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REVIEW

REVISED A review of the technology standards for enabling digital twin [version 2; peer review: 2 approved]

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Abstract

In the process of developing digital twin enabling applications, a lack of reference to standards related to digital twin terms, architecture and models leads to differences between users' understanding of digital twin, and it is difficult to realize the interconnection of data, models, and services between different enterprises or fields. Therefore, digital twin, by its nature of interoperability between multiple domains, requires standardization as a pilot tool for implementation. This paper provides the background and introduction of digital twin technology based on the digital twin five-dimension model, then refers to the latest developments of digital twin standardization. We further analyze the challenges and provide suggestions of future digital twin standardization. The analysis of the standards landscape for digital twin consolidates information from governing bodies such as the International Organization for Standardization (ISO), International Electrotechnical Commission (IEC), International Telecommunication Union (ITU), and Institute of Electrical and Electronics Engineers (IEEE)

Keywords

Digital Twin (DT), standard, five-dimension model

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REVISED **Amendments from Version 1**

According to the suggestions of reviewers, the paper is updated as followed. i) Some language expressions are modified in this paper for clarifaction ii) The standard "ITU - scdt" recently reached consent, so the definition of digitaltwin of this document was updated to newest version in chapter "Framework of DT standards". iii) Because digital twin technology is highly related to verticals, a short paragraph is added in chapter "Suggestions" to analyze what the type of vertical industry are urgently require of digital twin technology and its standards. In addition, two paragraphs are added to describe the challenging problems, methods and applications when implement digital twin in chapter "Challenges" and "Suggestions".

Any further responses from the reviewers can be found at the end of the article

Introduction

The Digital Twin (DT) is proposed by Professor Grieves[1]. It is considered to be as an organic whole of physical asset (or physical entity) as well as its digitized representation, which mutually communicate, promote, and co-evolve with each other through bidirectional interactions[2]. The digital twin originated in the military and aerospace fields[3], but it has been widely used in industry[4,5] and smart cities[6–8]. In recent years, the digital twin has continued to expand to vertical industries, such as transportation and health care, to achieve mechanism description, abnormal diagnosis, risk prediction, decision assistance, and other applications[4]. A major challenge for smart manufacturing is the need to enable each factory element to function with intelligence and as such providing timely response to the changing requirements. DT is a tool to overcome these challenges with characteristics such as virtual reality integration, real-time interaction, iterative operation and optimization, all element / all process / all business data driving, and so on[9]. DT has been widely studied by academia and industrial researchers. According to statistics, more than 1000 research institutions from over 50 countries such as the United States, China, and Germany have carried out digital twin theory and application research, and relevant research results have been published[4]. At the same time, Siemens, Tesla, ANSYS, GE, PTC, Dassault, and other global well-known enterprises have carried out the implementation and application practice of digital twins in their relevant fields[1,2,4–20]. In the process of creating digital twin enabling applications, interoperation and interconnection among different enterprises or fields will be inevitable and as such it is necessary to establish relevant standards to enable such inter-operations. With the purpose of building a closed-loop of an intelligent decision-making optimization system, DT applications rest on the cooperation of full/all elements from different domains. Standards ensure intra and inter-operability of products and services produced. Their compliance is mandatory for product commercialization, and the standard serves as a fundamental building block for product or process development and include methods for insuring usability, predictability, and safety of all parties involved in the manufacture of goods or delivery of services. Therefore, relevant standards about DT are the necessary conditions for the implementation of digital twins in various application fields.

Therefore, this research refers to the latest developments of digital twin standardization and provides the background and introduction of digital twin followed by an overview of the digital twin five-dimension model. In addition, we further analyze the challenge and provide suggestions for future digital twin standardization. The analysis of the standards landscape for DT consolidates information from governing bodies such as the International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC), International Telecommunication Union (ITU), and Institute of Electrical and Electronics Engineers (IEEE).

Motivation

The motivation of this paper is to satisfy the need to understand the application of DT for improving products and processes. For many verticals, such as smart manufacturing and smart city, a digital twin system needs systematic design, construction, operation, maintenance, and improvement. There are challenges related to implementing digital twin, such as consistent understanding of DT from different fields, interoperability, etc. Therefore, standardization is expected to be an important tool in the process of implementing DT. The motivation for this study is to summarize the existing digital twin-related standards, learn the lessons from them, and provide guidance for future standardization work. Besides, the systematic review of digital twin-related standards could provide useful information for researchers, and DT solution vendors to study and implement digital twin.

Computer-supported search and review method overview

The methodology for this research begins with a literature search on technical architectures of digital twin. Considering the systematic and granule factors, an appropriate DT architecture is identified. The DT 5-dimension architecture by Tao *et al.*[9] is the fundamental architecture for this work. Then, based on the extracted DT elements from the 5-dimension architecture, the research scope for each of these DT elements is summarized from the collection of research papers, and the key needs for standardization are also illustrated within the research scope. Simultaneously, a standards search based on reports from the leading standardization bodies yields standards that are relevant to each of the 5 elements in the 5D model and are included in the DT standard review.

The rest of the paper is organized as follows: Literature view for digital twins described in Section 2. Section 3 details standards for DT. Discussions about digital twin are presented in Section 4 including challenges and suggestions, followed by conclusions in Section 5.

Literature review for digital twin

This section provides a review of the research countered on digital twin, which targets deployment in various fields and cross-disciplinary areas of science. In order to maintain the focus of our core research on standards relevant to digital twin, the technical architecture, and the applications and challenges are reviewed. Our research requires a comprehensive architecture because the review on DT standards should build on a systematic decomposition of digital twin technologies so that an informative evaluation of current standardization work can be done.

DT architecture

Architecture is a unified structure for the purpose of implementing a technology. It can be used to decompose technology into key elements and help to integrate them into existing or new ecosystem with minimal efforts. There are many proposed architectures for DT. Some literatures[9,11–15] have DT architecture summarization.

