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Perspective

Digital twin for industrial internet

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A R T I C L E I N F O

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A B S T R A C T

Industrial Internet upgrades the traditional industrial manufacturing to digitization, networking and intellectualization era, which calls for brand-new technology supports. As a promising solution, the emergence Digital Twin (DT) offers enhanced digital mapping capability with strong feasibility, security, economic and intelligence, which fits well with the concept of Industrial Internet. In this paper, we focus on establishing a new reference architecture of DT to support the development of Industrial Internet. It is composed of three interdependent layers (i.e., physical layer, DT layer and DT networks layer) and four critical attributes (i.e., privacy, security, awareness and real-time). We illustrate our perspectives for the functionality and relationship of the three layers, and features and feasible solutions of the four attributes. With those efforts, the proposed DT architecture can provide both smart manufacturing and networked services for Industrial Internet era. Moreover, we also illustrate the relevant and open challenges. Finally, the conclusion and future perspective are pointed out.

1. Introduction

To facilitate industrial revolution, “Industrial Internet”, a concept from the U.S. (or similar concept, e.g., “Industry 4.0″ from Germany or “Made in China 2025″ from China) has received increasing concerns. By integrating advanced information (e.g., Internet of Things (IoT) and Cloud Computing) and industrial manufacturing techniques, Industrial Internet enables digital transformation to produce smart products, factories and services [1]. Digital knowledge is required to abstract virtual physical objects, which benefits the construction of smart features in Industrial Internet era. As a promising solution, Digital Twin (DT) is characterized by formulating a one-to-one mapping between a digital representation in digital space and a physical entity in real world [2]. It captures the historical, contemporary and future behaviors to prompt business outcomes [3]. DT enables the manufacturing industry shifting from knowledge-driven model to data-driven and knowledge-enabling model. In this scenario, an entity or system can monitor its physical states, predict the evolution, adjust the generation process, and design optimal products with better feasibility, security, economic, and intelligence [4]. With these advanced capabilities, DT is viewed as a promising technology to fill the gaps (e.g., model and methodology) between the perspectives and executions of Industrial Internet.

Up to present, several DT architectures, definitions and reference models have been presented [5], with potential applications in the fields of aviation, healthcare, 6 G and energy, etc. When multiple interconnected DTs form a larger-scale system, the DT should not be limited to an individual entity but should be extended to a wide range of services, leading to more potentials and challenges. To tackle those challenges, several studies focus on establishing networked or interconnected DTs. For instance, a DT-II reference framework was presented in ref [6], which offers an operation and execution mechanism of DT-II from three levels, i.e., product lifecycle level, intra-enterprise level, and inter-enterprise level. This framework supports the collaboration of different entities or enterprises to perform networked manufacturing, resulting in improved production and reduced cost. The study in ref [7] designed a DT with application to connected micro smart factory. It enables the utilization of Industrial IoT to monitor the current states and predict the future movement. On the basis of ref [7], the concept of network DT for Industrial IoT was proposed in ref [8]. This architecture employs software defined networking (SDN) to achieve the interaction between the network DT and DTs. In the same year, Wu et al. [5] presented and defined the DT networks that are extended by multiple DTs. Meanwhile, this study provides insights on the enabling technologies and applications for DT networks. The network DT or DT networks can offer well networked services, which is beneficial for the development of Industrial Internet. Although the existing research [5–8] have analyzed DT networks from different aspects (e.g., functionalities, enabling technologies and applications), they do not provide comprehensive analysis from the perspective of attributes enhancement. Note that one primary objective of Industrial Internet is to use the DTs to obtain satisfactory attributes or performances for system upgrading. This calls for new architecture that directly studies the DT and DT networks from the perspective of attributes enhancement.

