine of Web front-end (that is, the browser needs to support webGL2.0).

5) To improve the fidelity of the digital twin scene, SP (substance painter 2.6) is used to make model material maps (such as normal map, bump map, etc.).

2.2. Case analysis

In the experiment, we mainly focus on the advantages of manufacturing system integration application in I4.0 workshop and the verification of performance indicators. In the I4.0 workshop, the integrated application with the manufacturing system covers many aspects, such as PLC-Debugging in the design stage, MES in the operation monitoring stage, AR/VR virtual operation and maintenance and fault guidance in the after-sales stage, etc. the system architecture establishes

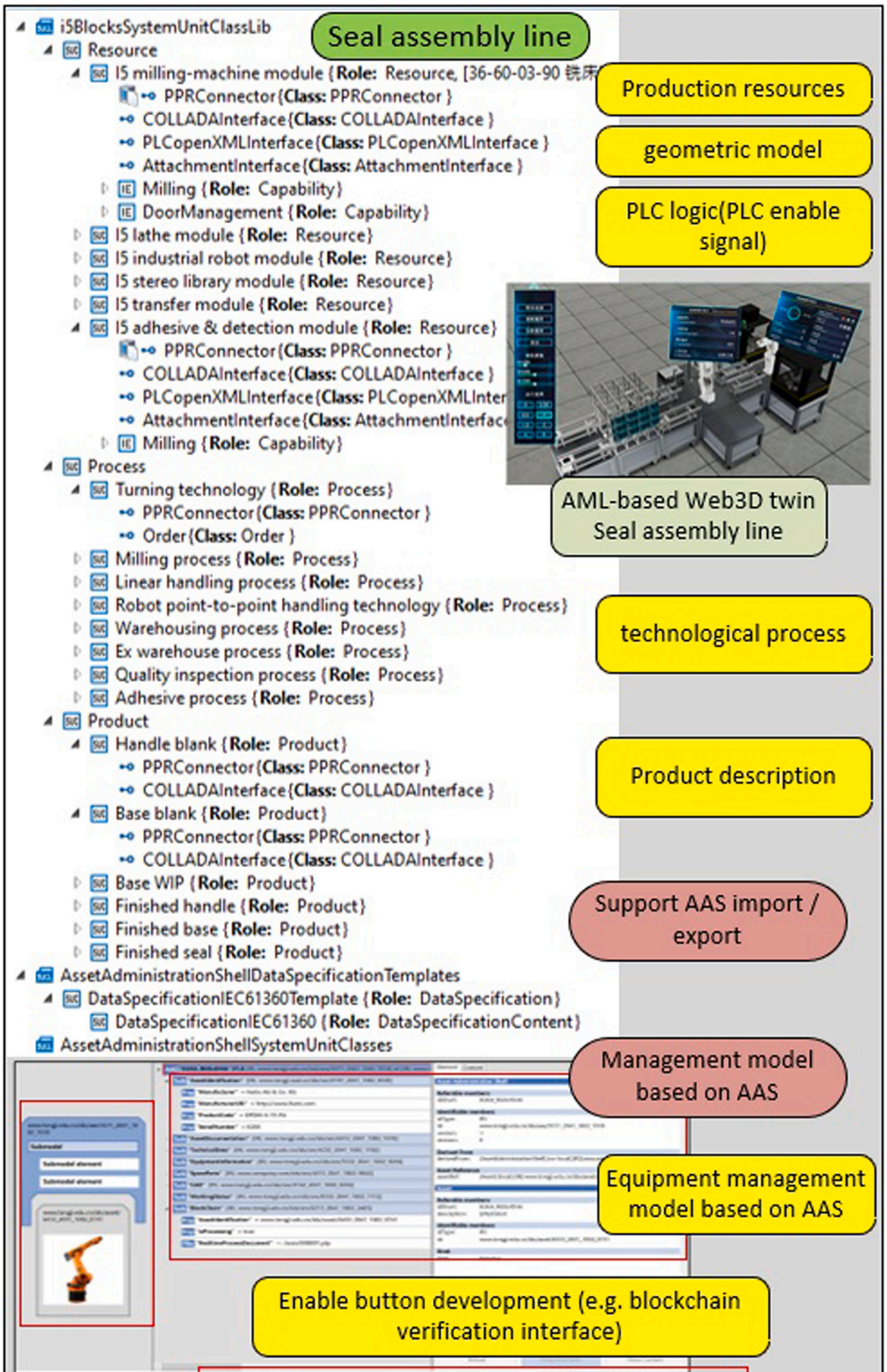


Fig. 13. Construction case of I4.0 workshop based on AML.

a comprehensive system solution from cloud-edge-browser, from AML design documents to DT scene reproduction, and then to the interface integration with multiple manufacturing systems, it adopts networked and modular deployment and implementation, supports the mainstream IIoT-platform technology, and through 3D lightweight, transmission, network heartbeat detection and web-based interest fast-loading of I4.0 scenes, users can quickly realize the construction of Web3D-based DT system.

