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RESEARCH ARTICLE

Coal Flow Detection of Belt Conveyor Based on the Two-Dimensional Laser

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ABSTRACT A method for detecting coal flow on a belt conveyor based on the two-dimensional laser is proposed in this paper to tackle the complications of poor accuracy and real-time detection of coal flow on a belt conveyor. This method collects the point cloud data of the conveyor belt surface and the lateral profile of the coal flow using a two-position laser probe and transmits the data with the industrial Internet to assure the real-time and reliability of the data transmission. The upper computer software of the detection system is designed using LabVIEW software. The improved wavelet threshold algorithm designed by MATLAB is employed for data preprocessing to enhance measurement accuracy. The results demonstrate that the method can accurately detect the coal flow of the belt conveyor, and the detection accuracy reaches more than 95%, presenting the advantages of real-time performance and high accuracy. It has broad application prospects in coal, mines, ports, electric power, and other fields.

INDEX TERMS Belt conveyor, two-dimensional laser, LabVIEW, coal flow, wavelet.

I. INTRODUCTION

The development direction of coal mining enterprises is "digital and unmanned", and various researchers have investigated the transformation of coal enterprises to "unmanned" [1]. Belt conveyor, as a kind of continuous transportation equipment in modern production, has the advantages of large transportation volume, long transportation distance, low energy consumption, low transportation cost, and high efficiency [2], [3], [4]. It is a crucial piece of equipment that coal mining enterprises need to transform. In the production process of the belt conveyor, it needs to measure the material transportation volume while being safe and energy-saving. The operating speed of the belt conveyor is adjusted according to the instantaneous coal flow [5], [6], [7]. The frequency conversion speed regulation control of the belt conveyor is adopted to make the conveyor run in the best load state [8], [9], [10], [11]. In this way, energy is saved. It is estimated that if the belt conveyor can control the variable belt speed following the real-time flow of materials, it can save 30% of electric energy and 20% of maintenance costs [12]. Therefore, the real-time detection of the coal flow of the belt conveyor has vital research significance in saving energy.

The traditional coal flow detection methods on belt conveyors mainly include electronic belt scales, nuclear scales, and ultrasonic range finders. The detection method of the electronic belt scale is contact measurement. The contact detection method is affected by factors such as conveyor belt tension, installation position, environmental noise and electromagnetic signal interference,which has poor measurement accuracy and reliability [13], [14], [15]. The nuclear scale detection method is a non-contact online detection method for bulk materials [16]. The online continuous metering of the coal flow conveyed by the belt conveyor was performed using the principle of materials absorbing γ-ray beams [17]. The use of radioactive substances [18], [19] is harmful to the environment and human body, and there are potential safety hazards. The detection method of the ultrasonic range finder uses the ultrasonic detection principle to realize the coal flow detection through the reflected sound wave, During the operation of the conveyor belt, there will be a large amount of dust, which will lead to the reflection of the ultrasonic wave

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and affect the detection accuracy. In recent years, the research on visual detection of coal flow has received extensive attention. Meng et al. [20] proposed a coal flow image recognition method for belt conveyors in coal mines and adopted wavelet analysis and neural network algorithms to identify coal flow boundaries and calculate coal flow. Yang et al. [21] designed a dual-viewpoint measurement method for materials on a belt conveyor and utilize a binocular camera to obtain the depth of the material contour, calculate the cross-sectional area of the measurement surface, and obtain the material flow. Dai et al. [22] provided a coal detection method for belt conveyors based on binocular vision depth perception, employed the Census transform image stereo matching algorithm to calculate the coal parallax map, and used the fuzzy reasoning algorithm to calculate the coal accumulation filling rate. However, the detection system using machine vision technology to detect coal flow is relatively complicated and has a high installation cost. Moreover, the site environment is harsh, and there is a lot of dust. As a result, cameras and light sources usually cannot work properly due to contamination, and the failure rate and maintenance costs are high. Given the above headaches, a two-dimensional laser-based coal flow detection method is proposed in this paper for belt conveyors. The main contributions of this paper are summarized as follows.

1) A detection method for the coal flow of a belt conveyor based on the two-dimensional laser is proposed to accurately detect the coal flow of the belt conveyor. It has the advantages of real-time performance and high accuracy.
2) An industrial Internet communication environment is created to guarantee the real-time and stability of data transmission.
3) The improved wavelet threshold algorithm is employed for data preprocessing to effectively curtail the errors caused by the vibration of the conveyor belt and the two-position laser probe.

The remaining sections of the paper are organized as follows. In Section II, the detection method of the belt conveyor without flow is introduced. The experiments and results analysis are presented in Section III. Finally, conclusions and expectations for future work are provided.

II. MATERIALS AND METHODS

The detection system of coal flow in a belt conveyor consists of two two-dimensional laser probes, a Industrial Ethernet switch, a speed detector, a computer and a PLC speed controller.The system adopts two two-dimensional laser probes to measure the lateral profile of the conveyor belt surface and coal flow. The running speed of the conveyor belt is detected by the Ethernet speed detector. The industrial Internet with fast transmission speed and high stability is employed for data transmission. The Industrial Ethernet switch is used to transmit the above data.The operation interface on the computer side is designed using LabView. The calculation of the data is performed with the MATLAB language because of its better calculation execution ability. The computer is used to realize the operation of software and the calculation of data. The structural diagram is exhibited in Figure 1.

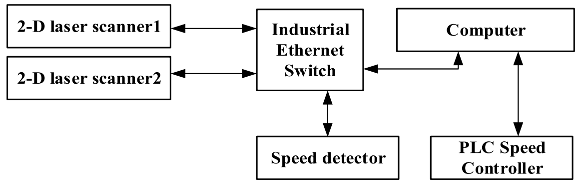

FIGURE 1. The structural diagram of system.

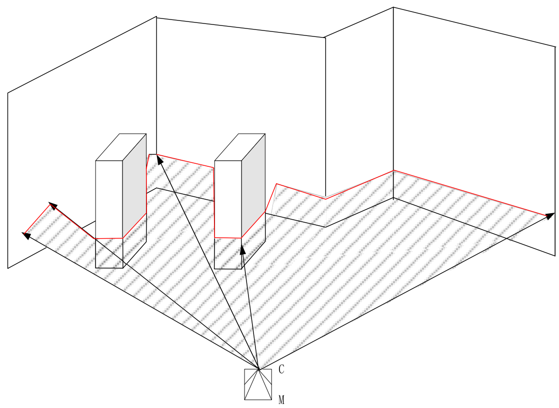

FIGURE 2. Measurement principle of two-dimensional laser.

A. PRINCIOLE OF LASER RANGING

The measurement principle of the two-dimensional laser rangefinder is illustrated in Figure 2.

The two-dimensional laser range finder is an electro-optic laser measuring sensor. It scans a laser around a plane to measure surrounding objects in two-dimensional coordinates. Two position-determining information, distance and direction, can be obtained when the scanning laser beam hits an object. The shaded area from point C to the obstacle in Fig. 2 is the laser scanning plane. The red line is the outline of a two-dimensional laser scan.

The principle of distance information acquisition. A pulsed laser beam emitted by a laser diode is reflected off an object. The reflected laser beam is detected and received by another photodiode. The distance information is calculated using the propagation time from the emission of the pulsed laser light to the reception of the reflected laser light.

Measuring principle of direction information. During the measurement process, the pulsed laser beam emitted by the laser scanner cyclically scans the surrounding objects. The scanning frequency is 50Hz. The pulsed laser beams are emitted at an angular interval of 0.33° for each scan. The laser scanner triggers and records the angle of the laser beam reflected by the surrounding objects through the angle encoder, so as to obtain the direction information of the measured object.

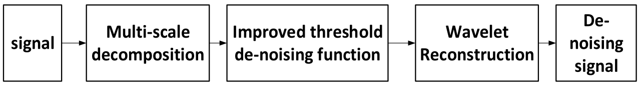

FIGURE 3. Improved wavelet threshold denoising process.

B. DATA PREPROCESSING METHOD

Influenced by factors such as the environment, there are systematic errors and measurement errors in the measurement data of the laser range finder. In this paper, the system error of the laser range finder LMS111-10100 is ±30 mm, and the continuous error is 12 mm. If the depth of material is 50cm, the maximum error will exceed 10% if the data is not preprocessed. Signal preprocessing is performed on the original curve data obtained by the two-dimensional laser rangefinder to lower data noise and reinforce the accuracy of the algorithm. Noise is removed using an improved wavelet threshold denoising algorithm. Its flow chart is displayed in Figure 3.

First, the appropriate wavelet base and decomposition layers are selected according to the characteristics of the original signal, and the wavelet coefficients of each layer are obtained through discrete wavelet transform. Then, the wavelet coefficients of each layer after processing are obtained by using the improved threshold function to process the wavelet coefficients. Finally, wavelet reconstruction is conducted. Specifically, the two-dimensional laser rangefinder signal is reconstructed in accordance with the obtained wavelet coefficients and approximate coefficients to obtain the denoised contour curve.

Since the threshold is the boundary between effective information and noise, its selection directly impacts the denoising effect. The traditional general threshold involves the same processing on the wavelet detail coefficients of each scale, while the distribution of noise is random. Processing with a fixed threshold induces the loss of useful information at some scales. In this paper, an improved threshold function is employed for denoising to overcome the issues such as the discontinuous traditional hard threshold function at the threshold and some lost high-frequency information caused by the soft threshold function.

$$\hat{d} = \begin{cases} ud + (1-u)\operatorname{sgn}(d) \times \left(|d| - \dfrac{2\lambda}{1+e^{(d|-\lambda)^n}}\right), & |d| \geq \lambda \\ 0, & |d| < \lambda \end{cases} \tag{1}$$

where d is the original wavelet coefficient, λ is the threshold, $\lambda = \sigma\sqrt{2\log(N)}$, σ is the standard deviation of the noise signal, and N is the number of samples.

C. BELT SPEED MEASUREMENT

The running speed of the conveyor belt is detected by an Ethernet speed detector. Ethernet Speed Detector is based on an STM32 microcontroller for core design. Using the contact detection method, the sensor is installed in contact with the upper and lower belt surfaces of the lower belt. The sensor rotates itself as the belt runs to obtain rotation data. STM32 calculates the running speed of the conveyor belt. Because the conveyor belt running speed is relatively stable, there will be no great changes in continuous operation. The algorithm first eliminates abnormal velocity values with large deviations, and then obtains the average value of the velocity data within 5s, which is used as the final velocity parameter. The purpose is to eliminate the error caused by the slip of the speed sensor and improve the reliability of the system. Finally transmits it to the host computer through the industrial Internet.

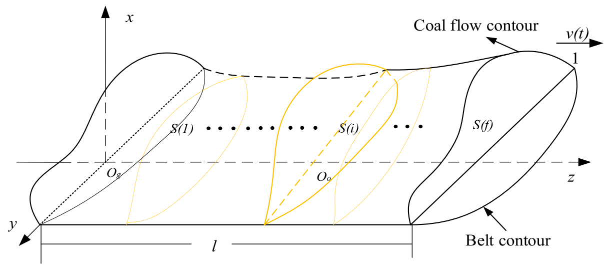

FIGURE 4. The schematic diagram of the coal flow structure.

D. CALCULATION METHOD OF COAL FLOW

The real-time coal flow is calculated by using the processed data. The flow rate of coal on the conveyor belt is the mass passing through an effective section per unit time, that is, the density of coal multiplied by the volume of coal passing through an effective section per unit time.

$$Q_t = \rho V_t \tag{2}$$

where Q_t denotes the flow of coal on the conveyor belt, the unit is t/s; ρ represents the density of coal,the unit is t/m^3; V_t indicates the volume of coal that passes through an effective cross-section per unit time,the unit is m^3/s.Figure 4 shows the schematic diagram of the coal flow structure.

Fig. 4 shows the contours of coal flow obtained by scanning within 1s. The scanning frequency of the two-dimensional laser rangefinder is f, the unit is Hz, suggesting that the time taken to scan a frame of coal pile cross-sectional area data on the conveyor belt is 1/f. v_t signifies the speed of the conveyor belt, the unit is m/s. Every time a frame of data is scanned, the distance traveled by the conveyor belt is v_t/f. S_i denotes the instantaneous transverse cross-sectional area of the piled coal on the conveyor belt,the unit is m^2. Then, the volume of coal passing through an effective section per unit time is:

$$V_t = \sum_{i=1}^{i=f} \frac{v_t}{f} S_i \tag{3}$$

The flow of coal on the conveyor belt is:

$$Q_t = \rho \sum_{i=1}^{i=f} \frac{v_t}{f} S_i \tag{4}$$

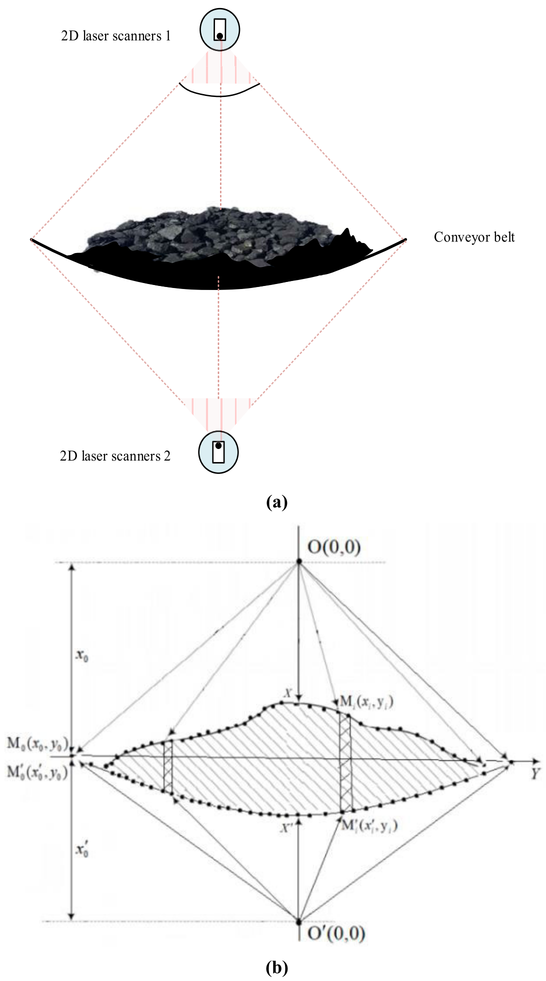

FIGURE 5. **(a) The schematic design of the coal flow measurementl; (b) The calculation principle of the instantaneous lateral cross-sectional area Si of the piled coal on the conveyor belt.**

where the density ρ of the coal and the scanning frequency f of the laser rangefinder are known; the speed v_t of the conveyor belt is obtained by collecting data from the speed sensor. Therefore, the flow rate of coal on the conveyor belt can be calculated as long as the instantaneous lateral cross-sectional area S_i of the piled coal on the conveyor belt is measured.

The schematic design of the coal flow measurement is shown in Figure 5a. The calculation principle of the instantaneous lateral cross-sectional area S_i of the piled coal on the conveyor belt is depicted in Figure 5b. The upper and lower two-dimensional laser rangefinders are in the same section. Two laser range finders obtain the edge position of the conveyor belt, respectively. Calibration and matching are conducted to enable the M_0 and M'_0 of the two laser range finders to coincide. The 2-D Laser rangefinder at the upper has a narrow viewing angle, and the number of acquisition points is recorded as n, while the 2-D Laser rangefinder at the lower has a wide viewing angle, and the number of acquisition points is recorded as m. The coordinates of the corresponding points of the upper and lower two-dimensional

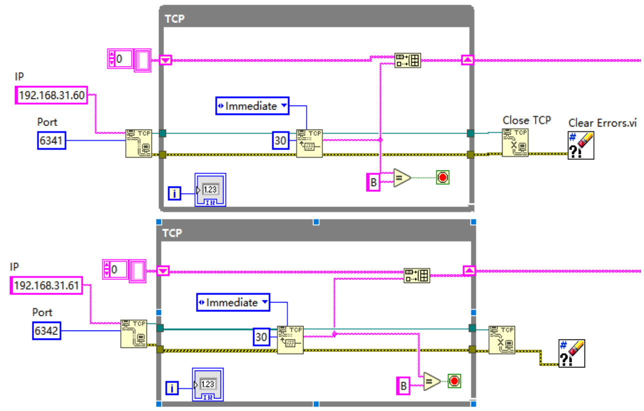

FIGURE 6. **The basic unit of communication.**

Laser rangefinder are recorded as $M_i(x_i,y_i)$, $M'_i(x'_i,y_i)$, where $x'_i = x_{mi/n}$.

The instantaneous lateral cross-sectional area S_i of the piled coal on the conveyor belt is obtained, expressed as:

$$S_i = \frac{1}{2}\sum_{i=0}^{i=n}[(x_0 - x_i) + (x'_0 - x'_i) + (x_0 - x_{i+1}) + (x'_0 - x'_{i+1})](y_{i+1} - y_i) \quad (5)$$

E. DESIGN SOFTWARE BASED ON LABVIEW

The host computer software designed in this paper has the following basic functions: 1) use industrial Ethernet for communication; 2) design an improved wavelet threshold denoising algorithm based on MATLAB; 3) display the coal flow of the conveyor belt in real-time on the host computer interface.

In this paper, industrial Ethernet is adopted for communication, and the TCP/IP protocol that comes with LabVIEW is employed to design the basic unit of communication show in Figure 6.

Besides, the improved wavelet threshold algorithm is used for data preprocessing. Considering a large amount of calculation of the wavelet transform algorithm, the mixed programming method of LabVIEW and MATLAB is adopted [23], and MATLAB's powerful mathematical calculation function is reasonably utilized for signal processing. The algorithm is designed through the Matlab script module in LabVIEW to realize the signal preprocessing based on the improved wavelet threshold algorithm show in Figure 7.The average calculation time is 18.6ms, and the data collection time is 20ms, so it can meet the requirements of real-time detection.

The graphical user interface developed using LabVIEW is presented in Figure 8. The human-computer interaction interface of the upper computer interface can display the outline of the coal flow section under the current state in

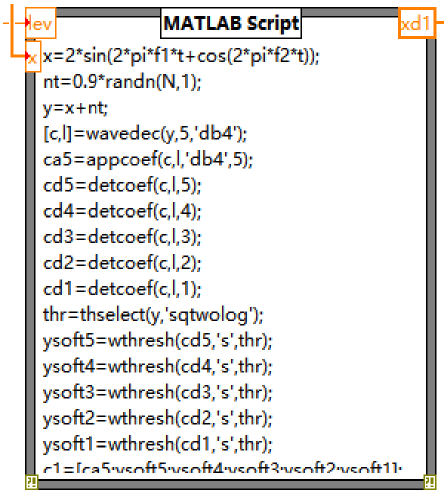

FIGURE 7. The improved wavelet threshold algorithm.

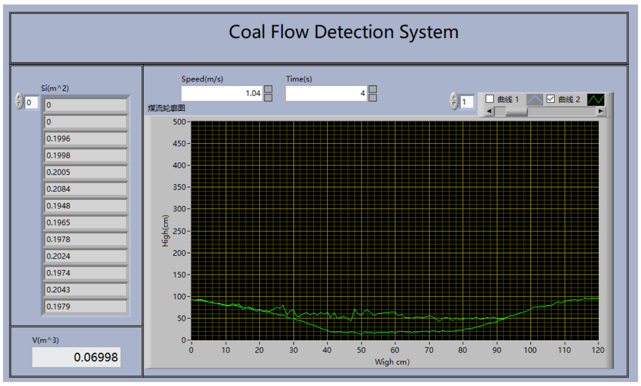

FIGURE 8. The graphical user interface.

real-time, calculate the area of the section, and obtain the flow information within a certain period of time.

III. RESULTS AND RESULT VERIFICATION

A. EXPERIMENT ENVIRONMENT

To verify the accuracy and reliability of the two-dimensional laser-based coal flow detection method for belt conveyors in practical applications, the team built a large-scale belt conveyor cycle test system. The system consists of two conveyor belts with a length of 25m and two conveyor belts with a length of 4m to form a rectangular circulation structure. Concurrently, the system has a belt speed adjustment function. The two-dimensional laser rangefinder is installed 2m above the conveyor belt and 0.4m below the conveyor belt. Conveyor belt width 1.2m. It can be approximated as three sections, 30cm as the bottom, 45cm on both sides of the inclined part, the inclination angle is 45°.When the material fills the conveyor belt, the cross-sectional area is about 0.2 m^2.The experimental environment is exhibited in Figure 9.

B. EVALUATION INDEX

The main performance indicators, AA(Average Accuracy) and RMSE (Root mean squared error), are utilized to better

FIGURE 9. The large belt conveyor cycle test system.

verify the performance of the method proposed in this paper. First, multiple measurements of the same experiment are performed. The actual value is denoted as x, and each measurement result is denoted as x_i. Then, the formula of AA is:

$$AA = \frac{\sum_{i=1}^{n}(x - |x - x_i|)/x}{n} \tag{6}$$

RMSE is the sum of the squares of the deviations between the measured value and the true value, and the square root of the ratio of the number of observations n. Since RMSE is very sensitive to extremely large or small errors in a set of measurements, it can well reflect the precision of the measurement.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_i - x)^2}{n}} \tag{7}$$

C. COMPARISON AND VERIFICATION

A belt speed suitable for material transport is required to measure the flow of coal on a moving conveyor belt. The speed of the conveyor belt should be compatible with the start-up profile and stable during start-up. The belt speed control system is adopted to set the belt speeds to 0.5 m/s, 1.0 m/s, 1.5 m/s, and 2.5 m/s. Standard containers of 0.06 m^3, 0.07 m^3, and 0.08 m^3 are taken to measure the corresponding volume of material. Additionally, a trough-shaped container that fits the contour of the conveyor belt is designed to hold the materials for facilitating repeated experiments and assuring that the actual volume of the materials in each experiment remains unchanged, it show in Figure 10. The cross section of the container is isosceles trapezoid, and the size is: the length of the bottom side is 30 cm, the length of the two sides is 60 cm, and the inclination angle is 45°.The material used is perlite instead of coal for experimental verification. To ensure accuracy, the scanning frequency of the 2-D laser rangefinder is set at 50Hz. When the conveyor belt is running at a speed lower than 2.5m/s, the section length of each scan

TABLE 1. **The test results of different speeds and standard volumes.**

No	Speed(m/s)	Volume(m^3)	Results of 5 repeated measurements(m^3)					AA(%)	RMSE
			1	2	3	4	5		
1	0.5	0.06	0.0589	0.0612	0.0587	0.0575	0.0609	96.44	0.002269361
2	0.5	0.07	0.0716	0.0695	0.0708	0.0687	0.0706	97.44	0.001826472
3	0.5	0.08	0.0805	0.081	0.0798	0.0788	0.0792	99.10	0.000787401
4	1	0.06	0.0585	0.0602	0.0585	0.0579	0.0611	97.04	0.001930285
5	1	0.07	0.0689	0.0705	0.0705	0.0691	0.0711	98.25	0.001394991
6	1	0.08	0.0795	0.0808	0.0796	0.0784	0.0793	98.72	0.001061131
7	1.5	0.06	0.0593	0.059	0.0602	0.0622	0.0586	97.44	0.001948333
8	1.5	0.07	0.0709	0.0698	0.0708	0.0702	0.0703	98.95	0.000823408
9	1.5	0.08	0.0805	0.081	0.0798	0.0808	0.0799	98.98	0.000866025
10	2	0.06	0.0564	0.0622	0.0577	0.0575	0.0569	95.02	0.003667424
11	2	0.07	0.0716	0.0715	0.0708	0.0711	0.0686	98.53	0.001371131
12	2	0.08	0.0815	0.082	0.0788	0.0811	0.0792	97.67	0.002080385
13	2.5	0.06	0.0579	0.0632	0.0627	0.0595	0.0619	95.48	0.003122499
14	2.5	0.07	0.0716	0.0725	0.0708	0.0667	0.0726	95.90	0.003402352
15	2.5	0.08	0.0835	0.0819	0.0768	0.0818	0.0782	95.31	0.003969383

FIGURE 10. **The trough-shaped container.**

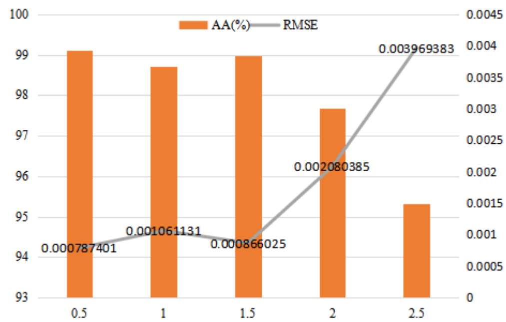

FIGURE 11. **The relationship between AA, RMEA and speed.**

is less than 50mm.The coal loose density depends on the size of the coal grains and is variable in various places of the conveyor belt, which introduces an additional error. In order to avoid the influence of this error on the calculation, the influence of density on the flow rate is temporarily ignored in the verification process, and only the volume is taken as the index of the accuracy of detection and evaluation.The effect of density on detection accuracy will be discussed in future work.

First, the empty trough container is put on the conveyor belt, and the system is turned on to obtain the measurement result of the empty state. The system is zeroed using no-load measurements. Then, materials of different volumes are put into the trough container in batches, and the system is operated to obtain the measurement results of different boring volumes at different speeds. The test results are listed in Table 1.

As observed in Table 1, In the test environment built in this paper, the detection accuracy of standard volume materials can reach 95%, suggesting that the coal flow detection method of the belt conveyor based on the two-dimensional laser proposed in this paper can accurately detect the coal flow. Besides, the calculation accuracy is slightly improved as the volume of coal transported on the conveyor belt increases. This is in that the proportion of system error and measurement error decreases as the volume of coal on the conveyor belt increases. However, with the increase of conveyor belt running speed, the stability of detection is reduced. Figure 11 shows the relationship between AA, RMEA and speed.

A comparative experiment is designed to verify the advantages of the improved wavelet algorithm used in this paper. The running speed of the conveyor belt is set at 1.5m/s,

TABLE 2. The comparative experimental results without using the improved wavelet denoising threshold algorithm.

Method	Results of 10 repeated measurements(m^3)					AA(%)	RMSE
No Wavelet	1#	2#	3#	4#	5#	92.4	0. 006572
	0.0885	0.0849	0.0708	0.0848	0.0789		
	6#	7#	8#	9#	10#		
	0.0874	0.0868	0.0768	0.0878	0.0726		
This paper	1#	2#	3#	4#	5#	99.0	0. 000847
	0.0805	0.081	0.0798	0.0808	0.0799		
	6#	7#	8#	9#	10#		
	0.0811	0.0809	0.0789	0.0809	0.0789		

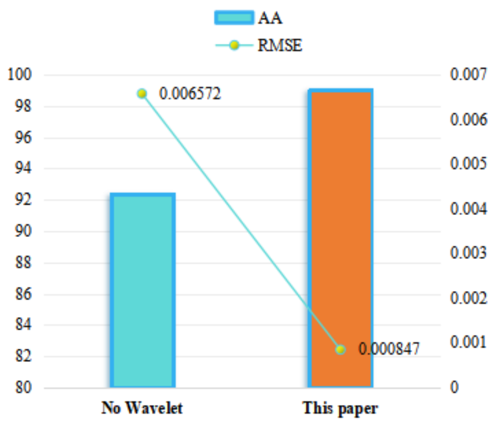

FIGURE 12. The statistical comparisons of measurements without and with the developed wavelet algorithms.

and 0.08m^3 material is placed in the container for testing. Firstly, the method in this paper was used for 10 repeated measurements to obtain experimental data. