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MetaTwin: The Foundation Element of Cloud Manufacturing Metaverse

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Abstract. The tread towards manufacturing digitalization facilitates the establishment of a uniform cyber-physical manufacturing world, which forms metaverse of cloud manufacturing (CMfg). As an enabling cyber-physical technology, digital twin (DT) has been widely applied to build vivid instances of physical manufacturing resources in CMfg world. However, current DTs are formulized on different granularities, which makes it difficult to organize and configure these granularities in a uniform CMfg metaverse. Hence, this paper proposes the concept of MetaTwin as the foundational elements of CMfg metaverse. The scientific characteristics of MetaTwin are defined and general relationships between MetaTwins are extracted and summarized to configure fine-grained MetaTwins into different logical DTs in CMfg metaverse. Finally, related cutting-edge technologies are given to develop and implement MetaTwins in terms of characteristics and relationship requirements.

Keywords. Industry 4.0, Cloud manufacturing, digital twin, MetaTwin, metaverse

Introduction

Cloud manufacturing (CMfg) migrates and extends the concept of cloud computing to manufacturing industry so that the distributed manufacturing resources and capacities can be virtually integrated and efficiently managed in a centralized way to satisfy the increasing production demands on personalized and customized with small quantity [1]. CMfg has changed the organization form of resources, towards a flatter way, due to service-oriented encapsulation and representation of resources in cloud. This flat organization form promotes the flexibility and reconfigurability of manufacturing systems through service collaboration [2]. Meanwhile, CMfg facilitates the absorption and integration of idle and scattered manufacturing resources, which forms an extremely large and scalable manufacturing services pool depending on new generation information and communication technologies [3].

The service-oriented construction of manufacturing resources has become the major dependency of CMfg to deliver production capacities. To optimize and intelligentize CMfg services, digital twin (DT) has been emerged as an underlying technology to establish vivid virtual entities of manufacturing resources for cyber-physical synchronization [4]. Both academic and industry are exploring to make more DTs

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connected to build CMfg networks of all scale. With the improving communication and security technologies, these CMfg networks tend to be converged into a larger single one, which can finally form a CMfg metaverse.

The emergence of the CMfg metaverse can bring great revolution to the manufacturing industry. First, it can promote the globalization of manufacturing, to break the barriers of geography, border, and organization. Global manufacturing resources can be digitalized into this metaverse through DTs which can be connected, coupled and collaborated to satisfy differentiated production needs. Second, the CMfg metaverse facilitates the establishment of uniform criterions to measure, assess and evaluate capacities, performances, and qualities of DTs. This contributes the transparency, credibility and sustainability of manufacturing ecosystem. Third, the CMfg metaverse can bring manufacturing intelligence to a new level. More knowledge can be extracted, improved and transferred via mass data generated in this metaverse to promote the intelligence of DTs. Meanwhile, the large-scale DTs can also enhance and evolve more swarm intelligence of the CMfg metaverse.

The successful formation of CMfg metaverse must depend on the fusion of DTs. However, there exists a series of challenges to manage the large-scale DTs in CMfg metaverse, as stated below.

(1) How can the granularity of DTs be defined with scientific characteristics to act as foundation elements to generate the CMfg metaverse?

(2) How can the relationship of DTs be abstracted in this metaverse so that it can generalize and formalize the complex permutation and combination of DT elements?

To address above challenges, this paper proposes a novel DT concept, called MetaTwin, as the foundational elements of CMfg metaverse. The natural characteristics of MetaTwin is defined in terms of constructing, representing and maintain a CMfg metaverse. Meanwhile, six types of abstracted relations are designed to configure, combine and assemble MetaTwins into different granularities so that they can be easily accessed, invoked and managed in CMfg metaverse. The rest of this paper is organized as follows. Section 2 makes the definition of MetaTwin and section 3 gives the general relations to configure MetaTwins. Section 4 illustrates core technologies for MetaTwin implementation. Finally, section 5 concludes this paper and outlines the future works.

