# A Life-cycle Digital-twin Collaboration Framework Based-on Industrial Internet

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**Research Article**

**Keywords:** Digital-twin modeling, Industrial Internet Identification and Resolution (I3R), Ontology modeling

**Posted Date:** March 25th, 2022

**DOI:** https://doi.org/10.21203/rs.3.rs-1457209/v1

# A Life-cycle Digital-twin Collaboration Framework Based-on Industrial Internet Identification and Resolution

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***ABSTRACT***

*While the new generation of smart manufacturing technology is enabling manufacturing upgrades, it is also making manufacturing systems increasingly complex. The integration of information and ontology across the full life cycle of a product involves multi-scientific and multi-disciplinary dimensions. It requires deep integration of industry chain alliance enterprises in the process of domain ontology sharing and digital asset collaboration to achieve efficient "new demand → existing ontology → innovation → new product → new ontology" agile manufacturing paradigm transfer. This paper presents a digital-twin and ontology collaboration framework based on the Industrial Internet Identification and Resolution System (I3R System). Taking flexible manufacturing systems (FMS) as an example, the four core key technologies required in this framework are described in detail: (1) A generic digital-twin modeling approach for the full life cycle of FMS; (2) Ontology for the full life cycle of FMS; (3) Real-time data collection technology for Human-cyber-physical system (HCPS) in smart manufacturing; (4) Distributed collaboration framework based on I3R. In order to illustrate in detail how the proposed methods and techniques can be applied in reality, we show different application scenarios based on the proposed methods and techniques in the various stages of the full FMS life cycle. At the same time, the implementation method of the I3R System-based digital-twin collaborative prototyping platform for industry chain alliance enterprises is discussed, as well as the idea of its derived top-level application.*

***Keywords*** *Digital-twin modeling, Industrial Internet Identification and Resolution (I3R), Ontology modeling*

## 1 Introduction

Smart manufacturing has enabled a fundamental business transformation of the traditional manufacturing economy, empowering a demand-driven dynamic economy where customers, partners and the public are key[1], while at the same time posing higher challenges for manufacturing: new products are increasingly demanding in terms of performance and quality, with faster product updates and smaller batch sizes[2]. In the 1990s, the Agile Manufacturing (AM) concept, proposed by the US Department of Defense, revolved around the concept of upstream and downstream enterprises in the industry chain combining innovative organizational and management structures, advanced manufacturing technologies (led by information technology and flexible and intelligent technologies), and skilled and knowledgeable managers in three main categories of assets, dynamically combined into a "virtual off-site collaborative team"[3] for a certain new product. Through the collaborative innovation and R&D of technology teams from different enterprises in the industry chain, the lean production capacity of each collaborating enterprise is flexibly mobilized to achieve new product development and manufacturing[4,5]. Due to the limitations of the information technology level and manufacturing production mode at that time, the in-depth collaboration and cooperation mode of cross-enterprise and cross-regional industry chain alliance enterprises did not receive wide attention or far-reaching development in time.

Digital-twin is a key technology in the field of smart manufacturing in the Fourth Industrial Revolution[6,7]. It implements a bidirectional mapping[8] between physical assets and Cyberspace objects, forming a digital-twin-object (DTO) of physical assets in Cyberspace. As shown in Fig. 1, RAMI 4.0[9] illustrates the asset-business relationships involved in each stage of the full product life cycle in Industry 4.0. Judgment, analysis, prediction and optimization operations at all stages of the full life cycle of a physical asset (concept[10], design[11–13], deployment, service[14], maintenance[15,16] through digital-twin-object[17] prediction, and optimization operations to enable feedback and interventions such as monitoring, simulation, verification[18], and dynamic optimization[19] of physical assets. Digital-twin-object (DTO), as a digital asset throughout the full product life cycle, enables collaborative management (creation, retrieval, recall, reuse, modification) between allied enterprises in the industry chain. To achieve this goal, the following 2 key enabling technologies are needed: (1) a generic ontologies digital-twin modeling approach for full life cycle, which can help industry chain alliance enterprises to achieve a unified, distributed and efficient digital-twin management of the full product life cycle[20]. (2) Covering the industrial chain manufacturing assets (physical assets and digital assets) identification and resolution system, it can realize manufacturing assets collaboration and management of cross enterprises, industries and regions.

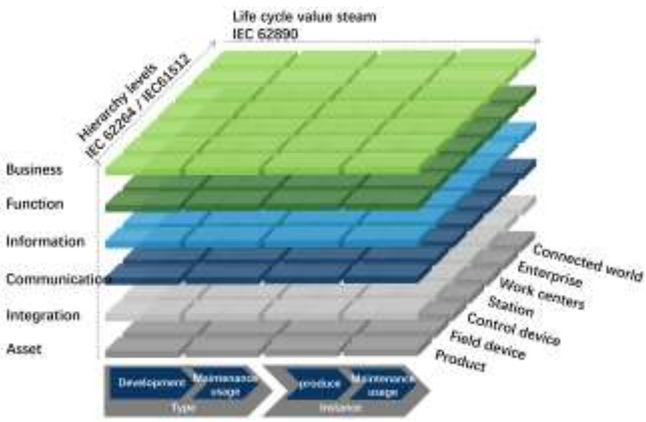


Fig.1 RAMI 4.0 asset management shell[9].

The digital-twin-object for the full product life cycle consists of two main types of digital assets: (1) the domain ontology to the model product; (2) the digital "experience" of the individual product during the manufacturing and use process, the digital-twin sample collection. The industry chain alliance enterprises extract new ontology of the digital-twin-object at different stages by analyzing the digital-twin sample[21].

The Industrial Internet Identification and Resolution ($I^3R$) system[22] is a key technology that emerged along with the development of the Industrial Internet[23] to achieve global unique identification coding and resolution of physical assets (machines, products, etc.) and digital assets (algorithms, programs, processes, data, etc.) [24]. In the process of cooperation among industry chain alliance enterprises, a large number of physical assets and digital assets need to be uniquely identified and coded to achieve information collaboration between teams and enterprises. The unified "Industrial Internet Identification and Resolution System ($I^3R$ System)" can reduce the credit risk of ontology sharing in the agile manufacturing model and increase the reusability of the digital-twin model in the industry chain alliance enterprises..

Flexible Manufacturing Systems (FMS), as a typical complex smart manufacturing Human-cyber-physical system (HCPS), is being favored by more and more manufacturing enterprises. Different sectors and industries have very different needs for FMS products. For the FMS asset management needs in RAMI 4.0 full life cycle process[25], this paper proposes a digital-twin and ontology collaboration framework based on $I^3R$ System to achieve digital-twin integration and domain ontology collaboration services in the FMS product manufacturing process.

The rest of the paper proceeds as follows: Section 2 provides an overview of current research and gaps in the fields of industrial internet identification and resolution ($I^3R$) and digital-twin modeling. Section 3 proposes a digital-twin and ontology collaboration framework based on $I^3R$; Section 4 delineates four key technologies to implement the framework; Section 5 describes the prototype implementation of the framework and a derivative application, with the final section summaries the main contributions of the paper and discusses future research.

## 2 Related works

To timely respond to the ever-changing market demand for new products, an effective digital-twin information and ontology sharing, distributed collaborative design, and the simulation optimization service platform for the full product life cycle are in urgent need for industry alliance enterprises. Digital-twin[26], smart manufacturing (ontology modeling) [27], knowledge graph[28] and $I^3R$ [29] have long been of interest to scholars and enterprises at home and abroad as key enabling technologies for the fulfillment of the platform.

### *2.1 Research of digital-twin modeling for smart manufacturing asset*

Prof. Grieves[30] 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, establishing mapping relations between physics and information. According to the level of data integration of digital-twin, Fraunhofer[31] put forward modeling theories on "Digital Model", "Digital Shadow" and "Digital-twin". Digital-twin modeling research in the field of smart manufacturing is one of the hot topics of interest for many scholars and companies. Lee[32] suggested a CPS digital-twin 5C-layered framework for smart manufacturing, and the five layers are a smart communication layer, a data-information conversion layer, an information layer, a cognitive layer and a configuration layer. Tao [11] discussed a 5D modeling concept, involving physical entity, virtual entity, service, digital-twin data and communication, which is applicable to smart workshops. Liu[33] brought up a system development method based on information-physical machine tools, and built an MTConnect-based information model to represent the logical structure of a machine tool and the real-time status of its component and processing process. Jiang[34] proposed a modeling approach for the rapid creation of virtual models and a mechanism for implementing a connection between a shop-floor level physical world production system with its mirrored virtual model. Lu[35] presented a practical method for easy virtualization of manufacturing assets, which constructs its digital-twin models for different layers of smart manufacturing system assets (i.e., component layer, device layer, production line layer and enterprise layer). In our early work[20], we further proposed the GHOST digital-twin concept around the "Digital-twin Data" dimension in the digital-twin five-dimensional modeling concept proposed by Tao[36], trying to meet the demand for multidimensional digital-twin modeling of the full life cycle of manufacturing assets in the new generation of smart manufacturing model (human-cyber-physical-physical system (HCPS))[37].