The literature review discovers many architectures that are similar in terms of research scope. For example, in 2014, Grieves published the white paper about DT, according to which, the basic DT model consists of three main parts: (a) physical products in Real Space, (b) virtual products in Virtual Space, as well as (c) the connections of data and information that tie the virtual and real products together[11]. Gartner proposed in its Internet of things (IOT) digital twin technology report that building a digital twin of a physical entity requires four key elements: model, data, monitoring and uniqueness[12]. From the perspective of standardization, architecture with properly refined elements is preferred, because it helps to map with each standard. Following this principle, we choose a 5-dimension architecture proposed by Tao *et al.*[9] as the base architecture for our research because of its fine gratuity which enables us to map standards with high clarity in its architectural level.

The selected architecture consists of a physical entity, virtual entity, connection, DT data, and services. The virtual entity is presented as the most important element, and it represents the digital presentation of the physical entity. It does not mean the virtual entity and the physical one is required to exist simultaneously. "Connection" ties different parts of the DT together. DT data fuses all related data from both physical and virtual aspects, and then provides more accurate and comprehensive information through data processing. The "services" (i.e., Ss) enable the various functions in the DT to be standardized and encapsulated, which can help implement easy and on-demand usage.

DT key elements

DT is a broad subject, and the applications are numerous. This subclause deals with publications related to DT. Key points, which are important for smart manufacturing and smart city, determine the classification and selection of papers relevant to the 5D model.

Key review points for the 5D model-physical entity. The physical entity is the bottom-most layer of the five-dimension model. It is the twin of the virtual entity. References[15–20] refer to the physical layer. The physical entity is hierarchical. It generally includes unit physical entity, system physical entity, and system of system physical entity according to function and structure[21].

One of the key elements about the physical entity is that the sensing capability to percept a physical entity is required to be enhanced due to the requirements in many application scenarios. In the process of physical entity perception, there exist some issues, such as heterogeneous interface protocols, cumbersome elements, multi-source interference, etc[21,22]. Some studies focus on the all-factor perception model, adaptive protocol analysis[23,24].

Another point about the physical entity is about the actuating capability. In application fields such as manufacturing, comprehensive and spontaneous actuating is strongly needed. Sensors integrate in-field and real-time raw data into the digital twin. It plays a crucial role in measuring different physical parameters and enabling monitoring, controlling, and decision-support capabilities.

With the development of sensor and communication technologies, more and more types and quantities of sensor data are acquired[18,19]. Reliable sensor measurements are vital for effective control and for the action-taking chain. Therefore, some studies focus on the reliability of sensor data, the deployment of sensors, the frequency of sensor data collection in the digital twin, and so on[21,25]. For example, a machine learning-based three-stage SFDIA (a general Sensor-Fault Detection, Isolation, and Accommodation) architecture with different applications for sensor validation is presented[15].

With respect to standards, protocols for sensing and actuating could facilitate the deployment, and thus should be considered by the DT community.

Key review points for the 5D model-virtual entity. The virtual entity is the most important element of the five-dimension model. It is the basis of all other capabilities. The fundamental issue about the virtual entity is modeling[10,13,25–34]. The goal of modeling is to represent the physical entity in the virtual space so that simulations can be done and provide valuable information to the operation of the physical entity. Model classification, modeling technology, model evaluation indicators, and so on are the research points concerned in this field.

Many studies tried to classify the modeling involved in the virtual entity. For example, in reference to 9, virtual entities are divided into geometric models, physical models, behavior models, and rule models. The digital twin network involves a basic model and functional model, in which the basic model includes the network element model and topology model[34]. In traffic field, the model is divided into the micro-simulation model, mesoscopic traffic simulation model and macro-simulation model according to the degree of detail and scope described by the model. Only by associating, combining, and integrating all dimensional models can we connect and integrate them into a complete virtual entity model with high fidelity at the information space level[10].

Two common modeling methods are prevailing among studies: knowledge-based modeling[35–38] and data-based modeling[13,39–41]. The model can be constructed in knowledge and data-driven way to improve the accuracy and interpretability of the model. Expert systems, fuzzy systems, knowledge graph, etc. are knowledge-based methods which is combined with prior knowledge and is interpretable. This kind of model cannot be updated in real-time and cannot be migrated to different scenarios, so the labor cost of establishing an expert knowledge base is high[42]. Data-driven modeling can solve these problems and it is suitable for nonlinear, multi constraint, and complex model construction. Deep learning, artificial neural networks, integrated learning, reinforcement deep learning, transfer learning, etc. are involved. Studies also note that data-based modeling method has high requirements on data and is weak in interpretability[43]. Some researchers are trying to integrate these two modeling methods[42–46].

In addition, some studies target on systematic evaluation theories and methods of model quality[26,27]. The goal of this research is to facilitate the construction, management, reconstruction and optimization, migration, and circulation of the model. A construction criterion of the digital twin model was proposed which includes "four modernizations, four possibilities, and eight uses". Based on the research of construction criteria, a set of the theoretical system of digital twin model construction is explored and established from six aspects[27]. Then Zhang and Tao refined eight model evaluation criteria, proposed a set of evaluation index systems of the digital twin model, and gave the reference method of quantitative calculation of the index[28].

With respect to standards, unified entity structure, information model, description of sub-models, interoperability, and evaluation framework are needed.

Key review points for the 5D model- digital twin data. Digital twin data is the driving force for digital twin. One of the key points about data in the digital twin is that the data generated by physical and virtual entities places additional requirements to data processing and management in the digital twin. It includes data representation, data classification, data storage, data preprocessing, data fusion, data use and maintenance, data testing, and so on. The data in different fields have different characteristics. For example, industry applications contain structured data, unstructured data, and semi-structured data as PLM (Product Lifecycle Management) and SLM (Service Lifecycle Management)[47]. In a digital twin network, the raw data generated by physical entities have the characteristics of multi-source, multi-scale, and high noise[48]. Some of these data may be congested if they are directly transmitted through the communication system. Therefore, data cleaning and data fusion are needed to improve the robustness and reliability of the twin data[48]. The entropy weight method is adopted for data fusion in intelligent detection robotics[49]. The Bayesian method is more robust when data is scarce and uncertain in aerospace design[50]. Data fusion is studied in many fields[50–55], such as shop floor, intelligent transportation, and city. Another key point about data in the digital twin is security and privacy. As an asset, the data transports between different enterprises and stages of product life cycles, and thus need an appropriate mechanism to protect the right of data ownership. Blockchain and federal learning are promising technologies to improve the reliability and security of the system and enhance data privacy[56–58].

