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A systematic review of a digital twin city: A new pattern of urban governance toward smart cities

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ABSTRACT

Many countries and governments consider smart cities a solution to global warming, population growth, and resource depletion. Numerous challenges arise while creating a smart city. Digital twins, along with the Internet of Things, fifth-generation wireless systems, blockchain, collaborative computing, simulation, and artificial intelligence technologies, offer great potential in the transformation of the current urban governance paradigm toward smart cities. In this paper, the concept of a digital twin city (DTC) is proposed. The characteristics, key technologies, and application scenarios of a DTC are elaborated upon. Further, we discuss the theories, research directions, and framework regarding DTCs.

1. Introduction

Governments around the world are beginning to tackle the problems caused by urbanization in the 21st century. Problems triggered by urbanization, such as urban poverty, high urban costs, traffic congestion, housing shortage, lack of urban investment, weak urban financial and governance capacities, rising inequality and crimes, environmental degradation, are exacerbating. (O'Brien et al., 2019).

The world is at an unprecedented level of urbanization. The United Nations (2018) estimates that 68% of the world's population will live in urban areas by 2050. An increasingly large share of the world's highly skilled, educated, and creative population dwells in cities, giving rise to highly concentrated and diverse pools of knowledge and knowledge-creation networks. Zhang (2016) examined the trends of global urbanization and the magnificent scale and rapid pace of urbanization in developing countries and the different characteristics of urbanization trends in developing and developed countries. Cocchia (2014) summarizes that the reason for the birth of smart/digital cities is because of the demand of citizens across the globe to their local governments to improve their quality of life through innovative design and reconstruction of urban spaces.

The digital twin, as an inevitable trend of digital transformation, helps cities realize real-time remote monitoring, and allows more effective decision-making. Angelidou (2017) examined the smart city plans of 15 major cities worldwide and observed the top-down coordination and practices of these cities. New York generated a strategy to become "the world's most digital city" with four core areas: access, open government, engagement, and industry. San Francisco had an ambitious goal of achieving zero-waste by 2020 with various smart city support mechanisms for its clean-technology and innovation firms (Lee

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et al., 2014). The British government proposed a Smart London Plan, which aimed at using the creative power of new technologies to serve London and improve Londoners' lives. Singapore started the "Singapore Intelligent Nation" plan in 2015 and uniquely began to consider itself a smart nation (Cavada et al., 2019). Chinese President Xi puts special emphasis on the modernization of the national governance system and governance capacity.

2. Inevitable trend of digital transformation for smart cities

Digital transformation is an essential choice of urban governance. Every major technological breakthrough redefines the world landscape. In the twentieth century, Manchester and Liverpool, cities that had a population of over 100,000 in the UK, led the first industrial revolution. New York and Los Angeles, cities that had a population of millions in the United States, led the world into the second industrial revolution.

At present, new technologies such as the Internet, big data, artificial intelligence (AI), blockchain, the Internet of Things (IoT), and fifth-generation wireless systems (5G) are rapidly iterating; new formats such as the sharing economy, driverless vehicles, digital currency, and smart marketing are emerging; new concepts, such as ecology and health, are attracting increasing attention. Leaders are actively thinking about how their cities can be updated through new technologies, new formats, and new ideas. The silicon-based revolution brought about a comprehensive upgrade of the "data, algorithm, computing power" decision-making mechanism, thus changing the approaches of data acquisition and processing. The amazing progress of information and communication technology (ICT) brought about by the silicon-based revolution provides a basis for intelligent operation. Data and algorithms are rapidly driving the smart economy. With citizen partition and co-design, governments will be able to make wiser decisions and respond more effectively and promptly.

Mergel et al. (2019) interviewed several national governments, and most interviewees pointed out that the motivation for digital transformation comes from the external environment (83%) rather than internal pressure. Modernized information and communication processes become a vital force of social evolution (Mergel et al., 2019). The revolutions have greatly improved the productivity of the cities. The efficiency of these cities attracts the labor force and, in turn, the concentration of the labor force improves the productivity of the city.