### *2.2 Research of ontology for manufacturing asset*

Ontology[21] was first created to be a philosophical concept used to study the existence and nature of entities, while avoiding the duality in "Metaphysics". An ontology is an existing systematic description of an objective. It is the abstract essence of the objective. Currently, "ontology" is an explicit formal statute for the conceptualization of sharing, which represents static ontology of a specific field[38] through classes, attributes, and the constraints between the two. Ontologies can be classified as domain ontologies, generic ontologies, knowledge ontologies, linguistic ontologies and task ontologies based on the theme of application[39]. Ontology is widely studied and applied in the field of smart manufacturing. Li[40] proposed an ontology triad definition for manufacturing task which includes the manufacturing task object ontology and the manufacturing task process ontology. It can express constraints or connections across object concept levels and categories, and thus enable ontology retrieval, recommendations and subscriptions. Zhao[41] combined Ontology Web Language (OWL) with dynamic description logic (DDL) as a hybrid logic description method for industrial robots to provide a semantic representation of the static and dynamic characteristics of sustainable manufacturing capability (SMC) and to segment the energy consumption of the industrial robot during its operation by the interval-state description method. For the early design and planning of manufacturing systems, Efthymiou[42] proposed an ontology -based framework to define, store and extract ontology based on former production process configurations. Ontology is extracted from the entire plant life-cycle digital-twin information through the virtual factory framework. Oriented towards manufacturing and assembly processes, Mikos[43] proposes the development of distributed ontology sharing and reuse systems in the Potential Failure Modes and Effects Analysis (PFMEA) area using ontologies based on description logic, which in turn enables ontology reasoning and retrieval. For the data generated by the workshop digital-twin system, Kong[44] proposed a workshop ontology model reflecting the workshop hierarchy and application characteristics, and verified the feasibility and effectiveness of the digital-twin system framework based on this model using tool wear prediction as an example. In the field of cloud manufacturing, Lu[45] proposed an ontology-based manufacturing asset and service description language to enhance the semantic interoperability of cloud service processes, thereby enabling asset virtualization and asset retrieval in the process of cloud manufacturing business collaboration. For re-manufacturing of manufacturing systems, Mabkhot[46] proposed an ontology-based multi-criteria decision-making approach that captures expert ontology through the use of manufacturing system monitoring and configuration ontology, which in turn enables decision evaluation of alternative configurations for manufacturing system reconfiguration.

### *2.3 Research of Industrial Internet Identification and Resolution*

An exponential growth in the number of industrial scenarios is now taking place[47] and the number of systems, devices and products in the manufacturing industry is increasing. Smart tracking of manufacturing assets (from orders for raw materials and sub-assemblies to product assembly, testing and distribution) can reduce the time required between value-added steps[48], improving the lean manufacturing capabilities of the enterprise and the efficiency of supply chain collaboration. Segura[49] investigated the feasibility of implementing an IoT tags system for the manufacture and assembly of crankshafts to read and write production data via embedded RFID-enabled bolts to capture, store and share manufacturing, assembly and service data within the plant. In order to realize the localization, tracking and monitoring of manufacturing assets in digital manufacturing workshops, Huang[50] proposed a real-time localization platform for various manufacturing elements in discrete manufacturing workshops consisting of RFID-based area localization and Ultra Wide Band (UWB) precision localization methods. Cao[51] proposed a framework for collaborative material and production tracking based on a supply chain view, which uses IoT tags and IT systems to collect material and production information in real time, enabling accurate material batch traceability and improving product quality management. Qu[52] proposed a method for driving Cloud Manufacturing (CM) execution systems through the response to real-time dynamics of IoT tags in the object layer. At present, individual enterprises have customized product coding systems, inconsistent descriptions and poor Operation ability[53], resulting in problems of collaboration and inconvenience in sharing digital assets among industry chain enterprises.

Therefore, although digital-twin and ontology modeling have received much attention in the field of smart manufacturing, there is a lack of research and discussion on modeling of products in the full life cycle dimension and in the context of a unified asset identification coding and resolution framework:

(1) Lack of research on digital-twin modeling under the Industrial Internet Identification and Resolution system. This has resulted in inconsistent approaches to digital-twin modeling and incompatible information among allied enterprises in the chain. It won't help facilitate the sharing and reusability of digital-twin information between enterprises.

(2) Very few studies have explored the relationship between digital-twin and ontology[44] from the full life cycle dimension. Due to the asymmetry in the professional fields of industry chain alliance enterprises, their respective "professional" ontology cannot be accurately and efficiently shared with upstream and downstream enterprises, thus increasing the credit risk of ontology sharing in the cooperation process.

(3) At present, although the application of asset identification based on internal enterprise standards has attracted much attention[49–51], there is a relative lack of digital assets with uniform tags for the smart manufacturing industry chain[28]. The redundant digital-twin and domain ontology management leads to inefficiencies in retrieval and reasoning.

In order to solve the above problems, this paper proposes a digital-twin and ontology collaboration framework for products based on the $I^3R$ System. By introducing the concept of ontology, our previously proposed FMS-oriented digital-twin modeling approach[20] is upgraded and the digital-twin-ontology relationship is investigated in a comprehensive manner. The limitations of the current specification for the encoding of industrial internet identification in the face of the digital asset description scenario of the RAMI 4.0 asset management shell are investigated, and corresponding solutions are proposed. Based on the $I^3R$ System and the identification and coding method of product digital assets (digital-twin and domain ontology) proposed in this paper, the implementation method of the digital-twin and ontology collaboration framework for the full product life cycle is further illustrated.

## 3 Framework of digital-twin based-on industrial internet identification and resolution

### *3.1 Digital-twin Hub framework based on industrial internet identification and resolution*

At present, more and more industry organizations, industry chain alliance and large enterprises are actively using industrial internet technology to enhance their competitive advantage in the process of upgrading smart manufacturing. The "$I^3R$ System" provides a unified global unique identity management platform for industrial assets (physical assets and digital assets) for a wide range of industrial enterprises and organizations: it enables the creation, retrieval, storage and recall of unified and standardized identity information, and provides an integrated management hub crossing industries, enterprises and regions alike for industrial assets through the full life cycle.

With the help of $I^3R$ System, enterprises and organizations can upgrade their internal informatization process identification management system: Registering physical assets (device, raw materials, components, products, etc.) with codes under the principle of unified industry norms, and building a digital-twin traceability system for the full life cycle of physical assets in the industry chain; registering digital assets (product ontology, algorithms, procedures, and operation and maintenance ontology) with codes according to the extended coding specification proposed in this paper to create and manage domain ontology, and then realize ontology collaboration among industry chain alliance enterprises.

Those industrial machine tool device products/production systems are characterized by the typical discrete agile manufacturing model:

(1) Variety of products.

(2) Agile manufacturing and customization of products.

(3) Clear division of labor in industry chain collaboration. The enterprises of the industrial chain alliance are involved in the manufacturing process of the different components of the products: cast beds, welded housings, major functional components (spindles, tool magazines, screws, guides, bearings), CNCs, servo drives, motors, etc. Few enterprises can complete the entire design and manufacture of CNC machine tools on their own.

(4) The full life cycle requires deep collaboration and cooperation among industry chain alliance enterprises.

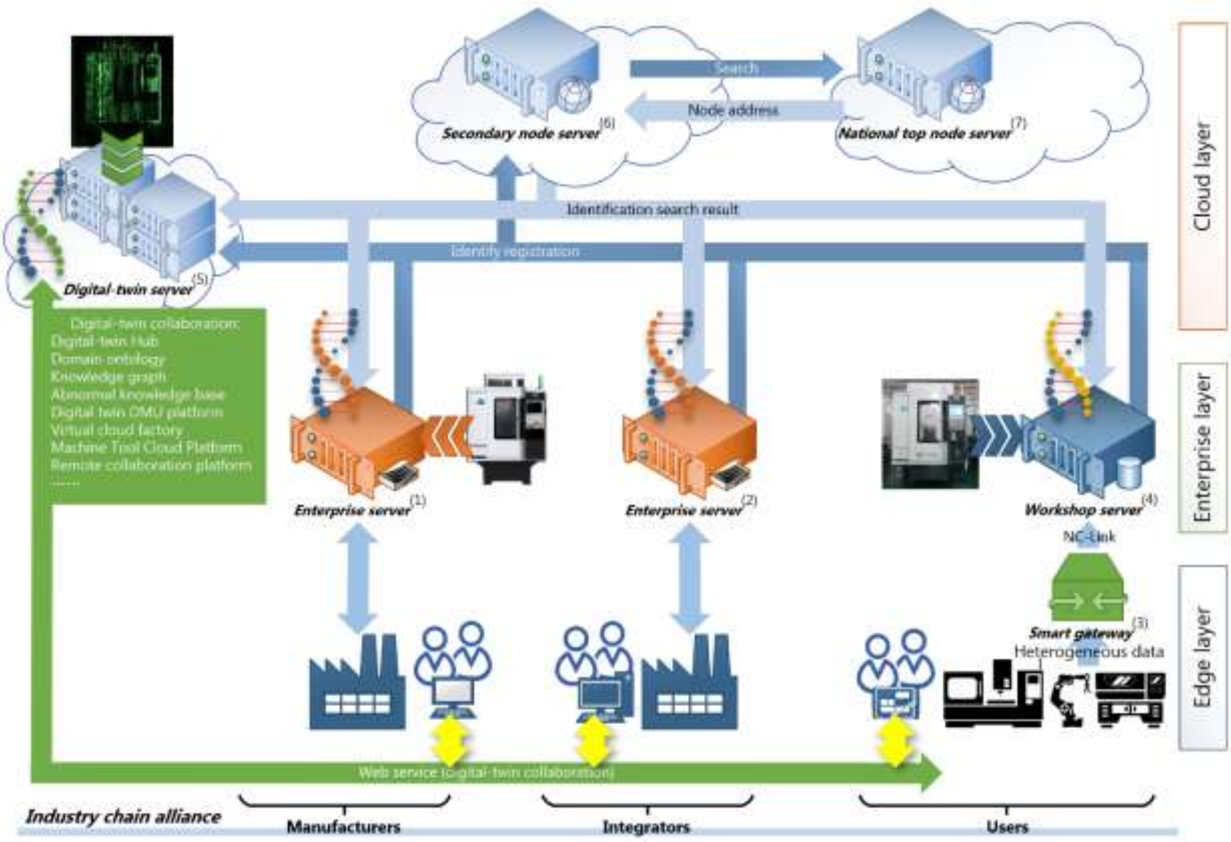


Fig.2 Digital-twin hub service framework based on industrial internet identification and resolution.

