IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received March 16, 2022, accepted April 25, 2022, date of publication May 11, 2022, date of current version May 20, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3174220

Digital Twin: Technology Evolution Stages and Implementation Layers With Technology Elements

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ABSTRACT A digital twin has recently received considerable attention in various industry domains. The digital twin replicates physical objects (e.g., people, objects, spaces, systems, and processes) in the real world into digital objects in the digital world. It also provides various simulations to solve problems in the real world or to improve situational operations. Therefore, the digital twin is a convergence of various technologies, such as advanced machine-learning algorithms, data analytics, super-resolution visualization and modeling, and simulation. Because the digital twin is a complicated technology, a step-by-step implementation that includes many technology elements should be considered to create a digital twin model. In this study, implementation layers are introduced to guide practical implementations of the digital twin. In addition, technology elements were suggested for the presented implementation layers. Because the suggested technology elements include clear technology definitions, various application domains (e.g., energy, transportation, logistics, environment, manufacturing, and smart cities) can easily utilize the introduced implementation layers and technology elements according to the intended purpose. Furthermore, this paper describes the evolution of digital twins. Digital twin technology has evolved continuously since 2002, when the digital twin concept was first introduced. In the described evolution levels, we show the future aspects of digital twin technology, according to the technological evolution direction. Therefore, the digital twin model can be efficiently created by considering the evolution direction and future aspects by using the suggested digital twin evolution levels.

INDEX TERMS Digital twin, digital twin technology evolution, implementation layer, technology elements.

I. INTRODUCTION

Digital transformation has become a massive trend recently, and various new technologies have emerged to accelerate digital transformation. Digital twin technology has been considered one of the crucial technologies for digital transformation and has received considerable attention [1]–[5]. Digital twin is a technology that replicates physical objects in the real world into digital objects in the digital world to address various real-world problems and optimize the real world through simulation or prediction of situations that can occur in the future [6], [7]. Thus, various advanced technologies should be considered to build a practical digital twin, such as advanced machine-learning algorithms, data analytics, visualization, and simulation [8]–[10]. The general concept of a digital twin is clear because it is well defined in many studies. However, aspects related to the specific technology and implementation of the digital twin implementation layer are unclear [11].

Recently, digital twin technology has been invested in many countries, and large digital twin projects modeled on cities or countries are being considered [6], [12], [13]. Federation or convergence technologies for many types of digital twins are required to optimize the real world in a large-scale digital twin.

However, most existing investigations mention abstract concepts about federation or convergence technologies among many digital twins. It is necessary to describe the essential technologies clearly, rather than abstract

The associate editor coordinating the review of this manuscript and approving it for publication was Tai-Hoon Kim.

descriptions. Digital twins can be built through many implementation steps, and various technologies should be considered for each step. Reference [14] described a generic digital twin architecture (GDTA) model that includes implementation layers for industrial energy systems. However, GDTA defines the basic structure and components of a digital twin without specifying or binding to certain technologies [14]. It is also necessary to predict and apply the evolutionary direction and future of digital twin technology to successfully deploy and set digital twin technology to various industrial sites or national infrastructure designs. References [15], [16] investigated the evolution of digital twin technology. Reference [15] briefly mentioned the digital twin, including the re-use of a digital twin, and [16] focused on only the functional aspects of the future of digital twins, such as prediction, synchronization, intelligence, and AI-digital twins. It explains the longer-term future of a digital twin using an abstract expression that is "digital twin will be more integrated, will eventually need to be dynamically created, configured, and verified and validated, and operate in an integrated environment."

In this paper, we introduce the digital twin technology and its implementation methodology. To understand and explain digital twin technologies clearly, we suggest the levels of digital twin technique evolution. Furthermore, implementation layers and their technology elements for each are introduced to present a practical implementation methodology. The specific contributions of this study are as follows:

1) Michael Grieves established the concept of a digital twin in his presentation about product lifecycle and management (PLM) in 2002 [17], [18], and digital twin technology has evolved continuously. This paper suggests the technical evolution levels of digital twin to help use the digital twin technology effectively.
2) Because the digital twin is a complicated technology, it is necessary to consider its step-by-step implementation. In particular, a digital twin on a large scale has to be implemented step-by-step. Therefore, we suggest five implementation layers of digital twin technology for practical implementation.
3) The technology elements for each implementation layer were introduced. It is difficult to implement digital twins using conceptual and abstract consideration points. Therefore, we suggest technology elements for the presented implementation layers to guide practical implementations of the digital twin.

The remainder of this paper is organized as follows. Section II explains the digital twin development status and related works. Section III describes the evolutionary direction of the digital twin. In Section IV, digital twin implementation layers are explained for digital twin implementation and operation. Finally, the concluding remarks are presented in Section V.