With respect to standards, unified guidance for data processing and management are needed including heterogeneous data conversion, multi-source, and multi-modal data syntax and semantic mapping rules, the rule for data exchange such as data element type, data structures, data library, and data type element.

Key review points for the 5D model- connection.
Connection is to support the interconnection of all components of the digital twin, including the connection between physical entities and virtual models, the connection between physical entities and data, connection between physical entities and services, connection between virtual models and data, connection between virtual models and services, and the connection between services and data. Connection requires unified communication interfaces and protocol. However, there are compatibility problems in connections. For example, industrial data communication is mainly organized according to the automation system Pyramid: standard IT protocol (Internet Protocol) is used at the top of the Pyramid, and M2M (Machine to Machine), Fieldbus system based on Ethernet is used for inter-machine and process communication (distributed controller layer) such as Profinet, Ethernet industrial protocol (EtherNet/IP), Ethernet for control automation technology (EtherCAT), Modebus transmission control protocol (Modbus/TCP), control & communication link IE (CC link IE), serial real time communication system (SERCOS) III, etc. Programmable logic controller (PLC), distributed control system (DCS), frame check sequence (FCS), supervisory Control and data acquisition (SCADA), and so on are used to control devices. Three problems about this system exist. Firstly, in this system, there are many protocol levels, different inter-layer protocols, fragmented interface standards, and difficult compatibility. Secondly, operation technology (OT) data usually need to be transmitted periodically for control tasks. Internet technology (IT) data such as word files, JPEG pictures, video, and other data is non-periodical. Thirdly, due to different real-time requirements, IT and OT networks are different. For microsecond motion control tasks, the network must have very low latency and jitter. For IT networks, sometimes there are no special requirements for real-time, but there are requirements for data load.

Therefore, one point about the connection is that more powerful and more compatible connection technologies are strongly needed in order to satisfy the above requirements, and the integration of 5G and proximity network technologies should be considered. Proximity network[59] refers to the network access technology of the end-side (of end-edge-cloud framework) equipment, such as OPC unified architecture (OPC UA)[48,60–67], short-distance communication (Sparklink, Wifi) and time sensitive network (TSN). OPC UA is proposed as a complete, secure, and reliable cross-platform architecture. It is compatible with a variety of hardware and software platforms. By Open Platform Communications Unified Architecture (OPC UA) different standard interworking functions are provided at the semantic level, but the latency is increased. TSN is an effective technique to ensure consistency between digital twin elements. 5G and deterministic network integration can help the vertical industry to realize the network interconnection and data interworking of the integrated system in wired and wireless environments, and meet the bounded business requirements of low latency, low jitter, and high reliability in various scenarios such as deterministic data transmission and accurate clock synchronization. At the same time, it solves the problem of information isolated islands caused by the current numerous industrial agreements.

Additionally, management of above connection technologies are needed as well[48,57,67–74]. The construction of a digital twin network is an effective method to improve the efficiency and quantity of connection[48,67]. The architecture of a digital twin network including 6G, 5G, edge network is proposed[36,64]. Based on digital twin networks, sensor fault detection, predictive maintenance, self-optimization, and so on are concerned. Blockchain, federated learning and other technologies for edge association in DT can empower networks such as 6G[57,68–74].

With respect to standards, unified guidance for interoperability between models is needed, such as intelligent interconnection standard specification and interface protocol of physical heterogeneous elements, heterogeneous data conversion, and communication standards and protocols, syntax and semantic mapping rules of multi-source and multi-modal data, virtual and real synchronous interaction interface of multi-dimensional model[75].

Key review points for the 5D model-services. Service is the result of the digital twin, and it is an essential component of DT in light of the paradigm of Everything-as-a-Service (XaaS)[21]. Many studies have been exploring possible services that digital twins can provide and related implementation technologies[21,76–84]. Some researchers proposed many digital twin applications including satellite/space communication networks, ships, vehicles, power plants, aircraft, complex electromechanical equipment, and so on[9].

The literature review discovers several services are showing extensive interest in DT, including for general purpose and for specific domains. Some of these services are prior to general purposes, such as prognostic health management (PHM), product life cycle management (PLM), while some are more domain-specific, such as digital twin network, digital twin smart city, and digital twin factory, and so on. In which digital twin network service involves network planning, automatic driving, network maintenance and optimization, traffic monitoring, fault diagnosis, scheduling optimization, and so on[81]. For the online prediction of man-hours based on real-time data neural networks are adopted and the dynamic scheduling for discrete assembly of aerospace products was elaborated in digital twin workshops[83]. Digital twin smart city focuses on energy and building monitoring, urban planning, circular economy and sustainability, traffic (mobility/fleet) management, pollution monitoring, and healthcare[84]. Aiming at the problem of unclear system performance and low optimization in Robotic Mobile Fulfillment System (RMFS) with multiple Automatic Guided Vehicle (AGV) distributed scheduling, a centralized scheduling approach based on digital twin was proposed[82].

Despite some research and application about digital twin service, there still exist two points that need to be mentioned in practical applications. One point is that most of the digital twin applications are limited to the design stage and process stage, and need to be extended to the monitoring, control, and optimization stage. Another point is that there are breakpoints between services in various stages of many applications, and continuous service flow has not been fully realized.

With respect to standards, unified requirements, service description model, service management, service QoS (Quality of Service), and so on are needed.

