

A Coal Loading Height Monitoring and Blockage Warning Method for Scraper Conveyors Based on Multi-Point State and Time Confirmation

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Abstract

INTRODUCTION: Accurate monitoring of coal loading height in scraper conveyors is important for maintaining continuous and safe operation in fully mechanized mining faces. In practical underground operation, a short-time rise in coal height may be caused by vibration, coal impact, or equipment passage, whereas continuous accumulation at adjacent positions may develop into blockage. Conventional fixed monitoring devices are easily affected by shearer passage, large coal impacts, and repeated mechanical disturbance. Meanwhile, warning methods based on single-point instantaneous thresholds may produce false alarms or missed alarms, which reduces the reliability of scraper conveyor monitoring.

OBJECTIVES: To improve monitoring stability and blockage warning reliability, this study proposes a coal loading height monitoring and blockage warning method for scraper conveyors based on multi-point state and time confirmation.

METHODS: An adjustable contact-type monitoring device was developed by combining a self-adaptive rotating mechanism with a quick-positioning detachable base. The device can yield under external mechanical interference and return to the preset monitoring position after the disturbance is removed. Each monitoring node converts the contact state caused by over-limit coal accumulation into a binary switching signal for PLC acquisition. Instead of using a single instantaneous signal as the warning condition, the PLC evaluates whether abnormal states appear in adjacent monitoring nodes and whether these states remain for a preset confirmation time. Isolated or short-duration abnormal signals are treated as possible interference, while continuous abnormal states in adjacent nodes are identified as potential blockage. A laboratory-scale scraper conveyor test platform was constructed to evaluate the monitoring response and warning performance of the proposed method.

RESULTS: Experimental results showed that the proposed system could distinguish normal, critical, and excessive coal loading states under the tested laboratory conditions. The response time for over-limit coal accumulation was less than 0.5 s. The observed false alarm rate and missed alarm rate were 1.22% and 0.82%, respectively. The adaptive monitoring structure reduces mechanical interference during the equipment's operation and still has the ability to recover after being disturbed. Compared with the traditional single-point threshold strategy, the multi-point state and time confirmation logic proposed in this paper reduces the unstable warning outputs caused by instantaneous impacts and local fluctuations.

CONCLUSION: The proposed method provides a laboratory-scale proof of concept for coal loading height monitoring and blockage warning in scraper conveyors. Under the tested conditions, the combination of adaptive contact sensing, spatial consistency assessment, and temporal persistence confirmation reduced unstable warning outputs caused by isolated and short-duration disturbances. The mechanical sensing device is specifically designed for scraper conveyors, whereas the associated decision logic can be interpreted as a potentially transferable spatio-temporal robust event detection pattern. Nevertheless, the 1:2-scale platform did not reproduce full-scale underground vibration spectra, long-term coal-dust deposition, electromagnetic interference, or mechanical degradation. Therefore, the reported response time, false alarm rate, and missed alarm rate should not be generalized to field operation until full-scale underground validation has been completed.

Keywords: scraper conveyor; coal loading height; blockage warning; multi-point state; time confirmation; PLC monitoring

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1. Introduction

The scraper conveyor, as the core transportation equipment in the comprehensive mining face, its operating conditions directly determine the efficiency of the entire process of coal feeding, coal loading, coal transportation, and the subsequent conveying. With the iterative development of intelligent mining technology, the monitoring dimensions of the scraper conveyor have no longer been limited to basic operating parameters such as motor current, chain speed, reducer temperature, and equipment start-stop status. The control system also needs to accurately identify the coal flow carrying conditions inside the middle trough and issue an early warning signal in advance if there are large-scale coal accumulation or stall faults in the trough [1].

During the actual operation of the equipment, the coal loading height in the middle trough is affected by multiple factors such as coal mining section depth, shearer haulage speed, roof rock conditions, coal body collapse morphology, and manual control operations. The temporarily high coal load can be quickly dispersed with the scraper chain transportation, but it may also remain in a local area of the trough for a long time and gradually evolve into a persistent coal accumulation abnormal condition [2]. If this abnormal state is not promptly identified by the system, it is very likely to trigger a series of faults such as increased conveyor operation resistance, scraper chain jamming, overload of the driving motor, and emergency shutdown of the entire machine. Therefore, the coal loading height detection cannot only be an independent height collection link, but also needs to be integrated with the coal blockage warning mechanism.

The traditional fixed monitoring devices still have obvious limitations in underground field applications. These devices are mostly rigidly fixed on the side of the middle trough and are continuously affected by equipment vibration, large coal and rock impacts, shearer passage, and underground maintenance operations [3]. Repeated external loading may cause component damage or displacement of the monitoring position. In addition, a single monitoring point can only represent the local coal-flow state. If the warning decision relies only on an instantaneous threshold, mechanical vibration and material impact may produce false alarms, whereas unstable or distorted sensing signals may result in missed detection of sustained coal accumulation. Modern non-contact monitoring approaches provide alternative means of obtaining coal-flow and conveyor-state information. Ultrasonic ranging methods estimate the distance to the material surface from acoustic propagation time and can provide continuous height information with a relatively simple sensing structure. However, their measurements depend on the quality of the reflected acoustic signal and may be influenced by irregular material surfaces, acoustic attenuation, airflow variation, and multiple echoes. ToF depth vision uses an optical depth camera to acquire depth and grayscale information, reconstruct coal-flow geometry from ToF images, and apply image restoration techniques

to suppress flight noise and multipath errors. Millimeter-wave radar can obtain range or three-dimensional surface information without relying on visible illumination and has potential advantages in dusty or hazy environments, although weak reflection, multipath propagation, calibration, and point-cloud processing increase system complexity. Computer-vision methods, including foreign-object classification and detection, can extract rich appearance and semantic information, but their performance depends on optical visibility, representative training data, camera installation, and computational resources.

These non-contact methods are particularly suitable when continuous height, volume, surface geometry, or foreign-object information is required. In contrast, the present study does not aim to reconstruct the complete coal-flow surface or classify foreign objects. It focuses on obtaining a robust binary indication of whether the local coal loading has exceeded a predefined warning height and then improving event reliability through spatial and temporal confirmation. Therefore, the proposed contact-type method should be regarded as a low-complexity event-detection solution and a possible redundant warning channel, rather than as a universal replacement for modern non-contact measurement systems.

In view of the above problems, the coal blockage warning logic needs to consider both the spatial distribution of abnormal monitoring nodes and the duration of abnormal signals [4]. It is not possible to directly trigger the alarm based on a single monitoring node's single over-limit signal. A more reliable determination method is to simultaneously verify whether the adjacent monitoring nodes simultaneously show abnormal signals and confirm that the duration of this abnormal state reaches the preset determination threshold of the system. The overall architecture of the monitoring system in this paper is shown in Figure 1, which relies on the industrial communication network to complete data interaction between the on-site perception unit, the PLC control decision unit, and the HMI human-machine interaction display unit.