1. MetaTwin Definition

The MetaTwin is defined as the most fine-grained DT entity that can maintain digitalization uniqueness and consistency to a physical object and enable atomicity, durability and composability during its lifecycle so that it can be (re-)configured to combine and collaborate logically to establish the CMfg metaverse. Specially, the five key characteristics of MetaTwin is extracted and illustrated as follows:

- Uniqueness

The uniqueness guarantees that there is only one MetaTwin for a manufacturing resource in CMfg metaverse. The uniqueness manifests in different respects. First, a MetaTwin must work in a singleton pattern to ensure that only one instance of the MetaTwin ever exists in the running environment. Second, a MetaTwin must provide a global access to its instance so that it can be indexed and invoked. Third, a MetaTwin must be given a unique identifier for identity recognition in terms of instance discovery, communication, data aggregation and service association. The uniqueness is the foundation to establish

CMfg metaverse because it keeps an exclusive abstraction and description of manufacturing resources during their digitalization.

- Consistency

The consistency strengthens the multi-dimensional synchronization between MetaTwin and its physical resource. The underlying dimension is lifecycle consistency so that a MetaTwin can be created, migrated, removed from the CMfg metaverse, in accordance with resource installation, transfer and retirement. Another dimension is data consistency. It restores real-time states of physical resources continuously to MetaTwins with a high fidelity and synchronizes the decisions of MetaTwins to resources for execution. The third dimension is environment consistency to ensure that MetaTwin maintains the same geographic and spatial relationship in CMfg metaverse as physical world. The consistency is the critical dependency to maintain the most vivid CMfg metaverse.

- Durability

The durability refers to the ability to persistent data in the form of objects, or records that are durable while the whole lifecycle. The durability of a MetaTwin manifests in two aspects: object durability and process durability. The object durability denotes that a MetaTwin can keep the consistency data into a persistent repository so that it can retrieve and restore all instantaneous states of a MetaTwin during its lifecycle. The process durability enables persistent storage of the runtime state of running process instances of a MetaTwin. Thus, a MetaTwin can continue execution of a process instance if the process stopped or encountered a problem at any point. Generally, the durability establishes the data basis for a MetaTwin to form a data-intensive digitalization of the physical resource.

- Atomicity

The atomicity defines that a MetaTwin is the indivisible granularity for the smallest controllable physical resource that is capable of communicating and sensing. Meanwhile, it also requires MetaTwin as the basic unit to execute a specific production task separately. The atomicity guarantees CMfg metaverse to be constructed on a uniform and fine granularity with both physical and logical concerns so that the MetaTwin could be flexibly coupled, scaled, and collaborated to suit the varieties of manufacturing demands.

- Composability

The composability empowers the atomic MetaTwins to configure their so that MetaTwins can be selected and assembly in various combinations to satisfy specific functional requirements. The composability manifests in two aspects. One is the physical composability that the manufacturing resources may be combined to execute production tasks. For example, a production line usually consists of a series of machines with definite processing parameters. The other aspect is the logical composability that MetaTwins are collaborated commonly on the CMfg metaverse as a whole to undertake production demands. Generally, the physical composability must result in logical composability, but not vice versa.

2. MetaTwin Configuration

Due to the atomicity and composability of MetaTwin, there are five basic relationships to (re-)configure MetaTwins as more complicated DTs that are logically for management and operation in CMfg metaverse. According to the coupling strength between MetaTwins, the description for each relationship is illustrated as follows.

- Dependency

Dependency is a relationship that a MetaTwin requires other MetaTwins for their specification or implementation. It is the loosest coupling and usually represents as a kind of usage relationship. Dependency maintains the independence of each MetaTwin and facilitates a peer-to-peer collaboration to take effect in CMfg metaverse. Since the dependency has been made on underlying communication, such as, APIs, any change in a MetaTwin for external communications will affects all other dependent MetaTwins.