Standards for DT

A standard is a document, established by consensus and approved by a recognized body, which provides for common and repeated use, rules, guidelines, or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context[85].

Standard developing organizations

Major standard developing organizations include and are not limited to ISO, IEC, ITU, and IEEE. Most of them have been working on the standardization work for the digital twin or digital twin related technologies.

The International Organization for Standardization (ISO) is an international standard-setting body composed of representatives from national standards organizations. In terms of digital twin standardization, ISO paying more attention to industry and relative fields, the automation systems and integration technical committee 184 was the first committee to develop the digital twin project, its subcommittee four titled “industrial data” published the very first digital twin standard series for smart manufacturing, and there are several digital twin standardization projects related to industrial data and systems created by this committee that are still under development. ISO also created a work group named ISO/IEC JTC 1/SC 41/WG6 which specifically focuses on digital twin standardization, including concepts, terminology, use cases and related technologies of digital twin.

The International Electrotechnical Commission (IEC) is an international standards organization that focuses on the “electrotechnology” field, such technologies involved in power generation, transmission, semiconductors, data models, data set as well as many others. IEC/TC65/WG24 provides guidance for Asset Administration Shell (AAS), which can be considered as an implementation method of digital twin in smart manufacturing. AAS provide solutions for real world asset representation in the information world by structures, properties, and services in order to benefit industrial operation and management process.

The International Telecommunication Union Telecommunication Standardization Sector (ITU-T) coordinates standards for telecommunications and Information Communication Technology. Compared to ISO and IEC, the standardization work of ITU is concentrated on applications, several active works on digital twin in smart cities and network are developing under ITU-T.

The Institute of Electrical and Electronics Engineers Standards Association (IEEE-SA) is an operating unit within IEEE that develops global standards in a broad range of industries. IEEE-SA Digital Representation Working Group (IEEE-SA DR_WG), with a focus on digital representation, provides a series of standards in digital representation for various elements in the digital twin.

Framework of DT standards

This section maps the DT-related standards to the five-dimension digital twin model introduced in the second section. As shown in Figure 1, each dimension consists of corresponding standards, those standards shown below are specifically for digital twin or digital twin technologies, many other standards related to digital twin but not specifically created for digital twin are not mentioned here, such as physical entity definition, data format, and interface standard. In addition to the five key points, the definition of digital twin serves as a foundation for the application of digital twin, but the definition of digital twin has not reached a consensus among standard organizations. For example, In the field of manufacturing, ISO 23247-1 defines the digital twin as "fit for purpose digital representation of an observable manufacturing element with a means to enable convergence between the element and its digital representation at an appropriate rate of synchronization"[86], but in the field of smart city, ITU- Y.scdt-reqts defined digital twin as "a digital representation of an object of interest."[87]. Current standards of digital twin vary according to application scenarios and object, a general definition of the digital twin is required to clarify and defines the core concept of digital twin, and this potential standard is ongoing in committee draft standard ISO/IEC AWI 30173 Digital twin – Concepts and terminology[88].

Physical entities. In a digital twin system, physical entities have two major functions: data collection and device control. The physical entities serve as data sources and actuating units for virtual entities.

The DT standards of various fields have slight differences regarding the boundary of physical entities, due to their specific requirements from the application scenarios. In the field of smart manufacturing, ISO 23247-2 identifies the "physical" object as an "observable manufacturing element", which includes personnel, equipment, materials, facilities, environment, products, and logical objects such as supporting documents and processes[89]. The standard IEC TS 62832-1 further expands the definition of logic objects to include intangible things such as software, concepts, patents, ideas, methods, and anything that could define as an asset of the industry[90]. However, these standards were created specifically for manufacturing or industry digital twin, a standardized definition of overall digital twin should be proposed.

Control and actuating are other important functions of physical entities, when a digital twin is applied to the physical system, the sensor and command interface should be considered. Standard such as IEEE 1451 already proposed a solution for sensor interface, it provides a common interface by creating a self-descriptive electric datasheet and a network-independent

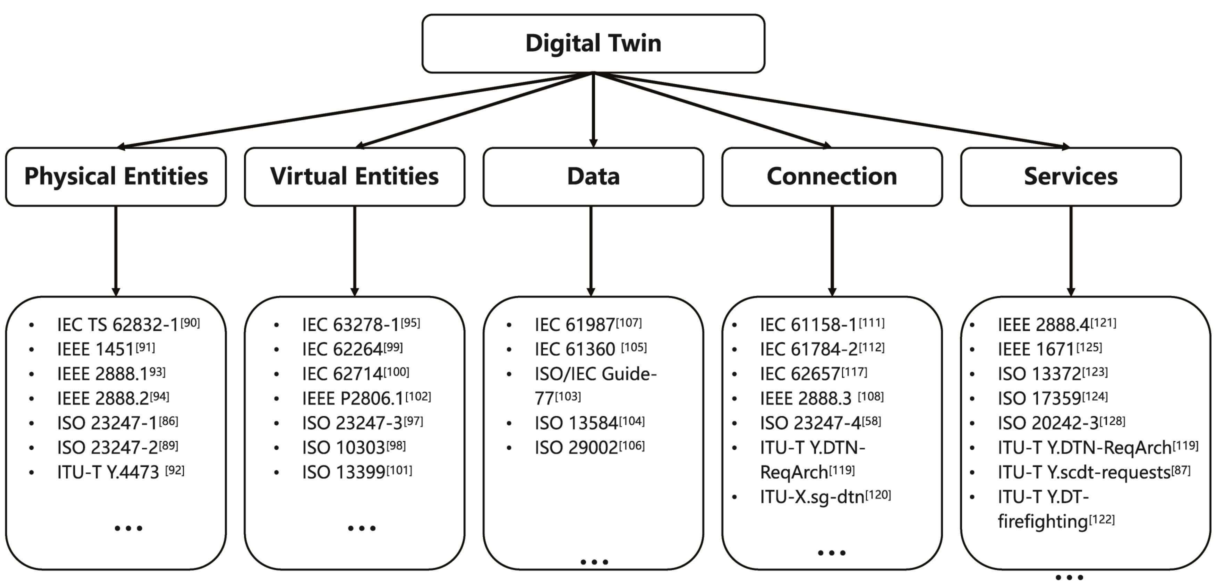

Figure 1. Framework of digital twin standards.