Based on the aforementioned research background and the existing technical limitations, this paper proposes a coal loading height monitoring and blockage warning method for scraper conveyors based on multi-point state and time confirmation [5]. The main contributions of this study are summarized as follows. First, an adjustable contact-type monitoring device with a self-adaptive rotating mechanism and a detachable positioning base was developed specifically for the geometric and operational characteristics of scraper conveyors. Second, a PLC-based decision method was formulated by combining local binary-state abstraction, spatial consistency assessment among adjacent nodes, temporal persistence confirmation, and conveyor operating-state gating. This decision layer is separated conceptually from the scraper-conveyor-specific sensing structure and can therefore be interpreted as a general spatio-temporal robust event detection pattern under defined applicability conditions. Third, a 1:2-scale laboratory platform was constructed to evaluate the

functional feasibility, response characteristics, and warning stability of the proposed method under controlled coal-flow and disturbance conditions. The experimental results are regarded as laboratory-scale validation rather than evidence of full-scale underground reliability [6].

2. Design and Analysis of an Adjustable Coal Loading Height Monitoring Device

2.1. System Architecture and Functional Allocation

As shown in Figure 1, the proposed monitoring system consists of three functional layers: the perception-execution layer, the control-decision layer, and the human-machine interface layer. The perception-execution layer includes distributed contact-type monitoring nodes and on-site audible and visual alarm devices. Each monitoring node converts a local over-limit coal-loading condition into a binary switching state. The control-decision layer receives the node states through the PLC input interface and generates warning or interlock outputs according to the proposed decision logic. The HMI layer displays the conveyor operating state, node status, warning location, and system-level decision result.

The three layers exchange status and command information through the industrial communication network, forming a closed information path from local sensing to decision output and operator visualization. This section defines only the functional allocation and interfaces of the system. The mechanical design of the sensing device is presented in Section 2.2, while the detailed signal-conditioning, PLC I/O, and timing implementation are described in Section 3.2.

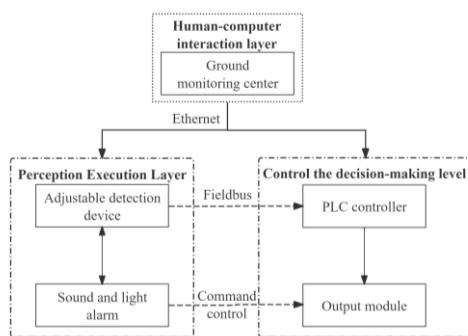


Figure 1. Functional architecture of the proposed monitoring and warning system

2.2. Key mechanical structure design and mechanical analysis

2.2.1. Self-adaptive rotation mechanism design and mechanical model

The coal loading height monitoring device is designed as a contact-type mechanical sensing unit. Its main components include the middle trough of the scraper conveyor, fixed base plate 1, rotating seat 2, detection base plate 3, detection rod 4, coal loading sensor 5, spring 6, spacer plate 7, and pusher ear plate 8 [7]. The overall structure is shown in Figure 2. The device is installed on the side of the scraper conveyor so that the detection rod can respond to the local coal loading condition without interfering with the normal movement of the scraper chain.

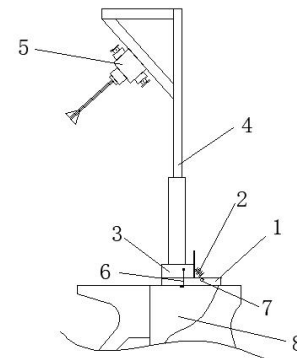


Figure 2. Overall structure of the coal loading height monitoring device

The pusher ear plate is arranged on one side of the middle trough, and the fixed base plate is mounted on its upper surface. The rotating seat is connected with the fixed base plate and provides the basic support for the detection unit. The rotating seat is connected to the fixed base plate through a rotating shaft, so the detection unit can rotate within a limited range. The spring is connected between the rotating plate and the fixed plate, providing both supporting force and restoring force. The detection base plate is fixed to the outer side of the rotating plate, and the detection rod is mounted on the upper surface of the detection base plate. The coal loading sensor is installed at the end of the detection rod to identify the contact state caused by over-limit coal accumulation.

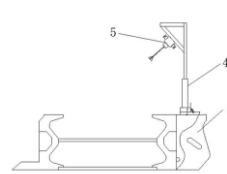


Figure 3. Normal monitoring state of the monitoring device

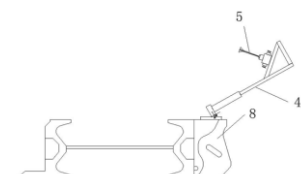


Figure 4. Deflected avoidance state of the monitoring device

Figures 3 and 4 show the two typical working states of the device. In the monitoring state, the detection rod is kept upright by the restoring force of the spring. The coal loading sensor is located at the preset monitoring height, and the node remains in the normal state when the coal

loading height is below the warning level. When excessive coal accumulation pushes the detection rod and the generated thrust exceeds the preset threshold, the rotating mechanism turns around the shaft and changes the output state of the sensing element. In this way, the mechanical contact condition is converted into a stable binary node state. The electrical interface and PLC acquisition process are described in Section 3.2.

In the equipment-passing or maintenance state, the detection unit can rotate outward under external contact. This displacement rotation structure can reserve the avoidance travel for the shearer passage, the impact of large coal and shale blocks, the coal cleaning operation inside the trough, and the manual maintenance underground. When the external load decreases or disappears completely, the reset spring can drive the rotating component to automatically reset to the standard monitoring position [8]. Compared with the traditional rigid fixed detection structure, this structure can effectively reduce the probability of device damage, thereby ensuring that the monitoring points maintain a stable working position even after multiple external force disturbances.

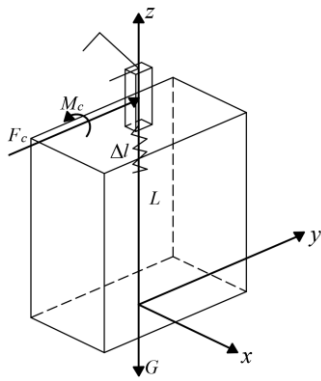


Figure 5. Mechanical model

To analyze the triggering condition of the mechanism, a simplified mechanical model is established, as shown in Figure 5. The center O of the rotating shaft is taken as the origin. The thrust produced by excessive coal accumulation on the detection rod and sensor is simplified as a concentrated force F_c acting at point P. The corresponding driving torque around the rotating shaft can be written as

$$M_c = F_c \cdot L \quad (1)$$

where L is the effective force arm from the force application point to the rotation axis.

