SmartCityOS: Making Tomorrow Smarter

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Abstract

With the rapid advancement and widespread adoption of information and communication technology, the information space has emerged as the third space, complementing the physical and social spaces to form the ternary space of human society. The coupling of the ternary space promotes urban development, leading to a new paradigm: the smart city, representing the intelligent transformation of cities within the ternary space. Smart cities are giant, open, and complex systems that integrate diverse information systems rather than simply aggregating them. They create a systematic ecosystem of interconnected systems, all relying on shared infrastructure and data resources with substantial operational overlaps. This interconnectivity necessitates the development of a Smart City Operating System (SmartCityOS). Geographic information systems (GIS) are utilized to establish connections between the ternary space, mapping the city's physical and social spaces into the information space. The information space then feeds back into the physical and social spaces, optimizing urban systems and delivering open, diverse, shared, and environmentally sustainable intelligent applications. The concept and scope of the SmartCityOS are explained through its logical layers and system architecture. Key technologies, including ubiquitous city perception, digital modeling, spatio-temporal big data fusion and analysis, 3D city visualization, and simulation and digital twin interaction, are emphasized as critical areas of focus. Essentially, the SmartCityOS abstracts the complexities of a heterogeneous environment, while facilitating open and diverse applications. It transitions from vertical to horizontal integration, embracing complexity while fostering innovation through openness.

1. Introduction

The concept of smart cities emerged in the 1990s (Gibson et al., 1992), driven by information and communications technology (ICT), it has since garnered increasing attention, eventually being elevated to the level of national strategy. The United States (Gore, 1999), Singapore (Ng, 2011), Europe (Caragliu et al., 2011; Paskaleva, 2009), and other developed nations have initiated development plans for smart cities (Pham, 2014; Bronstein, 2009), with China following suit (Liu and Peng, 2013). The development of smart cities can be categorized into three stages: the informatized city stage, the digital city stage, and the smart city stage (Li et al., 2014). In September 1993, the United States launched the National Information Infrastructure (NII) program (Andreotta, 1995). In 1995, China promoted the "Golden Shield Project" for national informatization, marking the beginning of urban informatization. In 1998, the United States introduced the concept of "Digital Earth" (Gore, 1999), and the construction of "digital comfortable communities" signaled the transition into the digital city stage. In 2008, International Business Machines Corporation (IBM) introduced the concept of the smart city (Dirks et al., 2009). In 2009, IBM CEO Samuel J. Palmisano proposed to U.S. President Barack Obama the promotion of smart infrastructure development, aimed at overcoming the financial crisis and generating new socio-economic momentum. This marked the transition from digital city to the new era of smart city construction.

Smart city is an open, complex system (Zhou, 2002; Ruhlandt, 2018), evolving from the integration of culture and technology based on information and communication technologies (ICT) to encompass political, legal, and procedural norms (Zanella et al., 2014). It involves multi-sectoral interests, rights, and the reallocation of resources represented by data and information. This system aims to achieve global optimization across economic, governance, livelihood, and industrial dimensions (Gil-Garcia et al., 2015). However, smart city is an integrated system rather than a mere collection of multiple information systems. It forms a systematic ecology of information systems (Guo et al., 2020), where each system relies on shared infrastructure and data resources, with significant operational commonalities. This necessitates a Smart City Operating System (SmartCityOS). Since cities exist within a geographic space, a digital representation of the physical city is required. All urban entities (objects and events) possess spatial attributes (points, areas, paths), and all data describe these entities, so the urban problems fundamentally spatial problems that must account for spatial relationships. Therefore, utilizing Geographic Information System (GIS) technology to integrate various data resources and establish a unified urban digital twin platform is a practical technical approach for developing the SmartCityOS.

Geographic Information System (GIS) represents physical and social spaces from a spatial perspective (Guo et al., 2018). It establishes correlations within the urban ternary space by mapping physical and social spaces to information space. GIS also integrates urban ubiquitous sensing, digital modeling, and spatiotemporal big data, merging these elements in the information space to create a unified foundational operating system for the fusion, analysis, and expression of the urban ternary space. On the basis of SmartCityOS, it provides open, diversified, shared and green intelligent applications for the city through cross-platform and multi-terminal three-dimensional visualization, city-level simulation deduction and twin interaction and open development architecture. In short, the connotation of smart city operating system is to shield the complex heterogeneous world downward and empower open and diversified applications upward, changing from vertical coupling to horizontal coupling, accommodating complexity and guaranteeing innovativeness with openness.