smart transducer object model, which allows sensor manufacturers to support multiple networks and protocols, thus facilitating the plug and play of sensors to networks[91]. ITU-T Y.4473 specifies the application programming interface (API) which provides a framework to interconnect Internet of things (IoT) devices, data, and applications over the Web, thus managing and retrieving observations and metadata from heterogeneous IoT sensor systems[92]. IEEE also proposed standard series IEEE 2888, this standard series comprehensively defines interface between cyber (digital twin) and physical world, IEEE P2888.1 and IEEE P2888.2 defines the vocabulary, requirements, metrics, data formats, and APIs for acquiring information from sensors and commanding actuators, providing the definition of interfaces between the cyber world and physical world, but the standard series are still in progress[93,94].

Even though there is no published standard for physical entities of the digital twin, many standards can be reused or referenced, existing fieldbus profiles, companion specification and other specifications that define device and component properties should be transferred into standardized dictionaries, and characteristics of conceptual assets, such as planning documents, should be included in standardized dictionaries.

Virtual entities. In a digital twin system, the virtual entities serve as the digital representation for physical entities. Virtual entities are composed of modeling, in order to describe physical entities via multi-temporal, multi-spatial scales.

From the structure perspective, IEC 63278-1 ED1-Asset administration shell (AAS) for industrial applications-Part 1: Administration shell structure is the very first standard related to the topic of virtual entity, it defines a semantic model that describes characteristics of assets, which is the serialization and exchange format between models, submodules, and AAS, so even though IEC 63278 was designed for industrial purpose, smart city and other verticals may also consider using or adapting this standard[95].

In the field of modeling, many efforts have been made by various Standard Developing Organizations(SDOs) even before the concept of DT draw much attention. ISO 23247[96] clearly stated its preference of using existing modeling standards for implementing the standard. The ISO 23247-3[97] have listed several standards such as ISO 10303 series "Standard for the Exchange of Product Model Data"[98], IEC 62264 series" Enterprise-control system integration"[99], IEC 62714 series "Automation Markup Language (AML)"[100], ISO 13399 series "Cutting tool data representation and exchange"[101], etc., those standard are not intentionally developed for the digital twin, but those standards can satisfy most of the use cases with implementation of XML, JSON, RDF, AML, OPC-UA, and any other common data description language or format. In addition to the existing standards related to modeling, activities on developing standards targeting at DT are noted. IEEE P2806[102] proposed digital representation for digital twin, it defines high-speed protocol conversion, unified data modeling, and data access interfaces for heterogeneous data situations in the digital twin. Therefore, it is recommended to adopt existing modeling standards in DT standardization work.

One point that needs special attention is that the DT for several common elements, such as gateways and cameras that are needed in both manufacturing and smart cities, need the cooperation between multiple communities to represent the full picture of interests.

Data. Data is a driving force for the digital twin. In the digital twin system, the models and information representations are not working independently, the cooperation between different digital twin systems is often involved in data and model exchange, therefore it is essential to standardize data structures, and data properties such as default value, data type, and data format.

Much of the technologies related to data processing and management in the digital twin can be achieved by adopting existing standards in data processing. Taking smart manufacturing, for example, current international standard ISO/IEC Guide-77, ISO 13584, IEC 61360-1, ISO 29002, and IEC 61987 set up a fundamental rules for data exchange, and standardized the data element type, data structures, data library and data type element for the industrial system[103–107]. ISO/IEC Guide-77 provides general advice and guidance for the description of products and their characteristics by the use of the ISO 13584 and IEC 61360 series of standards for the creation of computer-processable reference dictionaries.

However, the data processing and management associated with the virtual entities may need special attention. In several typical application scenarios of the digital twin, i.e., smart manufacturing, smart firefighting, the low-latency requirements might place additional technical requirements. For example, the models in the digital twin system are changing dynamically according to changes in the physical entities, this means further properties such as timestamps and validity statements are required to be standardized. In another example, the data produced by virtual entities should be ubiquitously identified as different from that from the physical entities, thus identification standards should consider these new features. These special requirements might lead to the necessity to update some of the existing standards, or even to establish some new ones.

Connection. The connection refers to the communication and interoperability, which jointly enable interconnecting between entities. IEEE proposed an capability framework for this interaction between namely 2888.3, this standard provides a framework overlooking interactions between general objects in cyber and physical world cyber and physical world, including capabilities to interact between physical things and digital things (cyber things), capabilities to easily integrate with back-end infrastructure / integrate with other external systems, capabilities to access to things by authorized parties, capabilities to describe physical devices, virtual devices, or anything that can be modeled[108].

For interoperability, multiple network coexistence should be considered, to solve this problem, an important standard is OPC UA[109]. With its semantic capabilities, OPC UA supports more than just data transmission, it also contains the information-centric data model, thus transfers heterogeneous data into unified information, which enables the secure data exchange industrial systems.

Digital twin network and connectivity are also essential for the implementation of the digital twin, the connection is not limited to the data exchange between different digital twin systems, but also includes the transmission link itself. Unlike conventional IoT communication systems, the digital twin requires more deterministic, higher broadband, better synchronization, and other augmented transmission capabilities to enhance digital twin services for diverse applications. In order to fulfill those requirements, much new technology, and corresponding standards are developed. Take manufacturing and industrial communication systems as an example, IEC and IEEE already offer sophisticated solutions for wired communication to fulfill the high requirement of the digital twin, such as IEEE 802.3, IEC 61158-1, and IEC 61784-2 standards series[110–112]. Moreover, industrial radio communication systems are also standardized in IEC 62591:2016 (Wireless HART), IEC 62601 (WIA-PA), IEC 62734 (ISA100a) and IEC 62948 (WIA-FA) to provide flexibility and mobility for wireless connectivity[113–116]. With the rapid development of communication technologies, the standard of heterogeneous networks integration starting to be concerned because various communication technologies coexist in digital twin systems.

