Original Research Article

A technical architecture model of agricultural digital twin system based on data elements

Shousen Chen, Jiliang Guo, Xuemei Li, Quanzhu Jiang

Shandong Business Institute, Yantai, Shandong, 264670, China

Abstract: This paper presents a technical architecture model for an agricultural digital twin system driven by data elements, aiming to advance agriculture's digital transformation and enhance productivity and quality. The model integrates IoT, 5G, SaaS, and AI technologies, forming a four-layer structure: perception, transmission, application, and decision-making layers. The perception layer uses sensor networks to collect high-resolution data on crop growth and field environments. The transmission layer supports reliable communication through WLAN, Bluetooth, and ZigBee. The application layer, based on SaaS, provides integrated services for agricultural operations. The decision-making layer utilizes cloud computing and big data analytics to process large datasets. By enabling real-time data acquisition, efficient transmission, and intelligent analysis, the model facilitates accurate mapping and smart management of agricultural activities. It supports data-driven decisions, helping producers optimize resources, reduce risks, and improve efficiency. This architecture not only boosts agricultural productivity and product quality but also fosters sustainable and environmentally friendly practices, offering a robust framework for the intelligent evolution of modern agriculture.

Keywords: New generation information technology; Digital twin system; Data elements

1. Introduction

With the rapid development of information technology, digital twin technology has become central to smart agriculture by enabling simulation, prediction, and optimization of real-world agricultural processes through virtual modelingp[1]. This enhances intelligent management and supports data-driven decision-making.

Globally, various applications have demonstrated its potential. At Cornell University, researchers Gourab Sen Gupta and Elad Salomons developed a digital twin-based farmland management system using real-time soil monitoring sensors to optimize decisions, improving land use and crop yields[2]. In China, the Smart Agriculture Demonstration Park of the Chinese Academy of Agricultural Sciences applied digital twin technology to simulate and monitor production, boosting crop quality and efficiency. Similarly, Blue River Technology in the U.S. created the “See and Spray” system to identify crops and apply pesticides with precision, reducing chemical use and environmental impact.

Countries like the U.S., Germany, and Japan are leading in integrating digital twins with IoT, AI, and big data technologies, advancing automation and intelligence in agriculture. China has also made notable progress, proposing digital twin models and achieving success in crop monitoring and management. However, issues such as incomplete data, low model accuracy, and weak system integration still limit broader adoption[3].

In conclusion, while agricultural digital twin systems are gaining global attention, challenges remain in implementation and optimization. Future research should focus on integrating digital twins with technologies like blockchain, edge computing, and AI to enhance precision, data integrity, and interoperability. These efforts will support more robust, scalable, and intelligent agricultural systems, accelerating the digital transformation of global agriculture[4].

2. Agricultural twin system

Based on comprehensive research into smart agriculture technologies, this paper proposes a technical architecture for a smart agriculture system centered on data elements, forming a closed-loop process from data acquisition to decision feedback.

The data acquisition layer utilizes IoT technology to capture multi-source heterogeneous data with high precision. An environmental monitoring network is established by deploying sensors for soil moisture, temperature, light intensity, and CO_2 concentration. Spectral analysis and image recognition enable non-contact crop monitoring. For instance, Cai Bin and colleagues developed a ZigBee-based precision irrigation system for cotton, improving water-saving efficiency by 28% over traditional methods.

The data transmission layer integrates 5G and LPWAN technologies, supported by edge computing nodes for data preprocessing and low-latency communication. Studies show this setup reduces agricultural robot response latency to under 10 milliseconds[5].

The data storage and processing layer builds a big data engine on cloud computing platforms, using distributed storage and unified stream-batch processing frameworks. Digital twin models are created by integrating physical crop models with machine learning, improving pest prediction accuracy by 40% and reducing pesticide usage by 35%.

The data presentation layer applies 3D visualization and intelligent decision interfaces. Using WebGL technology, it builds digital farmland twins that display multidimensional data such as soil moisture and crop health. GIS maps and expert knowledge bases provide actionable guidance on irrigation and fertilization. Multimodal interfaces, including voice and gesture control, help farmers detect and respond to issues 50% faster.

This architecture enables real-time, intelligent agricultural management and enhances precision, efficiency, and sustainability in agricultural production.

