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Digital Twin Service towards Smart Manufacturing

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Abstract

Digital twin provides an effective way for the cyber-physical integration of manufacturing. Meanwhile, smart manufacturing services could optimize the entire business processes and operation procedure of manufacturing, to achieve a new higher level of productivity. The combination of smart manufacturing services and digital twin would radically change product design, manufacturing, usage, MRO and other processes. Combined with the services, the digital twin will generate more reasonable manufacturing planning and precise production control to help achieve smart manufacturing, through the two-way connectivity between the virtual and physical worlds of manufacturing. This paper specifies and highlights how manufacturing services and digital twin are converged together and the various components of digital twin are used by manufacturers in the form of services.

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1. Introduction

The advances in new generation information technologies, such as Internet of Things (IoT), big data, cloud computing, artificial intelligence (AI), etc., and their wide applications in manufacturing, are driving the manufacturing industry toward smart manufacturing [1]. The powers of advanced computing and analytics in cyber world open a bright perspective to smart manufacturing. The notion of the cyber-physical fusion is increasingly embraced by manufacturers [2]. However, how to converge the physical and cyber worlds of manufacturing is still one of specific challenges.

Digital twin, which is to create high-fidelity virtual models for physical objects in digital way to simulate their behaviors [3], paves a potential way to realize the cyber-physical fusion. In virtue of digital twin, complex manufacturing process can be integrated to achieve the closed-loop optimization of the product design, manufacturing, and smart services, etc [4]. Digital twin is getting more and more attentions. Gartner classified the digital twin as one of top 10 strategic technology trends for 2017 and 2018 [5] [6]. The experts from Lockheed Martin predict that digital twin would be the most important technology in the defense and aerospace industries in the coming years.

In addition, as manufacturing is evolving towards socialization and servitization, service plays a more and more important role in manufacturing [7]. More and more manufacturers adopt service logic for their business to cope with the fierce competition and gain more revenues [8]. Services can shield the heterogeneities of resources, which are conducted by different vendors using various standards, and communication protocol/interfaces, and enable the interaction and integration between them [9]. With the characteristics of on-demand use, dynamic reconfiguration, and platform independence [10], services endow manufacturing with the advancement of large-scale sharing and collaboration.

In view of the concept of Everything-as-a-Service (XaaS), services could fully release the potential of digital twin. Through services, each component of the digital twin can be shared and used in a convenient “pay-as-you-go” manner [11], especially virtual models which are not easy to be created rapidly. Moreover, in the working process of digital twin,

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services are integral part, and a lot of actions require the support of third-party services. For example, multi-source data fusion requires algorithms, computing and storage services. In this paper, digital twin and service are combined, and how the digital twin are used as services is specified.

2. General digital twin concept model

The concept of digital twin was firstly presented by Grieves at one of his presentations about PLM in 2003 at University of Michigan [12]. To date, digital twin has become one of the most popular technologies. Due to its tremendous potential for disruptive development of industry, digital twin is receiving more and more attention from the industry. Many famous companies widely apply digital twin in their own businesses. The most typical companies are as follows (see in Table 1). Because of the frequent use by well-known companies, some explanations and definitions of digital twin were proposed. The most commonly used definition of digital twin was proposed by Glaessegen and Stargel in 2012, which is composed of three parts: physical products, virtual products and the connections between them [13].

From the table 1, digital twin reflects two-way dynamic mapping of physical objects and virtual models [14]. By building digital twin system that integrates the manufacturing process, the innovation and efficiency from product design, production planning to manufacturing implementation, can be effectively enhanced [4].

