Research on Digital Twin Technology and Its Application Prospects in Medical Resource Allocation

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Abstract: This study focuses on the issue of medical resource allocation during public health emergencies and explores the current application status and future prospects of digital twin technology. It analyzes the domestic and international status of digital twin technology and sorts out its functions. Based on the current technological development status, it examines its performance and limitations in different application scenarios. In response to the problems identified, suggestions are put forward. Finally, it proposes the integration of digital twin technology with emerging technologies such as the metaverse. Through cross-domain integration, it is expected to break through the limitations of traditional technologies and build a more efficient emergency response environment.

Keywords: Digital Twin Technology; Public Emergency; Medical resource allocation

1. Background

In recent years, with the rapid development of technologies such as the Internet of Things (IoT), big data, and artificial intelligence (AI), the application of digital twin technology has gradually expanded in fields like smart cities, smart healthcare, and smart transportation. Especially in public emergencies, digital twin technology holds significant application value.

2. Analysis and Summary of Functions and Current Status

2.1 Functional Analysis

It can realize real-time monitoring and accurate prediction of the epidemic[5], helping decision-makers take timely prevention and control measures. In addition, digital twin technology is also used for the dynamic allocation of medical resources. By integrating multi-source data, this technology can provide comprehensive and real-time epidemic information, offering strong support for scientific decision-making and precise prevention and control. As shown in the table below:

Table 1. Classification of Application Fields

Field	Typical Application Scenarios	Challenges and Limitations
Manufacturing	Real-time monitoring of production lines, fault prediction	Fusion of multi-source heterogeneous data
Healthcare	Remote surgery simulation, personalized treatment plans	Protection of patients' data privacy

2.2 Current Status Analysis

2.2.1 Domestic Research Status

(1) Parallel advancement of theoretical research and application exploration: The academic community in China has conducted in-depth discussions on the connotation, architecture, and key technologies of digital twins. The team led by Professor Tao Fei from Beihang University (Beijing University of Aeronautics and Astronautics) proposed a set of digital twin model construction criteria titled "Four Modernizations, Four Feasibilities, and Eight Applications". Based on the proposed digital twin model construction criteria, the team further explored and established a theoretical system for digital twin model construction featuring the "construction - composition - integration - verification - calibration - management" process, laying a foundation for systematic research.

(2) Driven by industrial Internet platforms: Domestic industrial Internet platforms include Haier COSMO Plat and Rootcloud (from Root Internet Technology Co., Ltd.), among others.

2.2.2 Foreign Research Status

Concept origin and early practice: The concept of "digital twin" was first put forward by Professor Michael Grieves in 2003, initially named the "Information Mirroring Model". Later, in 2012, NASA (National Aeronautics and Space Administration) of the United States provided a conceptual description of digital twins and took the lead in applying it to spacecraft health management.

Technology deepening and standardization: The main research focuses on high-fidelity modeling, real-time data fusion, improvement of simulation and prediction accuracy, and standardization.

Cross-field expansion and integrated innovation: The application of digital twin technology has expanded from high-end manufacturing to fields such as smart cities, healthcare, and energy grid management.

3. Key Technologies

The core function of digital twins lies in constructing a virtual mapping of physical entities and realizing bidirectional dynamic interaction and closed-loop optimization. Its specific functions include: multi-source data fusion, visual interaction, edge computing, and 5G.

3.1 Multi-Source Data Fusion

Internet of Things (IoT) sensors[7] , satellite remote sensing, social media, and other multi-dimensional data access. It integrates data to achieve comprehensive perception of physical entities. Real-time mapping and status perception: By integrating real-time data sources such as Internet of Things (IoT) sensors and SCADA systems, high-fidelity reproduction of physical entities is realized in the virtual space.

3.2 Visual Interaction

Virtual representation and model simulation: Using geometric models, physical models, behavioral models, and rule models, accurate digital representation of the structure, physical processes, operation logic, and workflow of physical entities is conducted in the virtual space.

Analysis, diagnosis, and prediction & early warning: By combining data and built-in data-driven models, in-depth analysis and prediction are performed on the health status, performance trends, potential faults, and remaining service life of physical entities.

Simulation optimization and decision support: Different operation strategies, control parameters, maintenance plans, or design changes are simulated in the virtual environment to predict their results and impacts. Based on the simulation results, data-driven decision support is provided for the operation optimization, control adjustment, maintenance decision-making, and design improvement of physical entities, so as to achieve better performance and efficiency.