Standards related to communication technologies are not proposed specifically for digital twins, but they can be reused to solve digital twin problems. these standards include TSN, 5G, new WLAN developments, smart mesh, 6 Lowpan. Much of these standards are currently under development, and only a few standards have been published or proposed. For instance, the IEC 62657 standard series provides the requirements for a wireless spectrum that specifies the predictable performance of wireless devices in multiple wireless network coexistence environments, and it provides coexistence management concepts and processes[117]. 5G ACIA also works with IEEE and IEC to explore the integration of 5G with Time-Sensitive Networking for Industrial Automation and Integration of OPC UA with 5G network for coexisting network management[118].

In terms of network management, guidance to deploying DT in network management are currently under development. ITU has proposed a new work item Y.DTN-ReqArch "Requirements and Architecture of Digital Twin Network (DTN)" to specify network resource management in order to provide analyzing, diagnosing, simulating, and controlling the physical network based on the network digital twin[119]. The security of digital twin networks has also been considered in ITU X.sg-dtn:" Security Guidelines for Digital Twin Network", this Recommendation describes security considerations and security requirements for DTN, it also provides countermeasures to strengthen the security, which could be helpful for the DTN security improvement[120].

Even though many existing standards can be reused, however, there are still many actions needed for digital twin and digital twin networks. First of all, it should be clarified which types of equipment and which parameters should be taken into account for network interoperable management, since 3GPP, IEC and IEEE already published many networks and connectivity standards, what extent standardization is needed for digital twin should be clarified. Secondly, the term "real-time" is the main characteristic of the digital twin, but there is no standard that defines this term or quantifies it for diverse verticals, therefore, parameters and methods for the evaluation of real-time communication should be summarized and uniformly defined in a standard. Thirdly, the standard of proximity network should take into account, though the standard of network digital twin already proposed, but it mainly focus on the core network or cell network, proximity networks such as TSN, OPC UA, field bus, Ethernet and their integration should also be considered, therefore, a digital twin proximity network requires a unified standard to monitor and manage all coexisting networks in order to enable a seamless transition.

Services. Providing services is the purpose of digital twins. User cases from various field are collected in standard work. In the field of smart manufacturing, ISO 23247-4 provided three use cases "Dynamic scheduling of manufacturing tasks between multiple robots" in international standards describes model digital twins of product, process, and resources for dynamic scheduling of manufacturing tasks between multiple robots[59]. IEEE 2888.4 proposed an architecture for virtual reality disaster response training system with six degrees of freedom[121]. In the field of smart cities, agent-based simulation modeling is proposed to find the best strategies and optimal parameters of parking in standard output text of draft recommendation ITU-T Y.scdt-requests[87]. Several use cases about digital twin networks are presented in standard draft ITU-T Y.DTN-ReqArch[119]. DTN needs to realize the complicated network operation and maintenance, improvement of efficiency of network optimization, speed-up of network innovation, more comprehensive measurement, implementing intent-based networking, network security strategy drills, and so on. In the field of smart firefighting, two use cases are considered: fire scene monitoring and rescue strategy development and training[122]. Based on these use cases, standards about digital twin service needs to be considered including service description, service test, service QoS and so on.

There are already many service standards. Though these standards are not proposed specifically for digital twin service, they can be reused to solve digital twin problems. We summarized these standards from three aspects:

As for the digital twin service description, two types of requirements and capabilities need to be satisfied and standardized. One is general requirements and capabilities, such as PHM (Prognostic Health Management), PLM (Product Lifecycle Management), simulation, and visualization. The other is specified requirements and capabilities combined with the considered scenarios. Most of these service descriptions have international standards. ISO 13372:2004[123], ISO 17359:2003[124], IEEE std 1671–2006[125] etc. are involved.

Service testing standards are relatively mature, such as IEEE 1232.3-2014[126], IEEE 1904.1 Conformance 01-2014[127], ISO 20242-3-2011[128], ISO 20242-4-2011[129], ISO/IEC 14393-1996[130], and so on. In the international standard classification, service testing involves many aspects, such as industrial automation system, information technology (IT) integration, information technology application, IT terminal and other peripheral equipment, interface and interconnection equipment, and so on. For example, IEEE 1232.3-2014 applies to artificial intelligence information exchange and service in all test environments. ISO standard 20242-3-2011 defines virtual device service interfaces which are independent of the computer operating system, the device connection technology, device suppliers, and technological device development in the future.

As for service QoS, ITU proposed a series of service QoS standards. Some of them are general. For example, recommendation ITU-T E.800[131] provides a set of commonly used terms in the study and management of quality of service (QoS) where the technical and non-technical terms related to the QoS are listed. And ITU-T E.800 defines service QoS as the comprehensive effect of service performance that determines the satisfaction of service users. E.800 takes into account the support capability, operation capability, business capability, and security of all parts of service performance. It is a comprehensive definition of QoS. ITU-T G.1010[132] and ITU-T G.1000 extend E.800. ITU-T G.1000[133] extends E.800, divides quality of service QoS into different functional parts, and links them with corresponding network performance. It expounds the QoS criterion from four aspects: customer QoS requirements, QoS provided by the service provider (or planned/targeted QoS), QoS obtained or delivered, and customer perception QoS. G.1010 complements G.1000 and proposes a framework that can meet the broad application needs of end-users (such as interactivity and fault tolerance). ITU-T E.802[134] defines the framework and methodologies for the determination and application of QoS parameters.