For smart production, from small as a piece of equipment and a production line, to big as a shop floor or entire factory, all of them can be considered as a digital twin. Therefore, from the perspective of smart production, digital twin can be divided into three levels, i.e., unit level, system level, and SoS (system of system) level [15]. The unit level, system level and SoS level digital twin is a systematic model with rank going forward step by step. The system-level digital twin can be considered as the integration of multiple unit-level digital twin, which cooperate with each other. Multiple unit-level digital twins or multiple system-level digital twins constitute the SoS-level digital twin, i.e., complex system. The unit-level and system-level digital twin meet the Glaessegen's three-dimensional definition of digital twin, i.e., physical entities, virtual models and the connections between them. As shown in Fig. 1, the unit level digital twin is the equipment. Equipment is the smallest unit participated in manufacturing activities. The optimization of manufacturing activities is achieved through the adjustment of equipment. With respect to system-level digital twin, a smart production line composed by machine tools, robot arms, etc. is system-level. For unit-level and system-level digital twin, the virtual models are the ultra-high-fidelity mapping of physical equipment through the digital description from the perspectives of geometric shape, function and operating status of equipment and production line [16]. The basic attributes, real-time status and other data are transmitted to the virtual models to drive the simulation and prediction. Then, the parameters of the virtual models are fed back to optimize physical entities. In the closed-loop interaction process, the physical entities and virtual models co-evolute [13]. For the SoS-level (e.g. shop-floor), accurate shop-floor management and reliable operations, which are inseparable from services, are very important for smart manufacturing. To further promote digital twin theories and technologies, service is added and the role of data is valued. As a result, the three-dimensional structure of digital twin is extended to five-dimension, which are physical entities, virtual models, services, fusion data, and the connections among them [14]. As shown in Fig. 1, ① Physical entities are the set of objective entities, which have specific functions to complete manufacturing tasks according to inputs and outputs. ② Virtual models are the digital images of the physical entities, which can completely and truly reflect the lifecycle of the physical entities. ③Services integrate various functions such as management, control and optimization, to provide application services according to the requirements. ④ Fusion data is the core driver of the digital twin, including the data from physical entities, virtual models and service, as well as their fusion data. ⑤ The connections among them connect the above four parts in pairs, ensuring real-time interaction and iterative optimization. Based on the five-dimensional structure of digital twin, the digital twin shop-floor provides a new way to practice smart manufacturing.

Table 1. The understandings for digital twin from 8 famous companies.

GE	PTC	Siemens	Oracle	ANSYS	Dassault	SAP	Altair
Through the integration of physical machinery and analytical techniques, the machines are tested, debugged and optimized in a virtual environment.	PLM process is extended into the next design cycle to create a closed-loop product design process, and help achieve predictive maintenance of product.	Based on the consistent data model across all aspects of the product life cycle, some of the actual operations are accurately and veritably simulated.	Through the virtual models of devices and products, the actual complexities of physical entities are simulated, and insights are projected into applications.	Combined outstanding simulation capabilities with powerful data analysis capabilities, it is to help enterprises gain strategic insights.	Through the 3D experience platform, designers and customers can interact with the product during product design or manufacturing process to understand how the product works.	Through building digitized models, product development and innovation are promoted based on real-time data acquisition and analysis.	By virtue of the leading virtual simulation technologies, it is to create virtual models superimposed with multiple physical properties, to make product have better characteristics.

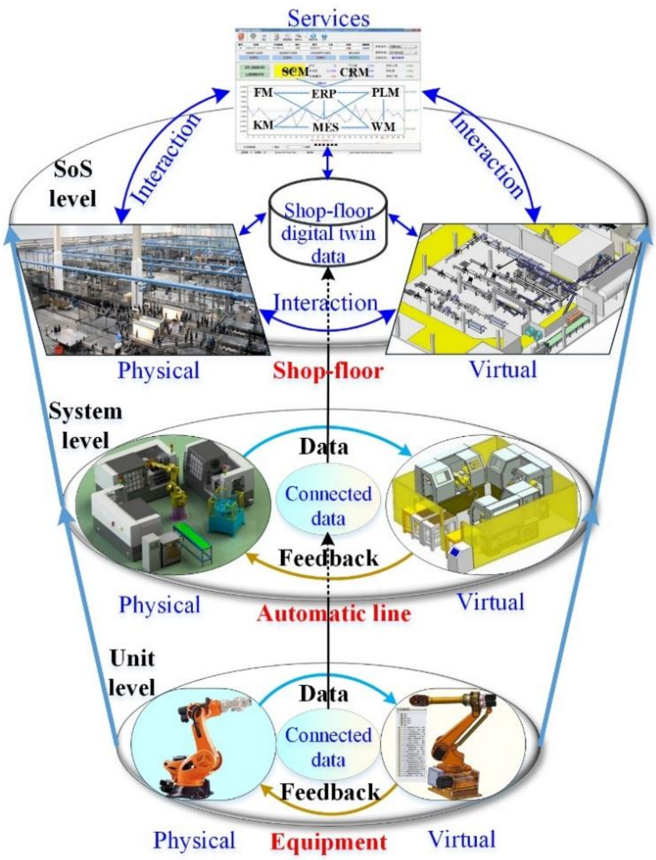

Fig. 1. The unit-level, system-level and SoS-level digital twin and five-dimensional model.