- Association

Association is a structural relationship that represents how two MetaTwins are linked, connected or merged each other to constitute a more complicated DT. It can form two major categories of association types. One is categorized by quantitative relations, including one-to-one, one-to-many, many-to-many associations. The other category is based on binary relationships, including bi-directional, unidirectional, aggregation and reflexive. Due to the structural feature, association maintains a long-term, static and stable relationship between MetaTwins, which cannot be temporarily or dynamically changed or removed upon relationship establishment.

- Aggregation

Aggregation portrays a part-whole or part-of relationship between MetaTwins, which forms a weak association. It specifies the direction of a MetaTwin contained in another MetaTwin. While, in aggregation, all MetaTwins have independent lifecycle so that a child MetaTwin can exist independent of its parent MetaTwin.

- Composition

Composition represents a whole-part relationship between MetaTwins and is a special kind of aggregation. Composition strengthens the lifecycle synchronization so that a constituent MetaTwin has a strong lifecycle dependency on its host MetaTwin.

- Generalization

Generalization describes the maximized abstraction relationship among MetaTwins so that the commonness can be extracted from similar CMfg resources. Generalization facilitates the reusability of existing MetaTwins as a template to generate a variety of derivatives. Meanwhile, a template MetaTwin can be taken as an instance in CMfg metaverse if the additional features of CMfg resources can be added through a dynamic way.

3. MetaTwin Implementation

To implement a MetaTwin, some cutting-edge technologies should be integrated in CMfg metaverse to enabling the features of MetaTwins, which requires transdisciplinary knowledge in different domains [5].

- Uniqueness implementation

Since uniqueness is critical to physical and cyber spaces, its implementation should consider both spaces' feature. Generally, the uniqueness of CMfg resources can be guaranteed by three levels. The bottom level is resource access uniqueness that requires each resource to be assigned with a unique resource identification through a consensus coding system. The media access control (MAC) address can be referred with further consideration of address capacities and resource lifecycle [6]. The middle level is network uniqueness that can mark a specific network location of a resource access identifier. IPv6 [7] like network protocol can be adopted to support this level. The upper level is session identity uniqueness to ensure that each resource can obtain an exclusive identity through a trusted identity certificate authorities for establishing sessions between MetaTwins. Furthermore, blockchain technology can be integrated as an underlying method of CMfg metaverse to act as decentralized authorities to issue and manage identities to maintain their uniqueness [8].

- Consistency implementation

The implementation of consistency depends on three kinds of enabling technologies. Communication technology is the most important to construct an underlying transmission channel between physical and CMfg metaverse. The high bandwidth and low latency of 5G make it more suitable as a wireless choice [9] and traditional high-speed wired network is alternative if wiring is allowed. Upon communication, gateway technology is critical to maintain the cyber-physical consistency. Generally, gateway is responsible for collecting real-time data from physical space and aggregating these data to corresponding MetaTwins [10]. The last but not the least technology focuses on consistent interaction, which allows end-users to operate MetaTwins just as to interact physically. AR, VR, MR and XR technologies can be adopted to build consistent interoperability to merge cyber-physical interactions [11].

- Durability implementation

The implementation of durability consists of three storage technologies, including block storage, file storage and object storage. Block storage splits data into singular blocks and then persists these blocks as separate pieces of data. Each piece of data has an independent address so that block storage follows a loose structure. The long-term preservation data of MetaTwin, such as operations data or running data, should be kept in block storage structure due to the large amount of data and privacy concern. File storage organizes and stores data in a hierarchical structure. Usually, data is stored in the format of file and further organized and retrieved using folders and directories. MetaTwins depend on file storage to store different keys, configuration files and statistical reports. Object storage takes each piece of data and designates it as an object. Since a MetaTwins has lifecycle feature with various state tags, object storage is critical to store instantaneous states of the MetaTwin.