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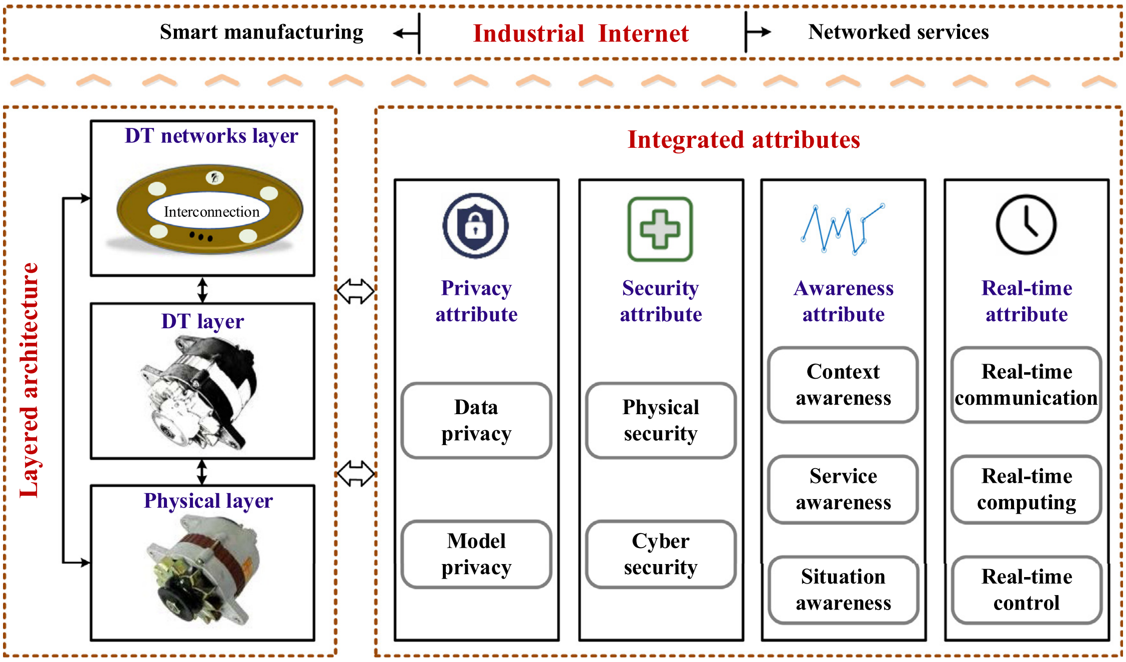

Fig. 1. A "three layers + four attributes" reference architecture of DT supporting for Industrial Internet.

To fill this gap, on the basis of ref [5], this paper presents a "three layers + four attributes" reference architecture of DT, as shown in Fig. 1. We provide insights and perspectives on DT for Industrial Internet, which takes into account layered architecture and enhanced attributes. In the proposed reference architecture, three layers refer to physical layer, DT layer and DT networks layer, which exhibit the hierarchical structure in the vertical. Meanwhile, four attributes refer to privacy attribute, security attribute, awareness attribute and real-time attribute, which elaborates the components, characteristics, and promising solutions in the horizontal to support the layered architecture.

2. Layered architecture: physical, DT and DT networks

In Fig. 1, it illustrates the layered architecture, which contains three interacting components, i.e., physical layer, DT layers, and DT networks layer. Next, we will introduce the major functionalities of each layer, and then show the interaction among the three layers.

(1) Physical Layer. This layer refers to the physical object in real world. It contains at least one physical entity. For different applications, the definition of physical entity may be different, e.g., a device, an equipment or a kind of material. An individual physical entity may be a composition of several physical components, e.g., a generator composed of screws, bearings and diodes. Multiple physical entities can be further interconnected and formed to a system (e.g., power system, healthcare system, smart city, transportation system [9]). The sensors and actuators are outfitted to collect the real-time data of the physical entity and environment and receive the feedback control signal to accomplish a specific task.