However, there are still many actions that need to be taken for digital twin service. Firstly, digital twin service has its characters such as connectivity between digital twin service and virtual entity, some DT service standards may need to be updated including DT service test framework, DT service QoS, DT service management, and so on. Secondly, non-functional digital twin service QoS standards (such as scalability and reusability), digital twin service test benchmark, etc. are absent. Thirdly, the standardization of the digital twin service level is absent at the time. Though a recommendation proposal on the digital twin maturity model was proposed in ITU-T SG20 in May 2021, it was rejected. As an important issue that needs the cooperation among DT community's joint efforts, it will have a significant influence on the road map of the application of DT in various vertical domains.

The standardization of digital twin service tests, service QoS, service levels, etc. is our future work.

Discussion

Based on the analysis of the standards related to DT, several challenges in the standardization work are identified and suggestions are provided. One observation on these standards is that most of them are initiated in the recent two years and are in development stages. It is partially because the concept of the digital twin is relatively new, and also the implementation of the digital twin is rare. The fact that standardization work progressed ahead of the actual industrial implementation could be beneficial to the industry, one compelling example to support this argument is that the standardization work in 3GPP helps the telecommunication industry with lower cost and higher efficiency. As a technology that needs enormous coordination, interoperation, intra-communication between different solution providers and service vendors, the digital twin has to use standardization as a pilot to help the implementation.

Challenges

Modeling, service, control optimization and other stages in digital twin of certain field may involve multiple domains, multiple time and multiple space, which may lead to complex problems and new features. Therefore, it is important to comprehensively consider the modleing and solving of multiple dimensions, becasue each dimensions could be coupled and interacted with other, the conventional method may not implenment digital twin properly. For example, when modeling and solving the network optimization problem in network digital twin, it is necessary to consider not only the continuity of the network itself in time, spatial distribution, and the uncertainty of the network performance, but also the time delay, reliability, and other requirements of the industry application field real-time business on the network. As a result, the problem becomes more complex, and single traditional optimization method may not be directly applicable.

The understanding of DT is different among different fields, the discrepancies in the understanding may lead to conflict between digital twin systems. Even identical applications may apply completely different technology to implement digital twin systems due to the understanding discrepancy, thus leading to the problem of openness in terms of compatibility and interoperability, moreover, the large-scale promotion of digital twins can become impossible due to the differentiation of understanding. Some conflicts in the content are observed among some standardization work. In the field of smart cities, the understanding of digital twin smart cities is not consistent among different standards. ITU-T draft Recommendation Y.scdt takes digital twin smart city as a tool for city development strategy investigation[87], while Recommendation Y.DT-interoperability regards digital twin smart city as the cooperation between various parts of the city functional administrations[135].

More efforts are needed from different parties along the DT value chain. The construction of a digital twin system requires joint efforts from different parties along the digital twin value chain, such as device makers, system integrators, service providers, etc. However, several of the ongoing work items have contributors from one institute only, and this monotonous background of contributors would lead to tremendous difficulties in implementation.

Suggestions

Identify the target and then roadmap of DT standardization work, for each specific domain. In the field of smart manufacturing, ISO 23247[96] provides high-level principles and reference architecture for digital twin manufacturing, and then IEC 63278 provides one implementation of DT in manufacturing, i.e., AAS[95]. Such coordination provides a good example for developing standards. the standardization work in the field of smart cities should take necessary coordination to ensure consistency in the work.

Identify the existing standards that can be adopted by the DT standard system and new ones that have to be developed. To maintain compatibility, use existing standards as much as possible when describing these capabilities in digital twin services. For example, in the corresponding services of manufacturing digital twin, the protocols AP232, AP238, AP242 and AP239 of standard ISO 10303 are to be used when describing the product, process, tooling, and keep the relation between the states of the physical instances and the equipment used respectively[98]. Standard ISO 10303-242 is used to describe the product assembly and ISO 23952 (QIF) is used to describe measurement results for hole depths, and are relevant standards[136,137].

Coordination between ITU-T, ISO and IEC has to be done so that many redundant works can be avoided. For key technology that can be generally adopted in multi-domains, such as 5G, the digital twin standards should be enacted with the joint efforts from diversified communities, i.e., both the manufacturing and smart cities.

Moreover, it is important to identify which industry actually need and urgently requires of digital twin and related standards, because digital twin technologies usually require massive hardware implementation, that hardware are costly and could be a burden instead of improvement for some industry. There are two types of industries may require digital twin, the first type is industry with high value product, and the second one is life-related service. The industry with high value product, such as manufacturing (automotive, aircraft, electronics), construction and powerplant, any mistake in those industry may cost millions of dollars lost, but the digital twin can help reduce the malfunctions by updating timely and detailed information to manager; and creating a digital twin of the object for testing is helping companies save time and money in real field test and experiment. The life-related services, such as healthcare and emergency service, the success rate is the primary factors in those services instead of the cost and expenses, the digital twin could provide a rehearsal for doctors or rescue team, so they can have better situation awareness and notice all possible dangers before actual service. In those industry, the main reason they are more suitable for digital twin is because the improvement and save is much more than the cost of digital twin itself, hence the standard is also needed for those industry.

The standardization of digital twin services, QoS, and tests are ongoing for future work.

Conclusions

The digital twin is expected to play a major role in the design, development, and operation of all industries in the future, providing new capabilities that far exceed today's level of life cycle management. Key technologies of digital twin such as model, data, connection, and communication accelerate the digital transformation of verticals, but as the concept and technologies of digital twin become more mature, a well-developed standard system is required to accelerate the engineering implementation of the digital twin in order to improve clarity, guarantee quality, and promote service. This research paper provides a consolidated literature review as the basic background and defines the state of the art for digital twins. The analysis of technical standards for digital twin is divided into five dimensions, the physical entity, the virtual entity, the data, the connection, and the service. This paper has analyzed those standards and states corresponding challenges and proposed possible suggestions. Due to the complexity of digital twin technologies, this work only covers key technologies and overall architecture of digital twin, however, many other detailed techniques have not been deeply investigated, such as modeling tool, platform, development process, and other engineering techniques. We believe those standards would be better standardized by company or industry to fit their specific demands. This paper could help scholars and industry practitioners understand the latest trends in digital twin technical standards. The research may also benefit those companies to implement digital twin applications by explaining standards in five perspectives. These research results also help guide researchers to develop possible standard ideas of digital twins.