In the last 20 years, the concept of smart cities has become popular almost everywhere and people have started thinking about innovative ways to develop smart cities. Zheng, Yuan, Zhu, Zhang and Shao (2020) reviewed 7840 studies about smart cities between 1990 and 2019. The authors point out that sustainability and sustainable development have become popular topics not only for scholars, particularly in the fields of environmental economics, technology and science, urban planning, development, and management but also for urban policy makers and professional practitioners. Caragliu and Del Bo (2019), Chourabi et al. (2012), Zhang (2016), and Zheng et al. (2020) regard smart cities as complex systems involving a symbiotic linkage among people, institutions, technology, organizations, building environment, and physical infrastructure. Smart cities use data and technology to improve efficiencies and sustainability and enhance the quality of life and the experience of working in the city (Albino et al., 2015). With ICT, smart cities can make more efficient applications to support economies and society. Bifulco, Tregua, Amitrano, & D'Auria (2016) regard ICT as a set of tools for the governance and management of urban and metropolitan areas.

3. Digital twin and digital twin cities

The digital twin is the inevitable goal of digital transformation. The concept of a digital twin was put forward by Professor Grieves in his course on product lifecycle management at the University of Michigan in 2003. A digital twin consists of three crucial parts: physical products, virtual products, and the connections tying them. A digital twin fully describes a potential or actual physically manufactured product from the micro atomic level to the macro geometrical level (Grieves and Vickers, 2017). Digital twin technology deeply integrates hardware, software, and IoT technologies to enrich and improve virtual entities.

NASA first applied digital twin technology in the field of aircraft and aerospace as an information mirroring model. A digital twin continuously forecasts the health of a vehicle or system, its remaining useful life, and the probability of mission success (Glaessgen and Stargel, 2012). In the manufacturing industry, researchers have proposed various frameworks of digital twin-based shop-floor smart production management methods or approaches (Tao and Zhang, 2017; Zhuang et al., 2018). Digital twins have been proven to be a practical method for integrating the physical world and the virtual world of manufacturing. Tao et al. (2018) present a new method for product design based on digital twin technology. Tao, Zhang and Nee (2019) explored efficient equipment energy consumption management in a digital twin shop-floor. Zheng, Yang and Cheng (2018) studied a digital twin case of a welding production line and described the details of the implementation scheme, application process, and the effects of this case. The digital twin becomes the basis for simulation-driven assist systems as well as control and service decisions in combination (Boschert and Rosen, 2016).

Digital twin technologies exhibit the following characteristics (Zheng et al., 2018): (i) integrating various types of data of physical objects; (ii) existing in the entire life cycle of physical objects, co-evolving with them, and continuously accumulating relevant knowledge; and (iii) describing and optimizing physical objects. Digital twin technology is not a simple technology or a single application. Qi et al. (2019) proposed a five-dimension digital twin model.

Governments will be able to perceive and predict the unmeasurable indicators in the past physical world and form a more comprehensive assessment. This paper outlines the blueprint of a digital twin city (DTC): all entities in DTCs will exist simultaneously in parallel with historical records that can be traced, a present state that can be checked, and a future state that can be predicted. In this blueprint, the digital twin becomes the most important power engine of urban wisdom. Decision-makers can achieve urban governance in a more orderly manner. Citizens can participate in urban governance processes and monitor government decisions.

The digital twin refers to the state of mutual symbiosis between digital entities and physical entities. Digital twin technology is a technology that integrates data, models, and physical entities. Digital twins refer to the mapping collection of entities in the digital world. A DTC collects digital twins of the entities of a city through digital twin technologies.

4. Advanced technologies applied in digital twin cities

DTCs aim to improve the efficiency and sustainability of logistics, energy consumption, communications, urban planning, disaster, building construction, and transportation. In this section, we list several key technologies in DTCs: Surveying and mapping technology, building information modeling (BIM) technology, IoT, 5G, collaborative computing, blockchain, and simulation.

The technologies mentioned above play different roles in DTCs. Surveying and mapping technology is the basis for collecting the static data of the buildings in cities. BIM technology is the basis for the asset and infrastructure management of cities. IoT and 5G are the bases for collecting dynamic data and feedback effectively. Blockchain technology is the basis for the trust mechanism of transactions, logistics, and human behavior. Collaborative computing with 5G is the basis for efficient real-time responses. Simulation technology is the basis for policy support, planning, and early warning mechanisms.