II. DIGITAL TWIN TECHNOLOGY

A digital twin can be defined as an intelligent technology platform for synchronizing physical objects and digital objects imitating them in (quasi) real-time, analyzing situations according to various purposes, and optimizing physical objects by predicting them based on analyzed results. The digital twin replicates physical objects (e.g., people, objects, spaces, systems, and processes) in the real world into digital objects in the digital world, and it provides various simulations for solving problems in the real world. Therefore, the digital twin is a "convergence technology platform between ICT technologies" necessary for building a safer and more efficient real world by finding the best solution and applying it to the real world. The following are the general purposes of the utilization of digital twin technology:

- Process optimization: What-if simulations based on digital twin behavior models can help find improved operation processes according to any change of associated personnel, equipment, production procedure, components, etc. [19].
- To prevent real-world problems in advance, past and present information collected from the real world is analyzed in the virtual world, and risk factors are identified.
- Efficient product design: Product design simulations by digital twin, using real-world data learned from how existing equipment, processes, and products perform over time, can support experiments with design iterations, more informed design and engineering decisions, and overall product roadmap enhancement [20].
- Cause analysis: The behavior models of a digital twin can reproduce the events happening to its physical entity. Reproductive simulation results based on past and log data can help analyze why these events occurred [19].
- Multi-disciplinary decision making: The federated interworking of digital twins can make it easier to identify the causes of a co-related and composite problem, analyze co-relations and mutual side effects occurring between industrial domains, and collaborate among stakeholders throughout the industrial ecosystem [20].

Fig. 1 shows the core technologies of the digital twin and its application services. Core digital twin technologies can be classified mainly into

- Visualization and operation technology
- Analysis technology
- Multi-dimensional modeling and simulation technology
- Connection technology
- Data and security technology
- Synchronization technology.

In addition, the digital twin can be utilized in a variety of industrial and public areas, such as manufacturing, energy, agriculture, defense, logistics, transportation, environment, and safety.

III. DIGITAL TWIN TECHNOLOGY EVOLUTION STAGES

Gartner's three-stage digital twin technology evolution model has been widely used, as shown in Fig. 2 [21], in which the real world is duplicated in the first stage, controlled in the second stage, and is optimized in the third stage. Therefore, in most existing investigations, after duplicating a single

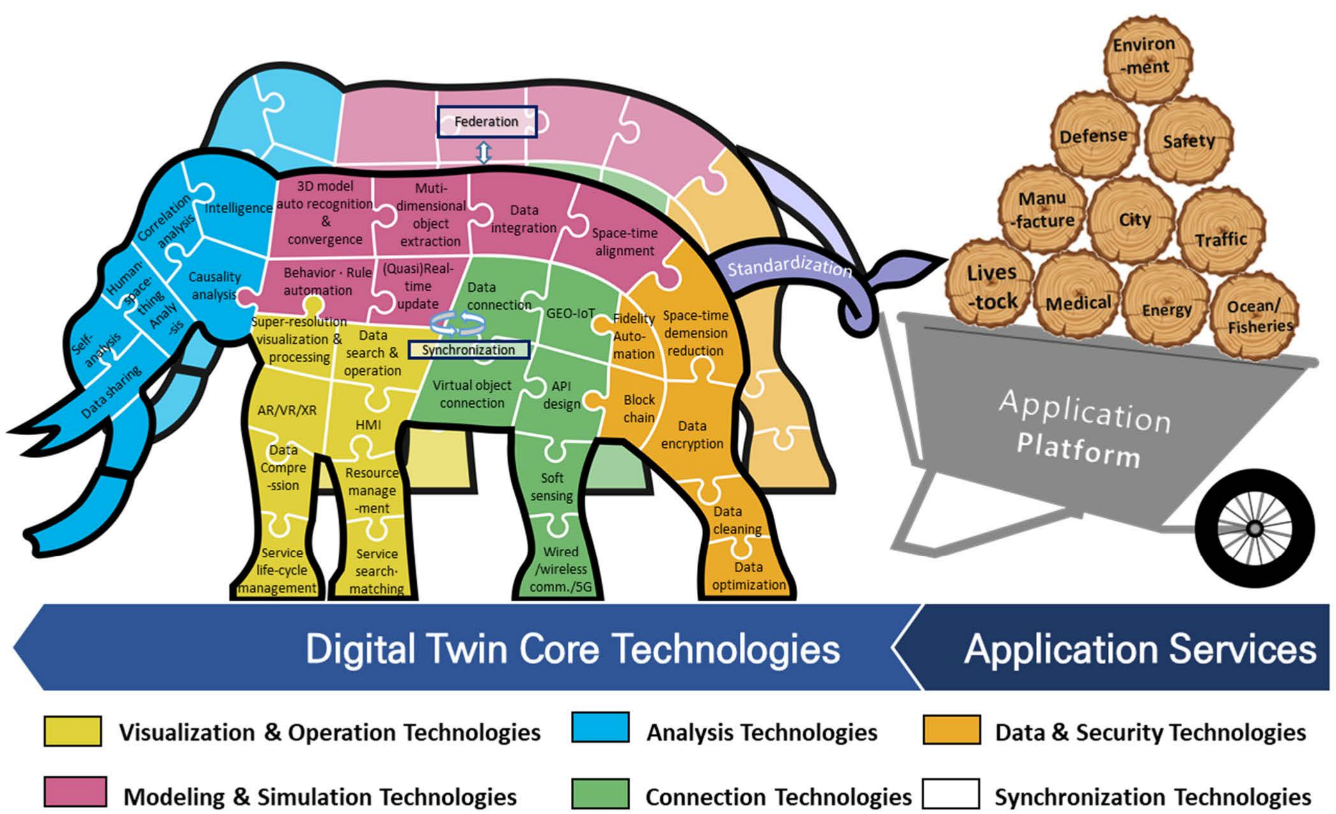

FIGURE 1. Digital twin essential technologies and application services.