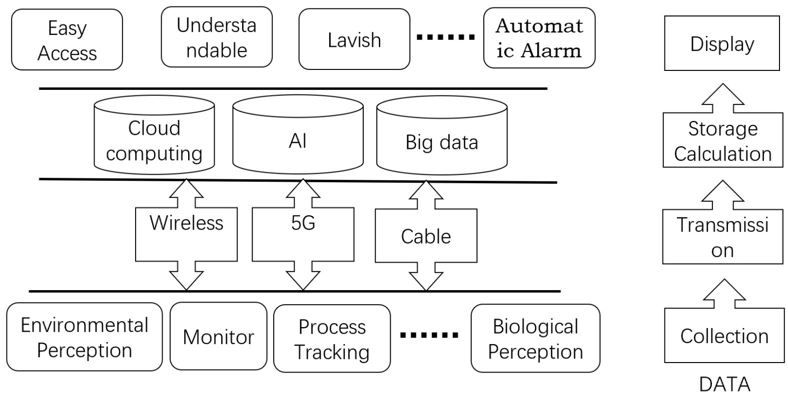

Figure 1. Technical architecture of the digital twin system based on data elements.

2.1. Data acquisition layer

The data acquisition layer forms the foundation of the digital twin system, responsible for collecting comprehensive agricultural data through multi-source heterogeneous sensing technologies. It features a hierarchical structure consisting of sensing nodes, transmission networks, and edge gateways.

Sensing nodes integrate high-precision soil sensors, spectral analysis modules, and miniature weather stations, enabling real-time acquisition of 12 key parameters, including soil conductivity, canopy temperature, and humidity. These nodes operate within a self-organizing LoRaWAN network. Using Time Division Multiple Access (TDMA), a single gateway can manage up to 2, 000 nodes across a 5 km radius with a data collision rate below 0.3%.

Edge gateways perform data cleansing and feature extraction, compressing raw data at a ratio of 1:15 to reduce transmission bandwidth. In grape cultivation, multispectral sensors collect NDVI data every 10 minutes. Combined with 3D point cloud data, this allows early disease detection, increasing monitoring efficiency eight-fold compared to manual methods.

In greenhouse applications, the system integrates 16 environmental variables to build crop growth models. With optimization algorithms like Particle Swarm Optimization (PSO), it achieves closed-loop control, increasing tomato yields by 19.2% and reducing energy consumption by 27%.

The system is highly adaptable to harsh environments. Sensor nodes operate reliably in temperatures from -40°C to 70°C with a 98.7% survival rate and comply with IP68 waterproof and dustproof standards. Communication reliability is further enhanced by frequency-hopping spread spectrum technology, which lowers error rates to below 10^{-6}.

2.2. Data transmission layer

The data transmission layer serves as a vital bridge in the digital twin system, linking sensing devices from the data acquisition layer to the data storage and processing units. It integrates 5G, wireless, and wired communication technologies to form a heterogeneous network architecture that ensures the efficient, reliable transmission of environmental and sensor data. Its core role is to deliver raw data—after initial processing and format conversion—from field devices to cloud or edge computing platforms, laying the groundwork for upper-layer analysis, decision-making, and intelligent control.

Designed for more than just basic data transfer, the transmission layer ensures real-time, accurate, and complete data delivery even in complex network environments. It is essential for maintaining the system's stability and coordination efficiency. In smart agriculture applications, it adopts multimodal transmission strategies and intelligent routing to meet diverse scenario demands, often structured in hierarchical network designs due to the wide area coverage and heterogeneous devices involved.

5G technology is particularly promising in this context. It offers high speed and low latency, while wireless networks add coverage flexibility, and wired networks contribute stability and bandwidth. Together, they form a complementary, integrated transmission system. To support data-intensive applications like environmental monitoring, the layer incorporates dynamic bandwidth allocation, data compression, and priority scheduling, boosting transmission efficiency and resource use.

To ensure data integrity and reliability, the layer includes advanced quality assurance mechanisms such as data validation, retransmission strategies, and redundant pathways. These design elements enhance the adaptability and robustness of the system, providing a solid, resilient infrastructure that supports the intelligent transformation of traditional agriculture.

2.3. Data processing layer

The data processing layer is the core of the digital twin system, functioning as both the "data hub" and the "intelligent engine." It processes massive volumes of agricultural data collected by the transmission layer, handling storage and analysis to support application-level decision-making. Built on cloud-based big data platforms and distributed computing frameworks, this layer efficiently manages multi-source, heterogeneous agricultural data in parallel.