3. Servitization of digital twin

Models and data are the cores of the digital twin. However, the creation of virtual models is complex and specialized project, so are the data fusion and analysis. For users who do not have relevant knowledge, it is difficult to build and use the digital twin. Therefore, it is imperative that models are able to be shared by users and data analysis are outsourced to the third-party professional organizations. Moreover, in the context of the manufacturing socialization, the physical resources involved in manufacturing are geographically distributed. With the characteristics of on-demand use, dynamic reconfiguration, and platform independence, services pave a way for the problems mentioned above. Through the Internet, users are able to access and use the various elements to establish the digital twin.

The service encapsulation is to translate various components of digital twin into services with uniform description [17]. As shown in Fig. 2, the first and the most important step of service encapsulation is to establish the information template, which consists of a variety of information [18]. For the physical objects, these information includes basic attributes (e.g., name, ID, address, etc.), QoS (e.g., time, cost, reliabilities, satisfaction, etc.), capacities (e.g., precision, size, process, etc.), real-time status (e.g., overload, idle, in maintenance, etc.), as well as input and output. The information template of the physical object can be described as Formula (1).

$$PO = \{ Basic, QoS, Cap, Status, Input, Output\} \quad (1)$$

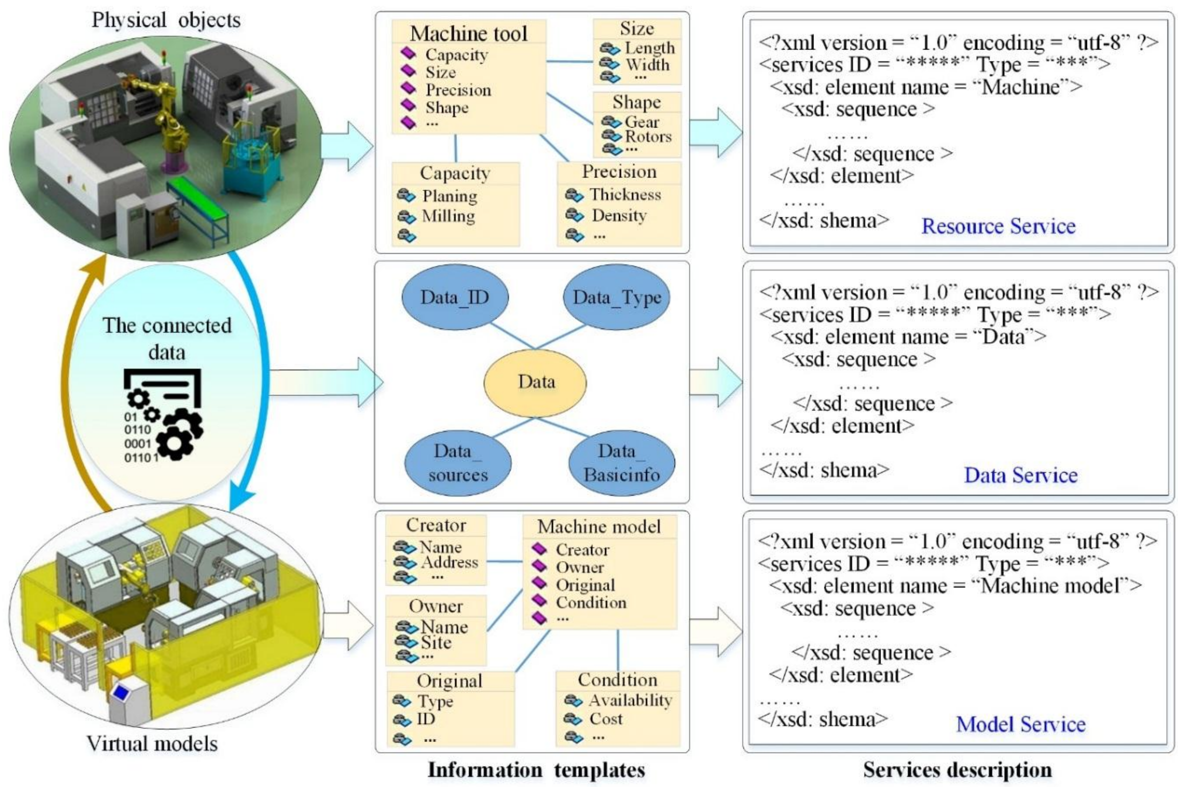

Fig. 2. The service encapsulation of digital twin.

Where Basic denotes the basic attributes to identify a physical object. QoS (quality of service) denotes the evaluation for the performance of physical object to conduct the user selection. Cap denotes the functions what the physical object can do. And Status indicates whether the physical object is available. Taking a NC machine tool as example, the production capacity includes the capacity for shape processing (e.g., plane, hole, thread, etc.), precision (e.g., roughness, deflection, etc.), parts processing (e.g., gear, plate, etc.), size (e.g., height, width, coordinates, etc.), and so forth. Status includes overload, idle, in maintenance, etc. For the input and output, a NC machine tool could be materials, such as steel, aluminium alloy, etc. And the output could be a part, or a small product. They can be formulized as (2)-(5):