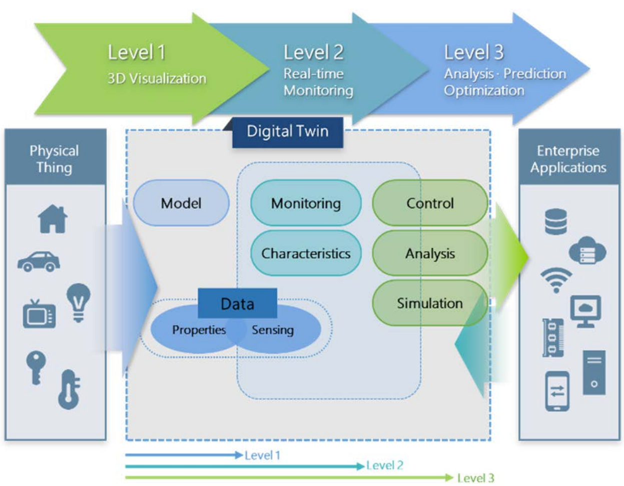

FIGURE 2. Traditional digital twin evolution model.

product or system in the virtual world, it can be optimized based on the simulation results of the duplicated model.

Because every phenomenon and every system in the real world are organic and complex, a digital twin for a single system cannot provide an overall optimal solution. In this paper, we suggest five evolution stages of digital twin technology, as shown in Fig. 3. The functional definition of each stage is as follows:

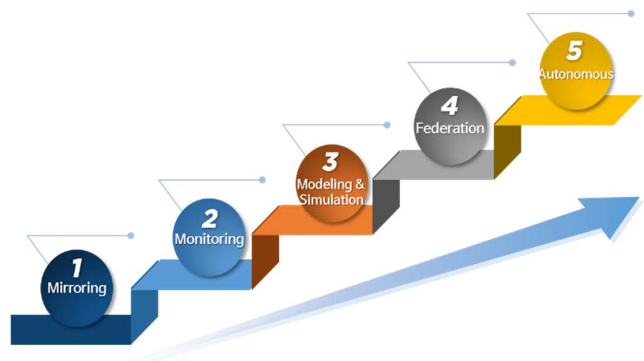

FIGURE 3. Digital twin technology evolution stage.

- **Stage 1 – Mirroring**: duplicating a physical object into a digital twin
- **Stage 2 – Monitoring**: monitoring and controlling the physical object based on the analysis of the digital twin
- **Stage 3 – Modeling and simulation**: Optimizing the physical object through the simulation results of the digital twin
- **Stage 4 – Federation**: Configuring federated digital twins, optimizing complex physical objects, and inter-operating federated digital twins and complex physical objects

- **Stage 5 – Autonomous**: autonomously recognizing and solving problems in federated digital twins and optimizing physical objects according to the federated digital twin solution

As shown in Figs. 2 and 3, the meanings of the first three stages (from stages 1–3) of the presented digital twin technology evolution model are similar to Gartner's evolution model. Gartner's traditional evolution model considers building a digital twin only for a single system, and does not include connection or federation between various digital twin models. Therefore, although the traditional evolution model is suitable for optimizing a single system, optimizing the complex or large-scale systems is difficult. To optimize the entire city or entire production process, many kinds of digital twins should be considered and connected. However, Gartner's model does not suggest the connection or federation of various digital twins. While our evolution model includes the federation stage in which each optimized single digital twin interwork with each other to optimize the complex real world. Therefore, the suggested digital twin model can address the optimization of complex real world. A detailed description of each evolutionary step we propose follows.

In the first three stages, a single physical object is as a single digital twin and optimized through the simulation result of a single digital twin. In the mirroring stage, a physical object is replicated as a digital object. Further, the main replicated elements should be selected to reduce the burden in the mirroring process. The main replicated elements may vary depending on the main purpose of the digital twin. In a transportation digital twin, traffic volumes and roadmaps can be the main replicated elements. In a smart farm digital twin, the type of vegetable or grain, sunlight, and water can be the main replicated elements. Therefore, focusing on duplicating the main elements is crucial to reduce the burden in the mirroring process. In addition, consistency between the replicated twin world and the real world must be considered to maintain the validity of the digital twin. Synchronization engines are usually considered for digital twins because digital twins need to manage and synchronize various sensors to ensure consistency. Therefore, in the mirroring stage, the synchronization engine can manage many sensors and maintain consistency between the replicated twin world and the real world.

The third stage builds a digital twin model based on the combination of mirrored objects from the first stage and executes various simulations to optimize the real world or to solve a real-world problem. In the first step (mirroring), the physical object is simply replicated as a digital object. The first step does not have additional processes such as simulation, testing, and optimization. The third stage, on the other hand, consists of the digital twin building, simulation, and optimization process. So the first and third steps are very different. However, in order to build a three-step digital twin model, steps 1 and 2 must be passed.