4.1. Surveying and mapping technology

The DTC focuses on instantaneity and accuracy, which requires highly automated mapping and surveying technology. Surveying and mapping in a DTC are the fundamental technologies that make it possible to deliver data integrated holographic results (2D/3D, aboveground/underground and indoor/outdoor) in real time. Surveying and mapping technology in cities has two segments: surveying the topography, environment, and spatial structure of the city; and mapping this information into an integrated system based on geographic information system (GIS). In the surveying part, four technologies are considered: tilt photography, unmanned aerial vehicle (UAV), 3D laser scanning, and global positioning system (GPS). In the mapping part, two technologies are considered: real-world 3D reconstruction technology and multi-source geographic data processing technology.

In recent years, with the maturity of tilt photography and UAV technology, real-time and accurate acquisition of local ortho, tilt, or Lidar point cloud data in cities can greatly reduce the workload of field mapping. These unmanned facilities make full use of their respective advantages to make comprehensive measurements of urban entities from the land, sky, rivers, and underground space while implementing iterative data updates. Gao et al. (2017) studied the rapid acquisition and processing method of large-scale topographic map data, which relies on the UAV low-altitude aerial photogrammetry system. Meouche, Hijazi, Poncet, Abunemeh and Rezoug (2016) used a UAV and other classical land surveyor instruments to investigate the possibility of exploiting and certificating it. The result indicated that the precision is satisfactory, with a maximum error of 1.0 cm on ground control points and 4 cm for the rest of the model. New-generation surveying technology, which focuses on the use of UAVs, is now widespread and operational for several applications. Yao, Qin and Chen (2019) provided a brief summary of existing examples of UAV-based RS in agricultural, environmental, urban, and hazards assessment applications, etc. In comparison with traditional topography, aerial photogrammetry provides faster data acquisition and processing and generates several high-quality products, with an impressive level of detail in the outputs at a lower cost (Beretta et al., 2018).

3D laser scanning technology is a low-cost technology using a high-speed laser scanning measurement method and laser ranging principle to accumulate large-area dense point cloud data. These data include three-dimensional coordinates, reflectance, and texture on the surface of the measured object. With the processing algorithm, this technology would create a 3D model of the measured object, as well as various map data, such as lines, areas, and volumes, promptly. With the rapid progress in urban planning, the cost of lightweight 3D laser scanning technology has decreased sharply, thus promoting the use of UAVs. Li et al. (2019) constructed a measurement system to acquire global coordinate point cloud data by combining 3D laser scanning and GPS, the positional accuracy in the global coordinate data was better than 10 mm.

Multi-source geographic data processing technology, as the basis of the mapping technology, must be strengthened while surveying technologies are innovated. With the development of tilt photography, UAVs, 3D laser scanning and GPS, the integration of the geographic entity with different accuracy, levels, and phases becomes much more difficult. Cao, Dong, Wu and Liu (2020), Chen et al. (2018), and Haklay (2010) provide efficient methods of multi-source data fusion in geographical fields, and they also analyzed examples in related fields. The data source of the urban GIS is upgraded from a single unit of GIS data to a fusion data set of multi-source, heterogeneous, multi-temporal space. It forms a holographic, high-definition, high-precision urban digital space, covering ground and underground, indoor and outdoor, and two-dimensional and three-dimensional structured entities.

The real-world 3D reconstruction technology is the key to mapping, based on the results of remote sensing and the fusion of multi-source data. In a city, this technology obtains 3D point clouds, 3D models, and real imagery through automated processes. The extraordinary location accuracy and geometric accuracy separate this technology from others. Nikoohemat, Diakité, Zlatanova and Vosselman (2020) introduced a complete workflow that allows generating 3D models from point clouds of buildings and extracting fine-grained indoor navigation networks from those models to support advanced path planning for disaster management and the navigation of different types of agents. Zhou, Wang, Love, Ding and Zhou (2019) proposed a method to improve the reconstruction effect of a 3D structure and model's visualization. Ma and Liu (2018) systematically summarized the up-to-date achievements and challenges for the applications of 3D reconstruction techniques in civil engineering and proposed key future research directions to be addressed in the field. Laser point cloud 3D construction technology will reflect the advantages of the automatic construction of 3D models in the DTC, and it has a very real, detailed, specific, and impactful visual experience.