(2) *DT layer.* The DT layer focuses on building high-fidelity digital representation for a physical entity, which is a one-to-one mapping. To model the DT, the physical model is considered to describe the dynamics behavior of the physical entity. Note that the physical model may not reflect the reality accurately. To address this issue, state-of-the-art big data analytics (e.g. machine learning) and visualization technologies (e.g., Java 3D model) are further employed to process data, extract hidden attributes, and improve the DT model. This hybrid modeling method enables to create high-fidelity DT model. The DT further offers insights and reflections, and then make decisions. The undesired differences between the DT model and the physical entity will be identified accurately from multiple spatio-temporal perspectives. Then, insight prediction, guideline and adjustment will be generated to improve the DT model and give feedback to the physical asset. To build the DT, three stages are performed, namely learning stage, replica stage and creativity stage. In the learning stage, the shape, dynamics, mechanism and other basis attributes are considered to establish basic-version DT model. Note that it is hard to form high-fidelity digital simulation by only considering visible attributes and mechanism analysis. Next, through bidirectional and dynamic interactions in terms of real data, all hidden attributes will be extracted and integrated into DT models. In the replica stage, a digital replica will be generated in the digital world to predict what happens in near real-time. On this basis, a DT is expected to achieve surreal tasks in the next creativity stage. Unprecedented products and individualization design will be uniquely created with visualized lifecycle manufacturing processes.

(3) *DT networks layer.* Different from a DT, DT networks are characterized as many-to-many mapping networks. Specifically, DT networks integrate all DT modes and enable deep coordination by making use of advanced network communication technologies e.g., IoT, Cloud and 5G/6G. In the DT networks layer, different physical entities and DTs can freely communicate, interplay and collaborate with each other to form a high-level networked system, which greatly increases the analytic complexity. The major functionality of DT networks is to achieve network management and evolution with high-level production line and high-quality service. Multiple complex situations, interactions, variations and influences will be considered in DT networks. With this effort, DT networks enabled management system is further embedded into service platform. This further offers multiple networked services for Industrial Internet, including data sharing, monitoring, maintenance, planning, co-operative optimization and control. The DT networks layer is also an effective bridge linking academia and industry via public platforms. In this scenario, it enables the platforms providing access to the researchers and engineers trading DT models for further academic research and business applications.

Based on the discussion above, the three layers are connected with each other via communication networks. The physical layer collects the real data from the physical world (e.g., the real-time profiles and operation states) and sends them to the DT layer and the DT networks layer. By using the real data, the DT layer will create one-to-one digital replica of the corresponding physical entity. Then, according to different applications and tasks, the DT layer will predict the future evolution, find the optimal solutions, and send feedback to the corresponding entity in the physical layer. The actuators will receive the well-made feedback signal and response to the corresponding operations. Considering cross-entity, cross-enterprise, cross-area, or cross-country cooperation, the DT networks layer performs many-to-many digital replica. It will record the model of individual DT from the DT layer and receive multiple objectives from the physical layer. Then, the DT networks layer makes decisions and generates feedbacks to the DT layer and the physical layer to update the models of DTs and perform real-time adjustment, respectively. Owing to the dynamic interactions among the three layers, the layered architecture enables both smart manufacturing and networked services.

3. Integrated attributes: privacy, security, awareness and real-time

(1) Privacy attribute. The privacy attributes contain the data privacy and model privacy. To build the DT and DT networks, it is needed to collect the real-data and mapping models. Those contain multiple types of privacy information. However, the physical entities may not want or even allow to upload their real data and DT models to other platforms, which degrades supports for the development of DT networks. As a promising solution, the federated learning with standard data sharing from GAIA-X project is capable of providing decentralized data trading and privacy-preserving concerns. However, this method suffers from limited applications. To obtain more universal solution, one potential way is to design a transformed DT with bidirectional transformation function. Specially, we can build two parallel DT mapping models in the DT layer, namely as real DT model and transformed DT model. As a traditional DT, the former is built upon the real-data. The latter is obtained based on the transformed data via a privacy and well-design transformation function known by itself only. The transformed DT model is more like a high-fidelity digital simulation of the physical entity in a twist space. Then, in DT networks, we only need to share the transformed data and transformed DT models to avoid privacy disclosure. The feedback signals are first converted through bidirectional transformation function, then estimated by the real DT, and finally sent to the actuators in the physical layer. Note that the bidirectional transformation function plays important role to achieve this concept. We may use the complex function to design the bidirectional transformation function. Meanwhile, the corresponding theoretical analysis methods can be used to guide the system operation. In this scenario, the real DT and the transformed DT are in real field and complex field, respectively.

(2) Security attribute. The security attribute of Industrial Internet can be classified as physical security and cyber security, which occur on the physical entity and cyber space, respectively. Multiple kinds of factors can cause the security issues with diversified forms. For instance, the fault, disturbance, maloperation and imbalance of physical entity may bring physical security issues. Meanwhile, the packet loss, time delay, threat, cyberattacks (e.g., false data injection and DoS) may raise the cyber security issues. From the perspective of system security, an ambitious vision in Industrial Internet era is to endow DT networks with the capability of smart evolution. It means that as the changes of economic, environment, human activities and system operation, DT networks can achieve smart response, evolution and upgrading in the composition, structure, operation mechanism, and industry chain to eliminate potential security risks. To achieve this goal, we consider four indispensable technology indexes to build high-security DT networks, i.e., global controllability, observability optimization and stability. The controllability enables the system obtaining whatever dynamic performance is acceptable under control input. The observability concerns the ability to see what is going on inside the system. The optimization implies that we can obtain the optimal solutions for the studied problem with multiple trade-off objectives subject to complex system constraints. The stability implies the capability of resistance to change or remaining within specifications. Multiple advanced technologies offer the potential possibilities to achieve this vision, such as the deep combination of reinforcement learning, federated learning, blockchain and access control, etc.

(3) *Awareness attribute.* Awareness means having knowledge or discernment of something to be happened. It is an important attribute to achieve smart manufacturing and service in Industrial Internet era. In this perspective, we consider three interrelated awareness attributes, i.e., context awareness, service awareness and situation awareness. Specifically, context awareness means being aware of every piece of information employed for characterizing the situation of an entity. Service awareness aims to use service requirement and related information to automatically identify and select optimal servers. Situation awareness refers to the cognitive process about dynamic environments, which contains perception, comprehension and projection to gradually understand the current state and predict the near future. Integrating those awareness attributes is the trend for future Industrial Internet. This can not only promote the upgrading for each of them but also provide the entire system with the capability of accurate awareness in the whole domain. It further enables DT networks linking context information, learning the physical entity, understanding the environment, predicting the development trend, creating full lifecycle processes, and providing high-quality networked services in a better way.

(4) *Real-time attribute*. The interactions among physical layer, DT layer and DT networks are built on the real-time information sharing and feedback. The requirements of real-time attributes include real-time communication, real-time computing and real-time control. Those are reflected in processes of physical-to-physical, physical-to-DT and DT-to-DT. Several advanced technologies offer promising solutions. The first one is the edge computing that moves computing resources from cloud center to the originating source. This kind of distributed computing framework enables DT networks being with fast response time and high reliability. The second is the emerging 5G/6G wireless technology with extensive network capacity, low latency and high efficiency. The last but not the least is the distributed optimization and control methods, e.g., consensus-based method, multiagent reinforcement learning and federated learning. By using those distributed methods, the global computation and control tasks are divided and assigned to distributed participants. This can significantly reduce computation burden and quickly response to system requirements.