$$Basic = \{type, name, ID, address, color, delivery\_time, \dots\} \tag{2}$$

$$QoS = \{cost, time, reliability, trust, Fun\_similarity, \dots\} \tag{3}$$

$$Cap = \{shape\_cap, precision\_cap, parts\_cap, size\_cap, \dots\} \tag{4}$$

$$Status = \{load, health, \dots\} \tag{5}$$

Similarly, virtual models can also be described by the information template. Different from the physical entities, the virtual models can be used by multiple users at the same time. Besides, the virtual models can be copied without repetitive creation for a same or equal physical object. Therefore, when the virtual models are encapsulated to services to be shared by users, not only creators of models can get benefits, but also users can reduce costs and time. The information template of the virtual model can be described as Formula (6).

$$VM = \{Ori\_phy, Creator, Ori\_ID, Cur\_ID, Owner, QoS, Online\_site, Input, Output, \dots\} \tag{6}$$

Where Ori_phy denotes the original physical object from which the virtual model is created. Creator is the one who builds the model based on his specialized knowledge. Ori_ID is the original identifying number when the model is first created. Cur_ID is the identifying number of current copy. Owner is the one who possess of the model. Owner who has copyright or may be a creator, can earn profits through renting out models or selling copies. Similar to the physical object, QoS denotes the evaluation for the performance of models, including cost, reliability, functions, etc. Online_site denotes the online address where users can access or download the models. Input and Output may different according to the specific models.

In addition, data is very important for smart manufacturing [19]. However, because of various standards, and communication protocols/interfaces, data is difficult to acquire and understand. Through using unified template to describe the data, users can conveniently use data. In general, the information of data includes the data provider who own the data, data sources where data is collected, data ID which is used to identify data, data type which denotes the kind of data, and data abstract which is the brief introduction of data value. Therefore, can be described as (7).