- Atomicity implementation

The atomicity implementation of MetaTwin draws inspiration from the finite element method (FEM). The core spirit of FEM, “divide and conquer”, is frequently applied in analyzing structural, mechanical, electrical, and thermal systems in engineering and applied science [12], [13]. In general, FEM divides the initial complex problem domain into finite simpler elements, for which unknown functions are approximated so that corresponding equations are easy to formulate and solve. Then simple elemental equations are connected into an equivalent system of equations, and certain boundary conditions are invoked to model the initial complex problem. FEM effectively captures local effects and builds a global solution.

Following the FEM principles, there are four basic steps in finite element-based MetaTwin atomicity implementation, as shown in Figure: (1) Divide an originally complex system into finite individual physical elements whose behaviors and operations are certain and straightforward; (2) Build up digital and operational models of all physical elements by reasonable abstraction/approximation, then combine physical elements and their DTs as MetaTwins; (3) Identify and dynamically update key boundary conditions among MetaTwins, namely, how MetaTwins connect and relate to each other;

and (4) Assemble all MetaTwins into a metaverse as a faithful representation of the original system and establish effective mechanism to manage MetaTwins.

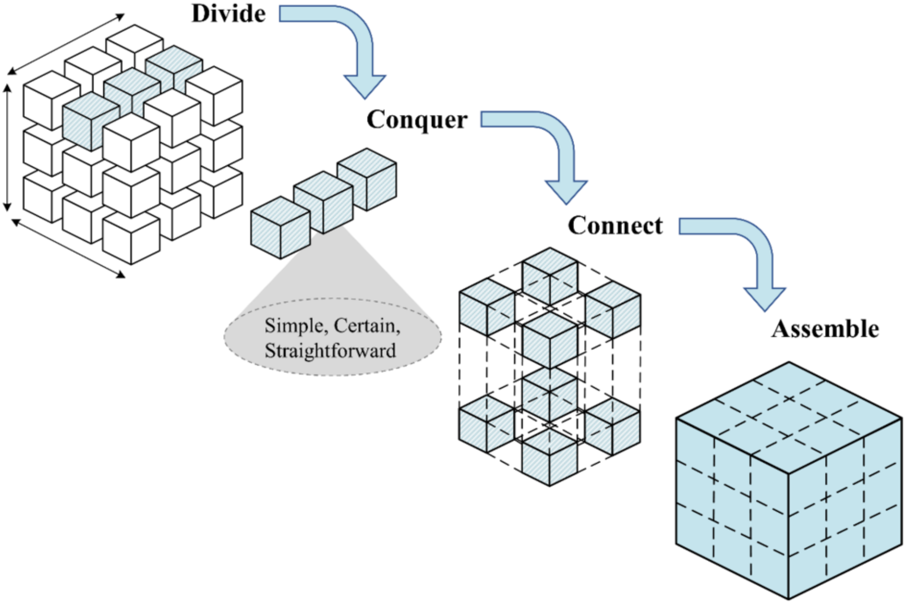

Figure 1. The schematic diagram of finite element-based MetaTwin atomicity.

Modern CMfg systems are usually characterized by the presence of distributed and heterogeneous manufacturing resources with complex and dynamic interactions. The “divide and conquer” spirit can be carried forward in the MetaTwin generation for establishing the CMfg metaverse. This study divides a complex CMfg system into smaller elements by meshing so that the inherent system complexity and uncertainty can be significantly reduced, and DTs can be easily managed and coordinated.

The first step aims to divide the complex organization and workflow of a CMfg system into finite smaller elements with simpler digital and operation models to reduce the overall complexity and localize uncertainty as the basis for digitization. Genereally, this step follows a top-down and hierarchical approach, discretizing the overall system into individual elements based on predefined criteria (e.g., spatiotemporal attributes, functionality, responsibilities). The logical scale of elements should be small enough to have simple behaviors while also large enough to have a complete operational mode. For example, a general workshop is naturally divided into a set of workstations. These workstations may differ in their configurations, responsibilities, and scales. Each workstation is subdivided into smaller discrete objects (e.g., operators, machines/tools, robots, etc.) whose behaviors and operational mode are readily understood and well-defined.

