American Journal of Innovation in Science and Engineering (AJISE)

ISSN: 2158-7205 (ONLINE)

VOLUME 4 ISSUE 1 (2025)

PUBLISHED BY
E-PALLI PUBLISHERS, DELAWARE, USA

American Journal of Innovation in Science and Engineering (AJISE)

Volume 4 Issue 1, Year 2025
ISSN: 2158-7205 (Online)
DOI: https://doi.org/10.54536/ajise.v4i1.4098
https://journals.e-palli.com/home/index.php/ajise

Design and Implementation of a Virtual Hoisting System: A Digital Twin Approach for Early Warning and Fault Detection

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Article Information

Received: November 16, 2024
Accepted: December 20, 2024
Published: January 14, 2025

Keywords

Digital Twins, Health Evaluation, Mine Hoist, Real-Time Monitoring, Virtual Simulation

ABSTRACT

Mine hoists are vital for efficiently transporting materials and personnel between surface and underground mining operations, making their safety and reliability paramount. However, conventional monitoring approaches, which rely on distributed sensors or video surveillance, are limited in their ability to capture the global dynamics of the system, leading to suboptimal decision-making and potential safety risks. This research introduces the integration of digital twin technology into the monitoring and management of mine hoists to address these challenges. This study uses Unity-based modeling to create a virtual system capable of real-time synchronization with its physical counterpart. The digital twin simulates dynamic load changes, predicts potential faults, and optimizes operational parameters through intelligent algorithms. A robust monitoring framework was developed, consisting of a multi-layered architecture that integrates physical systems, real-time data collection, and virtual simulations. Field tests on a multi-rope friction hoist verified the system's performance, with results demonstrating improved stability, accuracy, and predictive capabilities. A health evaluation model further enhances safety by categorizing the hoist's operational state into health levels such as 'healthy,' 'sub-healthy,' 'warning,' and 'fault.' This model identifies critical risks, such as wire rope tension anomalies, and provides early warnings, ensuring timely interventions.

INTRODUCTION

One promising technology in this context is the digital twin a disruptive innovation known for its ability to create dynamic, real-time virtual replicas of physical systems. By simulating operational conditions, digital twins allow for predictive maintenance, fault diagnosis, and optimization of processes. Digital twin technology has already gained significant traction across healthcare, energy, and smart city management industries due to its ability to integrate large-scale visualization with intelligent control. However, its application within mining, particularly for hoisting systems, remains relatively underdeveloped. This research seeks to fill this gap by designing and implementing a digital twin-based monitoring system specifically tailored for mine hoists.

The proposed system leverages a multi-layered architecture to integrate real-time data collection, virtual simulation, and predictive analytics. By combining hardware and software components, including sensors, microcontrollers, and Unity-based modeling, the system ensures synchronization between physical entities and their digital counterparts. This integration not only enhances safety and efficiency but also addresses limitations in traditional monitoring systems. Through comprehensive analysis and field validation, this study demonstrates the potential of digital twin technology to revolutionize mine hoist monitoring and management, setting a new standard for safety and operational excellence in mining.

LITERATURE REVIEW

The mine hoist serves as a critical link for transporting materials and personnel between underground and surface operations. Its operational state not only directly impacts the safety of coal mine production, but mechanical failures can also affect the stability of the system, potentially leading to safety incidents, significant economic losses, and bad social impact (Zabolotny, 2015). In the actual operation process, accidents such as sudden changes in hoist load, broken wire rope, and brake failure caused many casualties and economic losses. The main reason for many faults is that there is little research on the dynamic load change characteristics of the mine hoisting system. When the hoist has a perfect monitoring function, accidents caused by lifting loads can be minimized (Jimson, 2015; Lei *et al.*, 2019; Xue, 2017).

At present, the traditional monitoring method uses video monitoring or sensors distributed at multiple points to sense the state of some important links of the mine hoisting system. However, this method cannot fully understand the overall operation law of the system, and it is easy to ignore key information. Digital Twin (DT) technology is an important means to solve the above-mentioned large-scale and multi-domain visualization problems and improve the overall intelligence and safety of the mine hoisting system. Gartner once listed it as subversive technology and top ten strategic technology trends (Ma, 2012; Brenner & Hummel, 2017). Digital twin technology has been used in medical treatment (Yun *et al.*, 2017), electricity (Song *et al.*, 2022) Smart cities (Wang *et al.*, 2021) Extensive research and application were carried out. The research of digital twin technology in mines mainly focuses on fully mechanized mining face

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and tunneling systems, and related research on hoisting systems has not been carried out. Therefore, the digital twin technology is integrated into the monitoring of the hoisting system to realize global visualization and collaborative linkage control, and all information and scenes are integrated into the digital space for centralized display, thus improving the reliability and safety of the monitoring method.