The spring between the rotating plate and the fixed plate provides a restoring torque M_s . Let the spring stiffness be k , the original spring length be l_0 , the initial compression be Δl_0 , and the initial spring force arm be r_0 . When the rotating plate turns by an angle θ , the spring length and force arm change accordingly. The restoring torque can be expressed as:

where L represents the vertical distance from the point of application of force F_c to the center of the rotation axis O, namely the effective force arm.

$$M_s = k \cdot [\Delta l_0 + (l(\theta) - l_0)] \cdot r(\theta) \quad (2)$$

Within the effective rotation range of the device, the variation of the spring force arm is relatively small, and the change in spring length can be approximately regarded as linear with the rotation angle. Under this simplification, the restoring torque becomes:

$$M_s = M_{s0} + k_\theta \cdot \theta \quad (3)$$

where M_{s0} is the initial restoring torque, k_θ is the equivalent torsional stiffness of the rotating mechanism, and $k_\theta \theta$ is the incremental restoring torque caused by rotation.

The rotation state of the detection unit depends on the relationship between the driving torque and the restoring torque. Ignoring frictional damping in the quasi-static analysis, the equilibrium condition is

$$M_c = M_s \quad (4)$$

$$F_c \cdot L = M_{s0} + k_\theta \cdot \theta \quad (5)$$

Thus, the coal thrust required to rotate the mechanism to a given angle can be obtained as:

$$F_c(\theta) = \frac{M_{s0} + k_\theta \cdot \theta}{L} \quad (6)$$

When the rotation angle reaches the actuation angle θ_a of the coal loading sensor, the warning signal is triggered. The corresponding critical thrust is:

$$F_a = \frac{M_{s0} + k_\theta \cdot \theta_a}{L} \quad (7)$$

From Equation (7), it can be seen that methods such as adjusting the pre-compression amount of the spring, replacing springs with different stiffness, and changing the effective working length of the detection rod can all be used to adjust the trigger threshold of the device [9]. Based on this characteristic, this monitoring device can be adapted to various installation positions and different coal flow loading conditions. When the external thrust is less than the critical load, the restoring torque of the mechanism can drive the detection component to automatically return to the monitoring position, and the continuous cycle detection work can be carried out without the need for manual reset.

2.2.2. Removable base and quick positioning interface design

To improve installation convenience and maintainability, a removable base and quick-positioning interface are designed for the monitoring device. The interface connects the rotating seat with the fixed base plate on the pusher ear plate. Its assembly relationship is shown in Figure 6. The

fixed base plate remains on the scraper conveyor as a reference support, while the rotating seat and the upper detection unit can be removed when replacement, adjustment, or maintenance is required.

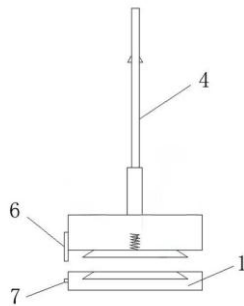


Figure 6. Assembly diagram of rotating seat and fixed base plate

The positioning interface adopts a protrusion-groove matching structure. A groove is machined on the upper surface of the fixed base plate, and a matching protrusion is arranged on the lower surface of the fixed plate of the rotating seat. During installation, the protrusion is inserted into the groove to form a constrained positioning pair. This structure restricts relative displacement between the rotating seat and the fixed base plate and improves the repeatability of the installation position. It also helps maintain the vertical attitude of the detection rod after the monitoring device is reassembled [10].

The protrusion–groove interface also provides a load-transfer path. That is, when the detection rod is subjected to lateral force or torque, the load can be transferred from the rotating seat to the fixed base plate and then to the pusher ear plate, and then to the moving ear plate. This can reduce the stress concentration in the connection area and improve the stability of the device under vibration, shock and repeated triggering conditions. Since the fixed base plate does not need to be disassembled during routine maintenance, the upper detection unit can be disassembled and reinstalled without changing the original reference position.

Overall, the adaptive rotating mechanism shown in Figures 2–5 and the detachable positioning structure shown in Figure 6 define the mechanical sensing characteristics of each monitoring node. The device responds to an over-limit coal-loading condition, yields under sufficiently large external contact, and returns to the preset monitoring position after the disturbance is removed [11]. These mechanical triggering and self-recovery characteristics provide the physical basis for generating the node states analyzed in Section 3.1.

3. Blockage Warning Logic Based on Multi-Point State and Time Confirmation

3.1. Signal Characteristics of Contact-Type Coal Loading Height Monitoring Nodes

In this study, a contact sensing unit was adopted as the monitoring node, and the output signal was determined jointly by the mechanical contact state between the detection rod and the coal accumulated in the trough. If the loading height of the coal flow did not reach the warning set height, the deflection angle of the detection rod did not reach the trigger threshold, the sensor would maintain the normal output. When the local coal pile height exceeded the warning point and applied sufficient lateral thrust to the detection rod, the rotating mechanism would trigger the deflection, and the output signal of the sensor would switch from the normal state to the alarm state. That is, this sensing signal is a standard binary switch quantity, which can be directly connected to the PLC digital input module for acquisition.

The summary of the signal characteristics of the monitoring node under different working conditions is shown in Table 1. Compared with the continuous measurement of height using analog signals, it can be seen that the binary signal contains less continuous numerical information, but is more suitable for the on-site application requirements of the underground control system. This monitoring unit does not need to collect the precise coal flow height at every moment, only needs to determine whether the local coal loading condition has reached the warning critical condition. This design concept is highly compatible with the core goal of coal blockage warning, and the control system focuses more on identifying dangerous coal accumulation conditions and determining whether this abnormality will continue to spread along the conveyor.

Table 1. Analysis of Monitoring Signal Characteristics for Coal Loading Height

Feature category	Feature description (simplified)	System design significance
Signal type	Digital (binary): 1=normal, 0=alarm	Direct to PLC DI module; simplified processing
Trigger conditions	$F_c \geq F_a$ (i.e., mechanism rotation $\theta \geq \theta_a$)	Mechanically fixed, stable threshold; needs model-based design
Response	Mechanical delay; total transition <100 ms	Meets real-time warning; can be treated as instantaneous
Signal retention	Self-holding: alarm persists while $F_c \geq F_a$	Prevents flicker from coal pile fluctuations; easy PLC capture
State recovery	Self-recovery: automatic reset when $F_c < F_a$ via spring torque	Enables unattended cyclic monitoring; key adaptive property

Anti-interference	Insensitive to minor vibration/impact due to threshold F_a	Enhanced reliability in harsh underground vibration
Signal-position mapping	Single sensor reflects only local coal state	Requires multi-point deployment for spatial blockage assessment

From the perspective of time-domain characteristics, the monitoring output signal exhibits a step-like jump feature. This signal jump is not merely a sudden change in the electrical signal but is closely related to the mechanical dynamic response of the adaptive rotating mechanism described in the second section [12]. The detection rod, spring, and sensor form a mechanical-electrical conversion path. When the coal thrust reaches the critical triggering force, the mechanical structure turns to the alarm position. When the thrust decreases below the threshold, the spring restores the structure to the normal monitoring position. Therefore, the node has both binary electrical characteristics and mechanical self-recovery behavior.

For the (i)-th monitoring node, the output state can be described as:

$$S_i(t) = \begin{cases} 0, & F_{c,i}(t) \geq F_a \\ 1, & F_{c,i}(t) < F_a \end{cases} \quad (8)$$

where $S_i(t) = 1$ denotes the normal state, $S_i(t) = 0$ denotes the alarm state, $F_{c,i}(t)$ is the instantaneous coal thrust acting on node i , and F_a is the triggering threshold.

The total response delay of one node includes the mechanical actuation time and the electrical signal-conditioning time. It can be written as

$$t_{\text{node}} = t_{\text{mech}} + t_{\text{elec}}, t_{\text{mech}} < 100 \text{ ms} \quad (9)$$

where t_{mech} is the mechanical response time and t_{elec} is the signal-conditioning delay. In the proposed system, the response of a single node is faster than the accumulation process of coal in the trough, so the signal can be used for real-time PLC acquisition.

To reduce false triggering caused by vibration and small impacts, the triggering threshold should be higher than the equivalent disturbance force produced by the underground environment. The threshold condition can be expressed as

$$F_a > k_s \cdot F_{\text{rms}} \quad (10)$$

where F_{rms} is the root-mean-square value of the random disturbance force, and k_s is the safety coefficient used for interference suppression.

As shown in Table 1, a single contact-type node can only reflect the local coal loading condition. It cannot independently determine whether a blockage is forming along the conveyor. For this reason, the subsequent warning logic should not rely on one node alone. The binary state of each node is treated as a basic input, and the PLC further judges the distribution and duration of abnormal states among multiple nodes [13].

3.2. Hardware Architecture of the Multi-Point Warning System

The hardware architecture of the warning system is arranged according to the flow of sensing, acquisition, judgment, output, and display. As shown in Figure 7, the system mainly includes monitoring devices, signal-conditioning circuits, PLC input and output modules, communication modules, on-site alarm units, and the HMI monitoring interface. The architecture is consistent with the layered system shown in Figure 1, but Figure 7 gives a more detailed view of the signal path and control path used for blockage warning.

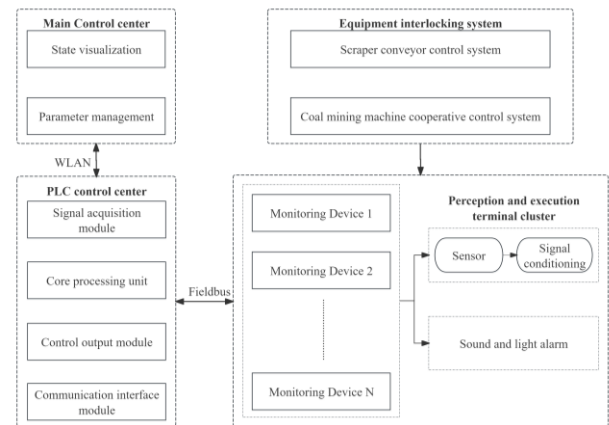


Figure 7. Hardware signal and command paths of the PLC-based warning system

The monitoring devices are installed along the scraper conveyor and form a distributed sensing network. Each device outputs a binary state signal after the coal loading condition reaches the preset triggering level. The signal is processed by the signal-conditioning circuit and then transmitted to the PLC digital input module. Since the node output is a switching signal, the PLC can collect it without complex analog conversion. This is useful for underground applications where wiring simplicity, reliability, and maintainability are important.

The PLC is the central unit of the warning system. During operation, it scans the input states of all monitoring nodes and stores them in the input image register. The control program then evaluates whether the abnormal state is isolated, adjacent, short-time, or continuous. If only one node is triggered for a short time, the signal is regarded as possible interference [14]. If several adjacent nodes remain in the alarm state for the required confirmation time, the PLC identifies the condition as a blockage risk and sends output commands to the alarm or shutdown module.

The timing design was evaluated using an end-to-end response budget. The total delay from the occurrence of an over-limit coal condition to the generation of the warning output should satisfy.

$$t_{\text{node}} + T_{\text{scan,max}} + T_c + T_{\text{act}} \leq t_{\text{response}} \quad (11)$$

where t_{node} is the mechanical and electrical response delay of the monitoring node, $T_{scan,max}$ is the maximum measured PLC scan cycle, T_c is the temporal confirmation delay, T_{act} is the output-command and actuator delay, and $t_{response}$ is the allowable overall warning-response time.

The PLC scan cycle is composed of digital-input refreshing, user-program execution, digital-output refreshing, and communication processing, as expressed in Eq. (12). Both the average and maximum scan-cycle values were measured under the complete warning program rather than estimated from the nominal CPU instruction speed.

where T_{scan} is the PLC scan cycle, t_{node} is the response delay of the monitoring node, and $t_{response}$ is the allowable response time of the warning system.

The total scan cycle includes input refreshing, program execution, output refreshing, and communication processing. It can be written as

$$T_{scan} = T_{DI} + T_{prog} + T_{DO} + T_{comm} \quad (12)$$

where T_{DI} is the input refreshing time, T_{prog} is the program execution time, T_{DO} is the output refreshing time, and T_{comm} is the communication delay.

After the system completes the judgment of the warning conditions, the PLC output module immediately activates the on-site audible and visual alarm unit. If the abnormal coal accumulation condition persists and is not eliminated or reaches the shutdown trigger threshold, the system will issue an interlock shutdown command to the main control system of the scraper conveyor. To meet the inherent safety explosion-proof regulations in underground coal mines, the output power of the module must be strictly limited within the rated allowable range:

$$P_{out} = V_{out} \cdot I_{out} \leq P_{max} \quad (13)$$

where V_{out} and I_{out} are the output voltage and current of the PLC output module, and P_{max} is the maximum allowable intrinsic safety power [15].

Based on the above hardware solution, the system can simultaneously collect the coal flow loading conditions at multiple measurement points, and complete the logical judgment for the verification of the time domain duration within the PLC. Then, The HMI displays the operating states and warning results of all monitoring nodes in real time. The operation and maintenance personnel can intuitively distinguish the distribution characteristics of abnormal signals: single-point independent triggering, simultaneous alarms of multiple adjacent nodes, or the spread of abnormal coal loading conditions to the long-distance sections of the conveyor.

3.3. Construction of the Multi-Point State and Time-Confirmation Warning Strategy

The purpose of the warning strategy is to convert the binary signals from individual monitoring nodes into a system-level blockage warning result. The proposed strategy includes two main parts: multi-point state judgment and time confirmation. Multi-point state judgment is used to identify whether the abnormal signals are distributed in adjacent monitoring nodes. Time confirmation is used to determine whether the abnormal state is only a short disturbance or a sustained accumulation.

For logical analysis, the alarm state of the (i)-th node is defined as:

$$A_i(t) = 1 - S_i(t) \quad (14)$$

where $A_i(t) = 1$ means that the (i)-th node is in the alarm state, and $A_i(t) = 0$ means that the node is in the normal state.

First, the PLC judges the distribution of alarm nodes along the scraper conveyor. A sliding window consisting of K adjacent monitoring nodes is introduced. If the window starts from node j, the number of abnormal nodes in this window is

$$C_j(t) = \sum_{i=j}^{j+K-1} A_i(t) \quad (15)$$

When the number of abnormal nodes in at least one sliding window reaches M, the spatial-consistency condition is satisfied:

$$C_{spatial}(t) = \begin{cases} 1, & \exists j \text{ such that } C_j(t) \geq M \\ 0, & \text{otherwise} \end{cases} \quad (16)$$

where K is the window length, and M is the minimum number of abnormal nodes required to identify a possible blockage region.

This judgment avoids direct alarming caused by an isolated node. For example, when one node is triggered by coal impact or vibration, the sliding window may not satisfy the threshold condition. When adjacent nodes are triggered at the same time, the abnormal state is more likely to be related to continuous coal accumulation.

Second, a time-confirmation process is added for each monitoring node. When a node changes from the normal state to the alarm state, the confirmation timer starts. If the node returns to normal before the timer reaches the preset value, the alarm state is cleared. If the alarm state lasts longer than the confirmation time, the node is regarded as a valid abnormal node. The time-confirmed alarm state is expressed as

$$B_i(t) = \begin{cases} 1, & A_i(t) = 1 \text{ and } T_i(t) \geq T_c \\ 0, & \text{otherwise} \end{cases} \quad (17)$$

where $T_i(t)$ is the duration of the alarm state at node i, and T_c is the preset confirmation time.

The final blockage warning decision is obtained by combining the adjacent-node condition, time-confirmed node states, and the operating state of the scraper conveyor.

Let $E(t)$ denote the conveyor operating state. When the conveyor is running, $E(t)=1$. otherwise, $E(t)=0$. The warning output can be expressed as:

$$Y(t) = E(t) \wedge (\max_j \sum_{i=j}^{j+K-1} B_i(t) \geq M) \quad (18)$$

When $Y(t)=1$, the PLC outputs a blockage warning command. If the abnormal conditions detected by the warning system persist and are not eliminated, or if the control program determines that the coal accumulation state has endangered the safe operation of the equipment [16], the PLC will issue an interlock shutdown command to the main control system of the scraper conveyor.

Compared with the conventional single-point threshold strategy, the proposed method does not rely on the instantaneous over-limit signal of a single monitoring point. Instead, it combines the spatial distribution of abnormal nodes with the duration of abnormal signals. This mechanism can respond to persistent coal accumulation while suppressing short-term operational disturbances. The resulting warning strategy is evaluated experimentally under single-point instantaneous interference, single-point continuous over-limit loading, multiple consecutive over-limit loading, critical fluctuation, and equipment shutdown conditions.

3.4. Generalized Spatio-Temporal Robust Event Detection Pattern

Although the sensing device developed in this study is specifically designed for scraper conveyors, the decision process described in Eqs. (14)–(18) can be abstracted as a sensor-independent spatio-temporal robust event detection pattern. The generalized pattern consists of four successive operations: local-state abstraction, temporal persistence confirmation, spatial consistency assessment, and equipment operating-state gating. First, measurements or contact states from heterogeneous sensing nodes are converted into local binary abnormal states. Second, short-duration state changes are rejected through a temporal persistence condition. Third, the spatial or topological consistency of the time-confirmed abnormal nodes is evaluated within a predefined neighborhood. Finally, an event output is generated only when the monitored equipment is in a valid operating state [17].

This pattern is applicable when a true abnormal event is more spatially correlated and temporally persistent than the dominant interference. Therefore, the decision logic may potentially be used in other distributed industrial monitoring applications, including belt conveyors, screw conveyors, bucket elevators, material transfer chutes, and distributed equipment-condition monitoring. However, such transferability applies primarily to the decision layer rather than to the mechanical sensing structure. For each new application, the sensing modality, node topology, node spacing, spatial-window length, minimum abnormal-node threshold, and confirmation time must be redesigned or recalibrated.

The proposed pattern is not intended to replace dedicated emergency protection for all fault types. A severe but spatially isolated or short-duration event may not satisfy the spatial and temporal confirmation conditions. Therefore, safety-critical applications should retain an independent hard-threshold or interlock channel for events requiring immediate response.

4. Experimental Verification and Performance Analysis

4.1. Experimental Platform and Test Scheme

To evaluate the functional feasibility of the proposed multi-point state and time-confirmation method, a laboratory-scale scraper conveyor test platform was constructed. The test system consisted of a 1:2-scale scraper conveyor prototype, an adjustable monitoring-device array, a PLC-based data acquisition and control unit, and a performance evaluation module. As shown in Figure 8, the platform reproduced four controlled coal-flow conditions: normal loading, critical fluctuation, local instantaneous disturbance, and continuous excessive coal accumulation.

The purpose of the platform was to compare monitoring and warning behavior under repeatable laboratory conditions rather than to reproduce the complete underground environment. Geometric scaling and controlled laboratory excitation do not preserve the vibration spectrum, structural resonance, or disturbance-energy distribution of a full-scale scraper conveyor. In addition, the platform did not reproduce long-term coal-dust deposition, humid dust adhesion, electromagnetic interference from high-power motors and frequency converters, grounding variation, long-distance signal cabling, or long-term mechanical wear. Consequently, the platform supports functional and comparative validation of the proposed strategy, but not direct verification of full-scale underground robustness.

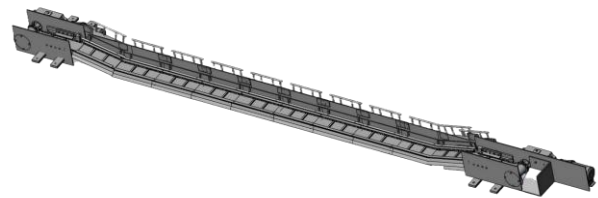


Figure 8. Simulated scraper conveyor system

The conveying capacity of the simulated scraper conveyor can be estimated by:

$$Q=3600 \cdot B \cdot H \cdot v \cdot \rho_b \cdot \psi \quad (19)$$

where B is the width of the middle trough, H is the coal loading height, v is the chain speed, ρ_b is the loose coal density, and ψ is the filling coefficient. By changing the coal height, chain speed, and feeding amount, different coal-flow states can be generated on the test platform.

In the proposed warning strategy, node spacing is treated as a spatial-resolution parameter rather than as a direct function of conveyor length. To ensure that a coal-accumulation region with a minimum longitudinal extent L_{min} activates at least M adjacent monitoring nodes, the node spacing should satisfy:

$$d \leq \frac{L_{min}}{M-1} \quad (20)$$

where d is the distance between adjacent nodes, L_{min} is the minimum longitudinal extent of a coal-accumulation region that must be reliably identified, and M is the minimum number of adjacent abnormal nodes required by the spatial-consistency condition. The corresponding spatial-window coverage is $L_w = (K-1)d$, where K is the number of nodes in the sliding window.

The previously considered expression involving $v^2/(g \tan \phi)$ represents, at most, a characteristic material-relaxation distance under a simplified constant-deceleration assumption. It does not directly guarantee that a specified blockage region will be covered by the required number of monitoring nodes and is therefore not used as a universal node-spacing law in this study.

Because each monitoring node generates a binary switching signal, the data-acquisition requirement is formulated in terms of reliable event capture rather than reconstruction of a band-limited analog waveform. Let $t_{p,min}$ denote the shortest valid abnormal-state duration that must be detected, and let N_s denote the minimum number of PLC scans required within this duration. The effective state-sampling frequency should satisfy

$$f_{s,eff} = \frac{1}{T_{scan,max}} \geq \frac{N_s}{t_{p,min}} \quad (21)$$

where $T_{scan,max}$ is the maximum measured PLC scan cycle. In this study, $N_s = 10$ was adopted as an engineering sampling margin. The value of $t_{p,min}$ was determined from the shortest valid alarm-state duration observed in the repeated loading tests. The configured digital-input filter time was also shorter than $t_{p,min}$, ensuring that a valid event was not removed by input filtering [18].

To evaluate the monitoring and warning performance, three indicators were used: accuracy Acc , false alarm rate FAR , and missed alarm rate MAR . They are defined as

$$Acc = \frac{TP+TN}{TP+TN+FP+FN} \quad (22)$$

$$FAR = \frac{FP}{TN+FP} \quad (23)$$

$$MAR = \frac{FN}{TP+FN} \quad (24)$$

where TP , TN , FP , and FN represent true positive, true negative, false positive, and false negative results, respectively.

The experimental program included normal loading, critical loading, excessive coal accumulation, single-point interference, and multiple-node over-limit conditions. The coal loading height tests recorded the measured heights and response times under different loading states, whereas the blockage warning tests compared the proposed multi-point state and time-confirmation method with a conventional single-point threshold strategy.

4.2. Coal Loading Height Monitoring Test

The main parameters of the test platform were set as follows: the chute width was $B=0.6$ m, the chain speed was $v=0.8$ m/s, the loose coal density was $\rho_b=850$ kg/m³, and the filling coefficient was $\psi=0.7$. According to Eq. (19), the theoretical conveying capacity can be calculated as: $Q=3600 \times 0.6 \times H \times 0.8 \times 850 \times 0.7 = 1.03 \times 10^6 \times H$ kg/h.

In the laboratory platform, eight monitoring nodes were installed at a uniform spacing of 0.15 m, resulting in a total monitored length of 1.05 m. The spacing was selected according to the minimum longitudinal extent of the artificial coal-accumulation region and the minimum number of adjacent abnormal nodes required by the warning logic.

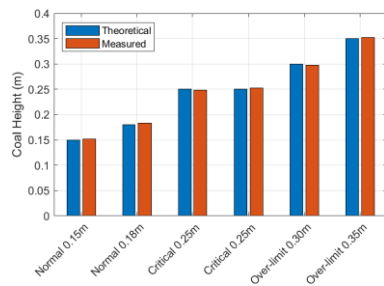
In the tests, the minimum accumulation-region length was $L_{min}=0.30$ m, and the spatial warning condition required at least $M=3$ adjacent abnormal nodes. According to Eq. (20), the allowable spacing was therefore $d \leq \frac{0.30}{3-1} = 0.15$ m.

The adopted spacing of 0.15 m satisfied this spatial-coverage condition while allowing eight monitoring nodes to be accommodated within the available 1.05 m test section. Therefore, 0.15 m should be interpreted as a laboratory-platform parameter rather than as a universal spacing for full-scale scraper conveyors.

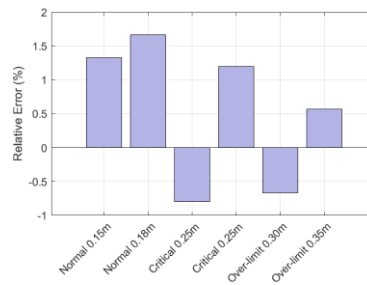
The coal loading height monitoring results are summarized in Table 2. The measured heights under normal, critical, and excessive loading conditions were close to the preset values. Figure 9 further compares the theoretical and measured coal heights, monitoring relative errors, and system response times. Under the tested laboratory conditions, the monitoring device distinguished the different loading states, and the response times under critical and excessive loading conditions were below 0.5 s. It should be noted that the results in Table 2 and Figure 9 were obtained from a controlled laboratory platform. They indicate the feasibility of the monitoring device under preset experimental conditions, but they should not be directly regarded as field accuracy under full-scale underground operation.

Table 2. Test Results of Coal loading height Monitoring Accuracy

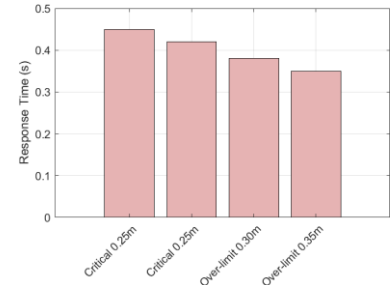
Operating condition (status)	Coal height (set / measured) (m)	Error ($\Delta H / \delta$)	Response time tr (s)				
Normal (Normal)	0.15 / 0.152±0.008	0.002±0.008 m / 1.33±5.33%	–	Critical (Critical)	0.25 / 0.253±0.005	0.003±0.005 m / 1.20±2.00%	0.42±0.10
Normal (Normal)	0.18 / 0.183±0.007	0.003±0.007 m / 1.67±3.89%	–	Excessive (Alarm)	0.30 / 0.298±0.004	-0.002±0.004 m / -0.67±1.33%	0.38±0.08
Critical (Critical)	0.25 / 0.248±0.006	-0.002±0.006 m / -0.80±2.40%	0.45±0.12	Excessive (Alarm)	0.35 / 0.352±0.003	0.002±0.003 m / 0.57±0.86%	0.35±0.06



a. Theoretical vs Measured Coal Height



b. Monitoring Relative Error



c. System Response Time

Figure 9. Coal Height Monitoring Accuracy Test Results

4.3. Blockage Warning Performance Test

To evaluate the effects of multi-point state judgment and time confirmation, the proposed warning method was compared with a conventional single-point threshold strategy. In the conventional strategy, an alarm is generated once any monitoring node reaches the preset warning state. Although this approach responds quickly, it is sensitive to short-duration impacts, vibration, and isolated abnormal signals. The comparison scenarios and test results are summarized in Table 3.

Table 3. Comparative Test Results of the Conventional Fixed-Threshold Warning Method and the Proposed Spatio-temporal Warning Model

Test scenario	Actual condition / expected output	Conventional fixed-threshold method (False / Missed)	Proposed spatio-temporal model (False / Missed; response time)
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Single-point instantaneous interference	Normal > Normal	[FT1] / 0	2 / 0;
Single-point continuous over-limit	Exceeding limit > Alarm	0 / [FT2]	0 / 0; 0.42 s
Multiple consecutive over-limits	Exceeding limit > Alarm	0 / [FT3]	0 / 0; 0.38 s
Critical fluctuation state	Critical > Warning	[FT4] / [FT5]	1 / 2; 0.45 s
Equipment shutdown status	Normal > Normal	[FT6] / 0	0 / 0;
Overall performance	Same laboratory -scale tests	FAR=[FTFAR]% ; MAR=[FTMAR] %	FAR=1.22%; MAR=0.82%; average response <0.5s

In the proposed method, the PLC first determines whether abnormal states occur at adjacent monitoring nodes and then applies the time-confirmation condition to verify whether the abnormality persists long enough to indicate continuous coal accumulation. The evaluated scenarios included single-point instantaneous interference,

single-point continuous over-limit loading, multiple consecutive over-limit loading, critical fluctuation, and equipment shutdown.

According to Table 3, the single-point threshold strategy produced unstable alarm outputs when the signal was caused by instantaneous interference or critical fluctuation. In contrast, the proposed method filtered most isolated short-time signals through time confirmation and identified continuous accumulation through adjacent-node judgment. The overall warning results are shown in Figure 10.

Based on the test records, the performance indicators of the proposed method were calculated as

$$\text{Acc}=(48+50+50+47+50)/250=98.0\% \quad (25)$$

$$\text{FAR}=(2+0+0+1+0)/(48+50+50+47+50)=1.22\% \quad (26)$$

$$\text{MAR}=(0+0+0+2+0)/(48+50+50+47+50)=0.82\% \quad (27)$$

The average response time of the warning system in the alarm scenarios was less than 0.5 s. The shortest response time occurred under multiple consecutive over-limit conditions, because several adjacent nodes reached the warning condition at nearly the same time. Under the critical fluctuation condition, the response time was slightly longer due to the time-confirmation process, which is consistent with the design purpose of suppressing transient disturbance [19].

Compared with the single-point threshold strategy, the proposed method improved warning stability under the tested laboratory conditions by combining adjacent-node state judgment with temporal persistence confirmation. It suppressed most isolated and short-duration triggers while retaining a rapid response to continuous coal accumulation. However, this improvement should be interpreted as an internal comparison between the two warning strategies under the same controlled conditions.

Because the 1:2-scale platform did not reproduce the full-scale vibration spectrum, coal-dust contamination, electromagnetic interference, long-distance wiring effects, structural wear, and sensor aging encountered in underground operation, the reported false alarm rate, missed alarm rate, and response time cannot be interpreted as field-level reliability indicators. Full-scale underground trials, long-duration operation tests, and disturbance-oriented environmental tests are required to determine whether the observed performance can be maintained in practical deployment. The transferability of the parameters, including node spacing, spatial-window length, abnormal-node threshold, and confirmation time, must also be verified for different conveyor dimensions and operating conditions.

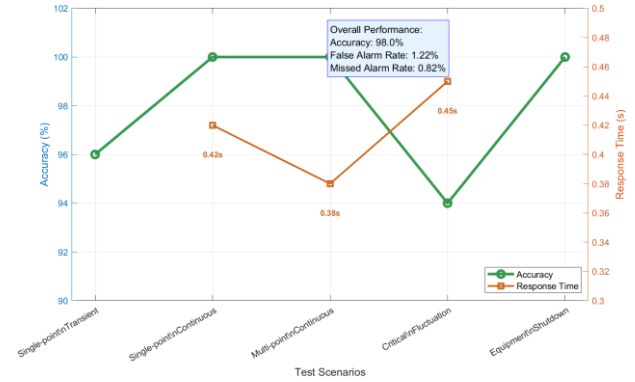


Figure 10. Laboratory-scale validation results of the proposed blockage warning method

5. Discussion and Application Boundaries

5.1. Validation Limitations

The current validation establishes the functional feasibility of the proposed sensing and warning process under controlled laboratory conditions. It does not establish underground field reliability. In particular, the scaled platform cannot reproduce the coupled effects of broadband structural vibration, repeated shock loading, coal-dust deposition, moisture, electromagnetic interference, cable aging, installation deviation, and long-term spring fatigue. These factors may alter the mechanical triggering threshold, reset performance, electrical signal integrity, and PLC input stability. Therefore, the present results define a laboratory performance baseline for subsequent full-scale validation [20].

5.2. Transferability to Other Bulk-Material Conveying Systems

The transferability of the proposed method should be considered separately at the sensing and decision levels. The contact-type mechanical sensing structure depends on the trough geometry, scraper-chain clearance, coal-impact direction, and installation interface of a scraper conveyor. Its direct transfer to belt conveyors, screw conveyors, bucket elevators, or other conveying equipment is therefore limited.

In contrast, the decision layer is not inherently dependent on a particular sensing principle. It may accept binary abnormal states generated by contact, vibration, pressure, acoustic, current, optical, or other sensing units. Its potential transferability depends on whether a true abnormal event produces a meaningful spatial or topological distribution and persists longer than typical interference. For a new conveying system, the sensor type, node topology, node spacing, spatial-window length, alarm threshold, and confirmation time must be redesigned

according to the corresponding material-flow dynamics and disturbance characteristics. The generalized decision layer may also receive threshold states derived from ultrasonic, ToF-vision, radar, or computer-vision measurements. Therefore, the proposed spatio-temporal confirmation logic is not restricted to the contact-type front end and may support heterogeneous sensor fusion. In a hybrid configuration, non-contact sensors can provide continuous or semantic information, while contact nodes can serve as independent confirmation channels at safety-critical locations.

5.3. Scaling of the Monitoring Network

The node spacing defined by Eq. (20) is a local spatial-resolution parameter and should not be scaled in direct proportion to the total conveyor length. For a monitored section with a length L_z , the required number of nodes is

$$N_z = \left\lceil \frac{L_z}{d} \right\rceil + 1 \quad (28)$$

Uniform deployment at the laboratory spacing of 0.15 m over a conveyor several hundred meters long would require an impractically large number of nodes. Therefore, a full-scale system should use zone-based deployment. Dense node arrays should be installed in locations with a high probability of abnormal accumulation, such as loading sections, transfer points, curved or variable-inclination sections, drive and tail sections, and areas affected by repeated equipment passage. Lower-risk sections may use larger spacing or conventional operating-condition monitoring.