4.2. Building information modeling technology

Many studies have been conducted to create BIM or city information modeling as the digital infrastructure to support various smart city programs (Chen et al., 2018). In a DTC, digital twin technology maps the physical city into a mirror city that can be disassembled, duplicated, transferred, modified, deleted, and operated repeatedly.

The identity technology is the basis of operations and maintenance in the DTC, which gives "identity information" to the physical objects in the digital world. Identity technology will certify the unique identification of each entity in the city and its "digital identification" is the only identification in the BIM system. After identity processes, indexing, positioning, and loading related information of the objects in the asset database quickly become possible. With identity technology, the BIM system can recognize each entity using several approaches, such as surveying and mapping technology. An information modeling system provides all the required tools and automation to achieve end-to-end communication, data exchange, and information sharing among identified collaborators. Xue, Chen et al. (2018) sought to understand the status quo and development trajectory of such RFID-enabled BIM systems and, finally, provided five-step guidelines for linking RFID to BIM. Accordingly, virtual 3D models, created through the BIM process, delivered as physical assets, monitored in real-time, and managed using building management systems, can adopt IoT designs and services.

4.3. 5G-enabled Internet of Things

The IoT technology, including the acquisition control and the perception process, is the basis for collecting dynamic data and relaying feedback. On the one hand, the acquisition technologies make communication between IoT infrastructure and entities possible through the sensor network. On the other hand, the perception technologies read the original data and transfer it to a machine-readable edition. However, both technologies rely on the IoT infrastructure.

The concept of the IoT dates back to the 1990s. It can be defined as a global infrastructure interconnecting physical and virtual things through interoperable information and communication technologies (Alavi et al., 2018). With the development of digitization, the conversion of analog information makes it easier to store, access, share, and process the information (Tilson et al., 2010), and the confluence of cost reduction and processing speed increase on sensors implies that the world has moved into the era of the IoT. The sensor is the key part of the IoT, which measures some property of the environment and translates the input into an electrical signal. To realize the system-level representation of a complex asset, where the physical entity has a dynamically coupled representation in the digital world, it is necessary to improve real-time sensors technologies. With the advancements in communications technologies, the vision of a vast array of interconnected sensors on machines, people, and products, coupled with intelligent controllers, becomes affordable (Olsen and Tomlin, 2020). The vision of real-time communication in IoT spreads widely, thus enhancing the timeliness associated with quality and completeness. Gubbi, Buyya, Marusic and Palaniswami (2013) present a cloud-centric vision for the worldwide implementation of the IoT and propose that the IoT has stepped out of its infancy and is the next revolutionary technology in transforming the Internet into a fully integrated future Internet. Advances in IoT technology monitoring techniques have led to the invention of various sensors that can be effective indicators. It has brought about improvements in the quality of real-time data, and there are many examples of the applications of real-time simulation to electrical systems including grids, power electronics, and control systems (Das and Saha, 2018).

In recent years, IoT has made it possible to monitor and manage the urban services of bicycle pool sharing and public parking, as well as water consumption, air and noise pollution, and traffic (Vojnovic, 2014). Bibri (2018) suggests that sensors can be classified according to the type of energy they detect as signals: location sensors (e.g., GPS, active badges), optical/vision sensors (e.g., photo-diode, color sensors, IR, and UV sensors), light sensors (e.g., photocells, photodiodes), image sensors (e.g., stereo-type camera, infrared), sound sensors (e.g. microphones), temperature sensors (e.g., thermometers), heat sensors (e.g., bolometer), electrical sensors (e.g., galvanometer), pressure sensors (e.g., barometer, pressure gauges), motion sensors (e.g., radar gun, speedometer, mercury switches, tachometer), orientation sensors (e.g., gyroscope), physical movement sensors (e.g., accelerometers), biosensors (e.g., pulse, galvanic skin response measure), vital sign processing devices (heart rate, temperature), wearable sensors (e.g., accelerometers, gyroscopes, magnetometers), and identification and traceability sensors (e.g., RFID, NFC). They generate business opportunities for companies or entrepreneurs that develop services for citizens or public authorities through a common platform (Grimaldi and Fernandez, 2019). The emergence of the digital twin offers a glimpse into the potential of IoT-enabled operations. The IoT technology in the digital twin is not simply a static digital representation of the physical object, but a dynamic digital representation of the object in use. It is important to create a digital world in the virtual space that maps and interacts with the physical world. Therefore, establishing a global, full-time IoT perception system with multi-dimensional and multi-level accuracy is a critical foundation for the DTC. By assigning unique digital identities to various urban entities, the IoT perception infrastructure would be able to match the one-to-one twinning world easily.