2.2.1. System application analysis

The operation of the system is mainly aimed at the practical application of the current I4.0 workshop. Through the AML-based web-twin workshop, in terms of implementation, operation, integration, user access, it further realizes the intelligent upgrading of MES system integration, production PLC programming logic debugging, AR/VR virtual training, virtual remote operation and maintenance in the stages of design, operation, debugging, operation and maintenance, training, etc. As shown in Figs. 13 and 14.

2.2.2. IIoT-based data acquisition

The data collection and Web3D integration are realized based on the IIoT-gateway. The device layer takes AAS as the carrier of data collection and edge management. In this study, the AAS package adopts C# secondary-development, the manager is developed based on Java, uses Tomcat publishing service, and the turnkey team publishes the final installation package (AASX) to the cloud platform. Users log in to the platform through authentication, download and install specific versions, and send data to the IIoT-based Web3D Virtual display platform through the development of AAS interface. Through web page access, these features well meet the application requirements of Web3D, which is more convenient than other UE/unity-based desktop-deployment architectures.

2.2.3. MES system integration

Based on Web3D workshop, the MES system is integrated in 3D scenes through browser modes such as Google to restore the real workshop online anytime, anywhere. Users can roam DT workshop, PLC station, production monitoring, production warning, equipment failure, production capacity, planned production scheduling, equipment status, etc., so the network implementation and access requirements of MES are just consistent with the Web3D-based I4.0 workshop, which greatly reduces the difficulty of implementation and improves the management advantage.

2.2.4. AR/VR-based training and maintenance

As an important enabling technology, AR/VR currently faces the difficulty of insufficient terminal engine performance. Based on the advantages of Web3D workshop system architecture, the cloud-edge-end mode is adopted. Users can roam the lightweight 3D workshop through AR/VR glasses or apps, and super apply MES data, PLC control data, simulation data and other virtual scenes to real scenes. Especially in the remote guidance of networked implementation, users can see the overall/local/unit production status of the workshop according to their needs.

2.2.5. PLC virtual debugging

The value of PLC virtual debugging lies in that user can dynamically monitor the motion state, control state, fault state and early warning state of equipment in the debugging stage of 3D workshop, so as to realize debugging and troubleshooting in 3D dynamic scene. Through Web3D integration architecture and IIoT-gateway integration, different debugging scenarios can be lightweight to realize network deployment and debugging, and realize real remote debugging (For example, networked multi-person shared debugging).

2.2.6. Performance index analysis

It is very important for Web3D to achieve better access effect in the hands of users, so this paper tests and analyzes the two indicators of initialization loading speed and web refresh frame rate in the actual test scenario (The initial loading time refers to the time between the user opening the web page and completing the browser display model; The frame rate reflects the fluency of the user when roaming the scene. The higher the frame rate, the better the user experience. However, in the actual research, it is found that the stability of the frame rate also needs to be considered, so that the user feels smooth from the vision, so the following experiment is to give consideration to both). As shown in Figs. 15 and 16.

In addition, through the comparison and synthesis of other relevant cutting-edge academic achievements in the field of 3D visualization, it shows the feasibility of the system architecture. Through the investigation report of relevant experimental literature, we found no-relevant research on the Web3D architecture under the I4.0 manufacturing system, and the cutting-edge technical literature is mainly concentrated in the BIM field. As shown in Table 6, the relevant literature in BIM also proves the rationality of performance. When the lightweight model processing is not so reasonable, it can also stabilize the browser refresh rate of 3D scene at 30–35fps, the overall loading time also fluctuates