Each monitored zone executes the same local sliding-window and time-confirmation logic. The zone-level warning results are then transmitted through distributed remote I/O or an industrial communication network to the central PLC. Consequently, extending the method to a long conveyor mainly increases the number of repeated monitoring zones rather than requiring a single sliding window covering the entire conveyor [21].

5.4. Comparison with Modern Non-Contact Monitoring Methods

A qualitative, literature-based comparison is made between the proposed contact-type method and representative modern non-contact monitoring approaches, including ultrasonic ranging, ToF depth vision, millimeter-wave radar, and computer vision. Because these methods were developed for different equipment, monitoring objectives, experimental platforms, and evaluation indicators, their published numerical results cannot be directly compared with the false alarm rate, missed alarm rate, and response time obtained in the present study. Therefore, the following discussion focuses on sensing output, environmental dependence, computational

requirements, maintenance characteristics, and suitability for blockage warning [22].

Ultrasonic ranging estimates the distance to the material surface from acoustic time-of-flight and can therefore provide continuous point-height information. Its hardware structure is relatively simple, and it avoids direct contact with the conveyed material. However, reliable measurement requires a stable acoustic propagation path and distinguishable echoes. Irregular coal surfaces, multiple reflections, airflow, temperature variation, and acoustic attenuation may cause measurement fluctuation. Compared with the proposed binary contact node, ultrasonic sensing provides continuous distance information but requires additional filtering and decision logic before it can be used for robust blockage confirmation.

ToF depth vision acquires depth and grayscale images and can reconstruct coal-flow surfaces or calculate volume-related information. It therefore provides substantially richer quantitative information than the binary contact signal used in this study. However, it requires an unobstructed optical observation path, depth-image correction, and additional image-processing resources. Flight noise, multipath interference, coal-dust occlusion, and contamination of the optical window must also be considered in underground deployment. Thus, ToF vision is more suitable for quantitative coal-flow reconstruction, whereas the proposed method is intended for low-complexity threshold-event detection.

Millimeter-wave radar can perform non-contact range measurement and surface reconstruction without relying on visible illumination. Radar-based material-level monitoring can provide range, echo-intensity, or three-dimensional point-cloud information and may therefore be advantageous in dusty or poorly illuminated environments. Nevertheless, weak or nonuniform reflection from bulk materials, multipath propagation caused by metallic structures, antenna installation, calibration, point-cloud processing, and higher system cost remain important engineering considerations. Compared with the proposed contact node, radar provides richer spatial information but requires more complex hardware and signal processing.

Computer-vision methods are particularly effective for locating, recognizing, and classifying foreign objects on belt conveyors. They provide appearance and semantic information that cannot be obtained from the binary contact node proposed in this study. However, foreign-object recognition and coal-loading-height warning are different monitoring tasks. Vision-based methods require representative image datasets and are influenced by camera perspective, occlusion, illumination, coal-dust contamination, and computing-platform performance. Therefore, computer vision is advantageous when object identity and location are required, whereas the proposed method focuses on the direct detection of local over-limit loading events.

Overall, the modern non-contact methods considered above provide richer continuous, geometric, or semantic information, but generally require more demanding

observation conditions, calibration procedures, signal processing, or computational resources. The proposed method sacrifices continuous geometric and semantic information in exchange for direct binary output, simple PLC integration, and low online computational demand. Its main advantage is therefore not universally higher measurement accuracy, but the ability to generate a simple local threshold-event signal that can be further validated through spatial and temporal confirmation.

Accordingly, the proposed contact-type method and modern non-contact methods should be regarded as complementary rather than mutually exclusive. In a full-scale monitoring system, ultrasonic sensing, ToF depth vision, or millimeter-wave radar may be used to obtain quantitative coal-flow information, while contact nodes may be installed at critical locations as independent confirmation or fail-safe warning channels. A direct experimental comparison under identical operating conditions remains necessary before quantitative conclusions can be made regarding relative accuracy, robustness, response time, and cost.

6. Conclusion

This paper proposed a coal loading height monitoring and blockage warning method for scraper conveyors based on multi-point state and time confirmation. An adjustable contact-type monitoring device was designed with a self-adaptive rotating mechanism and a removable positioning base. The mechanical analysis showed that the triggering threshold is related to the spring preload, equivalent torsional stiffness, actuation angle, and effective force arm. This provides a basis for adjusting the device according to different coal loading conditions and installation positions.

A PLC-based warning logic was then developed. Instead of using a single instantaneous threshold signal, the proposed method judges whether abnormal states appear in adjacent monitoring nodes and whether these states last for the preset confirmation time. This logic reduces the influence of isolated impact, vibration, and short-duration disturbance on the warning result.

This study developed a coal loading height monitoring and blockage warning method for scraper conveyors by integrating an adaptive contact-type sensing device with multi-point state and time-confirmation logic. The mechanical model provides a basis for adjusting the triggering condition through the spring preload, equivalent torsional stiffness, actuation angle, and effective force arm. The PLC-based decision method combines spatial consistency among adjacent nodes, temporal persistence confirmation, and conveyor operating-state gating to reduce unstable warning outputs caused by isolated and short-duration disturbances.

The 1:2-scale laboratory experiments demonstrated the functional feasibility of the proposed method under the tested conditions. The reported response time, false alarm rate, and missed alarm rate describe the performance of the system on the controlled laboratory platform and should

not be interpreted as full-scale underground performance. The present platform did not reproduce actual underground vibration spectra, long-term dust accumulation, electromagnetic interference, long-distance wiring effects, or mechanical degradation.

The mechanical sensing structure has limited direct transferability because it was designed for the geometry and operating characteristics of scraper conveyors. Compared with modern non-contact approaches, including ultrasonic ranging, ToF depth vision, millimeter-wave radar, and computer vision, the proposed device cannot provide continuous surface geometry, volume information, or semantic object recognition. Its advantages lie instead in direct binary output, simple PLC integration, low online computational demand, and the ability to combine multiple local events through spatial and temporal confirmation.

Therefore, the proposed method should not be regarded as a replacement for non-contact quantitative sensing. Contact and non-contact methods can be used as complementary monitoring channels. The multi-point state and time-confirmation logic can also accept threshold states derived from heterogeneous non-contact sensors and can be abstracted as a spatio-temporal robust event detection pattern. Future work will include direct comparative tests with representative non-contact sensors, heterogeneous sensor fusion, full-scale underground trials, long-term reliability evaluation, and adaptive parameter selection under varying operating conditions.

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