The second step is a bottom-up digitization process, aiming to transform heterogeneous and hierarchical physical objects into faithful DTs by deploying a set of plug & play, self-configurable, and scalable IIoT devices for creating highly visible, traceable, and interconnected CMfg environments. IIoT devices collect real-time data regarding key attributes, behaviors, and operations to build and update the digital and operational models of elements, which should be relatively simple, certain, and straightforward as the complexity and uncertainty of each element are slashed in the first step. MetaTwin is defined as the fundamental element of CMfg metaverse, composed of a physical object with IIoT devices and its equivalent DT. MetaTwins can act/interact with autonomy, sense the surroundings, analyze real-time data with reasoning, finally make decisions and measure the performance.

Subsequently, the boundary conditions (i.e., connectivity and relationship) among MetaTwins need to be identified and established using real-time IIoT data. Given the heterogeneity of CMfg resources, the actions/interactions among CMfg MetaTwins can be highly complicated and dynamic. On the one hand, the boundary conditions are multi-dimensional and thus should be described from multiple perspectives such as structural, functional, and belongingness. On the other hand, these boundary conditions are time-varying and play a critical role in representing and updating the whole CMfg system in real-time. In this regard, a set of primary boundary conditions are defined, and all MetaTwins are connected together with the combinations of these primary boundary conditions. Meanwhile, real-time IIoT data builds up cyber-physical visibility and traceability of the CMfg system, which promises to capture the dynamics of MetaTwins and update all boundary conditions.

Lastly, all MetaTwins are assembled into a whole CMfg metaverse using boundary conditions as a faithful approximation and representation of the original CMfg system. Seamless circulation of data and information between the physical and cyber world forms a solid basis for designing more advanced mechanisms. Benefit from the interconnectivity, visibility, and transparency in CMfg metaverse, advanced data analytics (both big data and real-time data) and innovative decision intelligence (both global decision and local decision) are integrated into the mechanisms. These mechanisms facilitate the management of MetaTwins and their operations and coordinate initially separated and distributed decision authorities, processes, and participants in CMfg to enhance the overall performance considering both global and local benefits.

- Composability implementation

The composability implementation consists of three enabling technologies. The first technology is the microservice-oriented architecture that abstracts and wraps each MetaTwin as a single microservice [14]. Since microservices can be easily and flexibly combined and connected, this generalizes the composability of MetaTwins. Meanwhile, the microservice-oriented architecture also contributes to maintain the atomicity because a microservice is the fine-grained service unit. The second technology is the application programming interface (API) based on representational state transfer (REST) architecture [15]. This allows the microservices can communicate in a loose way based on HTTP methods to access MetaTwin's internal resources via URL-encoded parameters and the use of structured text (i.e., JSON or XML) to transmit data. The third technology is low-code development schema that provides a development environment used to create an integrated DT application through a graphical user interface [16]. It encapsulates the working logic to associate with MetaTwins for specific situations so that MetaTwins can be combined as a whole with separated behavioral functions in CMfg Metaverse.

4. Conclusions

This paper has proposed a novel concept of MetaTwin as the foundation element to construct CMfg metaverse. The scientific characteristics of MetaTwin are identified and summarized for MetaTwin definition. Moreover, the basic relationships between MetaTwins are extracted to assemble MetaTwins into more complicated DTs that are logically for management and operation in CMfg metaverse. Finally, the cutting-edge methods and technologies are suggested to enable the development and implementation of MetaTwins.

Since this paper focuses more on the conceptual definition, configuration, and implementation of MetaTwin, a series of follow-up studies can be conducted, especially from three aspects. First, a real-life case study should be conducted based on the concept of MetaTwins and a CMfg metaverse can be established through configurations and implementation of MetaTwins. Second, to realize the flexible configuration of MetaTwins, many standardization works should be done in terms of architecture, protocol, and interface. Third, security and privacy concerns on MetaTwin should be further discussed to construct a real, trustful, and sustainable CMfg metaverse.

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