$$Data = \{D\_prov, D\_source, D\_ID, D\_type, D\_abstract, \dots\} \tag{7}$$

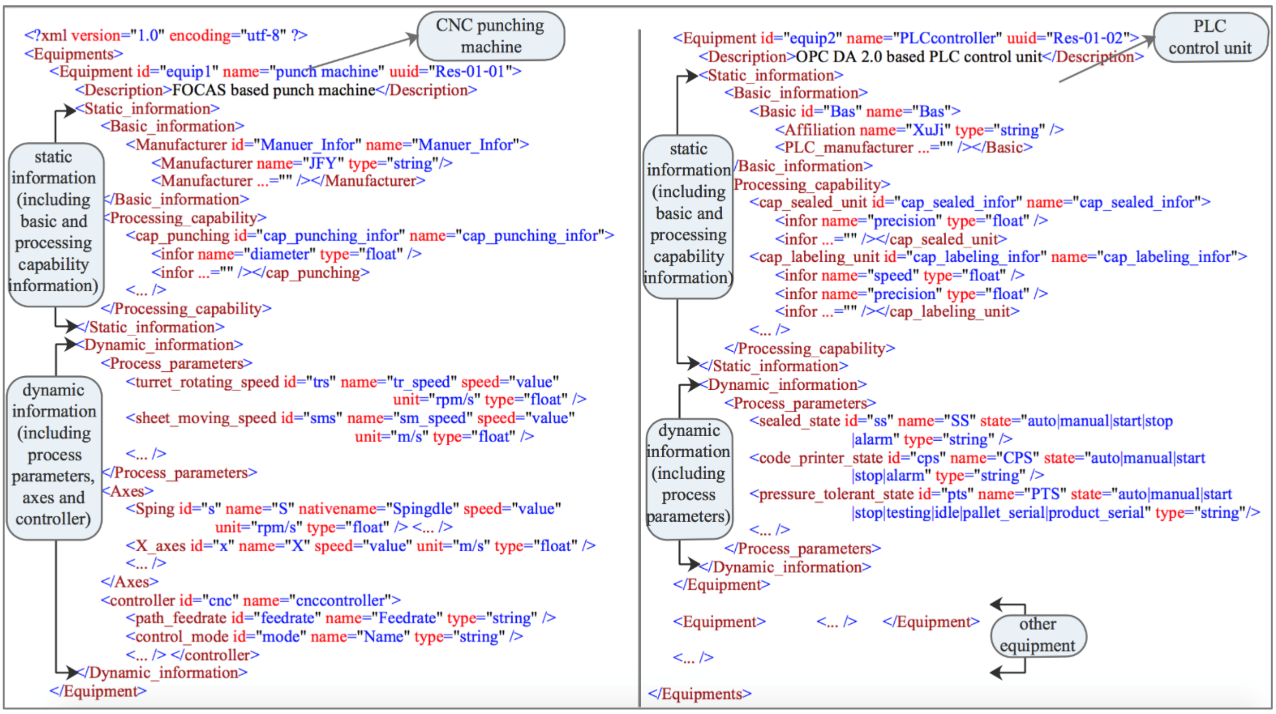

Fig. 3. Service encapsulation based on XML.

The information templates describe the most of the information that users want to know and have to know. After the information templates are established, various kinds of physical objects, virtual models and data are encapsulated to services based on the service description language such as XML language [18] (see in Fig. 2). As an example, the information template of a punching machine and PLC control unit is encapsulated by a service based on XML. Wherein, the information template includes basic information, processing capability, process parameters, and axes information of punching machine and PLC control unit. Fig. 3 shows codes of service for punching machine and PLC control unit based on XML.

4. Digital twin service applications

After services encapsulation, the digital twin services are published to the services pool and management platform, where they are managed to be shared by various users. As shown in Fig. 4, digital twin services consist of the equipment services, technology services, test services, data services, knowledge services, algorithms services, models services, simulation services, etc. In addition, there are many auxiliary services, such as financial services, logistics services, training services, equipment repair services and others. The services management includes searching, matching, scheduling, combination, transaction, fault-tolerance, etc. A task is submitted to the management platform. Then, it is decomposed into subtasks that can be accomplished by a single service. According to the QoS, the manufacturing service supply-demand matching and scheduling is carried out to select the optimal services [20]. After the service transaction, the selected services are invoked and combined to complete the task collaboratively. Finally, the results are fed back to the users.

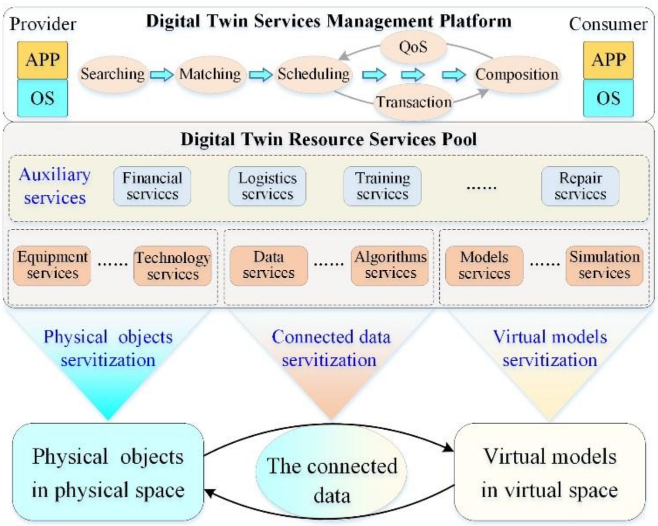

Fig. 1. The digital twin service management and applications.