As shown in Fig. 4, in the fourth stage, each optimized single digital twin interwork with each other to optimize the complex real world. Many types of digital twins have to be considered for building a large-scale digital twin, such as city digital twin. In addition, many types of digital twins must be systematically interconnected. Our suggestion defines the systematic interconnection of different types of digital twins as "federation." The federated digital twin structure is suitable for duplicating and optimizing the large-scale complex real world. In the federated digital twin, the individually optimized digital twins finally optimize the large-scale complex real world.

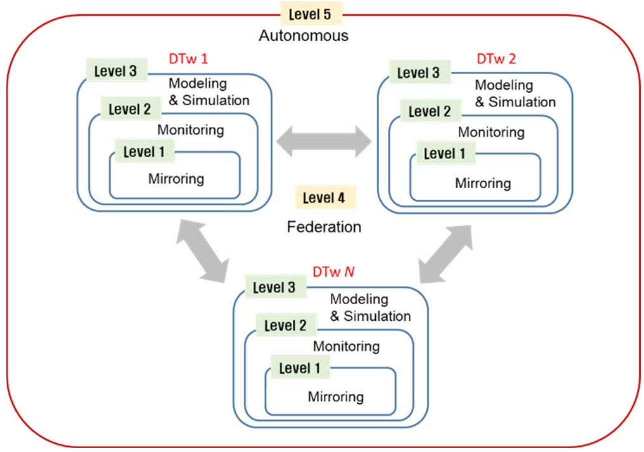

FIGURE 4. Conceptual diagram of digital twin evolution stage.

Synchronization of the operating states between digital twins and real world elements and federation of application services of digital twins must not be performed automatically because any unexpected event and malfunction can cause a severe situation for human users and private or social properties. Appropriate manual intervention is required to make sure for such actions. Human users are responsible for the final execution activities.

In the fifth stage, however, assuming that digital twin models are stable, reliable, and dependable for automatic action to the real world, the digital twin technology evolves to operate and optimize autonomously. The federated digital twins autonomously recognize real-world problems and provide solutions. Thus, autonomous federated digital twins operate as a digital twin ecosystem.

The evolution stages do not always have to proceed step by step. However, developing smartness for digital twins will stimulate implementing higher stage features.

There are many humankind creation myths in the history of the world. A similar but independent myth is the human was created by forming a human shape from the soil and putting the soul in. Here two foundational aspects are identified: structural and behavioral perspectives [19]. For the first stage, the structural shape of a physical object must be replicated as a digital twin. It may be enough for visualizing physical objects in the digital space. For the next stage, a requirement to synchronize the operating states of the twined pair can invoke establishing data connections between them. Then any change for one side can reflect the other side, and reactive controls can be possible. This is an evolved intelligence and is indicated as the level 2 stage. The level 3 stage accommodates structural and behavioral simulation models and supports what-if simulation features for optimization activities. It is a next-level intelligence. A complex system such as a smart city system requires individual infrastructure domains to interwork with each other to deal with correlated problems such as fine dust, energy supply, and security surveillance. The level 4 stage supports the federation of the interworking domains and can evolve collective intelligence for the interrelated domains. Then the autonomous operation of the level 5 stage can be evolved to support identifying situational problems, getting aware of their context, preparing alternatives to solve them, and determining and executing the best option via simulation in an autonomous way. It is the final stage of intelligence.

As digital twin technology develops and is applied to various fields, its utility and efficiency will be greatly improved. Steps 1–3 are utilized as an intelligent convergence service in the form of a single digital twin for individual application services. For example, when a disaster occurs in a downtown area, digital twins in Steps 1–3 analyze and infer the possibility and cause of disasters occurring in individual facilities and spaces and then apply inferred information to the real world. Stage 4 creates a federated digital twin, including individual digital twins that support the environment for estimating and addressing the spread of complex disasters. The autonomous digital twin of stage 5 can accomplish a stable and efficient real world by recognizing changes in the real world, autonomously federating related application domains, recognizing possible problems, and inferring and solving complex disaster problems. For example, when building a high-rise building in an urban area, in stage 4, a federated digital twin is created by linking related application areas, such as safety, transportation, and natural/social environment that may occur. Stage 5 autonomously analyzes the impact between each application domain in the federated digital twin. Through process analysis, we infer future problems and solutions to the problems and apply them to each application area to optimize the real world.

Recently, various research papers have considered large-scale digital twin structures [6], [12], [13]. For example, the government of Singapore has built virtual Singapore based on digital twin technology [20]. However, this initial approach has many limitations as the model has not been made publicly available. Hence, citizens cannot interact with the model or report feedback, which does not include urban mobility data [23].