Data availability

No data are associated with this article.

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Reviewer Report 20 September 2022

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✔ **Kaizhou Gao**

Macau Institute of Systems Engineering, Macau University of Science and Technology, Macau, Macao

This research paper provides a consolidated literature review as the basic background and describes the state of the art for digital twins. The analysis of technical standards for digital twin including ISO, IEC, ITU and IEEE is divided into five dimensions, the physical entity, the virtual entity, the data, the connection, and the service. Those standards and states corresponding challenges are analyzed and possible suggestions are proposed. The paper is written clearly and the analysis and its interpretation are appropriate. It could help scholars and industry practitioners understand the latest trends in digital twin technical standards and help guide researchers to develop possible standard ideas of digital twins.

However, there are few points can be improved in this research:

- This research paper only focused on the digital twin and digital twin itself, but digital twin technology is h add a short paragraph to analyze what the vertical industry urgently requires of digital twin technology and its standards, so this paper will not only help us understand what standards are required for digital twins themselves, but also their applications.

- The definition of digital should be updated, some standards that are mentioned in this article have just reached consensus (such as ITU-SCDT), and their definitions are slightly changes from previous versions, so the authors are suggested to confirm the latest definition.

- A few language expressions need to be improved.

Is the topic of the review discussed comprehensively in the context of the current literature?

Yes

Are all factual statements correct and adequately supported by citations?

Yes

Is the review written in accessible language?
Yes

Are the conclusions drawn appropriate in the context of the current research literature?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Intelligent manufacturing

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 12 Oct 2022
亚敏 王, China Mobile Research Institute, Beijing, China

Thank you very much for your careful review on our paper. Our responses to the comments are listed below:

(1) AQ1: This research paper only focused on the digital twin and digital twin itself, but digital twin technology is highly related to verticals, so I suggest the authors add a short paragraph to analyze what the vertical industry urgently requires of digital twin technology and its standards, so this paper will not only help us understand what standards are required for digital twins themselves, but also their applications.

Reply: Thanks for your suggestion. We have add a short paragraph in chapter “ Suggestions” to analyze what the vertical industry urgently requires of digital twin technology and its standards.

(2)AQ2: The definition of digital should be updated, some standards that are mentioned in this article have just reached consensus (such as ITU-SCDT), and their definitions are slightly changes from previous versions, so the authors are suggested to confirm the latest definition.

Reply: Thanks for your suggestion. After carefully check, we found “ITU-scdt” has new version of definition, so this definition has been updated to newest version in chapter “Framework of DT standards”.

(3) AQ3: A few language expressions need to be improved.

Reply: Thanks for your suggestion. We checked the paper and modified some language expressions for clarification.

Competing Interests: No competing interests were disclosed.

Reviewer Report 13 September 2022

https://doi.org/10.21956/digitaltwin.18827.r26974

Junqing Li
School of Computer Science, Liaocheng University, Liaocheng, China

Digital twin is an important enabling technology, but because of a lack of reference to standards related to digital twin, it is difficult to realize the interconnection of data, models, and so on between different enterprises or fields. This paper analyses the technologies and standards status of digital twin from five aspects, i.e., the physical entity, the virtual entity, the data, the connection, and the service. The standards cover ISO, IEC, ITU and IEEE. Then the corresponding challenges and possible suggestions are proposed. In my personal opinion, the paper is written clearly, the structure is complete and the analysis is clearly. This paper could help scholars and industry practitioners understand the latest trends in digital twin technical standards. The research may also benefit those companies to implement digital twin applications. The following revision should be addressed before indexing.

1. There are several concerns about grammar that needs to be improved.

   For example, on page 4, in the sentence "Expert systems, fuzzy systems, knowledge graph, etc. are a knowledge-based method which is combined with prior knowledge and is interpretable.", " a knowledge-based method" needs to be modified to "knowledge-based methods".

   In the sentence "Studies also notes this kind of model ...... ", the verb "notes" should not use three simple forms.

2. The format of the manuscript should be adjusted to adapt to the requirements of the journal.

3. The Conclusion section should be enhanced by including/expanding on topics such as the challenging problems and the possible improvement of the digital twin methods, the application of the digital twin.

Is the topic of the review discussed comprehensively in the context of the current literature?
Yes

Are all factual statements correct and adequately supported by citations?
Yes

Is the review written in accessible language?

Yes

Are the conclusions drawn appropriate in the context of the current research literature?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Intelligent manufacturing, digital twin technologies, optimization methods

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 12 Oct 2022
亚敏 王, China Mobile Research Institute, Beijing, China

Thank you very much for your careful review on our paper. Our responses to the comments are listed below:

(1) AQ1: There are several concerns about grammar that needs to be improved. For example, on page 4, in the sentence "Expert systems, fuzzy systems, knowledge graph, etc. are a knowledge-based method which is combined with prior knowledge and is interpretable.", " a knowledge-based method" needs to be modified to "knowledge-based methods". In the sentence "Studies also notes this kind of model... ", the verb "notes" should not use three simple forms.

Reply: Thanks for your suggestion. We checked the paper and modified some language expressions.

(2) AQ2: The format of the manuscript should be adjusted to adapt to the requirements of the journal.

Reply: Thanks for your suggestion. The format of the manuscript is satisfy the requirements of the journal now.

(3)AQ3: The Conclusion section should be enhanced by including/expanding on topics such as the challenging problems and the possible improvement of the digital twin methods, the application of the digital twin.

Reply: Thanks for your suggestion. We add two paragraphs to describe the challenging problems, methods and applications when implement digital twin in chapter "Challenges" and "Suggestions".

Competing Interests: No competing interests were disclosed.