Digital Twin Capabilities and Use Cases White Paper

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Executive Summary

Digital twin is a new stage in the development of IoT, which continues to receive high attention from various countries, industries, standards organizations and research institutions, and the related technologies and industries are deepened developing steadily. To further explore the core capabilities of digital twins and explore the typical application scenarios of digital twins, this white paper introduces the development overview and architecture of digital twins as well as highlights the key core capabilities necessary for the development of digital twins, further elaborates the application value of digital twins with actual cases in key vertical industries, and gives an overall outlook and suggestions for the future evolution of digital twin technology and industry development.

Abbreviations

Abbreviation	**Explanation**
5G	The Fifth-Generation Mobile Communications
AAS	Asset Administration Shell
AGV	Automated Guided Vehicle
API	Application Programming Interface
BIM	Building Information Modeling
DEM	Digital Elevation Model
DOM	Digital Orthophoto Map
GIS	Geographic Information System
IoT	Internet of Things
LoRa	Long Range Radio
MEC	Mobile Edge Computing
NB-IoT	Narrow Band Internet of Things
RFID	Radio Frequency Identification
SLA	Service Level Agreement
TSN	Time Sensitive Network
UPF	User Plane Function
UWB	Ultra-Wide Band

1 Overview of digital twin development

The digital twin is based on the integration and fusion of data and models as the core, through the construction of accurate digital mapping of physical objects (including physical objects, behaviors, processes, etc.) in digital space in real-time as well as based on data integration, analysis and prediction to establish a closed-loop of intelligent decision-making optimization. The digital twin originated in the military industry and is widely used in industry and smart cities. 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 application values.

The digital twin is a new stage in the development of the Internet of Things, and there is huge room for development. For three years in a row, Gartner has included the digital twin in its annual (2017-2019) top 10 strategic technology trend [1][2][3], arguing that it will produce disruptive innovations in the next five years. Meanwhile, according to Gartner, half of the large industrial enterprises will use digital twins by 2021, resulting in a 10% increase in efficiency for these enterprises [3]; by 2024, more than 25% of new digital twins will be adopted as a bundled feature of new IoT-native business applications [4]. Moreover, based on the Markets and Markets forecast [5], the digital twin market size will grow from $3.1 billion in 2020 to $48.2 billion by 2026 with a compound annual growth rate of 58%.

The digital twin is highly valued by various countries. All countries have introduced policies to guide the development of digital twin technology and industry. The U.S. Industrial Internet Consortium (IIC) and Germany's Industry 4.0 have incorporated digital twins into the industrial Internet of Things technology system. The UK has established the Centre for Digital Built Britain (CDBB) and released The Gemini Principles [6], which summarizes nine principles to guide the development and application of digital twins at the national level. Meanwhile, the Chinese government has also issued relevant documents to promote the development of digital twin technology, and the Alliance for Industrial Internet (AII) has established an Ad Hoc digital twin group to carry out industrial research on digital twin technologies, promote the development of relevant standards, and accelerate the promotion of industry applications.

The digital twin boosts the development of society and industry. For many vertical industries such as manufacture, medical, transportation and construction, based on digital twin technology, it can realize the innovation and upgrade of application scenarios, IoT products and solutions, and comprehensively improve the digital level of the industry. For example, in infrastructure management, the monitoring and predictive maintenance of municipal pipelines, buildings, bridges, tracks, towers, and other facilities can be realized by using real-world 3D modeling, real-time environmental measurement and operational status analysis. In industrial production, people create, test and produce the required equipments in a virtual environment to reduce production risks and operational costs, improve the efficiency of product innovation and help customize production.

The digital twin standards are constantly formulated and improved. International standardization organizations such as ISO, IEC, IEEE, and ITU have promoted the establishment of digital twin sub-technical committees and working groups to advance the construction of standards and initiate proof-of-concept projects such as testbeds. For example, since 2018, the WG15 working group of ISO/TC 184/SC 4 has released "Framework for Manufacturing-Oriented Digital Twin Systems" series of standards (ISO 23247). In November 2020, SC41 of ISO/IEC JTC 1 was renamed to Internet of Things and Digital Twin, and Digital Twin working group (WG6) was established to coordinate and promote the international standardization of digital twin.

The digital twin places new requirements on information and communication technologies. The digital twin integrates perception, computation, modeling, simulation, communication and other technologies to achieve virtual-physical mapping and interaction. The digital twin allows for efficient simulation of applications where trial and error is costly in the traditional way. It reduces the risks associated with the validation of new technologies in the physical space, as well as reduces the possibility of errors when deployed in physical environments, and as such enables low-cost and efficient research into innovative technologies. In order to achieve the above goals, digital twin relies on the collaborative development and breakthrough of various information and communication technologies, such as the construction of complex physical and mathematical models, highly reliable and real-time data transmission, high-precision visualization of 3D scenes, etc.

In order to clarify the concept and connotation of the digital twin, it is necessary to further distinguish the correlation and difference between the digital twin and related technologies. For example, simulation is one of the core technologies of digital twin. However, the simulation technology can only simulate the physical world in an offline way without analysis and optimization functions as well as does not have the characteristics of real-time synchronization and closed-loop optimization of digital twin. The Asset Management Shell (AAS) not only is a set of description language and modeling tools based on The German Industry 4.0 system designed to improve the interconnection and interoperability between assets, but also is one of the basic technologies supporting digital twin. In addition, digital thread is the data flow covering the whole life cycle of products, integrating and driving the product design, manufacturing, and operating with the unified model as the core. Meanwhile, it is also the core technology to realize data fusion of digital twin multi-class models.

Although the digital twin develops rapidly and attracts increasing attention from all sides, it still faces many challenges. At present, there is no consensus on the concept and connotation of digital twin in the industry, and the standardization is still in its infancy as well as lacking of the digital twin construction, evaluation, testing tools and platforms to meet business needs. The key technologies of digital twin, such as perception, network, modeling, simulation and visualization, are also awaiting breakthroughs as well. In addition, digital twin construction requires high technical capabilities and a long deployment cycle, resulting in relatively high costs.

2 Digital Twin System Architecture

Based on the continual information exchange and data fusion, the digital twin system is capable of simulating the behavior of the physical objects in order to represent the status of the physical world, thus collect past data, diagnostic current problem, predict future evolution and optimize physical world. At present, there is still no standard of digital twin general architecture. Therefore, this white paper will take ISO 23247[7] standard series as reference to demonstrate the architecture and capability of digital twin system. Even though the intention of this ISO standard is to define a framework for digital twin during the manufacturing phase of the product life cycle, but this could also reflect the key element and core concept of digital twin in consideration of the professionalism and authoritativeness of ISO. As shown in Fig. 1, the digital twin system include three layers：

The first layer is Data Collection and Device Control Entity, which includes Data Collection Sub-Entity and Device Control Sub-Entity. The Data Collection Sub-Entity collects information from the objects with monitoring and sensing devices, and then uses the collected information to synchronize the digital twin with its corresponding physical entities. The Device Control Sub-Entity controls and actuates the physical objects, including key functionalities such as execution, control, and identity.

The second is Core Entity, which consists of Operation and Management Sub-Entity, Application and Service Sub-Entity and Resource Access and Interchange Sub-Entity. The Core Entity digitally represents and maintains physical entities. The Operation and Management Sub-Entity operates and manages the digital twins in terms of digital modeling, presentation, representation, and synchronization. Additionally, the Operation and Management Sub-Entity supports capabilities related to operation and management of the overall Core Entity, including providing administration functionalities to the User Entity. The Application and Service Sub-Entity provides functionalities related to applications and services including simulation of the whole system, analysis of data captured from the physical entities and reporting of actions. The Resource Access and Interchange Sub-Entity provides access to functionalities of the Core Entity to the User Entity with controlled interfaces for application and service functionalities, administration functionalities and business functionalities in support of interoperability.

The third is User Entity, which can be any entity that utilizes the digital twin for manufacturing, including human, devices, manufacturing execution system (MES)/enterprise resource planning (ERP) systems, or even a peer digital twin.

In addition to the above entities, this manufacture digital twin system also consists of cross-system entity that resides across domains to provide common functionalities such as data translation, data assurance and security support.

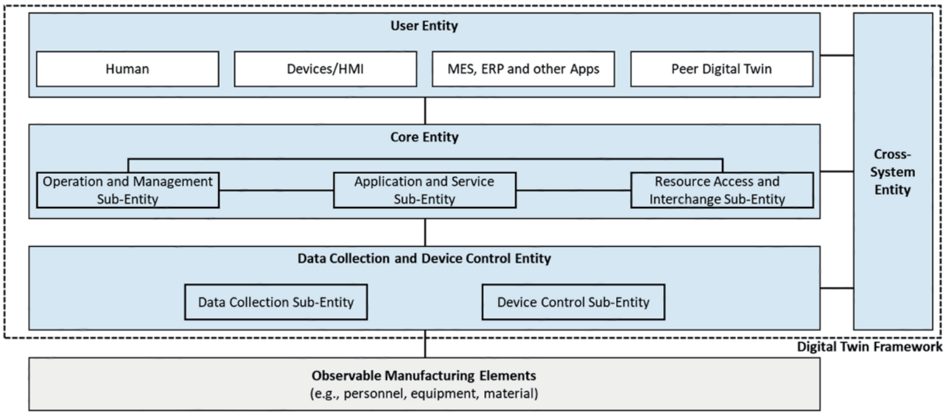

Fig.1 Entity-based digital twin reference model for manufacturing

3 Digital Twin Capabilities

In order to maximize the value of digital twin in terms of low-cost trial-and-error, intelligent decision and high efficiency innovation, the digital twin requires seven key end to end capabilities: universe perception capability, multi-source data fusion capability, heterogeneous network collaboration capability, high precision modeling capability, visualization capability, real-time dynamic simulation capability and safety and security capability.

3.1 Universe perception

Universe perception refers to the comprehensive use of sensing, measurement and computing technologies to collect and identify information from all types of target objects in the digital twin, in order to achieve universe perception in all space, all time, all elements and multiple dimensions.

In order to meet the needs of the complex natural environment, diverse infrastructure and personalized application scenarios of digital twin, it is necessary to build a multi-dimensional, refined, intelligent and standardized universe perception technology system with full coverage of the area, time-domain and objects. On the one hand, the universe perception system can build a powerful, flexible, opening and shared sensing capability to realize resource reuse, which reduces the cost of deployment and maintenance of sensors. On the other hand, data fusion can enhance the accuracy and reliability of sensing data, build new sensing capabilities and provide better data support. The digital twin universe perception usually requires the support of the following technologies:

(1) Sensor technology: At present, sensor technology is developing towards miniaturization. Multi-sensor capabilities are integrating into a single sensor module, which effectively supports more in-depth data acquisition. Through active sensing or passive sensing, it can provide the collection and monitoring of key information such as real-time status and topological relationship of field level equipment. In the future, sensors will be further miniaturized, integrated, intelligent and become more precise and environmentally friendly. Those properties enable sensors to reduce power consumption and be flexibly integrated with various terminals. Moreover, multi-source data fusion enables sensors obtain deep sensing results, thus enhancing the accuracy, reliability and fault tolerance of the sensing system.

(2) Mobile collaborative sensing: The digital twin requires massive information collection, but traditional sensing systems usually deploy a large number of fixed dedicated sensors, which may cause several disadvantages, such as high costs, space limitation, low single-point measurement precision, and difficulties in system collaboration or expansion. Mobile collaborative sensing can combine dedicated sensing devices with common users' mobile devices, therefore improve data quality, reduce construction costs and enhance system extensibility.

(3) Sensing quality management: Sensing quality management can be used for the comprehensive evaluation of perception capabilities. Combined with specific indicators, it can identify key elements that affect sensing efficiency and data quality. By constructing a unified sensing quality management framework and mechanism, along with comprehensive evaluation indicators and management tool, the system can improve the stability and operational efficiency in terms of perception system construction, data collection, network transmission and data processing.

3.2 Heterogeneous Network Collaboration

The information collection and control system of digital twin usually includes various type of sensors, smart meters and terminal devices. Those devices appear in different forms and access protocols, which require various networks for collaborative integration, including 5G, Wi-Fi, RFID, UWB, short-range communication and other industry proximity networks.

5G network has the characteristics of high bandwidth, low latency and massive connection, so as to meet the digital twin application needs of various vertical industries. In addition to 5G, the industry proximity network can connect various terminals, machines, sensors and systems to meet the diversified business needs of sensing, positioning, control and management. Common industry proximity network includes industrial Ethernet such as Ethernet / IP, PROFINET and EtherCAT, fieldbuses such as PROFIBUS, CC-link and CAN, short-range communication technologies such as Wi-Fi, Bluetooth and ZigBee, low-power wide area communication technologies such as NB-IoT and LoRa, and communication technologies such as time sensitive networks (TSN), millimetre wave, RFID and UWB. The industry proximity network can be combined with 5G to realize complementary advantages.

Fig. 2 shows the technical architecture of collaboration between 5G and industry proximity network [8]. It includes two major parts, the industry proximity access network and the industry proximity core network. The industry proximity access network is able to bridge heterogeneous industry proximity networks, such as passive communication, short-range communication, Bluetooth and TSN. The industry proximity core network performs data distribution mainly through UPF which is deployed at the edge of the industry proximity in order to process the proximity operation data uploaded by 5G, and implement the overall management of the network.

Take the collaboration between 5G and typical industry proximity network as an example, 5G combined with new passive IoT communication employs the separated architecture that separate power and communication part. The tag is powered by RF communication, but the command will be issued and returned through 5G, which not only further expand the communication distance of the tag, enhance the flexibility of passive RFID networking, but also reduce terminal costs. 5G combined with new short-range communication is based on a new wireless port design, which implements P2P communication while meets the transmission requirements of ultra-low latency, high reliability, fine synchronization, high concurrency, high efficiency and high security. 5G combined with deterministic network solves proximity wiring problems while meets the requirements of high reliability and determinism in communication.

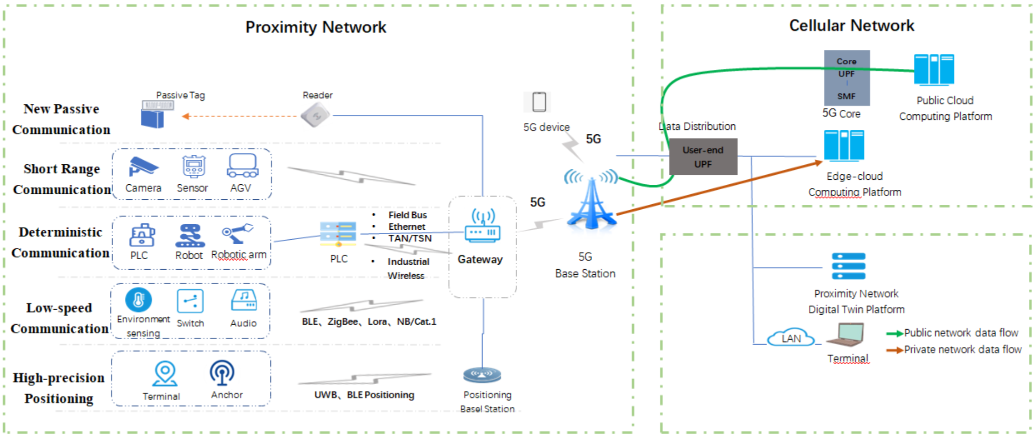

Fig. 2 5G and industry proximity network collaboration technology architecture

3.3 Multi-source data fusion

The digital twin is able to connect the dispersed digital twin entities and unleash additional value by the integration of data resources. Therefore, by utilizing GIS data, IoT data, BIM data, thematic data and other massive heterogeneous spatiotemporal data as the data source, and employ machine learning and deep learning algorithms to provide automatic identification, data mining and 3D reconstruction for spatiotemporal data, this enables data possesses spatial characteristics and purpose, which helps digital twin construct a holographic and high-fidelity digital space that covers comprehensive perspectives. Meanwhile, through developing unified definition, storage, indexing and service mechanism for data and forming TB-level data sets and distributed cluster management, it can realize unified data access, exchange and efficient sharing. The following multi-source data fusion is typically supported in digital twin systems：

(1) IoT Sensing Data

The digital twin can use various types of devices sense the physical world to achieve data collection and monitoring of different objects and scenes. Those data include data collected by dedicated acquisition terminals and data generated by user devices, such as smart phones and wearable devices in order to obtain the position, speed, acceleration, body temperature, heartbeat information, etc.

(2) Derived data of the scene

The digital twin system requires to process raw data into derived data through automated or semi-automated data processing, which mainly covers the processing and accessing of static data such as DEM, DOM, vector, tilt photography, BIM, laser-point cloud, artificial model, etc. Fig. 3 shows the schematic diagram of digital twin scene data processing.

Fig. 3 Scene data processing

(3) Industry Data

The digital twin system will contain system data of different vertical industries such as cities, transportation, aviation, port, healthcare, construction sites, energy, and water utilities within the full lifecycle of planning, construction, and management.

Taking video data and spatial data fusion as an example, by projecting the real-time camera images onto the 3D digital twin scene, splicing and fusing adjacent images together into a larger resolution spatial picture, thus monitoring, tracking, and tracing history, it not only provides a clear view of the actual location and spatial relationships of each video, but also is capable of using virtual camera roaming in the 3D space, which supports multi-angle, all-direction viewing, zooming, and perspective switching. Moreover, it provides a critical path automatic inspection and key areas subject fast targeting. Therefore, the data of the video-spatial fusion can provide intuitive assistance for real-time commanding, efficient daily management, and rapid processing of emergency events.

3.4 Efficient modelling

Modeling is the process of digitizing the physical world and is the core of digital twin. According to the modeling requirements of different application scenarios, in the future, digital twin modeling usually needs to have the capabilities of multi-scale, 3D automation, semantics, etc.

(1) Multi-scale modeling

Based on different accuracy criteria, multi-scale modeling can be application scenario-oriented to recreate larger-scale urban scenes (Fig. 4). The fusion of oblique photography, laser point cloud data, GIS basic data, IoT data and other business data is able to match different scales and different data granularity in order to generate multi-scale data fusion criteria, then customize data theme of different hierarchical levels based on this criterion, thus accomplish multi-scale modeling of people, events, sites and objects, and then realize the hierarchical mapping of physical space and digital space.

(a) Initial precision Model

(b) Medium precision model

(c) High precision models

(d) Highly realistic model

(e) Fully realistic model

Fig. 4 Multi-scale modeling

(2) Three-dimensional automated modeling

The traditional 3D modeling is based on aerial photography data, CAD drawings and two-dimensional models. It requires manually mapping by 3DMAX software to complete modeling, which based on geometric algorithms, but there are problems such as low efficiency and high workload. As a reverse modeling technology, the 3D automated modeling has the advantages of high efficiency, high accuracy and low cost compared with the traditional way. In addition, by employing laser point cloud and oblique photography as foundation, the 3D automated modeling of large areas and multiple specifications can be implemented through computer graphics, deep learning algorithms, visual information calculation, texture image creation, texture image editing and recognition, extraction and reconstruction of geometric features.

(3) Semantic modeling

The semantic modeling can reconstruct the spatial poses of cameras and the sparse cloud of feature points by employing multi-perspective images as input. In addition, semantic segmentation is performed on point clouds for event detection, and extraction of event-related elements and relationship in multiple scenes. And then it further performs semantic modeling of monomer in order to construct a 3D semantic model, which endows soul to the model, thus the model can be recognized by machines to realize scene perception and spatial high-precision positioning. Semantic information serves as a link between 3D models and the real world. With the help of semantic information, various data analysis, query and other applications can be carried out purposefully, laying the technical foundation for the support of fusion models and common capabilities in digital twin simulation.

3.5 Real-time dynamic simulation

Real-time dynamic simulation is a breakthrough from the traditional static information management. It is designed for complex application scenarios in multiple domains and multiple temporalities based on the integration of multidisciplinary and multi-scale dynamic simulation, which is also a key capability that a digital twin requires. However, the massive spatial-temporal multi-source heterogeneous data generated by various objects or activities during the process of production or ecology, are highly coupled and related. Those data will form a complex differential social movement process. Therefore, the way to use the existing technology for real-time dynamic simulation is the key and one of the most difficult problems to be solved by the digital twin.

In the future, by using deep learning, reinforcement learning and incremental learning synergistic technologies, people can analyze dynamic evolution, perform knowledge discovery and predict future development through data modeling in digital space. Then people can simulate, evaluate, compute and deduce specific events in physical space. In addition, they can also achieve optimal allocation of resource elements and provide feedback for management solutions based on the digital twin system.

3.6 Visualization

The digital twin visualization ability is based on the game engine, 3DGIS technology, mixed reality technology and multi-layer real-time rendering of complex 3D scenes. This capability realizes the visualization of spatial data from macro scenes to micro details and realizes the integration between static and dynamic data.

(1) Seamless visualization from macro scale to micro details

Seamless visualization realizes arbitrary rendering from large scale to micro details (Fig. 5). It supports 3D scene full area representation, and its viewing distance is from tens of kilometres to one meter, without obvious loading delay. This capability can support the visual processing of large scenes such as digital twin cities.

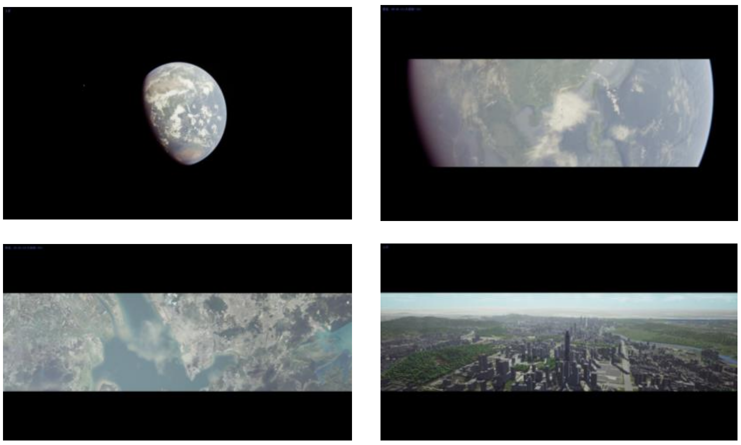

Fig. 5 From large scenes to fine scene rendering

(2) Indoor-outdoor integration

The level streaming function of game engines can help realize the integration of outdoor and indoor scenes. Different roaming and interactive modes can be realized under the condition of keeping the same spatial location and indoor and outdoor scenes. For indoor complex models and realistic rendering effects, special optimization of indoor visualization is required to meet the requirements of real-time rendering.

(3) Static-dynamic Integration

Under the circumstance of large-scale static 3D scenes, this integration supports the visualization of dynamic models of various intelligent traffic objects such as crowd flow and vehicle flow. It not only can support traffic flow and other trajectory animations but also support rich human skeleton animations, as well as various model animations of specific simulation objects, making the whole scene appear in high fidelity.

3.7 Security

Security runs through all aspects of the digital twin system, involving the availability, controllability, integrity, confidentiality and non-repudiation of information. With the variety of application and accelerated integration of the digital twin in vertical industries, security issues and risks are becoming increasingly prominent. Taking the smart manufacturing digital twin system as an example [9], on the one hand, due to the security vulnerabilities and lacking of security measures, the basic equipment and control system may face network security risks. On the other hand, because a large amount of internal and external data may be stored on multiple devices such as platforms, terminals or servers, the smart manufacturing system may face data security risks. Moreover, due to the possible existence of multiple services and platforms, the digital twin system may lead to a sharp increase in security risks and result in more intrusion methods and attack paths.

Once the digital twin system covering multi users, multi devices and multi processes is attacked, it may lead to large-scale user privacy leakage, false perception data interference, system denial of service and other serious consequences. Therefore, security will become an endogenous capability of the digital twin system in the future, with comprehensive protection in terms of technology, specification, mechanism and process. In addition, the development of key technologies such as blockchain, cryptography and security protection will provide more effective solutions for digital twin in terms of identity authentication, privacy protection and resistance to security attacks, thus realizing distributed and traceable security and privacy protection comprehensive services. At the same time, due to the wide variety of digital twin objects and the significant differentiation of twin system capabilities, except to technology, the establishment of security regulations and the standardized implementation of security mechanisms will further help eliminate security risks.

4 Digital twin use cases

4.1 Smart City Construction

Liaocheng, a city in Shandong Province, is a pioneer in building a smart city. As part of its plan "3 Year Action Plan to Develop a New Smart City (2019-2021)", the city government proposed the concept of "One Could, One Net, One Center". Based on the concept, the Liaocheng City Brain aims for a sensible, thinkable and decisional system, to enable the city with intelligent power, focusing on solving knotty problems in cities. As showed in Fig. 6, digital twin technologies provide a panoramic view of the city, enabling them to experience the scene in an immersive way, and bringing the power of City Brain closer to all citizens.

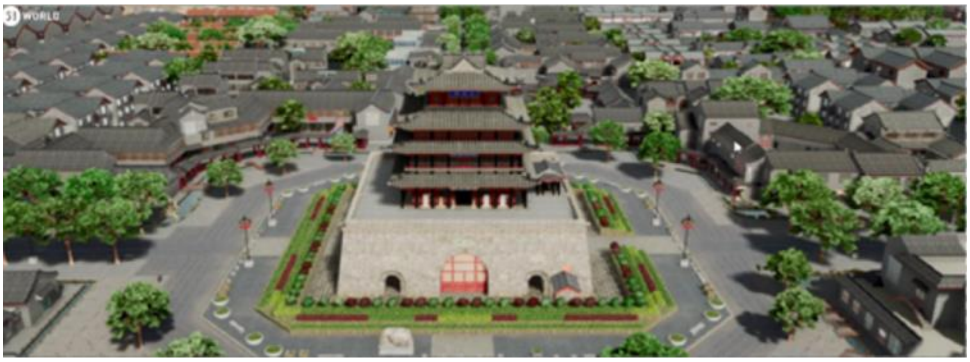

Fig. 6 Effect picture of the digital twin of Liaocheng

The core area of 200 square kilometres of Liaocheng including high precision landmarks has been transformed into its digital counterpart. All functions of Liaocheng City Brain including sensing, managing and decision-making process can be viewed on the digital twin platform. The City Brain provides a holistic and flexible view of the city with real-time data inputs. The digital twin platform can provide significant opportunities in scientific planning and development, early-stage collaboration with rapid optioning, simulating and testing.

By promoting the Data Centre and Integrated Command and Control platforms, massive urban data have been integrated and associated with the digital twin platform. On this platform, the complex interactions in the cities can be viewed intuitively on the screens and make governance closer to the actual needs of citizens. Thus, a unified urban management and dispatch system comes out with IoT sensing and AI-aided decision-making capabilities.

Liaocheng City Brain is supported by four systems such as security management and standard management. With the support of its digital twin counterpart, the public resources will be allocated accurately to where its need is the most. The City Brain will serve more in key public domains such as livelihood services, public security, urban governance, epidemic prevention and control, and smart transport, enabling the intelligent Liaocheng deeply.

4.2 Winter Olympic Games Preparation

Based on digital twin technologies, the Digital Trail Visualization and Analysis System provides comprehensive information integration, training monitoring and training history analysis to assist the athletes in preparing the 2022 Beijing winter Olympic Games.

The Digital Trail Analysis and Visualization System provides training assistance for athletes and coaches, including slope analysis, real-time training monitoring, record replay and record marking functions. By integrating body indices data and motion data which are collected by wearable flexible devices, training can be displayed on the digital twin 3D scenes in real time.

Trail Slope Analysis: 3D visualization of trail slope, and slope heatmap helps in analysis. 2D systems and trail maps were used by coaches and athletes in the past, however trail slope analysis was limited by these traditional methods. To increase the users' sensibility of the trail slope, the system takes the trail out of the terrain, stretches the trial by proportion, then overlays the trail with slope heatmap (Fig. 7).

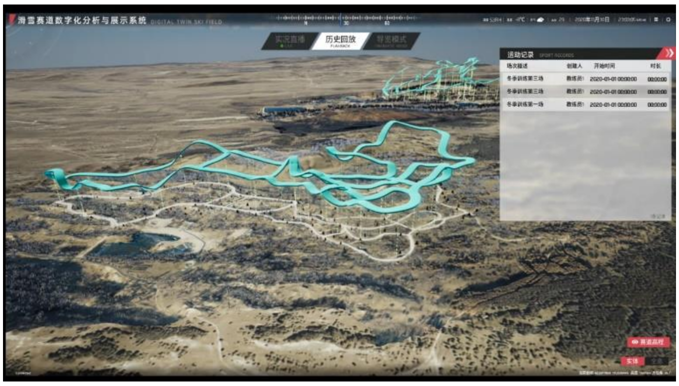

Fig. 7 Digital twin Winter Olympics stadium

Real-Time Training Monitoring: Displaying monitoring data in real time. By integrating the real-time health parameters (e.g., heart rate, pace, power, etc.) and motion parameters (e.g., location, speed, stride, etc.) collected by wearable devices, the real-time training status with the on-going training subject information can be displayed. The athletes can be located on the 3D scene in real time (Fig. 8). By means of analysing the synchronous health parameters and motion parameters, the coaches can provide advice and help the athletes to adjust in time to improve performance.

Fig. 8 Digital twin Winter Olympics data display

Training Record Replaying: Assists training review and increases training efficiency. In the past, training information was recorded by handwriting. Information was limited and hard to read, which was not user-friendly. The system provides training recording function, by which all the real-time training monitoring data can be saved. It also supports training record retrieving and replaying anytime and anywhere. With the marking function, coaches and athletes can mark out the points which can be improved on the training routes on the 3D scene and write down suggestions. This function assists in finding and marking out flaws in training, so as to help record analysis.

4.3 Factory Upgrade and Transformation

Based on the digital twin technology, a demonstration factory of the Binjiang 5G model has been built (Fig. 9). The data of factory physical model, sensors and operation history are converged to integrate the multi-discipline, multi-physical, multi-scale and multi-probability simulation process. The virtual space is mapping the actual factory operation to complete and reflect the full life-cycle process of physical equipment. Based on the virtual cloud platform, this system integrates the processing capability of the rendering engine, collects location information and sensor data through the 5G network, converges and processes space-time data, performs digital presentation, then achieves digital twin in the entire application of the industrial park. Based on the digital twin system, the specific scenarios include the automatic 5G assembly line, the warehouse visualization, the AGV scheduling system, the video preventive inspection system and so on.

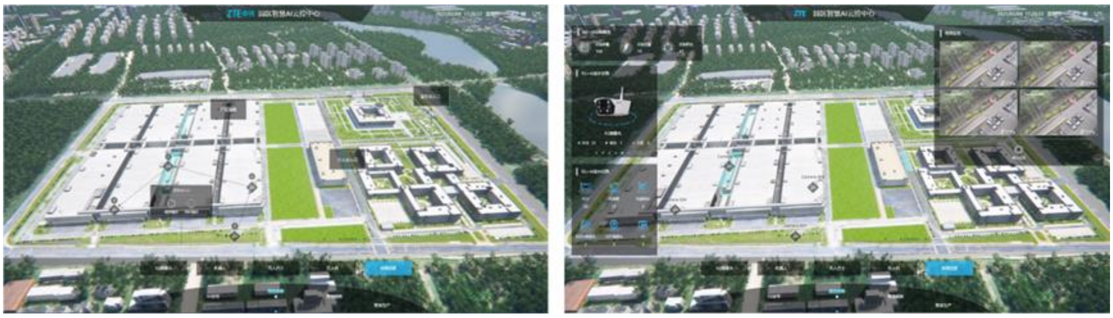

Fig. 9 5G Smart Factory Based On Digital Twin Technology

The automatic 5G assembly line: Based on the digital twin modeling technology, this scenario renders the assembly line with animation, and combines the digital world with the actual production process to present the operation status of the production line in real time. And this scenario tracks and displays equipment and AGV alarm information, realizes data simulation of production line production simulation, docks system data at the same time, and displays production information such as production dashboards, equipment dashboards, process parameters, status, and work orders in real time through virtual panels.

The warehouse visualization: This scenario builds a three-dimensional model of the warehouse (including equipment and materials), and the three-dimensional simulation display can be carried out from the warehouse environment. The layout of the warehouse to the building structure and independent equipment, and the adjustment and scene switching at any angle can be realized. Therefore the manager can preview the real-time status of the warehouse globally. Meanwhile, the real-time status of the workshop line is displayed with key warehouse equipment (such as shuttle vehicles and stacking machines) as the unit to ensure that the administrator can master the real-time situation of equipment operation.

The AGV scheduling system: Under the support of the digital twin system, this scenario integrates and opens up all the information systems of the 5G demonstration production line to build full-element, full-data, full-model and full-space virtual-real mapping and interaction integration, to form a new scheduling mechanism of virtual and real response, virtual and real interaction, virtual control and iterative optimization. Then the "workstation-machine-constraint-target" scheduling elements can be matched and optimized continuously.

The video preventive inspection system: Digital twin system with video collection and AI algorithm is used to implement automatic preventive inspection and automatic alarms, thus improving preventive inspection quality. Based on the digital twin system, security personnel can define the inspection route, inspection frequency and inspection time as needed, with a high degree of freedom and immediate effect. In accordance with hierarchical permission management requirements, the system can assign dedicated numbers to dedicated persons to achieve hierarchical management. The system also supports remote query at any time and any place, greatly saving labour costs.

4.4 Smart Transportation Upgrade

The first-period project of the construction of Shanxi Wuyu Highway Intelligent Networked Heavy-Load Highway Demonstration Base truly resets the entire 15-kilometer demonstration road section, builds a digital twin visualization and interaction system for micro-traffic simulation on one interface, and reproduces the middle and microscopic traffic flow operation process.

Through the IoT, Big Data, 5G technology and other technologies, strong coupling of human-vehicle-road-cloud and data interconnection can be realized to provide safe and reliable planning decisions for assisted driving and autonomous driving.

First of all, the digital twin system supports the development of simulation decision-making algorithms for heavy-load highway traffic sections, provides reliable tools for traffic flow problems such as congestion traceability and offers reliable decision-making basics of traffic wardens. Secondly, it supports communication and data interaction between connected automated vehicle, equipment, information systems and cloud, car-side, road-side platforms, and it performs networked and intelligent decision-making capabilities for perception, decision-making and control layer data statistical analysis. Finally, in practical operation, a variety of roadside smart sensors (such as cameras in highway sections, millimetre wave radars and lidars), which are set up for the road sections in the demonstration area, various smart devices in the tunnel (such as fans, firefighting equipment and weather sensors, lighting equipment, contour light strips, escape ports, etc.) and IoT equipment in the intelligent service area are effectively managed and controlled in their entire life cycle, building a standardized, systematic and intelligent networked business application show centre and supervision management operation centre. To use the proactive automatic prediction and risk identification capabilities in the system can reduce operational hidden danger at the most.

The digital twin can be used to enhance digital operations in more application scenarios of highway systems (as shown in Fig. 10), such as service areas, toll stations, bridges and tunnels, etc. It will improve operational safety supervision capabilities and networking intelligence capabilities to further advance the traffic safety and operational efficiency.

(a) Service area of Intelligent highway

(b) Toll station of Intelligent highway

(c) Tunnel of Intelligent highway

(d) Bridge of Intelligent highway

Fig. 10 Application scenarios on highway systems based on digital twin

4.5 Smart Grid Upgrade

Grid system has variety pain points in management, safety and efficiency. For instance, lack of intuitive classification and integration brings troubles in management. The working environment of substation is dangerous, and the existence of high-voltage equipment is a risk of staffs in routine job of inspection and troubleshooting. It is also a challenge for staffs to inspect all equipment because there is a variety of equipment in substation, which causes failure response delayed. Additionally, most of the transmission lines are built at remote areas, thus the efficiency of line inspection and the safety of the staffs cannot be guaranteed. And the complicity topology of power distribution network is also a challenge to locate breakdown.

To solve the problems mentioned above, a Digital Twin Grid System is developed based on IoT and digital twin technology. Substation, transmission network and power distribution network are reconstructed on 3D scene to provide the capabilities of overview of city power status, substation intelligent inspection, equipment management, safety management, personnel management, transmission line intelligent inspection and topology management of power distribution network. By data integration and business integration, the system provides a comprehensive and full lifecycle management of power transmission and distribution, which can solve the problem of data island and achieve the goal of safe and efficient management.

Relying on the construction of smart city, digital twin technology offers the possibility of combining the power management system and the related city power network (Fig. 11). By means of integrating city energy internet and other infrastructures, the system can provide failure forecast, dynamic prediction of power supply and demand, and effective grid planning. By building a multidimensional database, the system can help construct power data center and smart grid. By integrating grid data and city planning data, the system provides the capability of scientific and efficient grid planning.

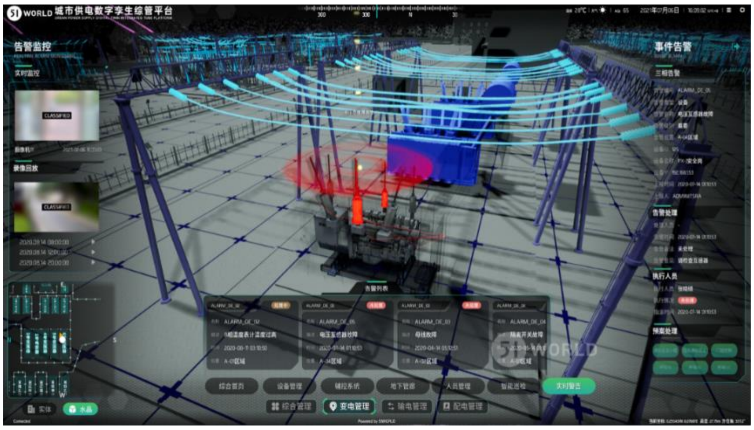

Fig. 11 Digital twin effect of electricity

4.6 Underground Station Intellectualization

Underground station monitoring, operation and maintenance management usually have some problems, such as data presentation and fault feedback are not intuitive enough, the information is lack of close connection with the actual model, the degree of integration of information is not enough, and the internal relationship between data is difficult to be deeply excavated, resulting in the reduction of operation and maintenance efficiency.

Based on the digital twin technology and the long-term operation date, the actual operation of the underground station can be monitored and displayed through information aggregation and visualization, so as to realize the digital upgrading of the operation mechanism of the whole underground station and improve the efficiency of operation and management. The digital twin technology can support the whole line monitoring and accurate deployment of safe operation in the underground station (Fig. 12). At the same time, based on the passenger flow simulation technology, it can realize the simulation of passenger flow pressure evacuation and safe operation of underground stations, support users to set their own operation mechanism, simulate the process of passenger flow changes affecting operation pressure, and constantly verify the effectiveness of underground station operation and control measures, so as to improve the emergency response ability.

Fig. 12 Digital twin underground station

(1) Real-time Surveillance

By generating a scene model of the whole station and the surrounding environment, a digital twin of the underground station can be built. It will display the current operation of the underground station and the dynamic changes of the whole station, judge whether the operation is safe by monitoring the abnormal information, judge the potential threats by monitoring the operations, and visually display the information statistics results.

(2) Practice & Simulation

This is used to practice and verify operations of the underground station. Based on the cloud computing platform, users can set constraints according to their simulation conditions, including scenario constraints and passenger flow constraints. Additionally, scenario constraints, such as the equipment status and the underground schedule, can directly affect the related settings for passenger flow. Consequently, these would help practice emergency plans then verify the feasibility and reliability of those plans, thus improving the emergency management capability.

4.7 Port Operation Management

Using digital twin technology, combined with key data such as port freight information, three-dimensional GIS and video monitoring, the digital twin port can be established, in order to carry out comprehensive visual management and intelligent scheduling for personnel, goods and terminals of the port, and greatly improve the logistics efficiency.

Digital Twin Port Operation Management System can help the ports in accelerating the construction of safety port, green port and smart port. It dynamically simulates the equipment operation and cargos on 3D scene in real-time, which has covered the operation scenarios from vessel importing/exporting, loading/unloading ship, horizontal transportation, loading/unloading truck and gating in/out truck. To achieve the synchronization between the physical port and virtual port, the 3D scene is driven by the real-time data of vessels, equipment, and cargos, to cover the full lifecycle of port management (Fig. 13). The main functions of the system are as below.

(1) Port Operation Management: the system supports the simulation of port production features and processes. It also provides the capability of history operation review, real-time operation monitoring, and operation plan preview for decision support.

(2) Port Safety Management: the system integrates real-time monitoring data of dangerous cargo, dangerous tank area and dangerous cargo yard to provide emergency response to fire event, leakage event and other emergency events.

(3) Port Scheduling: based on digital twin technology, the system provides process collaboration and consolidation management for all participants to achieve the goal of improving transportation efficiency and integrative collaboration of supply chains.

(4) Cargo Transportation Management: by integrating logistics information and standardizing data and workflow, digital twin technology assists in reducing the vessel waiting time and truck congestion duration.

(5) Infrastructure Maintenance and Management: the system provides statistics of infrastructure types and status combining with 3D models, and is helpful in infrastructure dynamic maintenance and management, preventive maintenance and predictive maintenance.

Fig. 13 Digital twin port

4.8 Industry Network Lifecycle Management

At present, the phenomenon of network isomerization and customization is common in industry networks, leading to problems such as a high degree of customization of networking solutions and configuration solutions, a large number of network element modules, and difficulty locating faults. In addition, different industries and different scenarios have different requirements for network performance, requiring lightweight management and deterministic protection of SLA. Traditional network management systems and agent maintenance teams cannot meet the operation and maintenance management needs of industry networks, with low efficiency and high costs. Based on digital twin technology, it can realize network visualization, simulation and intelligent operation and maintenance, and support the whole life cycle management of industrial network planning, construction, operation and maintenance and optimization.

(1) Network Planning

The factors considered in network planning include core network, access network, terminal network element equipment, etc. Diversified and customized terminal network service requirement can increase the complexity of network management. After the construction of digital twin for the related network elements, the network topology rules need to be designed, including physical and logical topology. The analysis model of each business service can be orchestrated and built. Therefore, digital twin technology can be used for network planning with the actual needs of users. In the network planning scenarios, the 3D vector mapping can be used to realize the flexible layout and deployment. Based on the network element equipment model, the coverage of network and the running state of network element are displayed dynamically and visually, which can comprehensively verify the business requirements and expected planning results (Fig. 14).

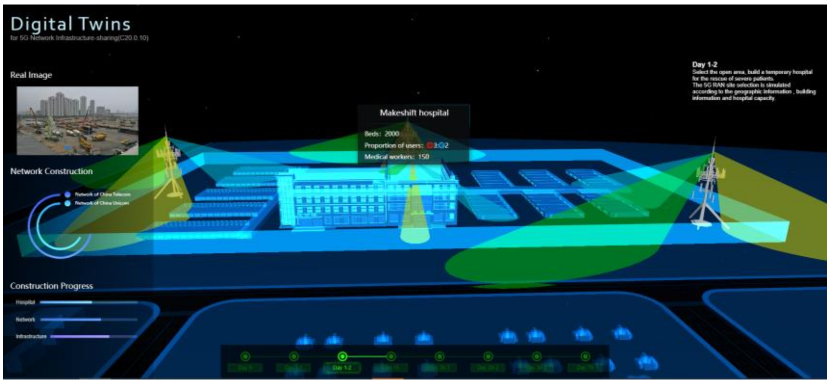

Fig. 14 5G RAN planning

(2) Network Construction

Based on digital twin technology, network construction can be firstly completed in digital space to search for the best construction design. Then, according to the best construction design, the network element equipment is deployed and constructed in the physical space. The sensing data is shared to the digital twin model of network element devices in physical space and digital space, so that the real network and twin network can run and interact simultaneously. The running state of real network and twin network can be dynamically visible. Furthermore, the digital twin technology can be used to modify the information of network equipment parameters, so that the constructed network can tend to the actual requirements of customers. For the upgrading of existing network, the digital twin technology can be used to quickly reconstitution and reappearance the operation status of the existing network. Through the digital twin technology, we can search for the best solution of upgrading network. To use the digital twin technology can avoid the problem of network reuse and resource adjustment, when upgrading and transforming the existing network.

(3) Network Operation and Maintenance

The network operation and maintenance based on digital twin technology can realize the real-time monitoring of network operation state, including the running state of network element equipment, the visual monitoring of network real-time operation status, etc. When there is an alarm or fault in the network operation, the root cause of the fault can be displayed quickly and visually. The operation and maintenance personnel can firstly find out the best solution to solve the alarm or fault in the network operation in the digital space. Then the solution can be simulated and verified in the digital space. After the verification, the solution can be distributed to physical space to solve the alarm or fault in the network maintenance.

(4) Network Optimization

The traditional network optimization process is always trivial and inefficient. Especially for the end-to-end optimization of multi-layer network services, it is difficult to achieve fast positioning and output optimization report. Based on digital twin technology, the network optimization can predict the health and reliability of network element equipment in advance (Fig. 15). Network digital twin can visualize the fault prediction and equipment operation life analysis. Moreover, during the network optimization, the measurement report, original data, network signalling data and quality management data can be combined to optimize the network. The best optimization scheme can firstly be simulated and verified in the digital space. After the verification, the optimization scheme can be distributed to physical space for execution.

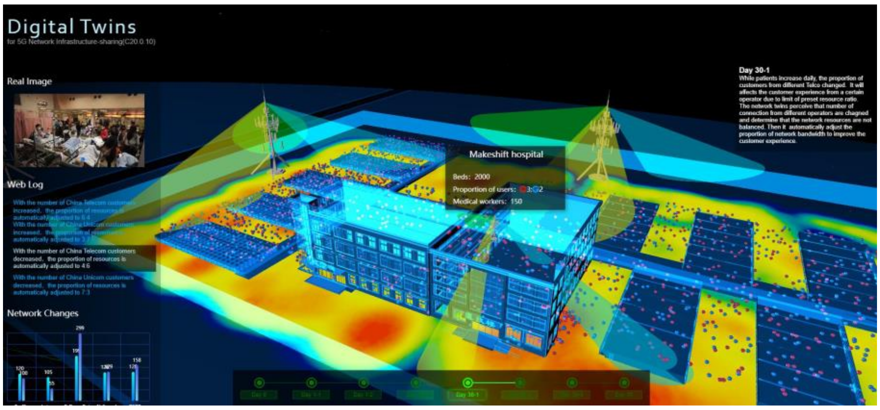

Fig. 15 Network autonomic energy regulation

5 Conclusion and prospect

As an important enabling technology to realize advanced concepts, such as digital, intelligent and service-oriented, digital twin is attracting much attention from various fields. With the rapid digital intelligence transformation of industrial, urban, transportation, medical and other vertical industries, digital twin, combined with AI, can contribute to the development of various fields. **In the field of industrial manufacturing**, the use of digital twin can create a virtual space for industrial production, in which equipment diagnosis, process simulation and other simulation predictions can be conducted. These simulation-based prediction can effectively prevent serious consequences from on-site failures and production abnormalities, which brings significant efficiency gains and cost reductions to industrial companies. **In the field of urban governance**, the digital twin can open the information islands between systems, which can sense urban signs, monitor urban activities and predict urban development, thus realizing digital, networked, intelligent, three-dimensional and precise urban governance. **In the field of intelligent transportation**, the digital twin promotes the continuous integration and interaction of transportation activities between physical and virtual space, as well as builds a modern transportation system, and as such is accelerating to become the main tool and core mode of future intelligent transportation. **In the field of health care**, the digital twin is combined with medical services to achieve dynamic monitoring, simulation and emulation of both human operation mechanism and medical devices, which not only speeds up the translation of research innovations into clinical practice and improves the efficiency of medical diagnosis, but also optimizes the quality control management of medical devices.

To further enhance the empowerment of the digital twin for vertical industries, it is necessary to reinforce the construction in terms of standards, evaluation system and ecological construction. **In terms of standards**, as the digital twin practice is still in the exploration stage and the understanding of all parties varies considerably, the basic common and key technical standards of the digital twin such as terminology, common architecture, model, data, technical services and platform are still in preparation, so it is difficult to provide normative guidance for system development and application. In future, digital twin-related standards need to further unify the core elements of the digital twin, such as identification, information model and data format, so as to gradually formulate a digital twin standard system and realize the synergy and interaction among standards. **In terms of evaluation system**, further evaluation framework need to be constructed in various dimensions in future, such as the maturity of digital twin modelling, the fineness of digital twin models, the connectivity between digital twin and physical world, the integration of digital twin systems with key technologies such as AI, and the degree of data sharing among digital twin systems, thereby forming a comprehensive evaluation system that is graded, classified, standardized and quantifiable. **In terms of ecological construction**, the digital twin industry value chain involves various parties, the technical system is complex, and the vertical industry barriers are high, so it needs all parties in the industry to collaborate and innovate, complement each other's advantages and form a synergy. In the field of infrastructure construction, technology integration, data sharing and capacity opening, the digital twin not only needs to strengthen exploration and realize synergistic interaction among multiple service organizations, but also deepen the exchange and cooperation of the industry value chain and demand matching to accelerate industrial upgrading and development, so as to achieve win-win outcomes.

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