Preprocessing tasks such as data cleaning, deduplication, and standardization improve data quality, ensuring a reliable basis for further analysis. Artificial intelligence algorithms—including machine learning and deep learning—are deeply integrated to extract features, identify patterns, and perform correlation analysis. These methods reveal valuable insights embedded in the data and provide algorithmic support for constructing agricultural digital twin models.

Using high-quality processed data and AI analytics, the system builds dynamic digital twin models that simulate all elements and stages of crop cultivation, from environment and growth to quality formation. These models allow agricultural producers to test various management strategies in virtual environments, optimizing resource allocation and reducing risk. Furthermore, the models interact in real-time with IoT devices, creating a closed-loop "data–model–decision" feedback system that enables intelligent forecasting and precision farming.

This layer plays a critical role in advancing the intelligence of agricultural production. Its ability to transform raw data into actionable insights lays a strong foundation for the digital transformation of agriculture, promoting efficiency, sustainability, and innovation across the industry.

2.4. Application layer

The application layer represents the final embodiment of the digital twin system. It is responsible for applying the processed data and models to actual agricultural production and management. Relying on digital twin models and artificial intelligence algorithms, this layer supports the development of core modules such as smart agriculture management systems, agricultural e-commerce platforms, and government decision-support platforms, forming a digital service matrix that spans the entire agricultural value chain.

Through the development of smart agriculture management systems, functions such as remote crop/product monitoring, intelligent alerts, and precision management are realized. With these systems, managers can view real-time data on crop growth environments, conditions, and quality, which helps in identifying problems early and taking timely corrective actions.

By integrating with the Internet, the system supports agricultural product marketing via e-commerce platforms and social media. For instance, the Yantai apple brand can be promoted and sales channels expanded. The quality data and orchard environmental information provided by the digital twin system offer consumers more transparent and trustworthy product information.

By digitizing the processes of production, sales, and traceability, the system also provides decision-making support for governments, aiding in policy formulation and optimization. Leveraging the industrial data and analytical results from the digital twin system, governments can gain more accurate insights into industry development and formulate more scientific and effective policies.

3. Conclusion

The data-element-driven digital twin system integrates advanced technologies with agriculture, transforming modern practices and industry structures. It begins with the data acquisition layer, where sensor networks in fields and facilities collect real-time data on soil, crop growth, and environment—forming agriculture's "digital nerve endings."

The data transmission layer uses 5G, LoRa, and ZigBee for fast, reliable transfer between edge and cloud, enabling real-time decisions. The processing layer leverages distributed computing and AI (e.g., machine learning) to turn raw data into structured insights, supporting models like crop growth and pest prediction.

At the application layer, insights become tools such as smart agriculture systems, e-commerce platforms, and decision-support tools for governments. These guide production, marketing, and policy.

Digital twin systems deliver value at three levels: enhancing efficiency and decision-making in production; enabling traceability and brand trust in industry; and supporting data-driven governance and rural revitalization strategies at the policy level.

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4. Suggestions and future research directions

The digital twin system creates a "virtual mirror" of agricultural production, allowing producers to optimize strategies digitally, reduce risks, and shift from experience-based to data-driven decision-making. Integrating IoT, 5G, cloud computing, and digital twin technologies, this architecture supports large-scale smart agriculture applications. Future research may focus on cross-regional data sharing, lightweight models for edge devices, and blockchain-based traceability and access control systems.

As IoT, big data, and AI continue to evolve, data-element-driven agricultural digital twin systems will see broader global adoption. Emphasis will be placed on integrating these systems with advanced technologies—such as using blockchain for product traceability and 5G for faster, low-latency data transmission. As agricultural digital transformation progresses, digital twin systems will not only boost efficiency but also contribute to sustainable and green agricultural development through more innovative, intelligent solutions.

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About the author

Chen Shousen, born in 1978, is a native of Longkou, Shandong Province. He is a male Ph.D. and a professor at Shandong Business Institute. His main research interests include big data applications and management information systems.

Jiang Quanzhu is a lecturer at Shandong Business Institute. Her primary research areas are IoT application technology and big data application technology.

Guo Jiliang is an associate professor at Shandong Business Institute, focusing on IoT application technology.

Li Xuemei is a lecturer at Shandong Business Institute. Her research interests include big data applications and management information systems.

Contact Person: Chen Shousen

Contact Information:

Mobile: +86 139 5359 5558

Email: chenshousen@sdbi.edu.cn

Address: Chen Shousen, Shandong Business Institute, No. 1001 Jinhai Road, High-Tech Zone, Yantai, Shandong Province, China

Postal Code: 264670

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