As shown in Fig. 2, the digital-twin integrated hub architecture based on the I$^3$R System organically intertwines the layers (edge layer, enterprise layer, cloud layer) and industry chain alliance enterprises through the I$^3$R System.

As shown in Fig. 2-(6) and (7), the Industrial Internet Identification and Resolution System (I$^3$R System) provides an identification and resolution management service for manufacturing asset objects, realizing asset identification registration, identification resolution, identification agent, data synchronization, business management, security management and other links and major steps (as shown in Fig. 3):

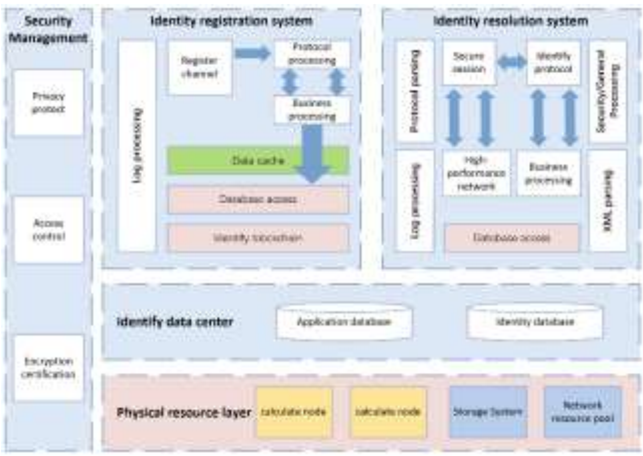

Fig.3 Functional modules of identity resolution serviced.

(1) The logo registration sub-system mainly provides services such as logo coding, logo registration and data query for product and device, and realizes logo management and query through an open API interface. (2) The logo resolution subsystem provides the service of logo coding retrieval and returns the access address of logo-related information. (3) The Marking Agent Service subsystem provides web-based data services. (4) The data synchronization sub-system guarantees users with a highly reliable and high performance data interaction. (5) The business integrated management sub-system realizes the task of opening up access to the $I^3R$ national top-level nodes and carrying down the task of enterprise logo allocation and auditing.

Product manufacturers and integrators (as shown in Fig. 2-(1) and (2)), add semantic domain tags to the digital-twin information of device product design, manufacturing and integration processes (the information that needs to be shared for collaborative cooperation in the industry chain) according to the rules of logo resolution, and register them in the "$I^3R$ System" to achieve the creation of domain ontology.

Generally speaking, the product domain ontology formed in the design phase is usually product model-oriented and is the generic ontologies domain ontology of the same model of device products; the domain ontology formed in the manufacturing and integration phase is usually individual device product-oriented and is the digital-twin ontology exclusive to the device. These static, domain-specific, explicit ontology assets are stored on the manufacturer's or integrator's own enterprise servers and can be retrieved, reasoned and reused via the "$I^3R$ System".

Fig.4 Smart gateway for Fanuc CNC and Siemens CNC.

When the device product is delivered to the user (as shown in Fig. 2-(4)) and put into service, the heterogeneous digital-twin information of its daily operation and maintenance status (device condition records, alarm experiences, maintenance records, repair records, etc.) is fused and unified through the edge smart gateway (as shown in Fig. 2-(3) and Fig. 4), and recorded in the user's workshop database. The access paths and service portals to the big data on the use of these devices are treated as digital assets, which are then given an "identity" and registered in the "$I^3R$ System". Manufacturers and integrators can retrieve the performance of device during service at any time by retrieving the "Domain Tag", which is an extension of the device 's product identification. The dynamic, invisible ontology enable big data analysis of the working conditions of the device, and improves the performance of the overall capabilities of the product.

In this paper, we proposed the full life cycle hub collaboration service (Fig. 2-(5)) to realize the above digital-twin and ontology collaboration of enterprises of an industry chain alliance based on industrial Internet identity resolution: the platform resembles Wikipedia in realizing the collaborative management of public ontology encyclopedia, which uses the information and ontology entries generated by industrial identity resolution to construct and manage the digital-twin and ontology archive of the full life cycle of an HCPS object with a specified identity.

The digital-twin hub archive of a specified HCPS object ($S_{\mathrm{a}}$) is expressed as Equation (1). Where the set of digital-twin and ontology lexicon of this object individual ($S_i$) is denoted as Equation (2) and the set of digital-twin and ontology lexicon of this object common ($S_{\mathrm{c}}$) is denoted as Equation (3).

$$S_{\mathrm{a}} = \{S_i, S_c\} = \{individual[e_{I^3R}], commality[e_{I^3R}]\} \tag{1}$$

$$\begin{aligned} S_{\mathrm{i}} = \{S_{ot}, S_{ar}, S_{sv}, S_{ar}, S_{mr}, \ldots\} = \{&owner\_traceability[e_{I^3R}], assembly\_relation[e_{I^3R}], \\ &status\_veiw[e_{I^3R}], alarm\_record[e_{I^3R}], maintenance\_record[e_{I^3R}], \ldots\} \end{aligned} \tag{2}$$

$$\begin{aligned} S_{\mathrm{c}} = \left\{S_{ps}, S_{pi}, S_{pf}, S_{rd}, S_{ta}, \ldots\right\} = \{&product\_summary[e_{I^3R}], product\_introduction[e_{I^3R}], \\ &product\_family[e_{I^3R}], related\_document[e_{I^3R}], top\_application[e_{I^3R}], \ldots\} \end{aligned} \tag{3}$$

The $e_{I^3R}$ in the above set of formulas (formula (1), formula (2), formula (3)) denotes the digital-twin and ontology lexicon resolved by a specific industrial Internet identity.

From the formula, we can see that the digital-twin and ontology files of HCPS objects are comprised of a set of personalized entries and a set of common entries. The set of personalized entries includes experience traceability, assembly relationship, status review, alarm records, maintenance records and other target individual twin data and ontology, and these entries are set up with relatively strict access management privileges; the set of common entries includes product summary, product basic ontology, product family in which the product is located, related documents, compatible top-level applications of shared entries for the same model and the same type of object, and these common entries are publicly retrieved, reasoned and reused.

The access rights of each entry in the archive are managed by the industrial Internet identity resolution system. Since this digital-twin and ontology archive system is collaboratively managed and improved by the cooperative enterprises in the smart manufacturing industry chain, it improves the domain coverage and coupling degree of the digital-twin and ontology of the full life cycle of the target object and reduces the trust risk of ontology sharing when the alliance enterprises cooperate in agile manufacturing.

### *3.2 Implementation of Industrial Internet Identification and Resolution*

As shown in Fig. 5, the manufacturing asset identifier is recursively resolved to enable information retrieval. Recursive parsing iterates through the responses returned by the authoritative parsing server until the enterprise application data is finally queried, which is then returned to the client, and the request results are cached locally.

Marking recursive parsing processes:

(1) The application initiates a logo query request to the $I^3R$ System's recursive resolution service system via the client.

(2) After receiving the request, the recursive resolution service system analyzes the query request from the client with its message being Handle or DNS protocol and sends a resolution query request to the national top-level node.

(3) The national top-level resolution service node system returns the address information identifying the secondary resolution service node.

(4) The recursive resolution service system continues to initiate query requests to the identification secondary resolution service node based on the results returned by the national top-level resolution service node system.

(5) The identity secondary resolution service node returns the result data to the query requester, and the recursive resolution service system obtains the address information of the enterprise resolution system for the identity.

(6) The recursive resolution system initiates an identity lookup request to the former address.

(7) The enterprise resolution system receives the request and returns the enterprise storage data.

(8) The client links to the corresponding information based on the identification enterprise application data returned by the recursive parsing service system.

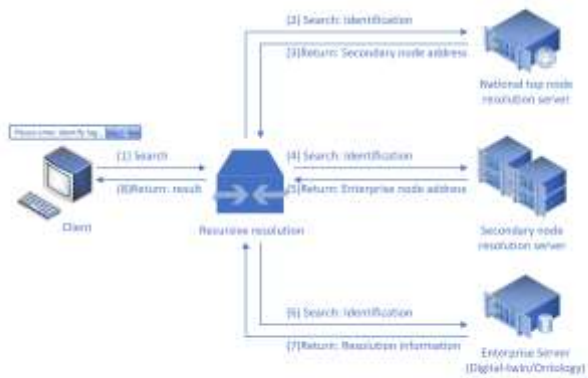


Fig.5 Recursive identification of industrial internet identification.

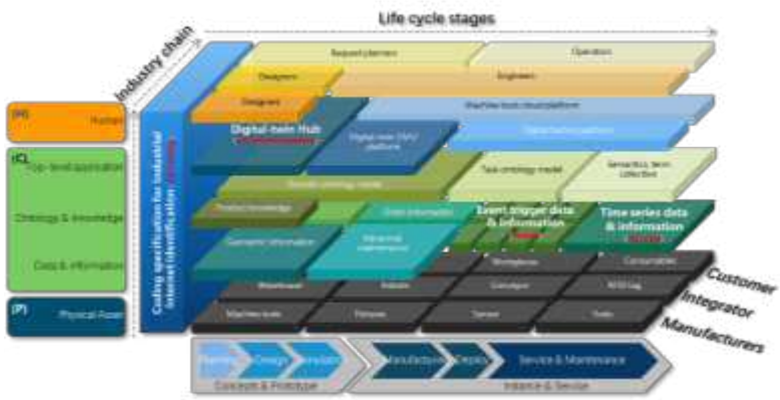


Fig.6 The relationship between modules in the digital-twin collaboration framework.