The DTC needs a large-scale deployment of multifunctional information facilities and intelligent gateways that support various distance communication protocol standards. With IoT, current authentication and access control solutions may induce a very high load on the core network and cause network failures (Behrad et al., 2020). Behrad et al. (2020) claim that 5G is expected to support a set of many requirements and use cases, such as handling connectivity for a massive number of IoT devices. Subsequently, the 5G-based IoT facilities aggregate and process the information collected by the sensors and upload it to the ubiquitous sensing and intelligent facility management platform.

4.4. Blockchain

A blockchain is a growing list of records that are linked with cryptography. Each block contains a cryptographic hash of the previous block, a timestamp, and transaction data, which are shared among the members of a network (Christidis and Devetsikiotis, 2016). Blockchain is considered a disrupter of the status quo, and it has been predicted that it will completely overhaul the digital economy. It uses a ledger to store a list of blocks, and the chain grows as new blocks are appended continuously (Zheng et al., 2017). A decentralized network of nodes is used to protect the lists of stored records against tampering or modification. Each participant in this network is allowed to visit the digital ledger fairly, which is shared through a distributed network in a secure way. In summary, blockchain technology is a combination of concepts, including peer-to-peer protocols, hashing algorithms, cryptographic primitives, such as public-key cryptography, and distributed consensus algorithms (Perera et al., 2020).

The applications of blockchain cover the areas of finance, insurance, logistics, energy, architecture, manufacturing, and transportation. Several senior researchers have explored the primary applications of the concept of a blockchain. Chen and Bellavitis (2020) studied blockchain-based finance technology, which can reduce transaction costs, produce distributed trust, and empower new business models, thus making the financial system more decentralized, innovative, interoperable, borderless, and transparent. A conventional financial system is characterized by the exchange of funds between customers, investors, lenders, and borrowers, where blockchain is the best proposed solution that can guarantee secure transaction management within a financial system. However, decentralized finance has to overcome several challenges and limitations before its large-scale promotion. Li, Shen and Huang (2019) proposed a blockchain-enabled workflow operating system to centrally share heterogeneous logistics resources with different customers. They also found that resource blockchain is an effective way to share real-time data reliably in e-governance. Yu, Jiang, Yu and Yang (2020) proposed a framework of a manufacturing management system with the resource operation blockchain as its core technology. The model shows that the blockchain-based shared manufacturing framework enables a peer-to-peer based resource sharing mode. Perera et al. (2020) studied the exponential uses of blockchain and several start-up projects contributing to Industry 4.0 and found that the blockchain has a credible potential in construction. Asadi Bagloee et al. (2019) formulated a tradable mobility permit to combat traffic congestion and discussed the future of blockchain-based applications, such as dynamic toll pricing, priority for emergency vehicles, heavy truck platooning, and connected vehicles.

For DTCs, it is important to focus on data acquisition and information feedback through 5G-based IoT sensor devices when conceptualizing smart cities. However, the amount of data generated in real time has become astronomical as the number and types of sensors increase. In addition, the current centralized communication model, as the client-server mode, makes it difficult to carry out faster automated communication among the IoT devices, where blockchain is proven to be an efficient solution for large-scale data management systems (Mistry et al., 2020). The digital twin maps the entities in the physical world to the digital world through digital means to form a virtual entity corresponding to the physical entity. Through the 5G-based IoT devices, the physical world provides sensing data, while the digital world feeds back service data. Blockchain technology records behavioral information between digital twins, guaranteeing the value, security, right, and ownership of the data. The digital twin of blockchain and 5G-based IoT will realize the connection, empowerment, and sharing, thus promoting the interconnection of all the physical entities in the future. Both decision-makers and citizens will enjoy the services of 5G-based IoT, and the integration of blockchain with IoT devices based on 5G in the digital twin cities.