2. Concept and Connotation of the Smart City Operating System

Smart city is the coupling of urban ternary space, is open and complex giant system. Experts from different fields, industries, and disciplines have varied understandings of smart cities, leading to the development of diverse concepts and construction paths (Acuto et al., 2018; Xue et al., 2020). Over the years, smart city construction has resulted in the creation of numerous systems such as city brains, digital twins, big data platforms, City Information Models(CIM), and operation and management centers. Various technologies, including computing power, networks, artificial intelligence, big data, IoT sensing, and geographic information space technology, have been applied in smart city projects. However, smart city represents the coupling of the urban ternary space, only by accurately mapping physical entities and social activities into the information space, and establishing strong correlations among ternary space, can we identify challenges, analyze them, propose solutions, and guide the development of the physical and social spaces. This process is essential for achieving the transformation into a truly smart city.

2.1 Urban Ternary Space

Physical and social spaces together form the binary structure of human society. With the rapid development and widespread application of information and communication technology, the information space has emerged as the third dimension, forming the ternary space of human society alongside physical and social spaces (Pan et al., 2016). To meet the demands of urban management and services in smart city, various information technologies must be employed to generalize and represent objects within the city's three-dimensional space using methods aligned with human cognitive abstraction. These representations will serve as information elements for managing and coordinating services in the smart city. The three-dimensional space of the city continuously generates vast amounts of spatial and temporal big data. To ensure efficient management and optimal utilization of this data, a smart city operating system must be built, integrating the existing physical, social, and information spaces.

In the information age, cities are shaped by various information elements across physical, social, and information spaces. Through methods such as urban mapping, element modeling, and Internet of Things (IoT) sensing, cities collect information from these spaces, generating fundamental spatio-temporal data, data on city management objects, and operational status sensing data (Li, 2014). Information fusion technology enables real-time access, dynamic fusion, and correlation of heterogeneous data from multiple sources. This process builds a digital city that mirrors the real one, providing foundational data support for the smart city operating system.

2.2 Logical Layer of Smart City

The operating system is fundamentally a public service platform designed to share resources and provide convenience (Figure 1). Initially, computers had no operating systems, and users operated them through manual controls. Later, computer operating systems simplified usage by abstracting physical characteristics and operational details, while efficiently managing system resources (Chen et al., 1996). SmartCityOS establishes a "virtual city geographic environment" using geographic information technology, leveraging "spatial location" as a foundation to integrate diverse urban data. It provides essential components such as data integration, fusion, visualization, spatial intelligence, and an open environment for secondary development, creating a public service platform that facilitates resource sharing and convenience across the city. As the foundational operating system for smart city development, it will offer intelligent services for economic growth and social communication, while supporting decision-making processes aimed at creating a low-carbon, green, and sustainable city.

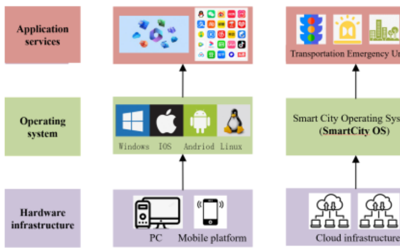

Figure1. Analogy between the SmartCityOS and computer operating system.

2.3 Architecture of Smart City Operating System

Based on the analysis of the relationship between the city in the information age, ternary space, computer operating system and smart city operating system, combined with the construction needs of all sectors of society for the smart city in the new era, the logical layering of the smart city is sorted out from the perspective of information, as shown in Figure 2. From the perspective of informatization, the smart city can be divided into four layers, i.e., perception layer, data layer, platform layer, application layer, and the user group on top of that.

The perception layer encompasses various information collection facilities and technical tools, functioning as the nerve endings of the smart city, capturing real-time operational data across multiple dimensions. The data layer consolidates heterogeneous data from multiple sources within the perception layer, storing and managing it after processing and extracting useful information. As the core of smart city, the platform layer provides common interface technology and public information services, connecting upwards to the application layer. Building upon this foundation, the application layer delivers smart application services tailored to the specific business needs of industries, governments, enterprises, and the public. By integrating the data and platform layer from the perspective of smart city informatization, foundational SmartCityOS is created, supporting the development of various applications.