## 4 Key technologies

Based on the service framework depicted in Fig. 2, we propose the relationships of the modules in the framework shown in Fig. 6. Due to space constraints, four key technologies (shown in Fig. 7) are selected from the many modules of the framework and are detailed below:

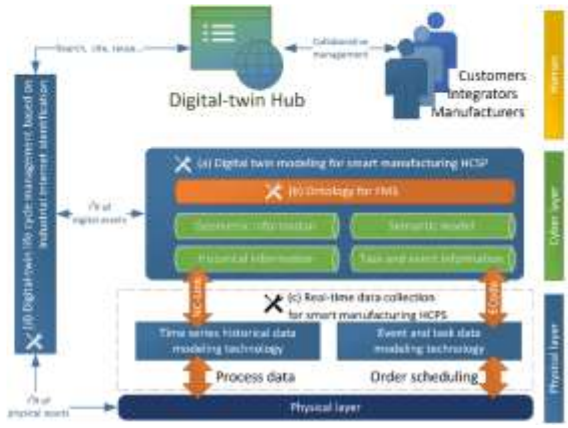


Fig.7 Four items of key technologies in the framework.

***4.1 Digital twin modeling for smart manufacturing HCSP***

Under the industrial revolution in the new era, a new generation of smart manufacturing technologies is gaining widespread attention and application. Digital-twin is a key enabling technology in the field of smart manufacturing. There is no unified digital-twin description method to meet the needs of digital-twin modeling of complex manufacturing HCPS (e.g., FMS) in the collaborative process of industry chain alliance enterprises. In the face of the rapidly changing requirements of the parts processing market, it is particularly necessary and urgent to propose a digital-twin descriptive modeling approach that is applicable to FMS manufacturing supply chain alliance enterprises and meets the full life cycle of the FMS. Based on the "life-cycle value stream" of enterprise assets described by asset management in RAMI 4.0, and based on the GHOST digital-twin description modeling method proposed in our previous research[20], we propose a digital-twin description modeling of manufacturing device based on the $I^3R$ framework method (Fig. 9-(a)), as follows:

$$iGHOST_{I^3R}(identity_{I^3R}) = \{G_{dt}, H_{dt}, O_{dt}, S_{dt}, T_{dt}\} \quad (4)$$

① $iGHOST_{I^3R}$ represents a digital-twin information set based on the $I^3R$ framework for organizations in all stages of the full FMS life cycle (industry chain alliance enterprises, integrators, users, re-manufacturing users, etc.). This set of information describes the conceptual planning, design development, simulation testing, manufacturing deployment, production service monitoring and maintenance of device assets (machine tools, tools, fixtures, workpieces, etc.) in the different phases of the manufacturing device life-cycle, as well as the re-manufacturing process in terms of identification rules, process capabilities (scheduling information), logic rules (PLC), functional behavior and operational status, domain ontology, etc. This digital-twin modeling description information can provide digital-twin data for the collaborative development of industry chain across enterprises in the full life cycle of manufacturing device, virtual production platform, planning and design simulation DMU platform[20], digital workshop platform for production enterprises, and machine tool Big Data maintenance guarantee platform.

② Identification of asset ($identity_{I^3R}$) refers to a unique identity for the full life cycle of manufacturing assets as defined by the $I^3R$ specification (national industry standard). Asset identifiers can represent not only the physical identity of the asset, but also digital asset information (e.g. control procedures, algorithms, domain ontology, etc.). The digital-twin (G,H,O,S,T as mentioned below) assets and their identifiers are constructed in different areas of the full product life cycle and registered to the "$I^3R$ System", which is a recursive resolution service system (as shown in Fig. 4), enabling a multi-domain, life-cycle-oriented and digital-twin distributed collaboration platform (shown in Fig. 5).

③ Geometric information ( $G_{dt}$ ) refers to the geometric information of physical assets [54]. This information realizes the modeling description of physical spatial information. Data is constituted by FMS device models, mechanical parameters, geometric features and other appearance-related structural elements. Examples also include DMU model libraries (smart machine tools, industrial robots, smart warehouses and AGV), gripper specifications, parameterized connector information, and CAD models for fixtures.

④ Historical samples ($H_{dt}$) refer to information that changes during the production system service. This information describes the continuous change process of some attributes of the object. Data is submitted by the smart device such as the CNC of a smart machine tool, the controller of an industrial robot, and various heterogeneous sensors. It's transmitted to the workshop manufacturing system via a smart gateway (in Fig. 2 -(3)) and the digital-twin server in the cloud. In most cases, historical samples include characteristic information on device behavior and status (e.g., position, command, status and temperature) and the exact acquisition time, such as the position of a smart machine tool, feedback position, motor servo current, cutter information and G code.

⑤ Ontology (($O_{dt}$) refers to an objective distillation of the logical ontology of the domain of expertise of the description object (as shown in Fig. 7). An ontology model consists of entities, which include classes, data attributes, object attributes, data types and individuals[44]. Domain ontologies are explicit, shareable, reusable[55] and are widely used in the domain ontology modeling process for smart manufacturing systems[56]. The ontology digital-twin description is achieved through domain modeling of model products.

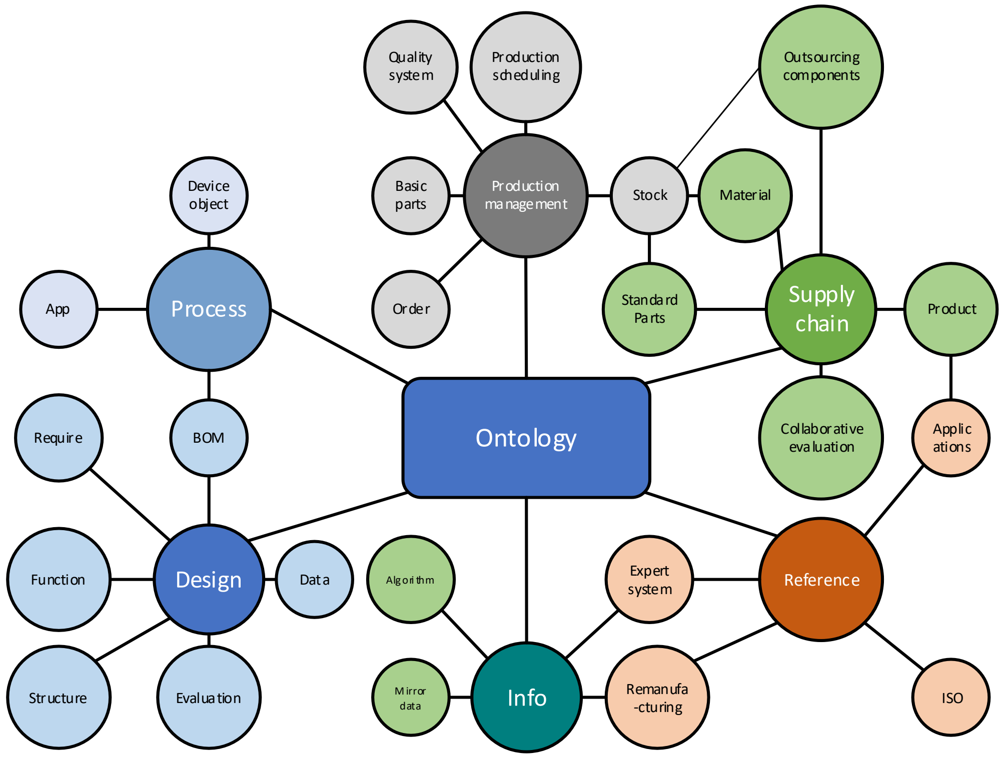


Fig.8 The multi-dimensional ontology expression model of FMS.

⑥ Semantic collection ($S_{dt}$) refers to a collection of domain terms recorded in each phase of the device 's full life cycle, and combined with  asset identification information. It enables more digital-twin information and domain ontology to be coupled and managed, improving the efficiency of computer analysis of digital-twin models, matching domain ontology and extracting new ontology.

⑦ Task model ($T_{dt}$) is designed for the discrete production model of smart manufacturing device and records information on the dynamics of discrete events in the service process. Based on the

Perti network, the task ontology is constructed to enable the modeling and management of work orders, production plans and other management scheduling information.

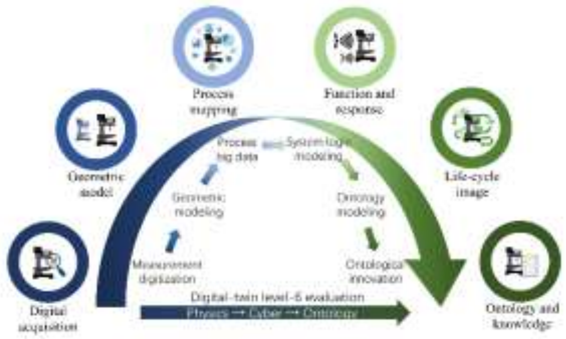


Fig.9 Digital-twin level-6 evaluation.

The $iGHOST_{I^3R}$ five-dimensional digital-twin modeling description method proposed in this paper is equivalent to a refined decomposition of the dimension of digital-twin data (DD) in the five-dimensional theory of Tao[57]. In contrast to previously proposed digital-twin modeling approach[20], the approach raised in this paper introduces the concepts of ontology and semantic model libraries. Ontology enables the generalization of 'experience' and 'ontology' from the full life cycle physical 'experience' to the information layer mapping. This paper explores a paradigm shift approach to inferring manufacturing ontology from manufacturing process digital-twin big data to achieve the business requirements of level 5 and level 6 of the "digital-twin level-6 evaluation" of digital-twin modeling proposed by Dr Feng of Dassault (shown in Fig. 9).

### *4.2 Ontology for FMS*

As a typical complex smart manufacturing HCPS, the planning, design, simulation, commissioning and optimization process of FMS require an in-depth collaboration between upstream and downstream enterprises in the industry chain; during its service, it needs to be flexible to meet the processing needs of multiple workpieces with different process routes, and needs to intelligently meet the simultaneous scheduling of multiple orders and device dispatch.

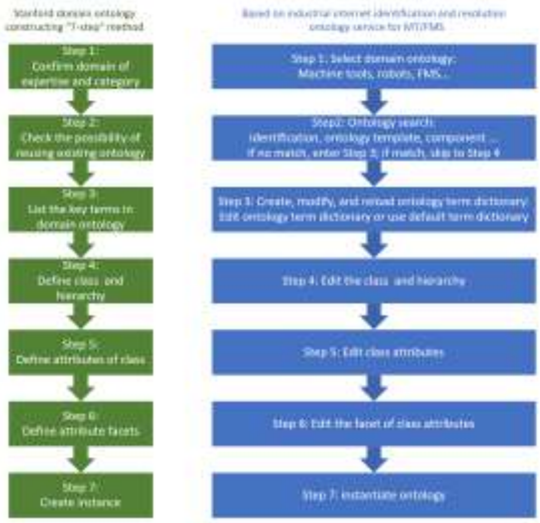

Fig.10 Constructing MT ontology based on Stanford University's "7-step" method.

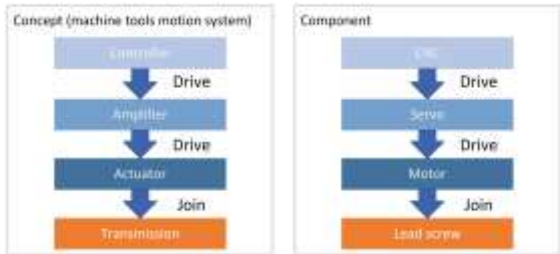


Fig.11 Machine tool motion control system relationship.

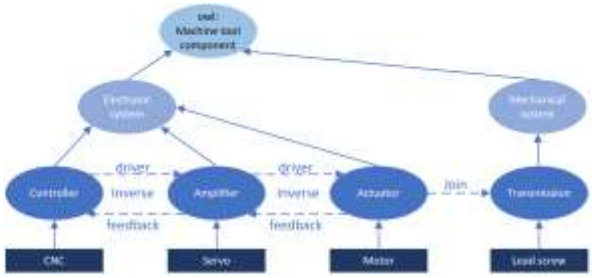

Fig.12 Logical hierarchical of ontology for MT CNC.

By sharing the ontology of domain experts (as in Fig. 9-(b)), the industry chain alliance enterprises can realize the cross-enterprise retrieval and invocation of domain ontology abstracted from the real ontology system. As shown in Fig. 10, based on the "seven-step approach"[58] proposed by Stanford University for domain ontology construction, digital-twin and ontology are created, associated, stored, retrieved and recalled in each stage of the full product life cycle with the help of industrial internet identification. The ontology is created, associated, stored, retrieved and recalled. As shown in Fig. 11, we have analyzed the relationships of a motion control system for a simple machine tool, through which the ontology construction process is concretely realized. Through analytical abstraction, the basic concepts of the machine tool motion system are as follows, controller, drive/motor, transmission mechanism. The scope of ontology of interest is the motion control system, the latter being the driving object of the former, and the class in which it is located is taken to be relevant only in terms of its properties, which is defined as a driving relationship. Take the example of the CNC ontology logic level of the machine tool in Fig. 12. Machine tool components consist of two subclasses: electrical components and mechanical components. Here the two sub-classes are mutually exclusive (owl:disjointWith). There are three sub-categories of electrical components: controllers, amplifiers and actuators. The controller has an object attribute drive; the amplifier has an attribute feedback and its value field is the controller; so obviously they are mutually exclusive (owl:inverseOf). The drive object of the amplifier has the value field motor and the feedback object of the motor has the value field amplifier. The two are also mutually exclusive. The value field of another object property of the actuator, 'Join' is the drive mechanism.

### *4.3 Real-time data acquisition technology for smart manufacturing Human-cyber-physical system (HCPS)*

The data acquisition needs of HCPS in smart manufacturing processes can be divided into 2 major categories: time-varying state data; and data triggered by tasks/conditions (e.g., Fig. 9-(c)).

#### *4.3.1 A real-time data collection and management method for smart manufacturing HCPS*

NC-Link enables the acquisition of time series data generated by HCPS during daily production. It draws on the designing ideas of the OPC-UA protocol and MT-Connect in terms of interaction interfaces, information models and data dictionaries, and is implemented in a JSON-based objectified data description language via the MQTT protocol. NC-Link adopts a three-layer architecture (adapter layer, agent layer and application layer) with "two light ends and a heavy middle". The adapter and application are MQTT clients; and the proxy has a built-in MQTT server. The application gets access to data based on the publish, subscribe and other interaction mechanisms of MQTT protocol with the adapter.

The functional composition of the device-oriented adapter is divided into three layers: the communication layer, the protocol layer and the data driver layer. The communication layer is responsible for receiving, sending and managing NC-Link commands; the protocol layer handles the information model, the data dictionary and the driver mapping of data interaction commands; the data driver layer realizes the data interaction between the underlying devices. Among other things, the information model and data dictionary describe the physical topology of the device and the data assets accessible to the device components. As an example, shown in Fig. 13, it converts CNC machine data into component objects, such as channels, axes as well as input and output modules. Another part of the data is defined as properties or variables of the object, such as feed coverage, actual position, tool length, etc.

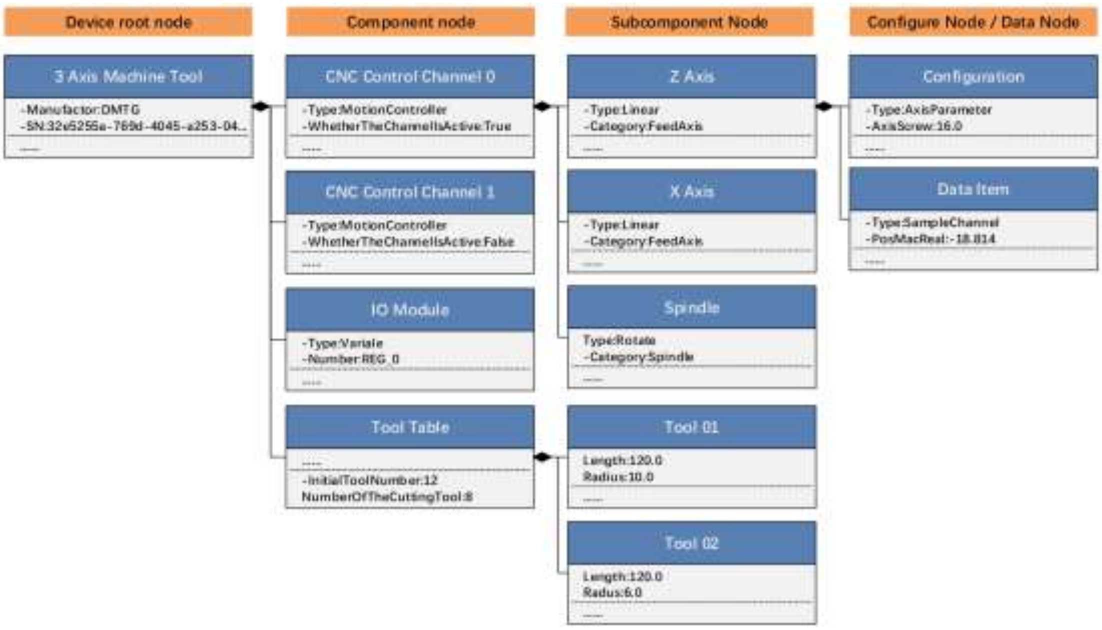


Fig.13 Descriptive model of machine objects in NC-Link Protocol[20].

#### *4.3.2 Discrete event modeling based on task ontology modeling*

Task ontology modeling is an effective way to address the need for modeling discrete task (order) information descriptions handled in manufacturing system simulation and service processes.

For user enterprises, the FMS-based task ontology enables simultaneous dynamic scheduling of multiple orders and dynamic dispatching of device assets. Compared with a single smart manufacturing device, FMS has the features such as composite processes, flexible reconfiguration and smart scheduling. In the scheduling session, the ECode model based on the task ontology concept is used to achieve an abstract description of the core content and execution details of the FMS process service capability and to establish a scheduling model. As shown in Fig. 14, the ECode model information consists of three main parts, namely the basic information, the logical control information and the execution parameter information. The basic information is used to describe the characteristics of the ECode itself: ECode number, description of the execution content, creation time, status, etc. Logical control information includes: instruction decomposition relationships, dependency relationships, affiliation relationships, etc. Execution parameter information is the conditional parameter information required to implement the business logic or operation. As shown in Fig. 15, ECode has its life-cycle, and each level of ECode has its life-cycle. The life-cycle of the parent instruction contains the life-cycle of the child instructions, and the life-cycle of all child instructions together constitutes the entire life-cycle of the parent instruction. ECode enables FMS scheduling through the scheduling engine based on digital-twin information such as device working status, workpiece process route, central tool storage status and order status in the FMS.

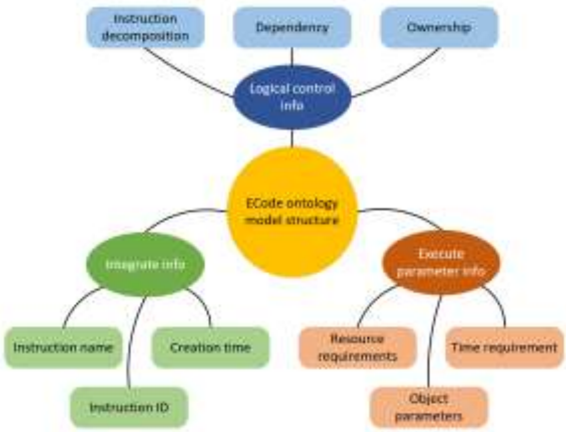


Fig.14 Composition hierarchical of ECode ontology.

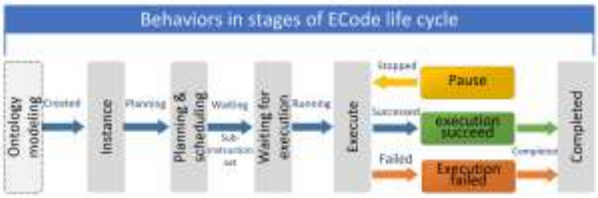


Fig.15 Behaviors in stages of ECode life cycle.

*4.4 Full life-cycle management of digital-twin based on the Industrial Internet Identification*

As shown in Fig. 9-(d), the "I$^3$R System" enables the unified identification, coding and resolution of manufacturing assets (physical and digital assets) for the industrial chain.

*4.4.1 Standard marking code specifications*

The marker code consists of a marker prefix and a marker suffix. The prefix is managed by the industrial internet identification alliance; the product category code in the suffix is managed by the industry alliance, while the product model specification, product serial number and other codes are defined by the manufacturers themselves. The prefix includes the national top-level node identification code, the secondary node identification code of the machine tool industry and the enterprise node identification code. The suffix consists of four parts: the product base classification code, the product series/specification code, the product serial number code and the enterprise custom code. The specific code composition is shown in Fig. 16:

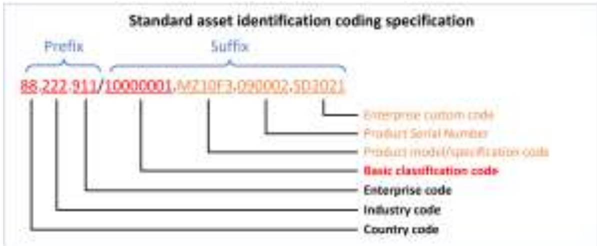


Fig.16 Industrial internet identification code for standard asset.

(1) The prefix:

①The national identification code, consisting of Arabic numerals, e.g. 88 for China Wuhan top-level node code.

②The industry identification code, consisting of bit Arabic numerals, e.g. 222 represents the secondary node code of machine tool industry.

③ The enterprise identification code, indicated by Arabic numerals or capital letters, to be applied for and assigned to the secondary nodal agency of the machine tool industry.

(2) The suffix:

① The product category code, consisting of 8 Arabic numerals or upper case English letters. The first 4 digits distinguish the major product categories and types, including complete machine tools and components, with machine tools distinguished by machining method and components by machine function. The last 4 digits subdivide the products in the broad category, while the components are subdivided in terms of function and use.

② The product series/specification code, describing production information such as product series or specifications, customized by the enterprise. When the latter product serial number code already contains product series or specification information, this part of the code is not repeatedly described and can be set to 0.

③ The product serial number code, customized by the enterprise.

④ The enterprise customized code, customized by the enterprise.

For example, the Industrial Internet Identification Code for a CNC device in a machine tool is: "88.222.1/10000001.0.S160UPF21A00013.2021". Machine tool manufacturers can easily update their existing BOMs to digital-twin-objects with the Industrial Internet Code information.

***4.4.2 Extensions to the logo coding specification for digital-twin***

During the full life cycle of a physical asset, the industry chain alliance enterprises generate a large amount of digital-twin information and domain ontology around the physical asset. Since physical assets are "unique" at the material level, there is no theoretical possibility of creating new material objects through "copying, inheritance, reuse, extension", etc., so the above-mentioned identification code specification is fully applicable to the identification of physical assets. The above specification of identification codes is therefore fully applicable to the identification of physical assets. But there are obvious problems and shortcomings when it comes to marking the vast amount of digital-twin and domain ontology. Specific issues included are as follows:

Firstly, current identification codes parse out large amounts of common, redundant data when identifying digital assets across their full life cycles. And it is difficult to guarantee the data consistency. Clearly, it is unacceptable to require simultaneous changes in multiple places when the generic ontologies attributes of multiple similar digital assets differ.

Secondly, the current coding structure emphasizes the uniqueness of the product itself, but describing the digital-twin and domain ontology of that product requires the construction of a large amount of complex ontology, which contains a large number of inherited and reused information relationships that cannot be fully expressed by a single code and the small amount of information it parses.

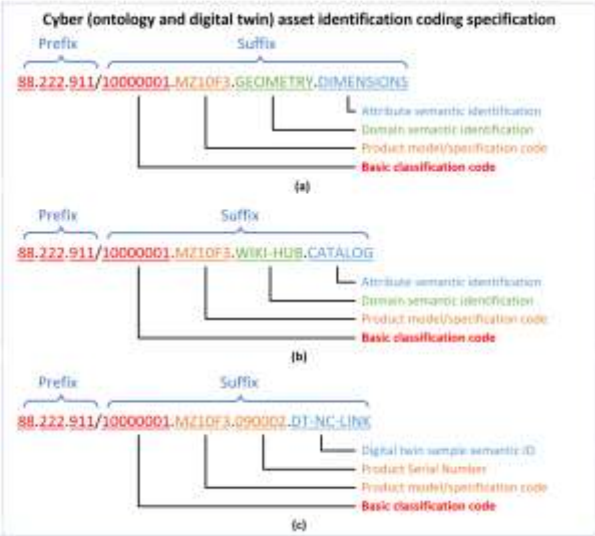


Fig.17 Industrial internet identification code for cyber asset of digital-twin.

For these reasons above, the last two group identifiers (product serial number codes and enterprise custom codes) have been defined on the basis of the current coding specification for digital-twin and ontology collaboration requirements (as shown in Fig. 17):

(1) When the identification code identifies a (model product) generic ontologies digital-twin asset, the meaning of the product serial number code changes to a domain semantic identifier, explicitly indicating the domain scope of the digital asset (digital-twin sample or ontology); the meaning of the enterprise custom code changes to an attribute semantic identifier, explicitly indicating the specific attributes of the digital asset in the professional domain. The symbol shown in Fig.. 17-(a) represents the external dimensional parameters of the generic ontologies domain ontology (geometry ontology) of the CNC model MZ10F3, through which information on the digital-twin and ontology of this product can be obtained in the "$I^3R$ System" (e.g., the search returns the parsed result "W:400mm, H:200mm, T:78mm").

(2) The meaning of the identification code shown in Fig. 17-(b) is to explicitly identify the CNC of model MZ10F3 in the "Wiki-Hub" platform (the digital-twin and ontology collaboration platform proposed in this paper) in the domain ontology of the "history catalogue". This allows the industry alliance enterprises to collaboratively manage their digital-twin biographical information throughout its full life cycle.

(3) For a defined product while inheriting the generic ontologies domain ontology set represented by its model identifier, the meaning of the enterprise custom code becomes a digital sample

semantic identifier that explicitly represents the access path to a certain digital-twin information. The logo in Fig. 17-(c) represents the NC-Link protocol subscription information retrieval code for the CNC of the MZ10F3 with product serial number 090002, which is parsed to return the real-time data subscription path and thus enable access to the device's real-time data.

#### *4.4.3 Extended coding specifications to manage implementation throughout the full product digital-twin life cycle*

As shown in Fig. 18, the relationship between digital-twin information and identification codes throughout the full product life cycle is like that of DNA in the biological field. The domain ontology and the individual digital-twin information are linked and extended by an extended encoding specification in an explicit format with a double helix structure. The "I$^3$R System" allows enterprises to manage the nodal data on the double helix structure, enabling digital-twin and collaborative ontology management throughout the full life cycle of products.

With the advantages of the "I$^3$R System" covering the industry, combined with the explicit advantages of the digital-twin extended semantic coding method proposed in this paper, the industry chain alliance enterprises can achieve digital-twin and ontology collaboration in the agile manufacturing process.

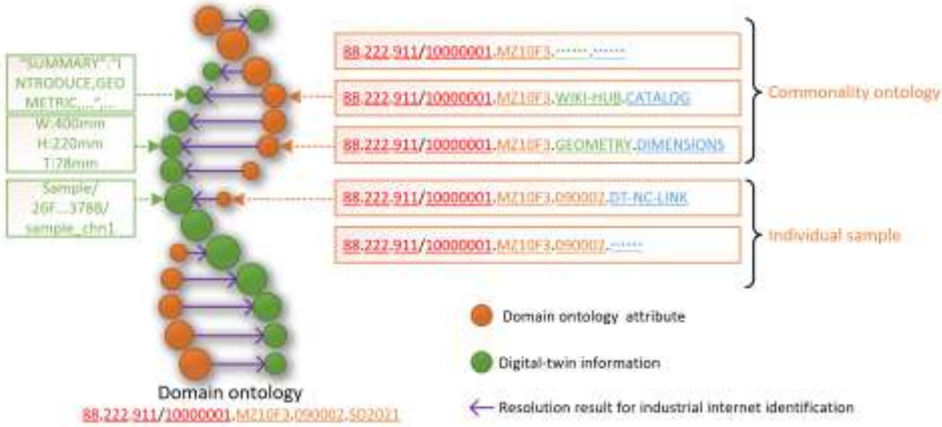


Fig.18 Dual-helix of digital-twin and domain ontology based-on resolution from Industrial internet identification.


Fig.19 Examples on the Digital-twin service based on industrial internet identification and resolution.

## 5 Experimental prototypes

### 5.1.1 Implementation of the prototype

Fig. 19 depicts different digital-twin application services based on the framework described in this paper at various stages of the manufacturing device life-cycle: visualization of the prototype simulation demons device ration in the concept planning phase (Fig. 19-(a)), virtual in-the-loop simulation of the digital prototype in the engineering design phase (Fig. 19-(b)), hardware in-the-loop simulation in the deployment and commissioning phase (Fig. 19-(c)), remote coaching in the optimization and training phase (Fig. 19-(d)), scheduling and digital-twin visualization in the device service and maintenance phase (Fig. 19-(e)), and so on. The digital-twin and domain ontology collaborative management in different stages of smart manufacturing HCPS mentioned above can be realized with the help of the digital-twin collaborative Hub proposed in this paper (Fig. 19-(f)).

***5.1 Prototype platform of digital-twin and ontology collaboration hub for industry chain alliance***

Like Wikipedia's multi-user approach to building a collaborative encyclopedia of human ontology, this paper proposes an I$^3$R-based RAMI 4.0 full life cycle digital-twin and ontology collaboration framework (shown in Fig. 20), jointly managed by industry alliance enterprises.

Fig.20 Conceptual demo of digital-twin-wiki based on.

The prototype plays on three features of the "I$^3$R System":

(1) Like a "pointer" in C Programming Language, the unique coding and asset (physical and digital assets) resolution and access is achieved through "parsing" (as shown in Fig. 19), without concern for the actual storage location and physical form of the asset, thus ensuring the uniqueness of the asset operation interface;

(2) The I$^3$R System ensures the correctness of the access rights of each identification code through a unified security mechanism (shown in Fig. 3), thus ensuring the uniqueness of the full product life cycle.

(3) With the flexible scalability of the specification (as shown in Fig. 18), it is possible to classify the domain characteristics of digital assets before they are registered with the "identification code", so as to improve the semantic explicit nature of the "identification code" and to pre-process the data for the numerous top-level applications of the digital-twin (as shown in Fig. 20).

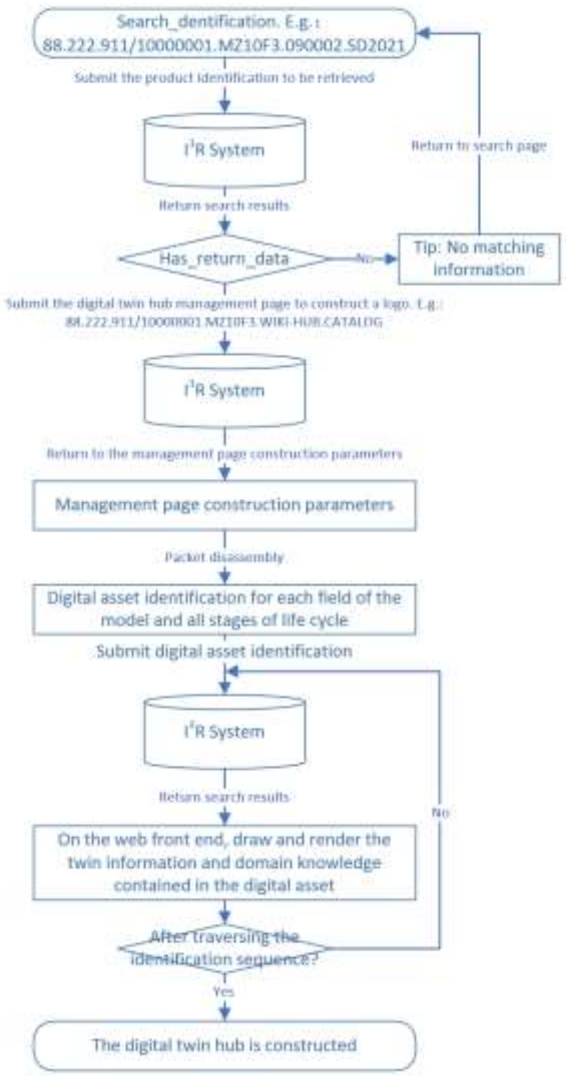


Fig.21 Process of digital-twin collaborative management.

Fig. 21 depicts the building process for retrieving the full life-cycle digital-twin and ontology co-management interface for a product. The digital-twin and ontology information for this product consists of 2 major parts: information common to the product model and information exclusive to the individual product. The common information of this product (product information, digital model sharing, application scenario ontology, technical documentation sharing, milestone events, recommended outreach applications, maintenance record collections, etc.) is managed by the manufacturer and integrator; the exclusive digital-twin mapping information of individual products (product BOM list, assembly level information, historical and real-time operation information, alarm history, operation and maintenance records, etc. ) are automatically updated and improved by the manufacturer's production process and the customer's use of the information system. Through the centralized management of information on digital assets of the same product at different stages of its full life cycle by enterprises and organizations up and down the industrial chain (manufacturers, integrators, users, research institutions, etc.), digital-twin and ontology collaboration is achieved for the full product life cycle in the industrial chain.

#### 5.1.2 Evaluation indicators

At present, there are few authoritative guideline studies for the evaluation index system of digital-twin and ontology collaboration in HCPS objects. Given the fact that the essence of this collaborative cooperation is the construction and management of domain ontology of the specified object, this paper referred to the domain ontology evaluation guidelines and indicators when determining the digital-twin and ontology collaborative evaluation indicators of HCPS full life cycle.

Domain ontology evaluation is a technical activity to verify the quality of ontology according to a reference framework, which is of central significance to ontology engineering support scenarios (e.g., evaluation of ontologies and validation, ontology selection, or ontology extraction algorithms), and its complexity stems from the different evaluation methods and metrics caused by the applicability of ontologies in various scenarios [59]. The requirements of collaborative application scenarios for digital-twin and ontology were conducted based on the HCPS full life cycle of the industrial Internet mark, and the main evaluation metrics needed to be based on the following 2 evaluation criteria:

(1) Whether the digital-twin and ontology archive collaboratively managed by the industrial chain cooperative enterprises can meet the shared ontology coverage of this described object in all stages of its full life cycle, different enterprises and different fields. This criterion reflects the macroscopic completeness of the evaluated ontology collection.

(2) Since the described object may change in different stages of its life cycle, the ownership, space and core value area. The same, similar and resembling concepts, attributes and category relationships may be defined and described for many times, resulting in the "duality" of domain ontology, increasing the redundancy of the ontology system and cutting its accuracy. Therefore, the ratio of digital-twin to the references in the ontology file was evaluated, and the degree of coupling between ontology maps could determine the ontology reuse of the file; meanwhile, the authority of the cited ontology entries could also be measured.

***Domain coverage indicators***

In this paper, with reference to the CMM concept coverage [60] evaluation index method used for ontology evaluation; the coverage of archives index method of asset objects in HCPS based on the digital-twin of industrial Internet mark resolution and ontology archives ($S_{\mathrm{a}}$) was proposed. See Equation 5 and Equation 6.

$$Coverage_{archives}(S_{\mathrm{a}}, gold\_standard) = \frac{\sum_{e\in E[S_{\mathrm{a}}]}\sum_{t\in gold\_standard} I(e,t) + \sum_{c\in E[S_{\mathrm{a}}]}\sum_{t\in gold\_standard} J(e,t)}{\mathrm{m}} \tag{5}$$

$$I(e,t) = \begin{cases} 1: if\ domain(e) = t \\ 0: if\ domain(e) \neq t \end{cases} \tag{6}$$

$$J(e,t) = \begin{cases} 1: if\ domain(e)\ \ni\ t \\ 0: if\ domain(e)\ \not\ni\ t \end{cases} \tag{7}$$

Where:

"gold_standard" refers to the relative gold standard, i.e., the standard ontology domain ontology (category, attribute, relationship) set. In the actual application scenario, there is not a stable and clear gold standard for reference; it needs to be generated and changed dynamically by specialized analysis and inference techniques (e.g., convolutional neural network technology);

"$e$" refers to the word sample;

"$E[S_{\mathrm{a}}]$" refers to the set of all ontology entries in the archive;

"$t$" refers to the word field classification mark in the golden rule.

In Equation 3-5 and Equation 3-6:

"$\mathrm{domain}(e)$" refers to the domain classification identifier in the extracted word "$e$";

"m" refers to the total number of entries in the digital-twin and ontology archive.

The synergistic method of digital-twin and ontology archives proposed in this paper used the industrial Internet mark resolution system as the synergistic management core of the archives. The industrial mark extension specification for digital-twin and ontology here makes the domain classification in the product archives clearer and more standardized, and it is relatively easier to obtain the latest and authoritative golden standard (the golden standard in the synergistic process of archives). On this basis, the dynamic collaboration mechanism of the archive system enables highly responsive and iterative improvement and updating of the terms in each product domain classification, thus improving the domain coverage of the whole digital-twin and ontology collaboration system.

***Ontology relevance indicators***

Considered from the dimension of ontology entry citation relevance (i.e., entry coupling), the coupling degree reflects the ratio of the number of cited entries to all entries in the file. Generally speaking, the higher the coupling degree, the more external entries are referenced. Although this causes the logical complexity between the ontology of archives, it improves the reuse of "existing" ontology and reduces the redundancy of ontology in the system, which is more helpful to the collaborative ontology management of the full life cycle of products. In this paper, we propose the method of coupling of entry metrics in the digital-twin and ontology archive ($S_{\mathrm{a}}$) of HCPS based on the industrial Internet identity resolution of asset objects as follows:

$$Coupling_{entry} = \frac{\sum_{k=1}^{m} K(e_k)}{m} \tag{8}$$

$$K(e_k) = \begin{cases} 1, & e_k \in S_{ref} \\ 0, & e_k \notin S_{ref} \end{cases} \tag{9}$$

"m" refers to the total number of entries in the digital-twin and ontology archive.

"$S_{ref}$" refers to the set of all referenced external entries in this archive, $S_{ref} = \{e_{ref1}, e_{ref2}, e_{ref3} \dots, e_{refk}\}, 1 \leq k \leq m$.

The collaborative approach of the archive proposed in this paper, whose word information is indexed and invoked called on the industrial Internet identity resolution system, which fundamentally breaks the digital-twin data and ontology sharing barriers between industrial chain enterprises, enables accurate cross-enterprise and cross-domain word collaborative management, ensures the correlation and synchronization between ontology, and changes the traditional paradigm of constructing and managing domain ontology graphs.

Not limited to the above 2 evaluation criteria, the digital-twin and ontology collaboration evaluation metrics of HCPS full life cycle can also be measured and evaluated with reference to ontology evaluation criteria from translatability[61], density[62], semantic similarity[60], scalability and historical evaluation[61]. Due to the limited space of the pages, no more discussions will be stated here.

**5.1.3 Performance test**

The digital-twin and ontology collaboration framework proposed in this paper was tested in a functional application in an industry chain alliance consisting of a machine tool enterprise, a

CNC enterprise and an automation integrator. The retrieval stress test (shown in Fig. 22) was conducted on the product identifiers of digital-twin and ontology containing 1,000 identifiers, and it shows that the average response time of the prototype system is 209ms, of which 50% of the requests are less than 113ms, 90% of the 1000 requests are less than 217ms and 95% of the requests are less than 272ms, which could meet the demand of collaborative management of digital-twin and ontology in product life-cycle. The framework approach proposed in this paper is effective and feasible.

### *5.2 A derivative top-application*

Based on the digital-twin and ontology collaboration framework proposed in this paper, we are developing a natural language description inference system for product failures: maintenance records are treated as a digital asset (containing anomaly description, solution, validity, etc.) are subjected to natural language semantic inference and classification of fault features by a convolutional neural network on a collection of maintenance records as shown in Fig. 23, and the domain classification of the anomaly is reflected by explicit semantic tags in its identification code. This results in a "maintenance ontology library" for the product type. Collaborating enterprises and organizations in the chain can use natural language to describe anomalies in the product and use convolutional neural networks to infer the anomaly domain tags to obtain effective maintenance recommendations in the "maintenance ontology library". By reasoning out professional domain classification results through anomalous natural language descriptions of products based on the $I^3R$ System, domain ontology sharing across enterprises, fields and professions is achieved.

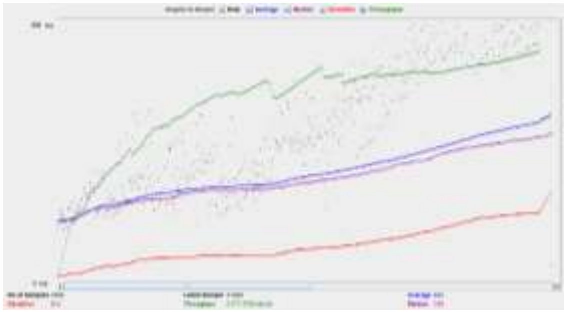

Fig.22 1,000 digital-twin logo retrieval test results.

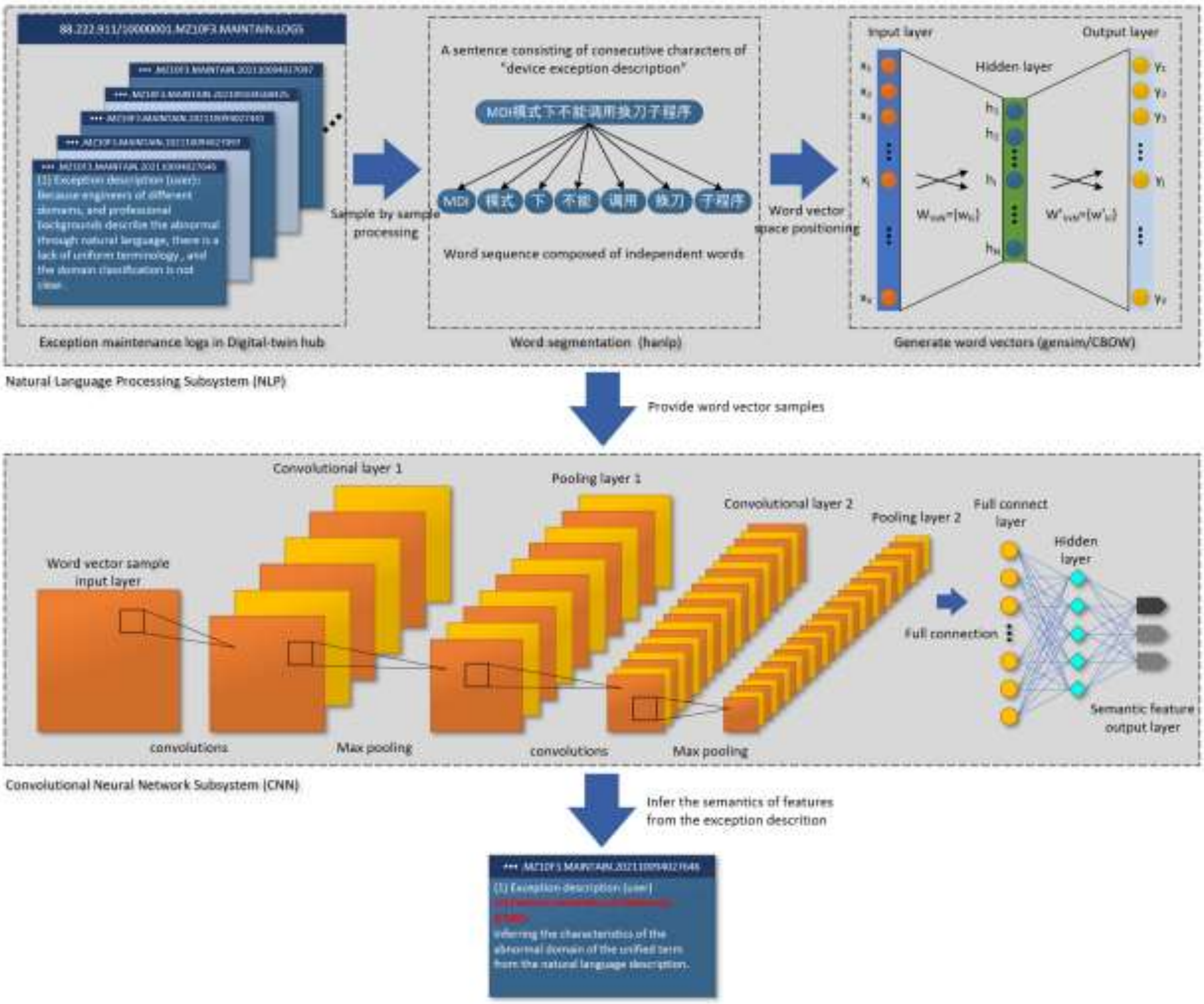


Fig.23 Inference system of device exception description based on convolutional neural networks.

## 6 Conclusions and future work

This paper proposes a generic digital-twin modeling method and ontology mapping service framework for smart manufacturing device based on the $I^3R$ System, providing digital-twin and ontology sharing, reasoning and invocation services for collaborative enterprises in the industrial chain in the agile manufacturing model. To implement the service framework, this paper highlights four key technologies and their implementation methods: (1) A generic digital-twin modeling description approach for the full life cycle of FMS; (2) Ontological concept for the full life cycle of FMS; (3) Real-time data collection and communication protocol for HCPS in smart manufacturing; (4) A digital-twin and ontology collaboration framework based on $I^3R$. Different top applications based on the conceptual realization and derivation of the paper's framework are presented around the various stages of the full life cycle of manufacturing device. Testing the feasibility and validity of the digital-twin and ontology collaboration framework through a prototype platform. At the same time, the implementation of a product anomaly natural language description reasoning system being developed using the prototype platform is also presented.

We will focus on the application scenarios of digital-twin and ontology graph distributed collaboration framework (digital-twin and ontology collaboration and product anomaly natural language description reasoning system, etc.) based on the framework proposed in this paper and further in-depth research in the future work. Based on the distributed collaboration of digital-twin throughout the full product life cycle realized by industrial internet identification, the digital-twin information of physical and digital assets in each stage of RAMI 4.0 asset management shell is distilled into ontology, providing cross-domain digital-twin sharing and ontology mapping collaboration for industry chain alliance enterprises.

***Acknowledgements:***

This work is supported by the National Key Research and Development Program of China (Grant No. 2018YFB1701002, 2018YFB1701003), the National Natural Science Foundation of China (Grant No. U19A2072).

***Declarations***

**a. Funding**

This work is supported by the National Key Research and Development Program of China (Grant No. 2018YFB1701002, 2018YFB1701003), the National Natural Science Foundation of China (Grant No. U19A2072).

**b. Conflicts of interest/Competing interests (Not applicable)**

**c. Availability of data and material (Not applicable)**

**d. Code availability (Not applicable)**

**e. Ethics approval (Not applicable)**

**f. Consent to participate**

All authors have Consented to participate.

**g. Consent for publication**

All authors have Consented to publication.

**h. Authors' contributions**

Fan coined the idea of the kind of system and gave the method to build to build the system.

Dai and wang performed the detailed design of system.

The digital-twin framework's solution method was given by Fan.

The implementation of the software was by Dai and Yan.

The preparation of the manuscript was by Fan and Hu, the revised and final version of the manuscript was decided by Hu.

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