4.5. Collaborative computing

With the challenges imposed by the rapidly growing IoT ecosystem based on 5G, massive amounts of data will be generated, which is far beyond the capacity of the cloud computing center (Xu, 2012). The industrial Internet, autonomous driving, video surveillance, etc. Have extremely high requirements for operation and maintenance in real time. Therefore, collaborative computing with the combination of large-scale cloud computing centers and small-scale edge nodes for lightweight processing has become a new pattern for an efficient response. In recent years, several studies on collaborative computing have been proposed, while cloud computing, which provides on-demand computing services, is gaining popularity (Zhao et al., 2020). Xu (2012) defined “edge computing” as any computing and network resources along the path between the data sources and the cloud server. Edge computing inherits the functions of the IoT platform to the brim of the user network to grant tardiness-free service/communication support (Kavitha et al., 2020). Alamgir Hossain et al. (2018) highlighted the development of the edge computing framework to process IoT data and edge computing provides a competitive advantage in terms of latency. With the use of edge computing services, the data moved to the remote server decrease significantly. This method has three main benefits: it can work with large data sizes, it guarantees low latency, and it focuses on location awareness.

5. Frontier research directions in digital twin cities

We discuss some frontier research directions for digital twin cities: the data center, the city information model (CIM), the urban smart brain, and the security guarantee mechanism.

5.1. Data center in digital twin cities

Data are the core strategic resource of digital twin cities. A data center, especially the super data center for a city, manages the entire life cycle of all the data in the DTC. With the growing use of mobile data, one challenge is to provide multifunctional, scalable, and flexible platforms that could address new problems with minimum cost and power. Ham and Kim (2020) proposed a new framework to bring crowdsourced visual data-based reality information into a three-dimensional (3D) virtual city for a model update with interactive and immersive visualization. Fan, Jiang and Mostafavi (2020) proposed an integrated textual-visual-geo framework to enhance social sensing techniques in the context of disasters, and this framework had been proved effective during Hurricane Harvey in 2017. However, owing to the explosive rise in the amount of data being generated by smart city devices, managing and storing these data on the data center is unreliable and inefficient. Uploading data to the cloud servers might cause long delays or even compromise data integrity. Therefore, it is necessary to explore the balance of efficiency and safety.

5.2. City information model

Establishing a CIM to realize the digitization of the whole process and all elements of the city is critical. This model integrates the geographic information model, the building information model, the IoT, AI, and big data technology. It is a full-space, three-dimensional, and high-precision CIM. It can achieve real-time visualization of the entire city, realize the simultaneous planning and construction of digital and real cities, and empower the entire process of urban planning, construction, and operation management.

The DTC of Atlanta is a virtual reality-based platform containing a fully modeled city of Atlanta in three dimensions. This platform is interactive and data-driven, enabling reciprocal spatiotemporal infrastructure. Through the analytics module, the platform can capture the information from infrastructure and society networks to monitor dynamic performance, such as operation, allocation of resources, and consumption (Mohammadi and Taylor, 2017). Therefore, richer insights are fed into a living digital simulation system for examining a variety of scenarios in the future.

5.3. Urban brain

In the field of the urban brain, many frontier directions have also been proposed. With the development of big data technology, it has become mainstream to integrate multi-source heterogeneous data through multi-perspective learning methods to achieve a comprehensive multi-dimensional perception of urban participants. With the growth of population in large cities, the increasing complexity of road networks has also become a problem for urban governance. Therefore, analysis, prediction, and intelligent intervention are also important tasks for traffic congestion management. Moreover, with the complexity of road networks, the complexity of modeling the urban brain system has also increased. The following two important tasks need to be considered: (1) through parallel heterogeneous computing, accelerating the computation and processing on massive real-time heterogeneous data networks; and (2) perceptually modeling in the urban environment and designing an adaptive vision algorithm that is robust to the environment. As for emergency management, future cities need the ability to respond quickly, thus searching quickly becomes very important. Therefore, carrying out the characteristic modeling of people and their behavior is of great significance for searching and recognition in monitoring data. In addition, city planning and public resource analysis are very interesting. Over a long period, the urban brain can collect data based on the laws of urban development. The analysis of these data can improve the efficiency of the infrastructure layout and public resource allocation.