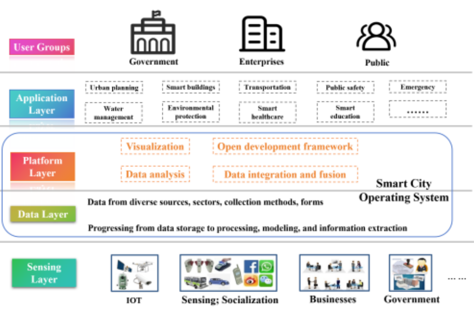

Figure 2. Architecture of the smart city operating system.

3. Main Key Technologies of Smart City Operating System

3.1 Urban Ubiquitous Perception and Digital Modeling

Driven by the need for value extraction and practical application, the demand for comprehensive, fine-grained, and pervasive perception and computation of the real world and physical environment is rapidly increasing (Jingnan et al., 2020; Hui et al., 2018). With the advancement of IoT sensing network technologies, ubiquitous sensing has evolved into the nerve endings and feedback system of cities. The development of 5G high-speed information transmission technology provides an effective means for processing and analyzing real-time information. Real-time data access brings the relatively static city to life by transforming static data into dynamic data, enabling the smart city to meet the requirements for dynamic targets, sensors, and real-time observation. This includes the acquisition, storage, management, analysis, and visualization of real-time data.

Given the growing demand for comprehensive three-dimensional urban scenes that encompass aboveground, underground, indoor, and outdoor environments (Guo et al., 2022; Gao et al., 2023; Biao et al., 2022), there is an urgent need for multidisciplinary cross-pollination and innovation in 3D modeling technology. This will enhance the role of surveying, mapping, and geographic information systems in not only geometric modeling but also in modeling behavioral processes and mechanisms. Breakthroughs in the integration of aerial and ground systems now enable real-time dynamic access to multi-detail, real-time 3D data. These advances facilitate intelligent processing of multi-disciplinary, multi-scale, and multi-modal spatial and temporal data. Under complex and incomplete data conditions, these technologies support fine 3D modeling of complex scenes. The combination of representational data and mechanistic models also contributes to constructing core technologies for the dynamic, life-cycle management of digital twin models (Qing et al., 2022).

3.2 Fusion and Analysis of Urban Spatio-Temporal Big Data

Urban spatio-temporal big data, a hallmark of smart city development, is characterized by continuity, diversity, multidimensionality, complexity, and sheer volume (Batty et al., 2013; Zhu, 2014; Li et al., 2015). It has been applied in various smart city management scenarios, such as trajectory prediction and intelligent navigation. However, the rapid growth of massive data stands in stark contrast to the absence of mechanisms for adding information value. Relying solely on traditional information technologies makes it difficult to quickly refine and generate geographic knowledge. The key challenge is to leverage emerging technologies, in combination with geographic information systems and geographic analysis, to rapidly mine, generate, and utilize spatio-temporal data.

Spatial intelligent analysis in the era of spatio-temporal big data has shifted from simple data sources to multi-source heterogeneous and complex data sources, from spatial analysis to spatio-temporal big data analysis, mining, and knowledge discovery. It has also evolved from management-focused analysis to assisted decision-making (Janowicz et al., 2020). The integration of large language models, knowledge graphs, artificial intelligence, and knowledge-based reasoning, alongside the new paradigm of first principles, will undoubtedly transform scientific research paradigms, spatio-temporal cognition, deep mining of spatio-temporal information, and the focus of geoinformation science in smart city research. These are key areas for further exploration and research (Lee et al., 2015).

In addition, Citizen feedback data is crucial for enhancing the responsiveness and accuracy of the SmartCityOS. Traditional urban management often relies on static data and pre-established decision models; however, these models are frequently unable to reflect the dynamic changes within the city and the evolving needs of its residents in real-time. Therefore, integrating citizen feedback into urban simulation models not only enhances the real-time capabilities of these models but also makes urban management more human-centered and adaptable. Citizen feedback can be integrated into simulation models in several ways: (1) Real-time collection of opinions and complaints: Through channels such as social media, mobile applications, and sensor devices, citizens can report issues in the urban environment (e.g., traffic congestion, pollution, infrastructure failures) in real-time. This data can be instantly uploaded to the SmartCityOS, thereby influencing city management and decision-making. (2) Feedback loop of dynamic urban data: By incorporating citizen feedback data into urban simulation models, city administrators can gain a more accurate understanding of the trends in urban changes. This dynamic feedback loop helps to adjust the models continuously, ensuring that the simulation reflects the actual needs and conditions of the city more effectively.