3.3 Edge Computing and 5G

Application of Digital Twin Technology in Healthcare Resource Allocation

Through localized real-time processing and ultra-high-speed, low-latency transmission, the core requirements of digital twin technology for data real-time performance and analytical agility are addressed.

Specific Closed-Loop Control and Full-Lifecycle Management

The optimal instructions or parameters derived from the analysis and optimization in the virtual space are fed back to the physical entity and used to guide its operations. Examples include adjusting equipment parameters, triggering maintenance work orders, and modifying production plans. This forms a closed-loop control of "perception-analysis-decision-making-execution," and this function runs through the entire lifecycle of the physical entity.

4. Application of Digital Twin Technology in Healthcare Resource Allocation

4.1 Core Application Scenarios and Technical Implementation

4.1.1Dynamic Optimization of Hospital Space and Bed Resources

A digital twin of the hospital's physical environment and equipment is built, integrating real-time data from the Hospital Information System (HIS) and Internet of Things (IoT) sensors. Managers can intuitively view bed occupancy rates, equipment usage status, and patient flow across the entire hospital. According to a pilot project by the UK's National Health Service (NHS), after the application of digital twins, the average length of stay for emergency department patients decreased by 15%, and the bed turnover rate increased by 8%.

Based on historical and real-time data, AI models are used to predict bed demand peaks in the next few hours to days. Proactive adjustments are made to nursing unit configurations or emergency plans are activated to achieve predictive allocation and specific optimization.

4.1.2 Intelligent Scheduling of Medical Equipment and Supplies

Digital twins are established for key medical equipment (such as MRI and CT scanners) and consumables. These twins integrate data on equipment operation status, appointment systems, inventory management systems, and RFID or barcode tracking. This enables the scheduling of medical equipment.

By simulating and optimizing appointment rules and sharing mechanisms, equipment utilization is improved. Additionally, the analysis of equipment usage duration, idle time, and appointment intervals helps identify bottlenecks.

4.2 Providing Decision Support and Data Support for Resource Allocation

4.2.1 Multi-Source Heterogeneous Data Fusion and Panoramic Visualization

Data silos among systems such as HIS, Laboratory Information System (LIS), and Picture Archiving and Communication System (PACS) are broken down. Data fusion and visualization under a unified spatiotemporal framework are realized within the digital twin. This provides decision-makers with an unprecedented "god's-eye view," allowing them to grasp the panoramic picture of resource allocation and demand pressure points in real time.

4.2.2 AI-Driven Predictive Insights and Automated Recommendations

Based on the massive historical and real-time data accumulated by the digital twin, machine learning models are trained to make accurate predictions, including:

Demand prediction: Patient flow, disease distribution, and demand for specific equipment/consumables.

Performance prediction: Risk of equipment failure, probability of process bottlenecks, and possibility of service delays.

Decision support: The system can automatically generate recommendations for optimizing resource allocation.

4.2.3 Closed-Loop Feedback and Continuous Optimization

Data on actual execution effects is continuously collected and fed back to the digital twin. Differences between simulation predictions and actual results are compared, and model parameters are automatically calibrated. This forms a closed loop of "decision-making - execution - monitoring - learning - optimization," enabling continuous iterative improvement of resource allocation strategies.

5. Conclusion

5.1 Challenges and Improvement Directions

Data Real-Time Performance and Accuracy.In the future, it is necessary to further optimize data and processing technologies to enhance the integration capability and real-time performance of multi-source data. This relies on the deployment of high-density sensors and high-speed data processing capabilities.

In-depth Integration of AI and Machine Learning.Greater efforts should be made to deeply integrate artificial intelligence and machine learning (into digital twin systems for healthcare resource allocation)[8]technology，Enhance the intelligence level of digital twin systems and facilitate the achievement of effects where real-time performance and accuracy go hand in hand, leveraging reinforcement learning and deep learning algorithms [4]，Achieve intelligent analysis and optimized decision-making for complex systems[6]。

5.2 Future Development Trends

Automated Response for Virtual Linkage. Metaverse and Digital Twin: Realize multi-party collaborative command through virtual space. Public Participation: Open up some functions of digital twin platforms to citizens. With "data-driven operations and intelligent decision-making," digital twin serves as a core tool for the integrated "prevention, control, and rescue" in public emergencies. In the future, it may become a standard technology for emergency management in public emergencies.

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