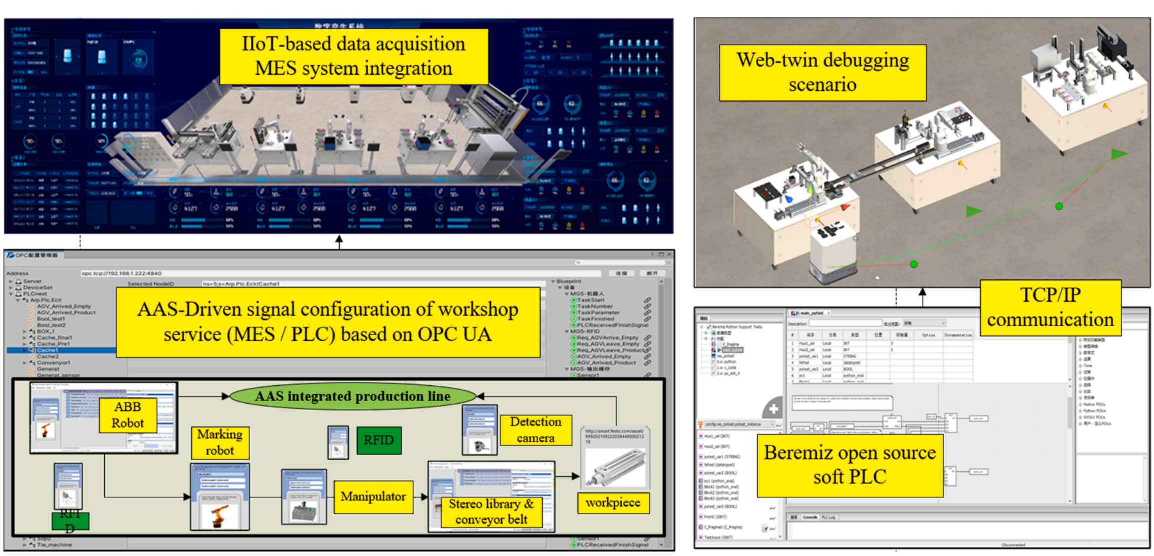


Fig. 14. AAS-Driven Workshop MES system/PLC-debugging case based on Web-Twin.

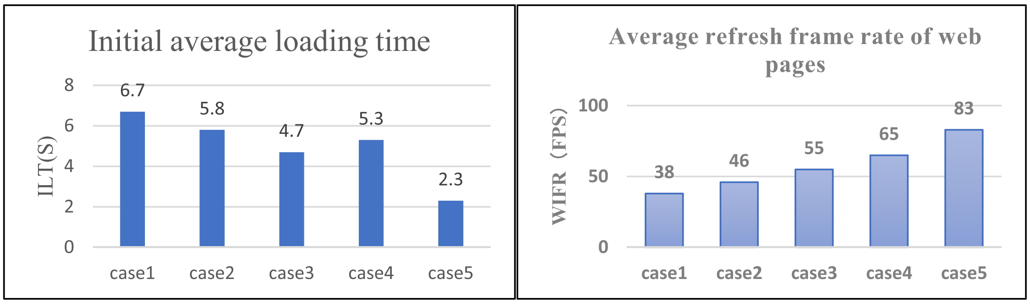


Fig. 15. Initialization load speed / Web refresh frame rate.

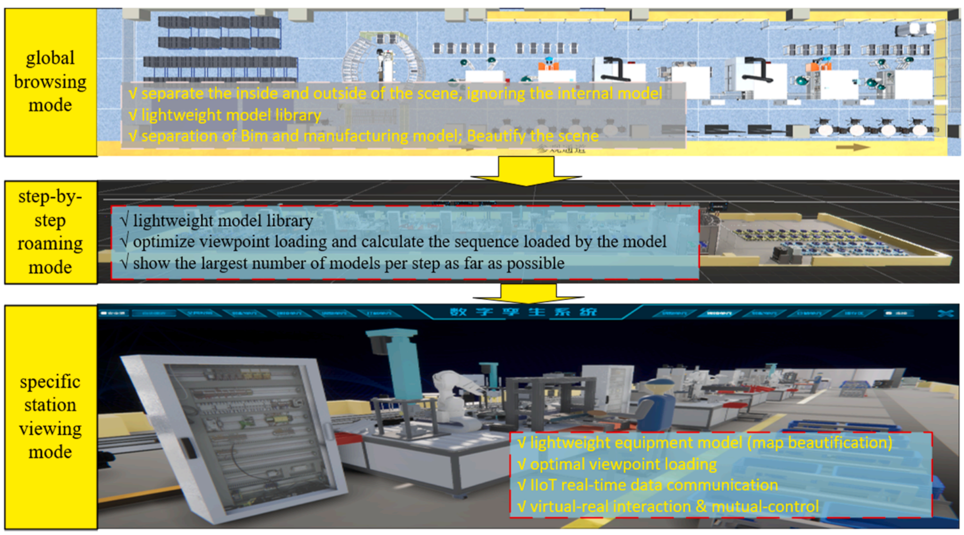


Fig. 16. Operation case of manufacturing system based on web-twin.

Table 6
Relevant cutting-edge academic achievements & experimental comparison.

Scene type	Scenario description	Comparative cases	IALT	FPS
Residential building (BIM)	The data volume is 120MB, and the number of patches is 1.98 million	Case5	5.3 s	30
Twin Towers BIM(BIM)	The data volume is 1.6 GB, and the number of patches is about 20million	Case2/case4	8.4 s	29
Cgm-Project-12 (BIM)	The data volume is 429MB	Case3	7.1 s	30
Large hospital (BIM)	The data volume is 2.2 GB, and the number of patches is about 33million	Case1	9.1 s	27

within 5–10 s[25,27].

This study has been tried in several I4.0 manufacturing workshops, and the average loading time is about 2–7 s (this is the full load time, but in practical use, progressive loading is realized according to the user's interest. In addition, it also includes maintaining connection with IIoT, interface instantiation, etc.). However, if it is the traditional pure web page loading mode, the average loading time is more than 15 s (Model + Map-package), and even web page collapse occurs frequently. In addition, from the perspective of user experience, it brings a smoother experience to the user through priority loading. The frame rate is kept at about 35–85fps (much higher than the basic requirement of 24fps), of course, the simpler the scenario, the better the performance. If the interference of PLC/MES/MOM integration is removed, FPS can reach a higher level in pure 3D scenes and basically meet people's visual needs. Therefore, the performance of the system has strong application advantages.

Through the above comparison, it is found that the overall performance of the system architecture we adopted is better than the technical route adopted in the cutting-edge direction. Of course, we have carefully compared the experimental conditions and found that the overall configuration of the computer we adopted is higher mainly in combination with the prevailing hardware conditions in the current industrial field (Ubuntu 16.04, Intel Xeon platinum 8163CPU, 23 GB memory, NVIDIA Tesla T4GPU, Network bandwidth 40 mb/s). In addition, the lightweight library of our model has been manually intervened, and the lightweight degree and artistic effect are better, this also has a very high impact on the overall loading performance. By constantly adjusting the size of the weight, it can present a variety of loading modes for different use conditions of users, such as global browsing mode of manufacturing scene, step-by-step roaming mode of first-person perspective and specific station viewing mode, so as to better solve the requirements of equipment control, fault alarm, MES management and so on based on DT integrated manufacturing system.

To sum up, based on the above research on the design, development, verification and implementation process of the system architecture, this study systematically answers the integration problem of the Web3D-based visualization framework for I4.0 manufacturing scenes: (1) Under the semantic environment of I4.0 workshop, the architecture design of manufacturing scene provides a theoretical and technical reference for the realization of I4.0 manufacturing scene based on Web3D; (2)Through the research and development of key algorithm models and technologies such as AML-based data analysis, lightweight resource library of manufacturing scene, user-oriented 3D resource scheduling strategy, and manufacturing system integration based on IIoT, it provides technical support for the design and implementation of system architecture; (3)Through testing and promotion in different practical engineering projects, this paper basically meets the final requirements of users in terms of technical indicators. At the same time, it also makes a horizontal comparison of relevant project research to prove the feasibility of the implementation of the scheme.

3. Conclusion

In view of the current situation that Web3D-based integrated workshop service in I4.0 manufacturing environment has not yet formed a unified system architecture, a Web3D visual integration framework based on AML is proposed. Through the establishment of IIoT-driven AAS modeling and management framework, AML-based web-twin kernel framework and web-twin visual integration framework of manufacturing system integration architecture, the rapid DT workshop construction of lightweight access engine (such as PC browser and mobile terminal) manufacturing system is realized. The design and development of system architecture contribute to the integration and application of Web3D-based DT system. However, it is found in the research that the following contents still need to be further discussed in the follow-up work:

(1) The theoretical research, development design and engineering application of I4.0 standard are still gradually improving. In this study, our case design is mainly aimed at the current mainstream requirements for DT workshop, such as workshop service system integration, PLC virtual-reality interactive control, AR/VR, IIoT-based 3D data collection, etc., the future DT workshop involves digital encryption (such as blockchain) and virtual workers based on digital agent, which puts forward more complex requirements for web-twin integration.

(2) Although from the current architecture design, the experiment on the scene with GB as the unit can fully support the integration requirements of I4.0 workshop manufacturing scene based on Web3D, it is found from the relevant preface that the future I4.0 workshop can realize the interconnection of all things, and some scholars[35,36] even put forward the DT-driven by big data, which is still a huge challenge in the web scene.

(3) Lightweight and highly realistic rendering of 3D scenes has always been a difficult problem in engineering practice, mainly because users have different aesthetic views, and it is too troublesome to completely manually lightweight. This paper combines BIM modeling standards, lightweight libraries of standard industrial equipment, and manual lightweight of non-standard equipment to meet the final industrial application needs. In the future, with the development of digital twin technology, fully realizing full-automation, modular configuration, accurately positioning user needs and high-fidelity DT system based on Web3D is the focus of research to improve the implementation efficiency.

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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