3.3 3D Visualization Technologies

High-fidelity three-dimensional city scene visualization is the user interface of the SmartCityOS. The mapping of physical space to information space integrates diverse data resources to create a detailed, high-fidelity rendered scene, providing the foundational visualization for the SmartCityOS platform. GIS is a technical science that represents and analyzes physical and social spaces from a spatial perspective. It provides vast amounts of spatial and temporal big data from various sources, including geographic data, urban management data, and urban sensor data.

GIS and game engines are two core technologies in digital twin cities, and their combined application holds significant potential (Ruohomäki et al., 2018; Dembski et al., 2020). Game engines, with their advanced lighting, shading effects, and particle systems, enhance 3D scene visualization, making it more realistic and engaging. The combination of game engine and GIS technologies enables high-fidelity visualization of large-scale, full-space 3D scenes. Integrating Level of Detail (LOD) and Potential Visible Set (PVS) techniques further enhances the efficient visualization of complex 3D environments (Hai et al., 2024). This approach is essential for achieving both high fidelity and smooth rendering of large-scale 3D scenes . This technique is a crucial method for ensuring the high fidelity and smooth visualization of large-scale, full-space 3D scenes (Figure 3). Additionally, multi-scale model is a key technology for digital cities, by dynamically adjusts mesh accuracy to meet diverse needs, enabling seamless transitions from high-poly to medium and low-poly meshes (Xu et al., 2024).

City-level 3D scene rendering is a core component of the smart city operating system platform. However, current mainstream GIS platforms are insufficient to fully support the construction of digital twin cities. Specifically, several critical limitations are observed: 1) The existing data management frameworks, which are primarily designed around basic geographic information, are inadequate for handling the multimodal and heterogeneous datasets generated by diverse economic and social activities. 2)The spatial indexing techniques, which combine horizontal tiling with vertical levels of detail (LOD), are unable to effectively accommodate high-intensity BIM indoor models. 3) The integration of multi-source heterogeneous urban data fails to support a comprehensive "fusion-storage-indexing-scheduling" system required for managing multidimensional, complex, and massive urban datasets.

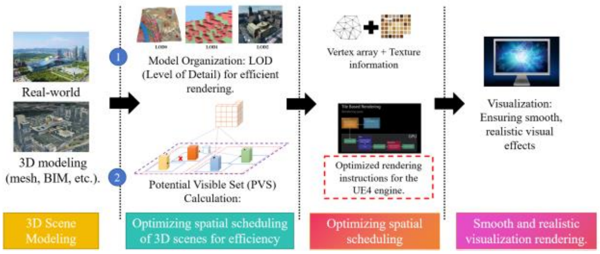

Figure 3. A high-fidelity and smooth visualization framework for large-scale scenes integrating game engines and GIS.

3.4 Simulation and Twin Interaction

The twin interaction (Shahzad et al., 2022) between information space and physical space is crucial to the intelligence of the Smart City Operating System. In the information space, spatio-temporal big data from the physical space is used for analysis, simulation, and decision-making. The results are then fed back to the physical space in real-time, altering the state of entities in the real world. The physical and information spaces establish a two-way twin interaction mechanism, enabling intelligent prediction and monitoring across the entire physical domain (Deng et al., 2019). This interaction allows for real-time data access and sharing of spatio-temporal big data through IoT devices, facilitating intelligent interactions within the 3D scene.

Typical scenarios include intelligent control of traffic lights within networked domains and position-based control systems, such as smart home robots and autonomous driving. The twin interaction between information space and physical space, along with the fusion of virtual and real environments, data-driven applications, and intelligent service integration, fosters a new governance model. This smart city twin interaction elevates urban intelligence to a higher level (Halúsková, 2023; Goodchild et al., 2024).

4. Typical Applications

4.1 Our Experience in Shenzhen: Shenzhen's SmartCityOS

Shenzhen's SmartCityOS seeks to establish an authoritative and comprehensive spatial-temporal information platform, which includes a unified spatial-temporal information base, an interconnected data-sharing platform, and a real-time service platform (Figure 4). This initiative aims to build China's first 3D spatial-temporal benchmark system that integrates both land and sea, enabling accurate geospatial perception. It also supports the Guangdong-Hong Kong-Macao Bay Area and connects with national spatial information resources. The platform integrates and innovates traditional geographic information system technology and Internet game technology, and builds subsystems for data access, fusion, analysis and visualization, realizing efficient dynamic loading, high-fidelity rendering and spatial analysis of urban large scenes and heterogeneous data from multiple sources.