The digital twin services can be used in product design, production planning, manufacturing execution, and equipment PHM (Prognostic and Health Management), and other applications [21].

In product design, it is the process of back-and-forth interactions between the expected, interpreted, and physical worlds [22]. The digital twin driven design is to turn the expected product in the designer's mind into the digital representation in interpreted world based on the existing physical products. To innovate product, designer have to study plenty of data to acquire valuable knowledge [23]. However, the data about product is one of the most important assets, which is not easy to access. Besides, the designers also do not have the professional abilities to process massive data. Service is an answer to above problems. Designers just simply submit their needs to the services management platform. Services managers will match the data services which designers need and the models and algorithms services that are used to process the data. Through invoking, combining and operating these services, the results are returned to the designers. As a result, designers acquire what they want in the "pay-as-you-go" manner [24]. Moreover, after the function structure and components of product are designed, the design quality and feasibility need to be tested. In virtue of digital twin, designers can quickly and easily forecast product behavior through verification of virtual products without having to wait until the product prototype is produced [25]. But the virtual verification need the models of manufacturing site (e.g., production line or shop-floor, etc.), which designers do not have. After services encapsulation, the models services can be used through services searching, matching, scheduling and invoking. Through services, digital twin can be easy applied in product design, which can make product design more effectively to reduce the inconsistencies of expected behavior and design behavior, and greatly shorten design cycles and reduce costs.

In general, product manufacturing is the whole process from the input of raw materials to the output of finished products, which is executed in shop-floor. To reduce cost, production time, and improve efficiency, production planning to predefine the manufacturing process is necessary. In the phase of production planning and manufacturing execution, digital twin provides an effective method to draw up the plan and optimize and execution process [26]. Firstly, a production task is submitted to services management platform and resource services supply-demand matching and scheduling are carried out to find available resources. Then, based on the real-time status of physical resources (e.g., machine tools, robot arms, etc.), production plan is drawn up. Digital twin shop-floor can simulate the plans in virtual space and finds out the potential conflicts before even during the actual manufacturing process [14]. However, the digital twin shop-floor is a complex and specialized work to be built, especially the models including geometry, rule, behavior, dynamics models. With the help of services, these models do not have to be created by manufacturer themselves. For physical equipment and pervasive rules, their models which have been established by other manufacturers, can be bought to use in the form of services. Current manufacturer only need to create the special models, which is only suitable for themselves. Besides, during the operation of the shop-floor, some services, such as data processing, shop-floor management, etc., need to invoke from the services system of digital twin shop-floor.

The performance degradation of physical equipment is inevitable. When the equipment malfunction, it would result in high maintenance costs and postponement of tasks. PHM is necessary to monitor the equipment condition, predict and diagnose equipment faults and component lifetime [27]. In digital twin driven PHM, the virtual models of physical equipment are synchronized with the real state of the equipment. The operation status of the equipment, and the health status of the components, are grasped in real time. A high-fidelity digital mirror for the equipment provides access to the equipment even out of physical proximity. Besides, the interaction of digital twin can reduce the disturbances from the external environment, improving accuracy. In above process, the models are accessed through services. Moreover, when the failures occur, repair services are invoked to repair, or replace the broken-down equipment.

5 Conclusions

Digital twin (DT) has provided a promising opportunity to implement smart manufacturing and industrial 4.0 by integrating the cyber and physical worlds in manufacturing. The service-oriented architecture may expand the functions of DT. Through services, DT can have high potential application in design, manufacturing and PHM. Combined with the services and the digital twin, how the various components of digital twin are encapsulated to services and used in the form of services specifies, are specified. At present, the research is just at its infancy. It still needs much more works to improve and enrich the methods of DT modelling and servitization.

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