IV. DIGITAL TWIN IMPLEMENTATION LAYERS WITH TECHNOLOGIES CLASSIFIED IN DETAIL

To implement digital twin technology efficiently, we propose a digital twin implementation layer model. The proposed implementation layer model refers to the development phase of implementing, operating, and servicing digital twin technologies. Digital twin technology can be implemented

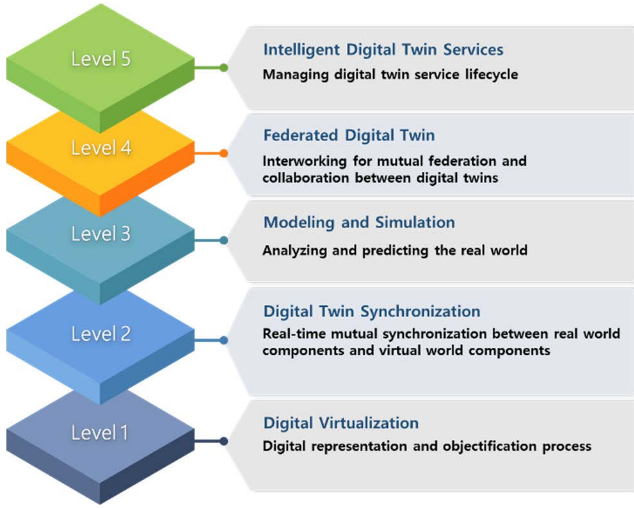

FIGURE 5. Digital twin implementation layers.

step-by-step according to the proposed layer. Fig. 5 describes digital twin implementation layers: digital virtualization, digital twin synchronization, modeling and simulation, federated digital twin, and intelligent digital twin service. The simple definition of each implementation layer is as follows:

Layer 1 – Digital virtualization: digital representation and objectification process of components making up the target real world, such as people, things, and spaces

Layer 2 – Digital twin synchronization: real-time mutual synchronization between real-world and virtual-world components, including static elements (e.g., things, space, and vision) and dynamic elements (e.g., behavior, process, and prediction)

Layer 3 – Modeling and simulation: analyzing and predicting the real world by simulating changes in virtual twin objects according to conditional changes

Layer 4 – Federated digital twin: interworking for mutual federation and collaboration between digital twins.

Layer 5 – Intelligent digital twin services: Managing digital twin service lifecycle based on intelligent and autonomous technologies and related platforms

The digital twin implementation layers provide the required functional goals to implement digital twin-based services step-by-step. However, because the digital twin is not a specific technology, but a service platform that integrates various intelligent technologies to implement each layer, various technology elements have to be considered.

For a practical implementation methodology, this study suggests the technology elements for each implementation layer. A technology element refers to technology required to build each implementation layer. The suggested technology elements for the implementation layers are shown in Fig. 6. Each digital twin layer comprises approximately 5–7 technology elements. Table 1 presents the definitions of the technology elements.

The digital twin developer can implement and improve the digital twin model according to the implementation layers

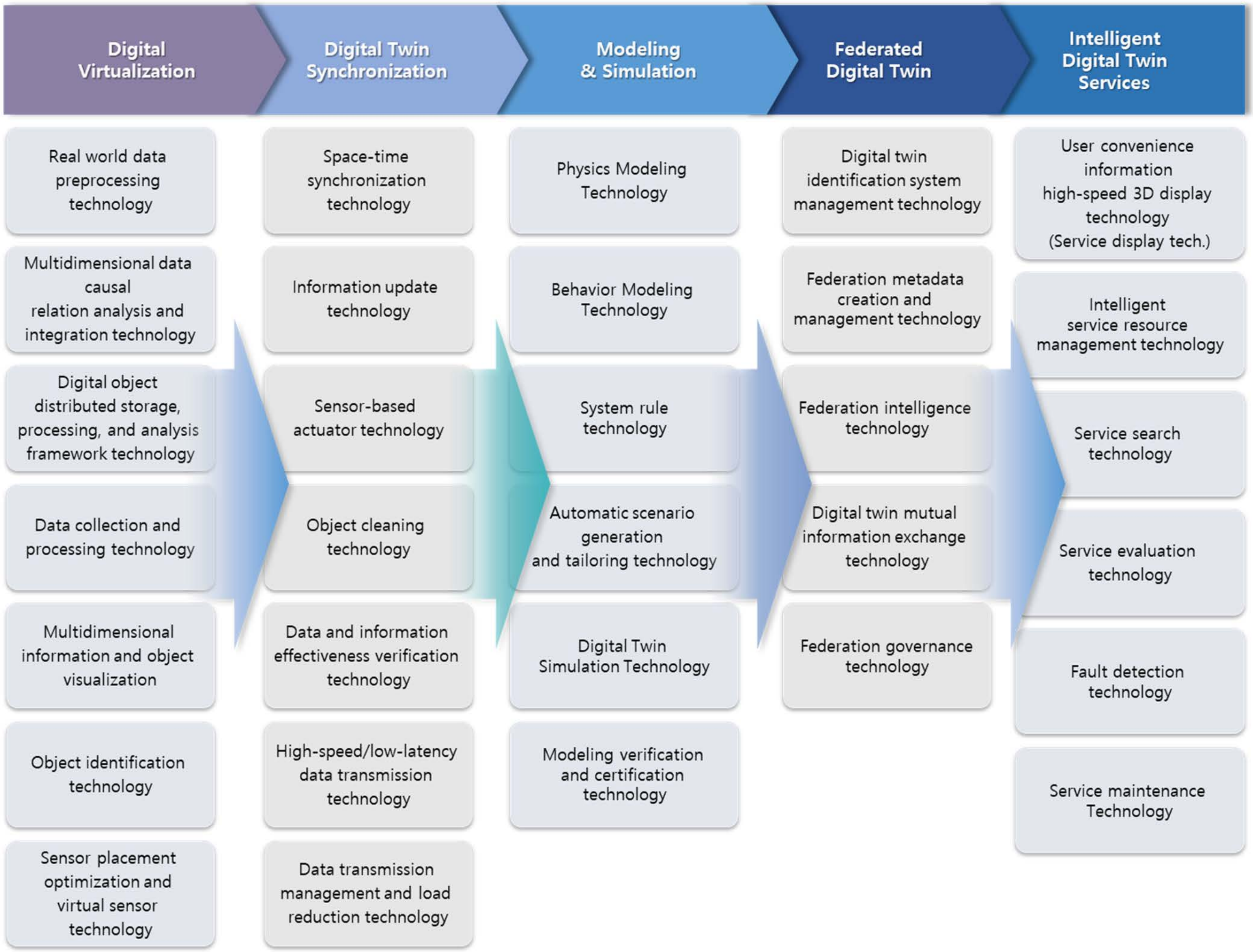

FIGURE 6. **Digital twin technology elements according to the implementation layers.**

and technology elements. After introducing the implementation layers and technology elements for each layer, Subsection F describes the city-level digital twin implementation example based on the presented implementation layers and technology elements.

A. LAYER 1: DIGITAL VIRTUALIZATION

Digital virtualization is the base layer for the digital twin implementation. In this layer, information of various target objects in the real world is collected and transferred to a digitalized virtual world. In addition, digitalized information is processed for the analysis and visualization of target objects. This layer consists of eight technological elements. The technology elements of this implementation layer are virtual sensor, sensor placement optimization, object identification, multidimensional information and object visualization, data collection and processing, digital object distributed storage, processing, and analysis framework, multi-dimensional data causal relation analysis and integration technology, and real-world data preprocessing.

Virtual sensor, sensor placement optimization, and object identification technologies are related to the sensing and detection of target objects. Reference [24] presented the modeling and implementation of redundant virtual sensors and validated the implemented model. Reference [25] showed an integration technique for synthetic sensing within a digital twin framework. Based on the described virtual sensing technique [24] and synthetic sensing technique [25], the digital twin can efficiently detect and store high-quality physical object data. For the visualization of virtual objects, multidimensional information and object visualization technology may be considered. Various studies have been conducted on visualization techniques [10], [26]. Reference [26] researched a three-dimensional visualization technology of the aerodynamic environment in a greenhouse. This research described an efficient multidimensional visualization method for a physical object using CFD and VR technology [26]. Furthermore, [10] presented movable dynamic data detection and visualization for a digital twin city. This paper has designed a platform that includes dynamic data detection, reconstruction, and visualization steps [10]. Therefore, these

TABLE 1. Definitions of digital twin element technolgies.

Layer	Technology	Definition
Digital Virtualization	Real world data preprocessing technology	Preprocessing technology based on data classification for integrating heterogeneous complex data of different characteristics collected in the real world
	Multidimensional data causal relation analysis and integration technology	Database management and correlation analysis technology for integrating preprocessed heterogeneous complex data and transferring information between digital twin components
	Digital object distributed storage, processing, and analysis framework technology	Intelligence framework technology for distributed storage, high-speed processing, and analysis efficiency of large data about digital twin objects
	Data collection and processing technology	Technology that converts multi-format (e.g., text, table, photo, and video) data acquired in the real world into an unified form
	Multidimensional information and object visualization	Technology that derives a relationship between various data and displays various information through multidimensional visualization/multidimensional data visualization/multi-scale transformation
	Object identification technology	Technology to classify, measure, and track the objects constituting a physical space using RFID·USN·IoT technology
	Sensor placement optimization technology	Technology to reduce redundant information, improve sensor utilization, and maintain stability of collected data
	Virtual sensor technology	Technology to calculate physical areas that are difficult to measure with hardware using knowledge and algorithms (SW)
Digital Twin Synchronization	Space-time synchronization technology	Synchronization technology between the real world and virtual world through the connection between real objects and virtual objects (Physical to Virtual)
	Information update technology	Technology that minimizes the error between the real world and the virtual world by updating the changed information of the real world within a predetermined (or permitted) time through minimal resources in the already built virtual world
	Sensor-based actuator technology	High-speed and high-precision control technology for an output device (actuator) that reflects optimization information inferred from the virtual world
	Object cleaning technology	Technology that minimizes defective elements, such as redundancy, errors, and incomplete and delayed data
	Data and information effectiveness verification technology	Technology that detects and corrects errors in information collected in the real world and delivers the event to the management system
	High-speed/low-latency data transmission technology	Technology that delivers various heterogeneous complex data collected in the real world to the virtual world to minimize the temporal difference between the real and virtual world and synchronize them
	Data transmission management and load reduction technology	Network resource management and load reduction technology to stably deliver information collected in the real world to the virtual world

TABLE 2. Definitions of digital twin element technolgies.