4. Advantages and examples

Compared to the exiting research [5–8], the advantages of the proposed reference architecture can be summarized as the following two aspects. On the one hand, the layered architecture possesses strong universality, which is suitable for different fields or systems, e.g., energy, transportation, and healthcare. The strong universality facilitates the integration of achievements coming from different fields, which jointly promotes the development of Industrial Internet. On the other hand, we provide comprehensive analysis to support layered architecture from four aspects, i.e., privacy, security, awareness, and real-time. The insights on the feasible solutions and enabled technologies are also proposed to enhance those attributes. Distinguished from the exiting research [5–8], we focus on the design and achievement of DT for Industrial Internet from perspectives of attributes enhancement. This fits well with the primary objectives of Industrial Internet directly.

To better understand the application of the proposed architecture, we take the energy interconnection system as an example. Specifically, Zhang and Sun [10] first proposed and investigated the optimal control and safe operation for energy interconnection systems. For such systems, all the physical entities (e.g., inverters, combine heat and power (CHP) units, power lines and heat lines) are in the physical layer. We can establish a DT for each physical entity (e.g., an inverter) to simulate its profile and dynamics in the DT layer. Then, the DT can be used to guide the smart manufacturing for the inverter in full lifecycle and generate a new product, such as the upgrading from single-phase inverter to three-phase inverter. DT networks encode the models of DTs or the ones of transformed DTs with the consideration of privacy attribute. Then, considering complex networked services, (e.g., the cooperative control and operation among inverters), DT networks enable the collaboration of DTs to predict the evolution of the energy interconnection system, find the optimal solution (e.g., optimal power generation), and send feedback to the inverters. In addition, DT networks are also beneficial for the improvement of individual DT model. For instance, there exists circulating current among inverters, which may lead to instability. The DT networks can identify this problem and attempt to design resistance strategy during the cooperation processes. New product requirement will be feedback to the individual DT such as re-designing hardware topology or being equipped with isolator to restrain the circulating current, which offers new commercial opportunities.

5. Challenges

Although the concept of DT to support Industrial Internet has been proposed for several years, there are still many open challenges needed to be tackled, especially for the development of DT networks, as follows:

- Standard. DT networks are large-scale complex systems integrating multiple DTs, each of which may utilize different standards and protocols. The conversion among different data formats and standards will lead to unnecessary waste of computing resources and increase the security risks. Thus, how to establish uniform and standard model, data and protocol to link diversified DTs and improve the compatibility of the whole system is a significant challenge for DT networks.
- Technology. Although we have pointed out some promising solutions to enhance the privacy, security, awareness and real-time, they may pose new technological challenges. For example, the transformation function/model plays important roles in the reference architecture. Thus, how to design the transformation function with better flexibility and expansibility is an open issue. Moreover, the accurate analysis of big-data, cost-saving computation and high-reliability connectivity of DT networks call for new technological methods.
- Policy. The development of DT requires a lot of human and financial investments with a variety of uncertain risks. Futuristic and unrealistic goals result in the weakened motivation for companies to invest heavily in establishing DT networks. Meanwhile, there is currently few collaborations between academia and industry for the investigation of DT. It is attractive to make more policy incentives to support the individual company and promote the deep collaboration of academia and industry.

6. Conclusion and future perspective

In this perspective, we proposed a “three layers + four attributes” reference architecture of DT in Industrial Internet era, where three layers contain physical layer, DT layer and DT networks layer, and four attributes contain privacy, security, awareness and real-time. We focus on elaborating the components, structure, features and promising technical methods of the proposed architecture from perspectives of attributes enhancement. With those efforts, the proposed reference architecture has strong support for the development of Industrial Internet considering wide and high-quality cooperation and service. Moreover, we analyzed the advantages of the proposed method by comparing with the existing studies and took the energy interconnection system as an example to show the application procedure. Finally, we have pointed out the open research challenges in terms of standard, technology and policy. In future, we will focus on the specific implementations of key technologies, experimental verifications in typical scenarios, and the design of standardization.

Declaration of Competing Interest

The authors declare that they have no coflicts of interest in this work.

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