Shenzhen's SmartCityOS integrates and consolidates the city's "land, building and housing rights" data (Figure 5), encompassing 150,000 parcels of land, 650,000 buildings (of which 590,000 are permanent structures), 13 million housing units, and 21 million residents. It also integrates the city's semantic address database, which contains 12 million entries linked to the locations of land and buildings, enabling efficient address query, location services, and batch mapping.

It also integrates and provides access to historical, current, and planning data, including electronic maps covering 1,900 square kilometers of the city (2010-2020), 50 phases of remote sensing imagery (2001-2020), public facilities and points of interest (125 categories, 1.5 million entries), and six levels of basic grids. This data set also includes master plans, statutory maps, land use, basic ecological control lines, marine monitoring, and other categories. Moreover, it incorporates planning and natural resources data, establishing a platform service system with large-scale capacity, multi-source integration, high-fidelity rendering, and development compatibility.

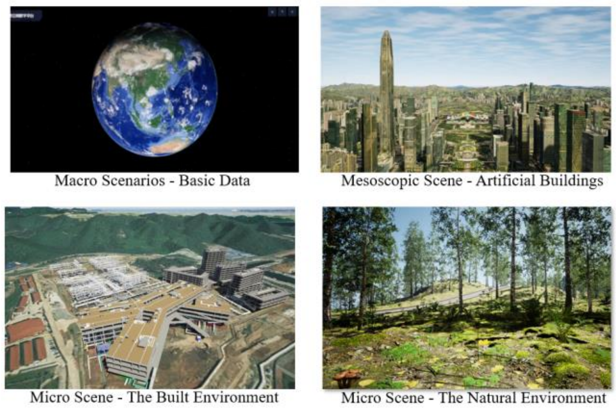

Figure 4. Shenzhen's SmartCityOS integrates macro, meso, and micro-levels of analysis and visualization.

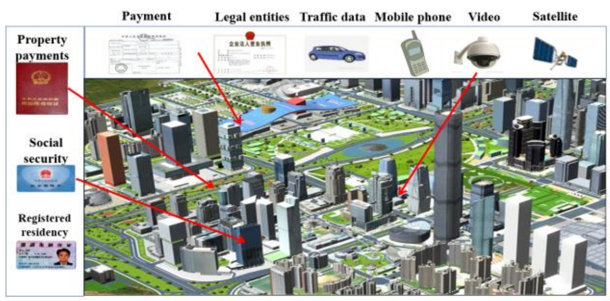

Figure 5. Shenzhen's SmartCityOS integrates land, building and housing rights.

4.2 SmartCity OS - Hull's journey to becoming a programmable city

The project, SmartCity OS is being delivered by Hull City Council ((Figure 6)), technology company Connexin and Cisco. Connexin has been working with cities such as Newcastle Upon Tyne to deliver smart city technologies, impacting on everything from lighting, mobility, security and waste. "Developing Hull as a Smart City will give us the opportunity to work with public and private sector partners to deliver real benefits to communities, businesses and visitors to Hull," says Councillor Daren Hale, Deputy Leader of Hull City Council.

Figure 6. Hull’s SmartCity OS.

5. Conclusion

Smart city represents the intelligent transformation of urban environments within the framework of ternary space. Using GIS, it establishes associations among the city's physical, social, and information spaces, mapping the physical and social spaces into the information space. The system integrates ubiquitous urban sensing with digital modeling and spatio-temporal big data, creating a unified operating system for the integration, analysis, and representation of the city's three-dimensional structure.

Based on this framework, the SmartCity OS enables open, diverse, shared, and environmentally sustainable intelligent applications through cross-platform, multi-terminal 3D visualization, city-level simulation, twin interaction, and open development architecture. Typical applications of the SmartCitOS represent the research frontier of next-generation science and technology and act as the core drivers of smart city development. This will bring both new opportunities and challenges, making it crucial to focus research efforts in areas such as big data, artificial intelligence, the Internet of Things, distributed GIS, and social science in uncertainty, to further accelerate the high-quality development of smart cities.

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