

# Design and Implementation of the Visual Management System for Intelligent Twin Grain Silos

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**Abstract:** This paper, based on digital twin technology, designs and implements a lightweight intelligent grain silo visualization system to address issues in small and medium-sized grain depots, such as inaccurate environmental monitoring, lack of visualization methods, and untimely warning responses, providing a digital tool for clear observation and precise management. The system adopts a four-layer architecture and, with the help of IoT sensor devices, achieves real-time collection and monitoring of the grain depot environment. A 3D simulation of the grain depot is constructed based on the Unity3D engine. WebGL technology is utilized to enable lightweight, cross-platform deployment, and JSLIB bridging technology facilitates bidirectional communication between the Vue frontend and the Unity scene. Ultimately, a closed loop of data collection—transmission—processing—feedback is formed. Experimental results indicate that the system can monitor the grain depot environment in real time and issue timely warnings, providing an economically feasible technical solution for the digital transformation of small and medium-sized grain depots.

**Keywords:** Digital Twin; Grain Depot Management; Virtual-Physical Mapping; Unity3D; Internet of Things

## 1. Introduction

Food is the foundation of human life, and safety is the priority of food. Food security, as an important component of national security, its management core focuses on grain storage facilities. As the key hub for grain storage and circulation, the management efficiency, safety level and quality of grain storage facilities are closely related to the stability of grain supply [1]. Currently, the traditional grain storage management relying on manual inspection and

periodic checks has problems such as inaccurate environmental control, delayed abnormal response, and low management efficiency.

In the current era, with the global wave of the fourth industrial revolution, information technologies such as the Internet of Things, cloud computing, and big data are undergoing rapid iteration and popularization, providing solid opportunities and technical support for solving the pain points and difficulties of traditional grain storage management [2].

As a new generation of digital technology born under the background of the fourth industrial revolution, digital twin technology digitizes physical entities to create virtual models and uses data models to simulate the conditions and actions of physical entities in the actual environment. It also adds or expands new capabilities for physical entities through means such as virtual-real interaction feedback, data fusion analysis, and decision iterative optimization [3]. Digital twin technology aims to achieve bidirectional mapping and real-time interaction between the physical world and the virtual world, ultimately achieving the goal of virtual control of the physical world, providing core technical support for the implementation of intelligent management of grain storage facilities. Currently, digital twin technology has shown its potential in the field of intelligent manufacturing. Zou Mingzhe et al. used digital twin technology to design a production line visualization system, achieving virtual scene roaming, human-computer interaction and data visualization [4]. Wang Kun et al. based on digital twin technology developed a monitoring system for the hydraulic oil pump vehicle test bench, achieving equipment health monitoring and fault diagnosis [5]. At the same time, digital twin technology also holds great potential in grain storage. Peng Hailong et al. combined digital twin technology with grain storage management to provide a practical basis for the implementation of this technology in the grain

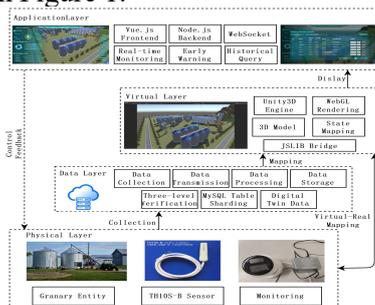
storage industry [6]. Ma Xuedi et al. designed a grain warehouse intelligent ventilation system integrating measurement, control, inspection and storage, achieving synchronous control of physical and virtual grain warehouses [7]. However, the existing digital twin grain storage systems have a distinct heavy-duty feature, and small and medium-sized enterprises find it difficult to provide high-performance workstations to support their operation and also find it difficult to pay the expensive commercial engine licensing fees. These various factors have become obstacles to the promotion and application of digital twin technology in small and medium-sized grain storage facilities. Therefore, developing a smart twin grain warehouse visualization management system to promote the digital transformation of small and medium-sized enterprises has important practical significance.

This paper addresses the above issues and designs and implements a set of smart twin grain warehouse visualization management system. The main contributions include: (1) achieving cross-platform virtual grain warehouse scene construction based on WebGL (2) constructing a complete closed loop of twin data collection - transmission - processing - feedback.

## 2. Digital Twin System Architecture Design for Grain Storage

### 2.1 Digital Twin Framework for Grain Storage

The essence of digital twin is a two-way mapping between reality and virtuality. It achieves bidirectional driving between physical entities and virtual models through sensor data [8]. This paper focuses on the application scenario of grain storage environment monitoring and designs a data-driven digital twin system architecture for grain storage, as shown in Figure 1.



**Figure 1. Overall Architecture Diagram of the Digital Twin Grain Warehouse System**

The system consists of four components: the physical layer, the data layer, the virtual layer, and the application layer. The functional positioning and key technologies of each component are shown in Table 1.

**Table 1. Key Technologies of Each Layer of the Grain Warehouse Digital Twin System**

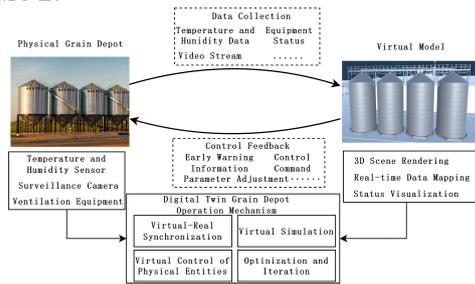
Level	Functional Position	Key Technologies	Main Components
Physical Layer	Data Acquisition, Equipment Control	RS485, Internet of Things	TH10S-B, Hikvision cameras, fusion device
Data Layer	Data Processing and Storage	JSON Parsing, Verification	Node.js, MySQL, WebSocket
Virtual Layer	3D Scene Construction and Rendering	Unity3D, WebGL	3D Models, Material System, JSLIB
Application Layer	User Interaction and Visualization	Vue.js, Message Response	Monitoring Panel, Early Warning Management, Historical Query

The physical layer encompasses various hardware facilities such as the warehouse building, temperature and humidity sensor network, surveillance cameras, data fusion equipment, etc. It serves as the data collection source and physical carrier of the entire system, as well as the foundation for the construction of the digital twin system. Its main responsibility is to collect and report various environmental data. The data layer acts as the core bridge connecting the physical layer and the virtual layer, undertaking the duties of data reception, verification, processing, and storage. The virtual layer uses the Unity3D engine and WebGL technology to build the three-dimensional model of the grain warehouse and render it on the web, and dynamically change the color of the sensor model based on the environmental parameters transmitted by the data layer. The application layer uses the Vue.js framework to provide users with an interactive interface and supports functions such as scene roaming, data monitoring, and early warning management.

### 2.2 Operation Mechanism of Digital Twin Grain Warehouse

The operation of the digital twin grain depot follows the core logic of virtual-real mapping - data-driven - closed-loop feedback, as shown in

Figure 2.



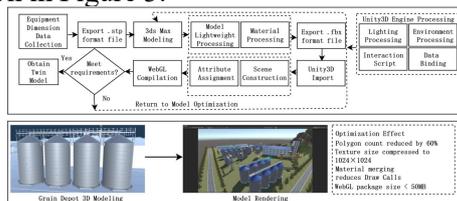
**Figure 2. Diagram of the Operation Mechanism of the Digital Twin Grain Warehouse**

The operation mechanism consists of four key components: During the synchronization of reality and virtuality, the physical layer collects data every three seconds and reports it to the virtual layer, providing the latest data for the virtual layer. In the virtual simulation stage, the virtual layer uses the latest data received to visualize the temperature and humidity distribution and issue abnormal status alerts. Users can intuitively understand the latest situation in each area through the three-dimensional scene. In the stage of controlling reality through virtuality, the administrator sets the temperature and humidity thresholds in the virtual scene and issues them to the data layer through the data layer, providing a basis for subsequent warning judgment. In the optimization and iteration stage, the system continuously optimizes the warning thresholds, adjusts parameters, and optimizes algorithms based on historical data analysis to improve the system's prediction accuracy and management efficiency.

### 3. Construction of Digital Twin for Grain Storage Facilities

#### 3.1 Modeling of Physical Grain Storage Facilities

The construction of the digital twin of the grain depot follows the technical route of physical entity → CAD model → optimization model → twin [9]. The construction process of the twin is shown in Figure 3.



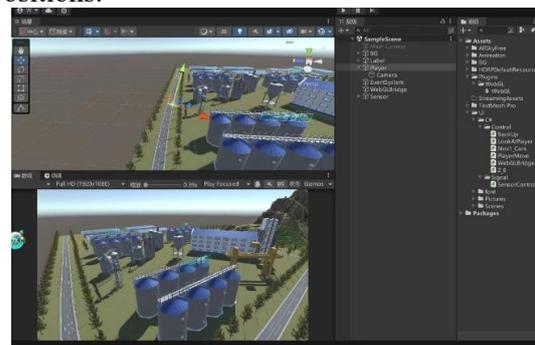
**Figure 3. Flowchart of Twin Body Construction**

Before starting the modeling work, a site inspection of the grain depot is necessary. The inspection content includes geometric information such as building dimensions, sensor positions, and equipment layout. Based on this information, a 3dsMax virtual three-dimensional model of the grain depot is constructed at a 1:1 scale, including the structure, shape, and sensor equipment of the grain storage. At the same time, techniques such as mesh simplification, texture compression, and material merging are used for lightweight processing to ensure the visual effect while reducing the complexity of the model to meet the requirements of real-time interaction. The optimized model is exported in FBX format and imported into the Unity3D engine. This format can completely retain the geometric information, material properties, and hierarchical structure of the model.

#### 3.2 Virtual Scene Construction and Rendering

The construction of the virtual scene directly affects the visualization effect and user experience of the digital twin system [10]. In this paper, the scene was built in Unity3D, and the results are shown in Figure 4.

The system uses the Terrain tool to create the terrain and landform, and then imports, arranges and arranges the virtual models according to the actual building layout of the grain depot. The sensors in the warehouse are organized in a hierarchical structure. Under the top Warehouse node, there are multiple Unit node sub-nodes, and each unit node contains multiple Sensor node sub-nodes. The hierarchical path is used for positioning such as Sensor/Warehouse1/unit1/1, representing the 1st warehouse unit's 1st sensor, which is convenient for subsequent batch management and status updates. All sensor models are installed according to the actual positions.



**Figure 4. Virtual Grain Storage Construction Scene in Unity**

After the virtual scene is built, it will be compiled into WebGL and compressed using the Brotli format, and the memory allocation strategy will be optimized to reduce the resource volume. The front end embeds the Unity WebGL instance through an iframe, taking into account the necessary communication between Vue and Unity and maintaining the Unity scene. After testing, the initial loading time of the Unity WebGL scene is approximately 8 seconds, and subsequent accesses can complete the loading within 5 seconds through the browser cache.

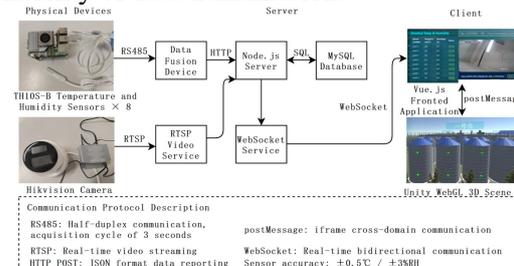
#### 4. Twin Data and Real-Imaginary Interaction

##### 4.1 Hardware Deployment and Data Collection

The system's hardware architecture adopts a hierarchical networking design, as illustrated in Figure 5.

The temperature and humidity sensor uses the TH10S-B sensor, which has superior stability and high anti-interference capability. The measurement accuracy can reach  $\pm 0.5^{\circ}\text{C}/\pm 3\%\text{RH}$ . All sensor nodes are connected to the bus network through the RS485 interface and operate in a master-slave communication mode. To comprehensively monitor the

environmental data at different positions in the warehouse, each grain warehouse is equipped with 8 sensors located at different positions of the grain pile. The data fusion device completes the collection of all sensor temperature and humidity data in the warehouse every 3 seconds and sorts, verifies, summarizes, and reports all the temperature and humidity data to ensure the reliability of data transmission.



**Figure 5. System Hardware Architecture Diagram**

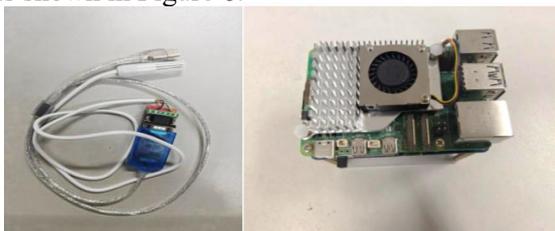
To ensure the stability of the monitoring service, the video monitoring equipment uses the Hikvision DS-IPC-T12H-1A camera, which is connected to the local area network via wired network and enabled with RTSP streaming service. The backend uses FFmpeg to pull the video stream, transcodes the picture using the HLS protocol, and pushes it to the front end. The digital twin design of the grain depot includes various types of data as shown in Table 2.

**Table 2. Classification Table of Grain Warehouse Data Twin System**

Data Type	Data Name	Collection Method	Update Frequency	Usage
Static Data	WarehouseDimensions	Manual Entry	One-time	ModelConstruction
Static Data	Sensor Position	Manual Configuration	One-time	Spatial Mapping
Dynamic Data	Temperature Value	TH10S-B Acquisition	3 seconds	Status Monitoring
Dynamic Data	Humidity Value	TH10S-B Acquisition	3 seconds	Status Monitoring
Dynamic Data	Video Stream	Camera Acquisition	Real-time	Remote Monitoring
Control Data	Warning Threshold	User Settings	On-demand	Warning Triggering

##### 4.2 Twin Data Processing Procedure

Data processing is the core link of the digital twin system, and it is related to the accuracy and real-time performance of the synchronization between the virtual and the real [11]. The system has constructed a complete data processing chain from the physical layer to the application layer, as shown in Figure 6.



**Figure 6. Actual Image of the Sensor**

The data processing process is crucial for ensuring the accuracy and real-time performance of synchronization between the virtual and real worlds, and it is the core of the digital twin system. The TH10S-B sensor collects temperature and humidity data every 3 seconds and transmits it via the RS485 bus to the data fusion device. The fusion device performs CRC verification to ensure data integrity, removes abnormal data, and then encapsulates all the data into a JSON data packet containing fields such as warehouse\_id, timestamp, temperature1-8, and humidity1-8. This data packet is then reported via HTTP POST to the Node.js backend. After the backend receives the data from the fusion device, it completes the data processing flow through a three-level verification

mechanism consisting of UUID verification, temperature and humidity value range verification, and warning value comparison. The UUID verification stage is responsible for verifying the validity of the sensor UUID field format. Data that fails this verification will be rejected from being entered into the system and an abnormal log will be recorded. The temperature and humidity value range verification task is to determine whether the temperature and humidity values at each measurement point are within a reasonable range (temperature  $-20^{\circ}\text{C}$  to  $60^{\circ}\text{C}$ , humidity 0% to 100%). Data outside this range will be regarded as abnormal data and discarded. If a certain field's temperature and humidity data is repeatedly discarded, it is considered that the sensor is in an abnormal state. The warning value comparison stage is responsible for comparing the temperature and humidity values with the warning threshold, and if the threshold is exceeded, the warning process will be triggered and a warning message will be broadcast via WebSocket. The data retained after the three-level verification will be used to update the virtual model state and be persistently stored in the database in separate tables. The system will also calculate the average value of the valid measurement points as the overall indicator of the warehouse. The data table structure is shown in Table 3.

**Table 3. Structure of Sensor Data Table**

Field Name	Type	Explanation
sensor_id	VARCHAR (36)	Sensor ID in UUID format
warehouse_id	SMALLINT	Grain warehouse ID
timestamp	DATETIME	Data collection timestamp
temperature	DECIMAL (4,1)	Average temperature ( $-20\sim 60^{\circ}\text{C}$ )
humidity	DECIMAL (4,1)	Average humidity (0~100%)
temperature1~8	DECIMAL (4,1)	8 measurement point temperature values
humidity1~8	DECIMAL (4,1)	8 measurement point humidity values
connection_status	TINYINT	Connection status (0 disconnected/1 normal)
ventilation_volume	DECIMAL (6,2)	Ventilation volume ( $\text{m}^3/\text{min}$ )

Similarly, when the temperature and humidity values change by more than 0.5, the system will also broadcast the latest data update to the front

end via WebSocket, reducing the system's data pressure while ensuring the information is real-time and effective. Additionally, the system has a disconnection detection mechanism. If the timestamp of the sensor data is more than 15 seconds different from the current time, it is determined that the sensor is disconnected, and the color of the virtual sensor model is changed to gray and the status is marked as "signalLost". When the backend receives the latest data from this sensor, it will automatically update the status, as shown in Figure 7.



**Figure 7. Detailed Information of the Sensor**

#### 4.3 Real-Imaginary Mapping Mechanism

The virtual-real mapping is the core feature of digital twin technology. This system realizes the mapping from the physical grain depot to the virtual one from three dimensions: geometry, state, and behavior [12]. The geometric mapping establishes the correspondence between the positions of physical sensors and the coordinates of the Unity scene. After coordinate conversion, the installation positions of physical sensors are mapped to the Transform parameters of GameObjects in Unity. The sensor numbers and GameObject paths form a one-to-one mapping. For example, Sensor 1 of Warehouse 1/unit 2/3 corresponds to Warehouse1/unit2/sensor3.

The state mapping converts the numerical data collected by sensors into the visual state of the virtual model. The system determines the sensor status level based on the relationship between temperature and humidity values and the warning threshold and maps it to the corresponding display color. The state mapping rules are shown in Table 4. The behavior mapping defines the corresponding relationship between physical events and virtual responses. When the physical sensor detects an excessive temperature, the virtual model triggers a color change animation and displays a warning pop-up window. When the sensor is disconnected, the corresponding model switches to gray and displays an offline identifier.

**Table 4. State Mapping Table**

Status Name	Temperature Condition	Humidity Condition	Display Color	RGB Value
normal	≤ Threshold	≤ Threshold	Green	#00FF00
warning	> Threshold	> Threshold	Yellow	#FFFF00
error	Severely Exceeds Limits	Severely Exceeds Limits	Red	#FF0000

**5. System Implementation and Verification**

**5.1 Development Environment and Deployment Architecture**

The system adopts the technical selection as shown in Table 5, and implements the separation of front-end and back-end using the B/S architecture.

From the deployment perspective, the system adopts a three-layer architecture: The front-end

application is compiled and packaged into static resource files. Nginx is responsible for hosting and efficient distribution of resources, and it also undertakes the core responsibility of reverse proxying the back-end API. The back-end Node.js runs independently on the server and provides RESTful interfaces and WebSocket services for the system. The Unity scene is compiled and presented in WebGL format and embedded in the front-end page in iframe mode, achieving sandboxed isolated operation.

**Table 5. System Development Technology Stack**

Level	Technology Selection	Version	Main Responsibilities
Frontend	Vue.js + Element Plus	3.2	User interface and interaction
Backend	Node.js + Express	4.18	Business logic and API services
Database	MySQL	8.0	Data persistence storage
3D Engine	Unity3D (WebGL)	2021 LTS	3D scene rendering
Real-timeCommunication	WebSocket	ws 8.x	Real-time data push

**5.2 Bidirectional Communication of True and False Information**

Bidirectional communication between virtual and real worlds is necessary in digital twin systems because the WebGL scene runs in an iframe sandbox environment and cannot directly call functions from the parent page. Therefore, a specific bridging mechanism is required to achieve cross-domain communication. This system adopts the JSLIB bridging technology to overcome the communication difficulties between the Vue front-end and the Unity WebGL scene. For example, in the uplink, when the user clicks the sensor model in the Unity scene, the C# script calls the SendSensorClick function through the [DllImport (\_\_Internal)] feature, and the JSLIB layer uses mergeInto(LibraryManager.library, {... }).

In addition, this system also completes the task of injecting JavaScript functions into the Unity

runtime environment. When Unity processes click events, it calls window.parent.postMessage() to send the click event data to the parent page. The Vue front-end listens for and processes the Unity messages through message event listeners. In the downlink, the global functions exposed by Unity will be accessed by the contentWindow object of the front-end iframe. When the user clicks the grain depot switch button, the front-end calls the Unity global function and uses the SendMessage mechanism to trigger the C# script to quickly jump to the target grain depot. Similarly, when the temperature and humidity data of a certain sensor is abnormal, after the front-end receives the abnormal WebSocket broadcast, it will immediately call the setSensorState method to notify Unity to update the sensor color. The system defines a series of interfaces to achieve bidirectional communication, as shown in Table 6.

**Table 6. Definition Table of Bidirectional Communication Interface**

Communicationdirection	Interface name	Function description	Parameter description
Unity → Web	SendSensorClick	Sensor click event	sensorPath
Unity → Web	UNITY_READY	Scene loading completion notification	None
Unity → Web	UNITY_PROGRESS	Loading progress update	progress (0-1)
Web → Unity	handleButtonClick	Switch warehouse view	warehouseIndex
Web → Unity	setSensorState	Update sensor status	warehouseId, sensorId, status

To avoid placing excessive pressure on the backend through HTTP polling while ensuring real-time updates of information, the system employs WebSocket technology and uses the subscription-publish model to update data in real time. Once the temperature and humidity changes exceed 0.5 or trigger the warning threshold, the backend will proactively push the latest data to the frontend. This not only ensures that the displayed information is real-time and accurate, but also reduces system pressure and optimizes system performance.

### 5.3 System Function Presentation

To clearly display all the data, this system adopts a classic layout - a three-column layout on the left, center and right, as shown in Figure 8. The left panel displays the current weather information, the storage status of each grain warehouse, and the attendance information. The center part is the Unity 3D scene display section, which presents the status of each sensor in an intuitive visual feedback manner. Users can perform operations such as moving, rotating the view angle, and clicking sensors for interaction. The right panel displays various statistical indicators, such as the number of on-duty personnel, the statistics of today's inbound and outbound storage, and the statistics of camera conditions. It also provides a series of buttons for users to quickly switch the perspective of each grain warehouse.



**Figure 8. System Main Interface**

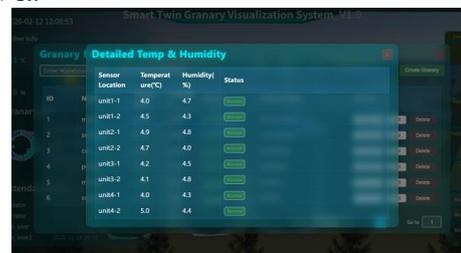
When the user clicks on the overview information of the grain storage on the left panel, a dialogue box for the grain storage details will pop up. Besides, when the user clicks on any sensor model in the Unity 3D scene, the same dialogue box will be triggered to pop up. The specific presentation effect is shown in Figure 9. This dialogue box is divided into three core modules: sensor status viewing, inbound and outbound record query, and detailed data browsing. The sensor status viewing module updates the color of the sensor based on the measured temperature and humidity data, with

four status indicators: green (normal), yellow (warning), red (abnormal), and gray (offline). The inbound and outbound record module is responsible for storing and presenting complete inbound and outbound records, and supports users to add inbound and outbound information according to their actual needs. The detailed data browsing module enables users to browse the real-time temperature and humidity information and status information of each sensor position in the grain warehouse, so that users can quickly grasp the situation inside the grain warehouse.



**Figure 9. Details of the Grain Warehouse**

The interface of the warning module is shown in Figure 10. If the temperature and humidity data exceed the warning threshold, this module will be triggered. After triggering, the behaviors of this module include but are not limited to changing the color of the sensor model, marking abnormal information after the temperature and humidity data, and pushing the abnormal data to the front end via WebSocket so that users can view it.



**Figure 10. Temperature and Humidity Warning Information**

After multiple tests, this system is capable of performing real-time monitoring of the grain warehouse environment and providing visual warning for abnormal situations. The delay from the occurrence of an anomaly to the user receiving the alert is no more than 10 seconds. Additionally, thanks to the B/S architecture feature, this system can be accessed using a browser and does not require the development of additional software. It also reduces compatibility issues arising from cross-platform access and is easy to maintain. This provides an economically feasible technical solution for the intelligent upgrade of small and medium-sized grain warehouses. Although the grain warehouse

management system based on smart digital twin technology can meet basic requirements such as grain warehouse management and environmental monitoring, the system still has issues such as visual movement relying on the mouse, being not friendly to mobile devices lacking a mouse, lacking a multi-person approval mechanism for sensitive operations, and the absence of grain condition prediction function based on historical data. In the future, this system will be specifically adapted for mobile terminals, introducing large models to achieve intelligent grain condition warning, and adding a workflow approval mechanism to enhance system security.

## 6. Conclusion

This article focuses on the digital transformation needs of small and medium-sized grain storage facilities and designs and implements a set of intelligent twin warehouse visualization management system. The system adopts a layered architecture, divided into the physical layer, data layer, virtual layer, and application layer, clearly defining the functional positioning and interaction relationships of each layer. A complete twin data closed loop from data collection, transmission, processing to feedback is constructed, and a three-level data verification mechanism and dynamic table storage strategy are designed to ensure the accuracy of data processing and the scalability of the system. In terms of virtual visualization, the virtual warehouse scene of the system is based on WebGL and is built using the Unity3D engine, providing high-fidelity three-dimensional models that support lightweight access from the browser. The bidirectional interaction mechanism based on JSLIB bridge ensures real-time communication between the Vue front-end and the Unity scene, achieving the effect of controlling reality through virtuality. In the future, this system will introduce cutting-edge technologies such as large models and generative AI to promote its transformation from a digital tool to an intelligent decision-making engine. Through precise grain condition prediction, multi-terminal intelligent control and other technological upgrades, the system will significantly reduce grain loss risks, improve warehouse management efficiency, and at the same time connect the entire grain data chain, build a traceable digital twin platform and connect with the regulatory intelligent computing system, to assist in the construction

of modern grain storage facilities and the intelligent transformation of the industry.

## Acknowledgments

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