5.4. Sound information security guarantee mechanism

The construction of a DTC requires a complete security system as a guarantee to ensure the normal operation of various applications and to ensure the safety of various fields. It is necessary to further strengthen network information security management and build a security system.

The digital twin in the field of architecture is still stuck in an early stage with respect to buildings. Lu et al. (2020) examined the operation and maintenance phase, which has the longest time-span in the asset lifecycle. They proposed a digital twin system targeting city-level buildings according to studies on multitier architectures.

The DTC demonstrator integrates heterogeneous data sources from Cambridge (a case study of the West Cambridge campus), supporting effective data querying and analysis. The improved buildings system supports decision-makers in operations and maintenance management, bridging the gap between human decisions and cities.

Here are several frontier scenes for the blockchain in digital twin cities:

(1) Smart healthcare

The contradiction between the limited resources and the ever-growing demand brings forth the need for efficient, intelligent, and sustainable healthcare. Blockchain technology is the best solution as shown in the following steps (Vora et al., 2018a):

Step 1: IoT sensors collect and monitor the patient's health information, such as pulse rate, blood sugar level, heart rate, respiratory rate, blood pressure, and body temperature.
Step 2: The administrators monitor the collected data and generate the patient's report.
Step 3: The received report is analyzed by the doctors who then recommend the required treatment.
Step 4: Doctors may choose to share the treatment reports using a distributed database for further analysis.
Step 5: The validated report is shared in an encrypted format.
Step 6: The patient requests the "cloud service provider (CSP)" for access to their treatment record.
Step 7: After successful validation, the encrypted file of the treatment record is received by the patient.
Step 8: Patients decrypt the received encrypted file with their own private key to access their original treatment record.

(2) Smart transportation

Blockchain technology can effectively handle security and privacy issues related to the intelligent transportation system. In vehicle networks, vehicles can communicate with the roadside unit or with each other without the involvement of any central authority. However, in such an autonomous environment, adversaries might inject misleading or false information to exploit personal benefits. Therefore, vehicle authentication is needed to guarantee secure data exchange between these vehicles.

Step 1: IoT sensors collect and monitor the information of vehicles, such as model size, speed, driving direction, and load.
Step 2: The distributed network nodes monitor the collected data and generate a real-time package for communicating.
Step 3: The received package will be used to calculate the behaviors of vehicles. The process of sharing will be recorded on a "CSP."
Step 4: Vehicles request the "CSP" for access to the information associated with them.
Step 5: After successful validation, vehicles will run the algorithm to determine their behaviors. Successful results will be recorded to improve the algorithm.

(3) Smart supply chain

Globally, complex supply chains have enabled the manufacture and sale of numerous products, but the entities (e.g., retailers, distributors, transporters, and suppliers) in these supply chains possess very limited knowledge about the product lifecycle. However, such product information is necessary as the consumers require the information to enhance their trust, and entities require the information to make business decisions or predict market trends. Blockchain technology in digital twin cities can be a solution. Blockchains track the detailed product information, prevent the entry of forged products into the market, and share information among various entities to optimize the decision-making process:

Step 1: IoT sensors collect and monitor the information of entities, such as logistics, specifications, affiliation, and value.
Step 2: The distributed network nodes monitor the collected data and generate a real-time package for communicating.
Step 3: The received package will be used to calculate the behaviors of vehicles. The process of sharing will be recorded on a "CSP."
Step 4: Retailers, distributors, transporters, and suppliers can request the "CSP" for access to the information associated with them.
Step 5: After successful validation, entities will get the information they need.

6. Framework of digital twin cities

This section proposes a framework for digital twin cities. Digital twin cities have common characteristics with other digital twin systems: self-perception, self-decision, self-organization, self-execution, and self-adaptation. They are composed of infrastructure construction, urban brain platforms, and new applications, as shown in Fig. 1.