Modeling & Simulation	Physics modeling technology	Multiple modeling and physics simulation technology including simulations of fluids, structures, air, acoustics, thermodynamics, etc.
	Behavior modeling technology	Technology to model and simulate virtual objects according to actual physical phenomena, motions, and behaviors through images, graphs, networks, etc.
	System rule technology	Technology that automatically models and simulates rules using large amounts of historical data and knowledge through big data and machine learning algorithms
	Automatic scenario generation and tailoring technology	Scenario automatic generation for modeling and simulation and model tuning technology for simulation by mission based on basic model sharing
	Digital twin simulation technology	Technology that reduces the probability of error occurrence, uncertainty, cost, etc. through simulation that reflects the real world such as multiphysics, multiscale, and probability
	Modeling verification and certification technology	Modeling and simulation verification and certification technology to maintain precision, sensitivity, and robustness
Federated Digital Twin	Digital twin identification system management technology	Classification, identification and management system operation technology of moving objects for joint collaboration between digital twin models
	Federation metadata creation and management technology	Technology that creates and manages metadata about the functions of various federators (elements) that make up the digital twin model
	Federation intelligence technology	Federation intelligence technology for efficient digital twin federation (e.g., data generation, management, learning, and matching)
	Digital twin mutual information exchange technology	Technology for exchanging and sharing information based on reliability/convenience of digital twins using information sharing technologies such as blockchain
	Federation governance technology	Purposeful context Life cycle management technology (such as creating, sharing, maintaining, renewing, and decommissioning) for federating with each other; and digital twin multi-role management technology for multi-role/role-specific federations
Intelligent Digital Twin Service	High-speed visualization and service information presentation technology (service display tech.)	High-speed visualization (including AR/VR/XR) and service information presentation technology to present digital twin model information including optimal information in the real world in various forms (e.g., number, diagram, and 2D/3D)
	Intelligent service resource management technology	Life cycle management technologies such as reliability and history of various resources (sensors, actuators, devices, systems, etc.) that make up the real world; and technology to efficiently collect, classify and organize digital twin resources (model/algorithm/data tools, etc.)
	Service search technology	Appropriate service search technology based on matching algorithms according to user needs
	Service evaluation technology	Objective evaluation techniques, such as service time, cost, reliability, feature similarity, security, maintainability, and satisfaction
	Fault detection technology	Fault elimination technology that tests faults that can be damaged due to service, demand, network, application, etc. and measures necessary in the event of a fault
	Service maintenance technology	Technology to provide service mobility (continuity) over time and space movement

visualization techniques can transform physical objects into virtual objects. In addition, the remaining technologies can be utilized for the analysis of the corrected data.

B. LAYER 2: DIGITAL TWIN SYNCHRONIZATION

In this layer, real-world objects are connected and synchronized with digital objects in the virtual world. There are seven technology elements: data transmission management and load reduction, high-speed and low-latency data transmission, data and information effectiveness verification, object cleaning, real-world actuation, information update, and space-time synchronization technologies.

Network management and data transmission technologies are considered, including data transmission management and load reduction technology. Data verification and management processes are executed based on data and information effectiveness verification and object cleaning technologies. Finally, technologies for synchronization between real-world and virtual objects and information update are considered, including real-world actuation, information update, and space-time synchronization technologies. Reference [27] described the purpose and function of the communication network in a digital twin model. In the digital twin model, the communication network mainly aims to effectively transmit/receive the data collected by the sensors (which include the operational and environmental parameters)/actuators [27]. Furthermore, [28] depicted a practical example of synchronization between a digital twin and physical construction robots.

C. LAYER 3: MODELING AND SIMULATION

In this layer, to solve real-world problems or optimize real-world situations, digital twin objects are modeled, and various simulations are executed. Both tangible and intangible objects are considered in this layer. The technology elements considered in this layer are physics modeling, behavior modeling, system rule technology, automatic scenario generation and tailoring, digital twin simulation and modeling verification, and certification technologies.

First, various modeling and verification techniques should be considered to find appropriate modeling solutions, such as physics modeling, behavior modeling, system rule technology, and modeling verification and certification technologies. Reference [29] described the modeling and implementation method of a digital twin based on a physics simulation for a material handling system. This paper described the modeling method of a material handling system for manufacturing a digital twin and presented the practical modeling results [29]. Reference [30] explained the modeling method for a digital twin of a proportional integral derivative (PID) controller. The paper suggested a PID controller modeling method for digital twins, timing diagrams, and test results [30]. Then, scenario generation technology for digital twin simulation is applied, which accommodates automatic scenario generation and tailoring functions. Finally, a digital twin simulation and verification procedure is performed using digital twin simulation technology. Reference [5] presented a validation method for the performance optimization of production lines in a digital twin simulation. This study can be a proper example for the simulation and verification of a digital twin model [5].

D. LAYER 4: FEDERATED DIGITAL TWIN

This implementation layer presents a way to build large-scale digital twin systems consisting of various types of digital twin models. Therefore, technologies for interworking and collaboration between various digital twins may be technological elements. This layer accommodates the following technologies: digital twin identification system management, federation metadata creation and management, federation intelligence, and digital twin mutual information exchange technologies.

To build large-scale digital twin systems accommodating various types of digital twin models, digital twin identification and metadata creation technologies should be applied, such as digital twin identification system management and federation metadata creation and management technologies. A federated digital twin is built and managed based on digital twin metadata through federation intelligence, digital twin mutual information exchange, and federation governance technologies. A verification procedure was performed using the digital twin simulation technology. Then, data verification and management processes are adopted through data and information effectiveness verification and object cleaning technologies. Reference [31] introduced an IEEE 1451 smart sensor digital twin federation (IEEE 1451 is a family of smart transducer interface standards). In this study, from a wide range of cyber-physical system (CPS) simulations and experiments, a universal CPS environment for federation (UCEF) was developed. The federated experiment of a digital twin federation using UCEF is described in detail, and the experimental results are provided in [31]. Reference [6] provided an overview of the concept of the city-scale digital twin. In this study, digital twins are linked in a single cooperative system that allows one digital twin to use data produced by other digital twins [6]. This study can be a simple and practical concept of digital twin federation [6].

A complex problem arising from interrelations across multiple domains must be solved through a federation between the digital twin domains. For example, environmental concerns, such as find dust and air pollution, have been caused by various domain sources (e.g., factories, transportation, and power plants). The federation exploits different levels of management objects: problem-based contexts, domain-dependent problem sources, source-induced attributes, and attribute-based managed objects. A hierarchical identification system of digital twin for these functional objects can support a systematic cooperation process. In addition, all functional objects are syntactically formalized in metadata.

Every problem source within a domain works over its own behavior model. With various problem sources, a domain should aggregate its behavior models into its digital twin model. This is a domain-specific federation intelligence, and federating different digital twin domains results in cross-domain federation intelligence. The federation is always realized by the corresponding data exchanges among the functional entities involved.

E. LAYER 5: INTELLIGENT DIGITAL TWIN SERVICES

This implementation layer deals with a common platform for digital twin services and digital twin service management.

In the first step, related digital twin service technologies are high-speed visualization and service information presentation and intelligent service resource management technologies. Related digital twin service management technologies include service search, service evaluation, fault detection, and service maintenance technology. Reference [32] described an architecture for an intelligent digital twin and its required components, with use cases such as plug and produce, self-learning, self-healing, and predictive maintenance. Reference [33] provided an overview of the application of intelligent digital twin technology in the fault diagnosis and condition monitoring of wind turbine mechanical components.

F. APPLICATIONS

The digital twin implementation layers intend to provide generic technology elements to be used selectively in designing and establishing various digital twin applications [34]. Application domains, such as energy, transportation, logistics, environment, manufacturing, and smart cities, have different working environments and service requirements [35]–[38].

It isn't necessary that all the digital twin technology elements have to be applied. That means some of them can be applied selectively by required functionalities according to intended purposes. For a example, when a city wants to implement an application service for intelligent traffic light control-digital twin system (ITLC-DT). A floating population-digital twin system (FP-DT: Stage 3) that simulates and predicts the floating population and a traffic light control-digital twin system (TLC-DT: Stage 2) that automatically controls the traffic lights according to the traffic volume are established in a city. Through the federation of these two digital twin systems, we intend to develop an intelligent traffic light control-digital twin system (ITLC-DT: Stage 4) based on floating population and traffic volume prediction. ITLC-DT has a traffic volume prediction engine based on the traffic volume data monitored from TLC-DT. ITLC-DT generates messages to control the traffic lights in a city. at time 't' based on the floating population prediction result delivered from FP-DT and the traffic volume prediction result of the target time 't' from the prediction engine of ITLC-DT. These messages are sent to TLC-DT for controlling the traffic lights in a city.

By reusing the previously established twin system, economic effects such as reduction of development time and elimination of overlapping investment can be obtained.

G. FAILURE MANAGEMENT

Digital twin implementation can be efficiently executed using the implementation layer model. However, ensuring the stability of the proposed digital twin model is crucial. Therefore, data validation and failure management are essential processes in the overall implementation layers.

First, a data manager is required, which validates and manages the life cycle of digital twin data across all implementation layers. The failure monitoring agent is considered for the stable operation of the implemented digital twin model. The failure monitoring agent evaluates the operation and output result of the digital twin in real time and detects anomalies, when the operation functions or output results cross the thresholds. In this process, the real-time failure monitoring agent continuously evaluates the consistency of the output, synchronization operation, and digital twin operation function. Through the data manager and the failure-monitoring agent, the digital twin can be implemented and managed based on the proposed implementation layer model.

V. CONCLUSION

Because a digital twin is a convergence technology platform that includes a variety of ICT technologies, the development and implementation of digital twin models are complicated. Therefore, this paper suggested digital twin evolution levels, including future aspects of digital twin technology and digital twin implementation layers. In addition, technology elements for each implementation layer were introduced. Based on the digital twin evolution levels, digital twins can be efficiently modeled and designed by considering future aspects and evolution direction. The suggested digital twin implementation layers and technology elements can work as a step-by-step implementation method and can be applied for the implementation of digital twins. Furthermore, because digital twin technology elements include clear technological definitions, digital twin technology elements can guide practical implementations of various digital twins. A digital twin implementation example is described based on the presented digital twin implementation layers and technology elements. The example described conceptually explains how multiple digital twins can be federated to build a city-level digital twin.

We will research digital twin service models and related technologies for various ICT application domains based on the presented digital twin evolution model, implementation layers, and element technologies. Recently, ICT technology is regarded as an essential technology in various engineering fields such as national defense, cities, logistics, disasters and safety, agriculture and livestock, marine, healthcare, and so on. Furthermore, these fields continuously demand various services using digital twins to increase production efficiency or to optimize their service environments. Therefore, we would like to present the digital twin service models required in the various application domains and explain the implementation plan based on the presented technologies and implementation layers of this paper.

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