Design of Virtual Hoisting System Based on Digital Twin

Twin Frame Design

Digital twinning focuses on the construction of a twinning frame, which refers to the use of digital technology to build a virtual model that is the same as the physical object in the physical world, to deeply understand and study the physical object through the frame in both directions. The

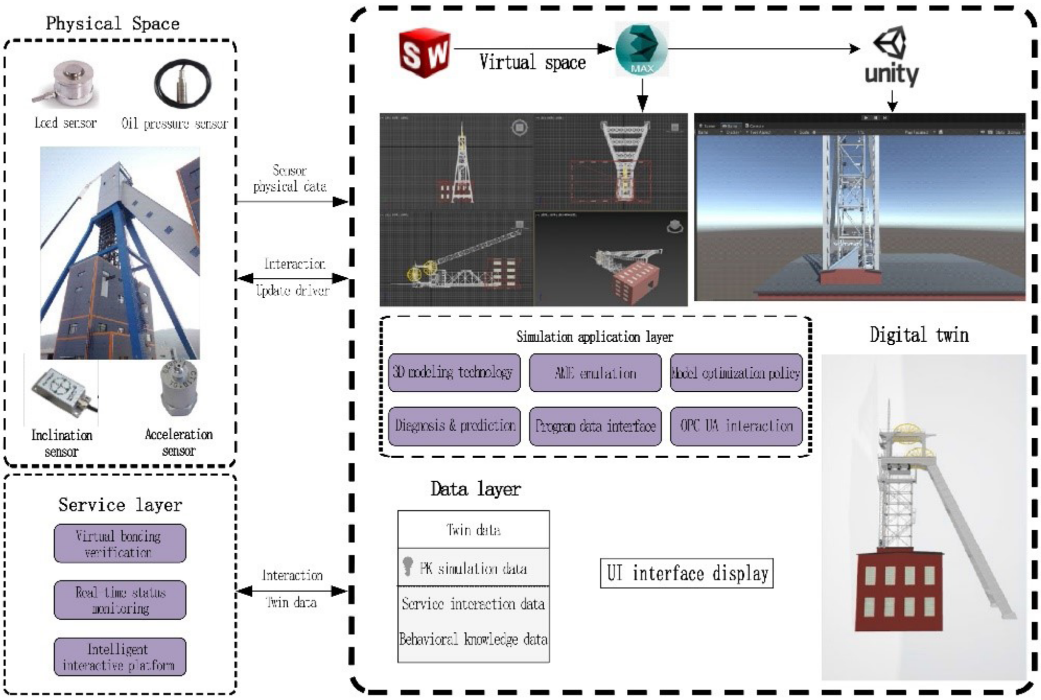

Figure 1: Main hoist digital twin architecture

mine hoisting monitoring system based on digital twin development is still based on the physical entity at first, and at the same time, the physical entity is fed back by the continuous dynamic evolution of the twin. Reference number twin five-dimensional model (Dassault, 2018), Put forward the digital twin architecture of mine hoist as shown in Figure 1.

As shown in the above figure, the Mine Hoisting Digital Architecture (MHDA) is divided into five levels (Ruan *et al.*, 2023), expressed by the following mathematical relationship:

MHDA= {MHSE, MHDSL, MHSDTM, MHSSAL, CTLOMHS} (1)

Mine Hoisting System Entity (MHSE), as the basis of the whole digital twinning, develops with the ontology, no matter the establishment of the model or the evolution and optimization of the twinning data. Mine hoisting system data layer (MHSDL) is the driving core of the digital twin model. The Mine Hoisting System Digital Twin Model (MHSDTM) consists of the high-precision three-dimensional model, simulation model, fault mechanism model, knowledge model, and behaviour rule model. The Communication Transmission Layer of Mine Hoisting System (CTLOMHS) specifies the transmission format and communication mode of twin data in the model. Mine Hoisting System Service Application Layer (MHSSAL) is another core of the virtual hoisting system. When the twin system needs the service layer to provide parameters or data, it can make service requests through the encapsulated interface. Based on the multi-dimensional and multi-scale modelling technology, the virtual model framework of a mine hoisting system with the combination of reality and reality, bidirectional driving, and adaptive self-perception is established by the interaction of the above five modules.

Technical Scheme Design

The virtual lifting system is mainly developed by C/S architecture (Li, 2013), The client is the upper computer installed in the computer room of the coal mine site; The server is a data processing-oriented service background. The client communicates with the server through OPC UA. After the server reads the data from the client, it calculates the edge, puts the data that needs pre-processing on the edge, and inputs other big data into the virtual space after being processed in the server or background, and carries out secondary development such as simulation and prediction by combining with the existing virtual engine. The overall technical scheme (Latif *et al.*, 2023) is shown in Figure 2.

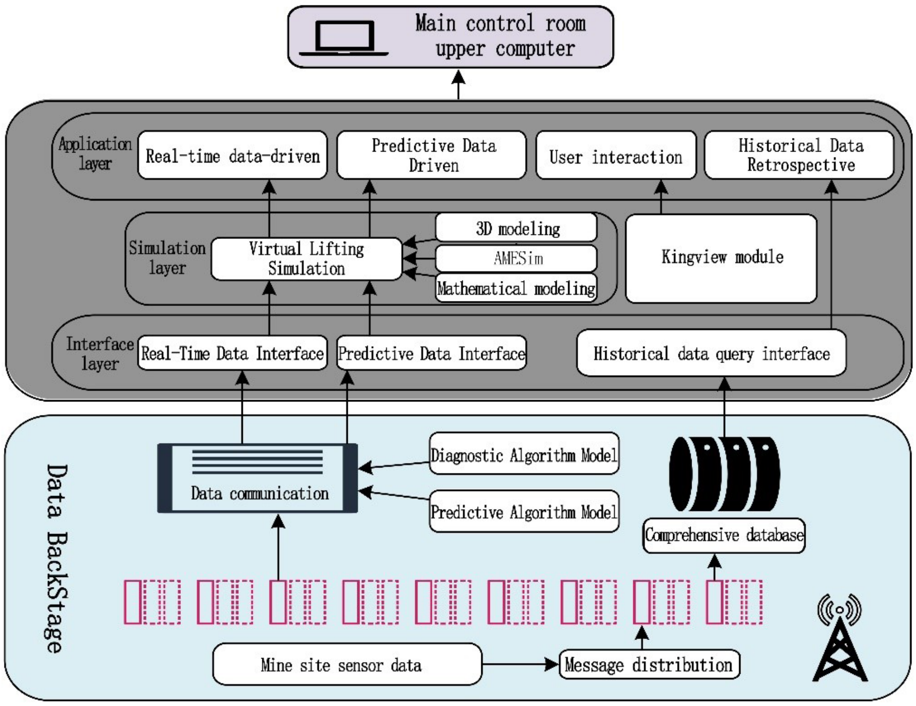

Figure 2: Technical scheme of the virtual lifting system

The client adopts a three-layer structure, which consists of an interface layer, a simulation layer, and an application layer from bottom to top. The interface layer is used to receive the data transmitted by the lower layer and distribute the data to different component modules, such as the real-time data interface and the historical query interface. As a bridge between the upper layer and the lower layer, the interface layer not only transmits messages to the upper layer but also interacts with the lower layer. The simulation layer carries out dynamic simulation in virtual space according to the data transmitted from the interface, in which the source of simulation data not only comes from the mine site but also covers the data processed by the algorithm model.

The server is divided into a database, a distributed server, and a data processing unit (Li, 2013). After receiving the data, the database stores it to facilitate the upper historical data interface to be called at any time; After receiving the data, the algorithm model predicts and diagnoses, and at the same time, the processed results are transmitted to the simulation adapter to facilitate the multi-scale simulation of twins in virtual space. The data communication server uploads data to the interface layer so that the upper layer can call the lower layer service.

Construction of On-Site Monitoring System

To ensure high consistency between twins and physical entities, a field monitoring system is designed to collect real-time data to drive twins to run. The field monitoring system selects STM32 as the main control chip of the system, in which the ADC module collects data, the DMA and UART modules carry out data handling and transmission, upload data through the combination of Lora and RS485, and finally enter Kingview for data storage and human-computer interaction. The specific scheme is shown in Figure 3.

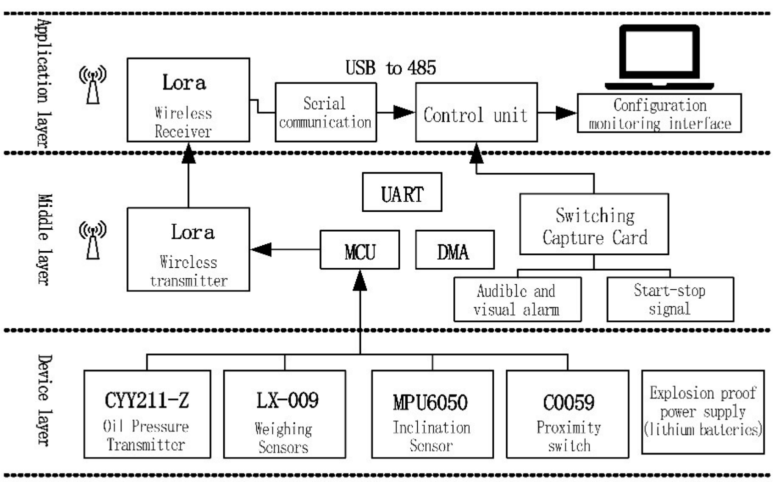

Figure 3: Hoist load monitoring system program

The signal acquisition and transmission device are fixed at the top of the lifting container, and its main function is to collect the data from the weighing sensor and the oil pressure sensor in real time and transmit them wirelessly to the wellhead. With STM32F103ZET6 chip as the core. Its working voltage is 3.3 V, a 12-bit analog-to-digital converter is configured in the single-chip microcomputer, and single-ended input voltage signals are collected through multiple channels. After continuous analog-to-digital conversion, the data is further processed by a digital filtering algorithm, and finally, the data is transmitted to the upper computer through the Lora digital transmission station according to the data format specified by Modbus RTU to realize data interaction.

Taking a coal mine site in Anhui as the background, the software and hardware system designed above was tested in the process of main shaft hoisting to verify its stability and practicability. According to the structure of the multi-rope friction hoist, sensors are installed at the lifting container and tension balance device on the north and south sides to sense its running state, and the MCU chip controls the ADC module to collect real-time data, which is transmitted to the Lora module through the serial port after DMA handling. After receiving the data packet, the upper computer parses and stores it in the historical database for technicians to call. The topology structure of the field installation of a monitoring system is shown in Figure 4.

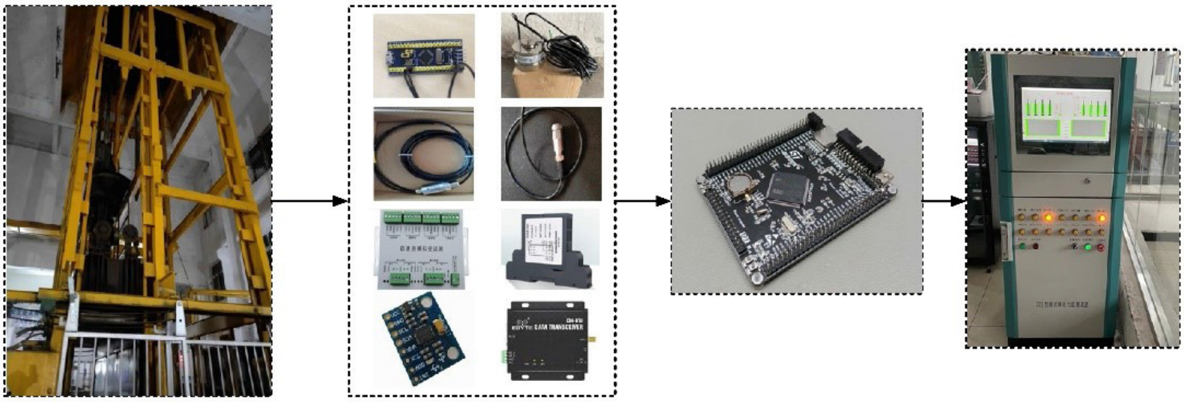

Figure 4: Field commissioning topology diagram

Because of the harsh working environment of the hoist and the safety problems such as coal falling impact, it is necessary to design a protection device to improve the service life of the hardware before installing the sensor on the hoist skip. Considering that the external wiring harness of the sensor is generally exposed and easy to break, the device needs to protect the external wiring harness while wrapping the sensor unit, so steel or hydraulic oil pipes are selected, as shown in Figure 5.

The installation position of the tension sensor is 3 in the figure, which is wrapped by the protection device 4 and ballasted between the piston rod 2 and the slider 5, which is not only beneficial to the fixing of the sensor position but also can prevent the module from being damaged by a large impact in the lifting process. 6 is the cross beam of the middle plate, which is used to buffer the impact received by the slider. 7 points are the installation positions of power supply boxes, and they enter the 9

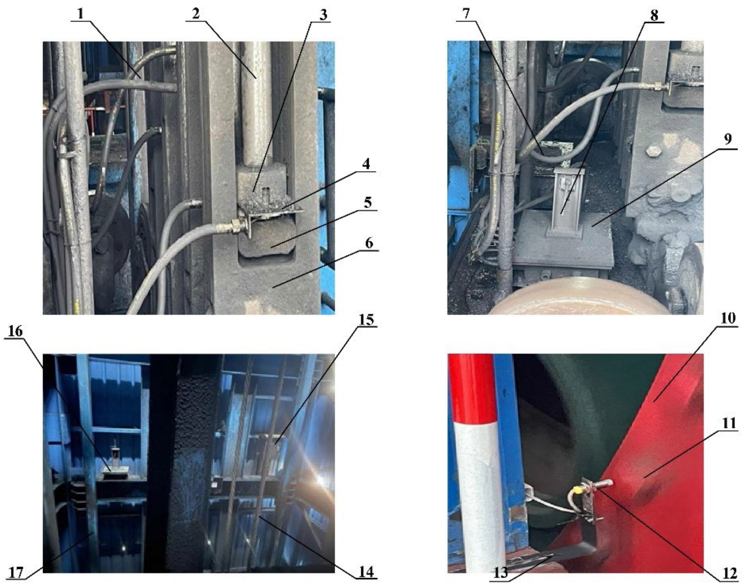

Figure 5: Monitoring system site installation

signal acquisition boxes through the bell mouth and the wrapped cable of the hydraulic oil pipe to supply power to each module. 8 is the antenna base, which cooperates with the Lora module in the transmitting box to upload data. 10 is the drum of the main shaft room. The distance between the protective bracket 13 the proximity switch 12 and the bolt 11 on the outside of the drum is detected, and the counter converts the pulse number, to obtain the position information of the hoist during actual lifting. At 17, the guide beam is lifted, and the steel wire rope 14 lifts the skip to the unloading point. At the same time, the receiving box 16 communicates with the launching box 9 on the skip, and the received data is summarized in the integrated box 15, which reaches a certain amount of data and is uploaded to the upper computer of the computer room as a whole. The site installation diagram of a monitoring system is shown in Figure 5.

Virtual System Construction And Simulation Model Building

The research object of this paper is the multi-rope friction hoist with the JDS-17.5 model. According to the equipment parameters and modelling process, the three-dimensional model of each part of the hoist is established, as shown in Figure 6.

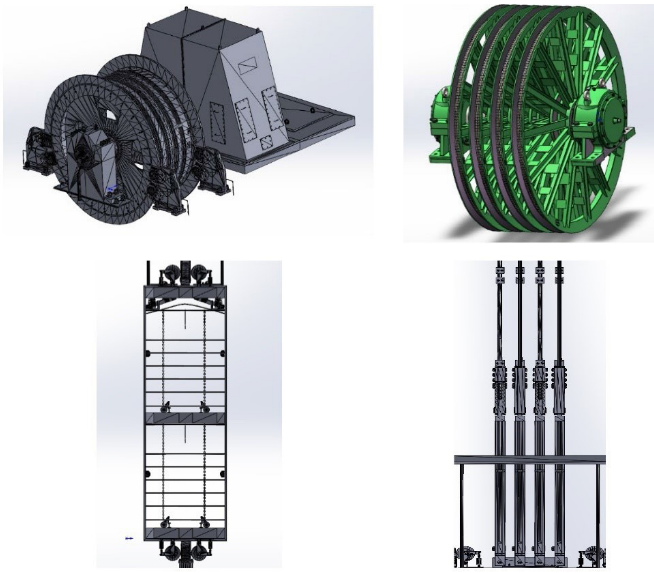

Figure 6: Three-dimensional model of hoist components

As shown in Figure 7~12, the file is exported in SolidWorks in. stp format, and the part model is imported into 3DMax for lightweight processing. The main operations include deleting redundant vertices, optimizing the number of simplified faces, optimizing materials, and rendering maps.

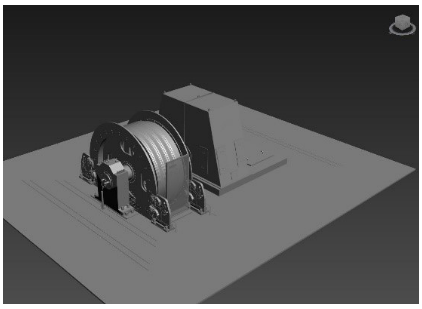

Figure 7: Initial cage model of importing 3dMax

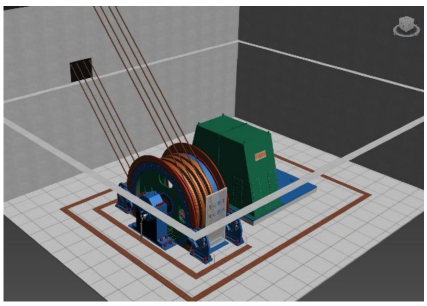

Figure 8: Cage model after mapping and rendering

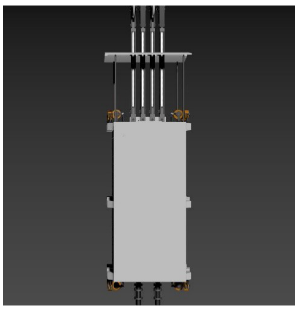

Figure 9: Initial hoist model with 3dMax imported

Figure 10: Model of hoist after mapping rendering

Figure 11: Initial hoist model with 3dMax imported

Figure 12: Model of hoist after mapping rendering

Simulation Motion Realization

To make the data of the hoisting system collected on-site accurately enter the Unity terminal, the problem of data format adaptation needs to be solved first. Classify and define the metadata of the field data according to each equipment model (Chen, 2016), including timestamps, data labels, and data values. In addition, to map metadata to corresponding sub-objects according to the hierarchy of lifting model structure, the simulation data is defined as the following structure:

MHS_ Simulation_ Data =(MHS_id,MHS_group,Meta)
Meta=(time_stamp,data_name,data_value) (2)
MHS_group=(name,sub_group)

MHS_Simulation_Data Represents the simulation data of the mine hoisting system, MHS_id Indicates the arrangement number of each module part in the lifting system, MHS_group Represents a module object corresponding to an arrangement number, sub_group Represents all the child objects at the next level contained in the upper-level module object, Meta Then the initial metadata is represented. In the metadata format time_ stamp represents the time stamp corresponding to the acquisition of each sub_group, data_name Represents the data name, and data_value Represents a data value. According to the relationship between the structure of the lifting system and the driving force, the rollers are arranged downwards. sub_group the first level, followed by lifting wire rope, sheave, lifting container, and other modules. The structured data under each time node is applied to the data object corresponding to the motion state of the model, to realize the function of Unity reading, merging, and parsing the lifting data. Finally, the data under the corresponding structure is read through the C# script, and the model lifting motion is driven.

Disassemble the actual lifting process into three work units as shown in Figure 13, and map the actions of each module to the virtual model through motion decomposition to realize the motion mapping from the physical model to the virtual model. Based on the operating principle of a multi-rope friction hoist, the simulated lifting motion is divided into three actions as shown in Figure 13: rotation, support, and lifting. Wherein, the rotating action is that the motor drives the roller to rotate, which drives the steel wire rope to be wound or released; The supporting action is to support the steel wire rope by the crown block, and the winding or releasing action in the previous step drives the steel wire rope to move; The lifting action is to connect the skip or cage with the steel wire rope after the first two steps to realize lifting or lowering.

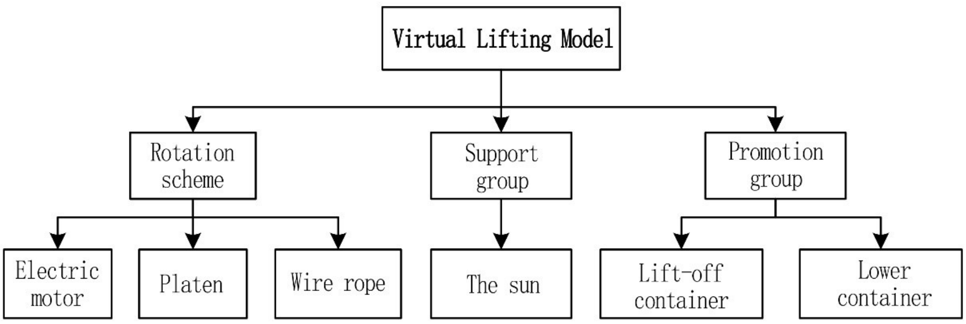

Figure 13: Virtual lifting model motion structure division

After the lifting action decomposition and model deconstruction are completed, the next step is to divide the lifting data received by Unity according to the above-mentioned movement units (Zhang *et al.*, 2024). Among them, the rotating group data includes parameters such as motor speed, motor temperature, drum speed, etc., the supporting group data includes parameters such as crown block mass and moment of inertia, and the lifting group data includes parameters such as skip weight and lifting speed. The structural levels of the three groups of data are shown in Table 1.

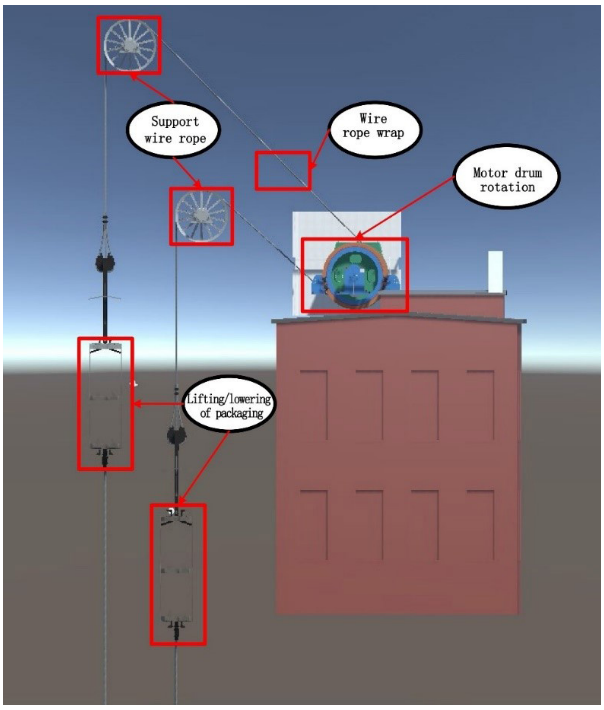

Figure 14: Virtual lifting model operation action breakdown

Table 1: Structural hierarchy representation of three groups of twin data

Group	Data name	Structural description
Rotating Group	Motor speed	Rotate/ Electric machine
	Motor power	Rotate/ Electric machine
	Unit weight of wire rope	Rotate/ Wire rope
	Number of ropes	Rotate/ Wire rope
Support Group	Wheel weight	Prop up/Hoisting sheave
	Rotary inertia	Prop up/Hoisting sheave
	Deflection	Prop up/Hoisting sheave
Lifting Group	Weight of the bucket	Rise/ Hoisting vessel
	Lifting speed	Rise/ Hoisting vessel
	Bucket load	Rise/ Hoisting vessel

Taking the above process as an example, the physical connection between modules has been realized in the previous section, and then the motion simulation of the whole model can be realized only by configuring the specific driving functions of these modules. The lifting container module can simulate the actual running process by referencing Vector3.MoveTowers() function and Vector3.Lerp() function in the library function (Khajavi *et al.*, 2019). The MoveTowards() function is applied to the uniform straight-line segment in the five-stage speed, and only the values of current, target, and maxDelta need to be defined according to the parameters of the uniform segment in the actual lifting process. Since the return value of MoveTowards() is Vector3, it is only necessary to define the position of Vector3 in the update function to receive the updated container position value of the previous frame, and finally iterate the whole operation process based on this position value (Mukherjee & DebRoy, 2019). The Lerp() function is applied to the variable-speed straight line segment in the five-stage speed. The definition of this function in the library is similar to the MoveTowards() function, but it can be used to realize variable acceleration or deceleration through interpolation. In the Lerp() function segment, firstly, the time float t is limited to a range by the Clamp function, and then the acceleration and deceleration effect in this range can be simulated by returning to new Vector3 in a way similar to solving the acceleration and deceleration curve.

Table 2: Correspondence of motion scripts

Group	Motion script	Motion function
	Motor	HingeJoint.motor()

Rotating Group	Roller	Slerp()
	Wire rope	MoveTowards()
Support Group	Sheave	Slerp()
Lifting Group	Lifting container	MoveTowards(), Lerp()

The Slerp() function in the library function is used to simulate the actual running process in the hoisting sheave module, and the Slerp() function is a spherical interpolation function to realize the movement of the rotating parts by simulating the change of the angle value, while the motor module uses the HingeJoint. motor() function in the library function to simulate the actual running process, and the configuration process is relatively simple. Based on the above analysis and the decomposition of the model structure, the scripts of different defined motion functions are mounted to the corresponding component groups to realize the action mapping from physical entities to virtual models. The corresponding relationships of different motion scripts are shown in Table 2.

Early Warning Research

To establish the health evaluation model of the hoisting part, it is necessary to summarize the common faults and occurrence positions of the hoist in the actual operation. Then, a health assessment framework is established based on the hierarchical idea (Li & Yang, 2013). The sub-system health membership degree is obtained through index weight distribution and evaluation matrix calculation. On this basis, the health evaluation results and state change reasons for the promotion part are obtained according to the sub-system weight and the maximum membership principle.

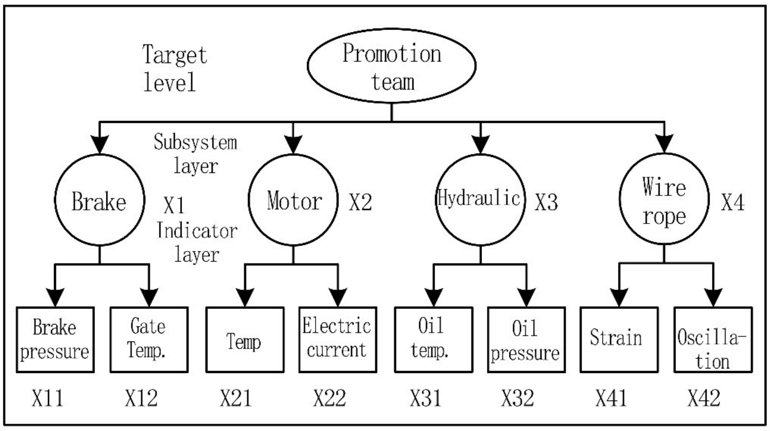

Figure 15: Health condition evaluation index system of hoisting machine

According to the location and evaluation index of the above common faults, the hoisting system can be divided into the following five subsystems (Liang *et al.*, 2023). According to the evaluation index of the bottom data, the health status of all subsystems in the middle layer is reflected, and finally, the health status of the top system is deduced by combining the evaluation results of all subsystems. In addition, a deterioration factor with a value range of [0,1] is introduced (Ahmed *et al.*, 2020). To represent the health degree of the promotion part, and construct the mapping table between health grade and health degree.

Table 3: Mapping relationship between health level and health degree

Health level L	**Health degree D**	**Health status P**
L1	[0.8, 1]	Healthy
L2	[0.4, 0.8]	Sub-healthy
L3	[0.15, 0.4]	Warning
L4	[0, 0.15]	Fault

According to the evaluation system and health grade table, the system set, evaluation set, and state set of the subsystem based on a single index are established and their health degree is calculated. As shown in formula 3, X_i represents thei-th subsystem; X_{ij} represents j-th evaluation indicators of the i-th subsystem; L_i represents the health status of i-th subsystems;D_{ij} represents the health degree of thei-th subsystem based on the j-th evaluation indicator.

$$\begin{cases} X_i = [X_1, X_2, X_3 \ldots X_n] \\ X_{ij} = [X_{i1}, X_{i2}, X_{i3} \ldots X_{in}] \\ L_i = [L_1, L_2, L_3 \ldots L_n] \\ D_{ij} = [D_{i1}, D_{i2}, D_{i3} \ldots D_{in}] \end{cases} \tag{3}$$

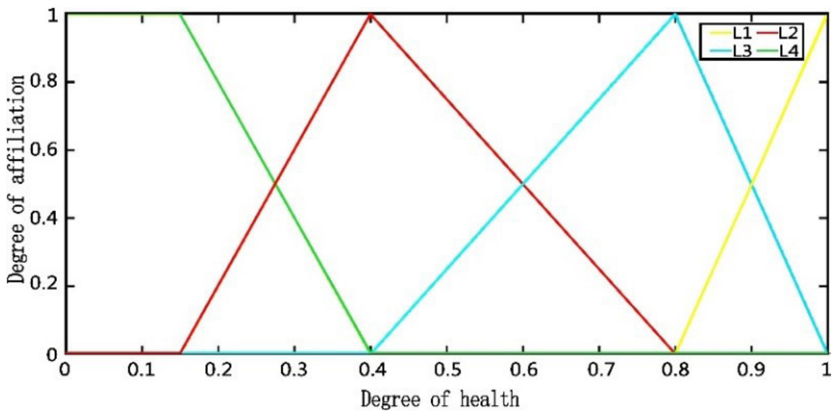

Figure 16: Degree of health and affiliation

$$p_{L1}(x)=\begin{cases}1 & x\geq 1\\ 5x-4 & 0.8<x<1\\ 0 & x\leq 0.8\end{cases} \quad (4)$$

$$p_{L2}(x)=\begin{cases}2.5x-1 & 0.4<x<0.8\\ -5x+5 & 0.8<x<1\\ 0 & x\leq 0.4, x\geq 1\end{cases} \quad (5)$$

$$p_{L3}(x)=\begin{cases}4x-0.6 & 0.15<x<0.4\\ -2.5x+2 & 0.4<x<0.8\\ 0 & x\leq 0.15, x\geq 0.8\end{cases} \quad (6)$$

$$p_{L4}(x)=\begin{cases}1 & 0\leq x\leq 0.15\\ -4x+1.6 & 0.15<x<0.4\\ 0 & x\geq 0.4\end{cases} \quad (7)$$

According to the affiliation function in different health states, the health degree can be established. D_{ij} Evaluation matrix between health grade and health grade P_{ij}:

$$P_{ij}=\begin{bmatrix}p_{L1}(D_{i1}) & p_{L2}(D_{i1}) & p_{L3}(D_{i1}) & p_{L4}(D_{i1})\\ p_{L1}(D_{i2}) & p_{L2}(D_{i2}) & p_{L3}(D_{i2}) & p_{L4}(D_{i2})\\ \cdots & \cdots & \cdots & \cdots\\ p_{L1}(D_{ij}) & p_{L2}(D_{ij}) & p_{L3}(D_{ij}) & p_{L4}(D_{ij})\end{bmatrix} \quad (8)$$

The judgment matrix is obtained by comparing the extraction subsystem and index layers' corresponding elements. $A_{ij}=(a_{ij})_{(n\times n)}$, through the AHP algorithm (Van Houdt, 2019) After normalization, subjective weights are obtained Q'_i; Based on the CRITIC weighting method (Lin *et al.*, 2018) Calculate the objective weight between different indicatorsQ''_i; Finally, the comprehensive weight of a single evaluation quantity is calculated according to Formula 11 (Yang *et al.*, 2017) Q_i:

$$Q'_i=\left[\frac{(\prod_{j=1}^{n}a_{1j})^{\frac{1}{n}} \quad (\prod_{j=1}^{n}a_{2j})^{\frac{1}{n}} \quad \ldots \quad (\prod_{j=1}^{n}a_{nj})^{\frac{1}{n}}}{(\sum_{i=1}^{n}(\prod_{j=1}^{n}a_{ij}))^{n}}\right] \quad (9)$$

$$Q''_i=\frac{T_i}{\sum_{i=1}^{n}(T_i)}, T_i=1+k\frac{1}{ln(n)}\sum_{j=1}^{n}s_{ij}\cdot ln(s_{ij}), s_{ij}=\frac{a_{ij}}{\sum_{j=1}^{n}a_{ij}} \quad (10)$$

$$Q_i=\frac{\sqrt{Q'_iQ''}}{\sum_{i=1}^{n}\sqrt{Q'_iQ''}} \quad (11)$$

Thereby determining the weight set of each element of the subsystem layer and the index layer, wherein Q_i Is the subsystem weight set, Q_{ij} Weight sets for subsystems based on a single evaluation index:

$$\begin{cases}Q_i=[Q_1 \quad Q_2 \quad \ldots \quad Q_n]\\ Q_{ij}=[Q_{i1} \quad Q_{i2} \quad \ldots \quad Q_{in}]\end{cases} \quad (12)$$

Then, the subsystem is obtained by the composite operation of the weighted average factor and matrix X_i health evaluation matrix based on V_i:

$$V_i=P_i\circ Q_i=[v_i(L_1) \quad v_i(L_2) \quad v_i(L_3) \quad v_i(L_4)]$$
$$v_i(L_i)=\sum_{j=1}^{n}min(Q_i,p_{Li}(D_{ij})), j=1,2,3\ldots m \quad (13)$$

Multiply the health of each subsystem in different operating States by the corresponding weighting factors and then add them to get the overall health of the improved part D:

$$D=\alpha V_{L1}+\beta V_{L2}+\chi V_{L3}+\delta V_{L4} \quad (14)$$

Table 4: Operating values of indicator parameters

Index code	Acceleration value	Deceleration value	Constant speed value	Indicator type
X_{11}	0.3	0.3	0.3	Class B
X_{12}	0.58	0.58	0.58	Class C
X_{21}	41	39	40	Class D
X_{22}	2.47	2.52	2.73	Class B
X_{31}	29	29	28	Class C
X_{32}	27	26	27	Class C
X_{41}	2.5	2.8	3.2	Class C
X_{42}	4	2	3	Class B

According to Table 4, formulas 3 to 13 are carried out to calculate and solve the health degree of the improved subsystem, and the health degree of the improved subsystem is obtained based on the evaluation result of the subsystem health state and combined with formula14.

$$P_1=\begin{bmatrix}0 & 0.2 & 0.8 & 0\\ 0 & 0 & 0.64 & 0.36\end{bmatrix}$$
$$P_2=\begin{bmatrix}0 & 1 & 0 & 0\\ 0.162 & 0.838 & 0 & 0\end{bmatrix}$$
$$P_3=\begin{bmatrix}0 & 0.714 & 0.286 & 0\\ 0.657 & 0 & 0 & 0.343\end{bmatrix} \quad (15)$$
$$P_4=\begin{bmatrix}0.482 & 0 & 0.518 & 0\\ 0 & 0.36 & 0.64 & 0\end{bmatrix}$$

Combine formulas 9 to 11 to calculate the comprehensive weight and health degree of indicators of each layer, as shown in Table 5. According to Formula 13, calculate the probability that the subsystem layer belongs to any health level, as shown in Table 6, thus completing the calculation of health degree.

Table 5: Comprehensive weight and health degree of the indicator layer

Index code	Comprehensive weight	Health degree
X_{11}	0.5327	0.48
X_{12}	0.4773	0.45
X_{21}	0.3859	0.72
X_{22}	0.6141	0.74
X_{31}	0.4742	0.62
X_{32}	0.5258	0.65
X_{41}	0.6928	0.88
X_{42}	0.3072	0.83

Table 6: Subsystem affiliation probability

	L_1	L_2	L_3	L_4
X_1	0	0.924	0.076	0
X_2	0	0.752	0.248	0
X_3	0.421	0.579	0	0
X_4	0	0.082	0.875	0.043

According to formula 14, the overall health degree of the lifting part is 0.549. Based on this, Table 3 shows that the hoisting part is in the sub-health state interval, and after tracing back the health state of the subsystem, it can be seen that the wire rope group is in the early warning state, and the tension index exceeds the established threshold, which is within a reasonable range compared with the theoretical calculation value and accords with the actual situation.

CONCLUSION

This paper integrates digital twin technology into hoist monitoring, developing a virtual hoisting model synchronized in real time with its physical counterpart to enhance safety management. The digital twin enables simulation and predictive analysis to identify potential issues and abnormal faults proactively, optimizing design and parameters for improved efficiency and reliability. Real-time data collection combined with intelligent algorithms ensures early fault detection and timely intervention, reducing mechanical risks and associated losses. Additionally, a health evaluation model classifies the hoist's operational state into distinct levels, offering actionable insights for effective maintenance and safety strategies.

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