The city brain platform is the intelligence hub for the operation of cities, which includes: the BIM + GIS-based city geographic information platform, integrated city data asset platform, intelligent application management platform, infrastructure information perception, and feedback platform. The city geographic information platform integrates the city

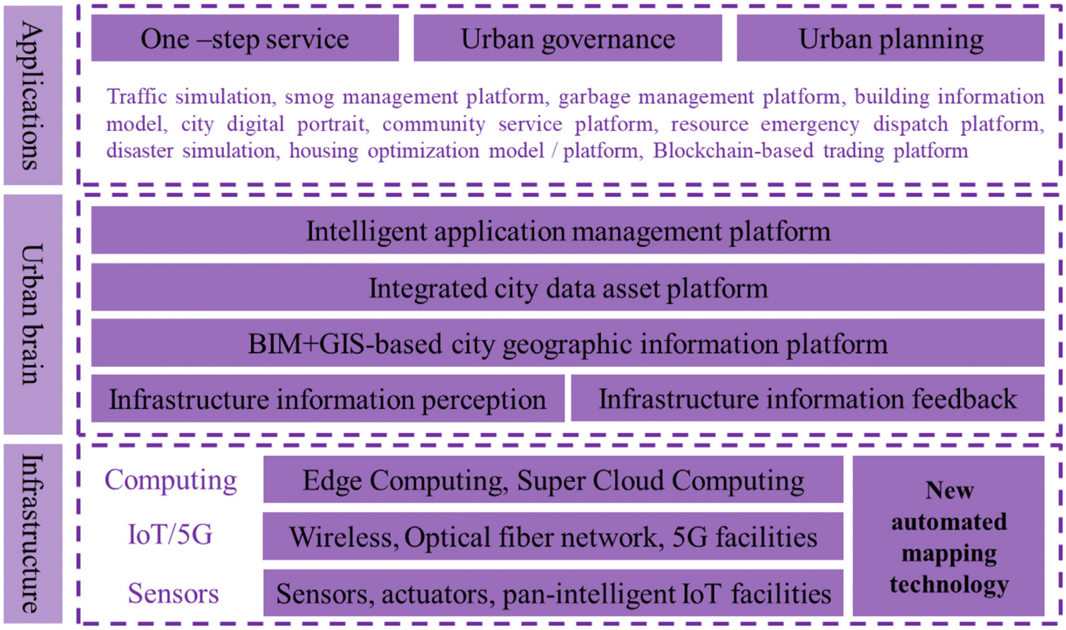

Fig. 1. Composition of digital twin cities.

information from the physical world and maps it to the digital platform, thus creating the base for digital twin cities. The integrated city data asset platform assembles the cities' administration data and the cities' basic data collected by sensors, and it is an important foundation for smart urban governance. The infrastructure information perception and feedback platform are key sections to connect the digital cities and the physical ones. The infrastructure based on commercial 5G promotes collaborative innovation and data synchronization in both the digital and physical worlds. The intelligent application management platform enables the data by utilizing the emerging AI, big data, and IoT technologies via AI, operations optimization algorithms, and simulation capabilities.

Infrastructure construction is the touchpoint and handler for building cities. It provides data support for the urban brain platform, analyzes and executes data, and provides feedback to the real-time physical world.

The emerging application layer is a modular application collection. It invokes CIMs and city data to deliver scenario services, data services, and simulation services. The scenario services include the provision of real-time data on urban architecture, geo-space, and environments. The data services include tracing and tracking the past behaviors of physical entities, monitoring current behaviors, and predicting future behaviors. The simulation service includes the simulation of time, events, and scenarios, and it will simulate services and assist decision-making through the design of pre-plans.

7. Conclusions

As a new model for building smart cities, the DTC will reshape the city governance structures and rules and inject a continuous momentum for the development and transformation of cities. Many of the important cities around the world have launched plans to build digital twin cities. The rapid development of digital twin technologies has also made it possible to construct digital twin cities. By analyzing the existing digital twin technologies, based on the development of smart cities, this paper proposes a pattern of digital twins. A self-perceiving, self-determining, self-organizing, self-executing, and adaptive platform for urban operation and maintenance is constructed through surveying and mapping technology, IoT perception, collaborative computing, simulation, and deep learning. The development of DTCs will create a new management pattern that can trace past events and explore frontier directions, which will be a trend for future research on DTCs.

Declaration of competing interest

The authors declare no conflict of interest.

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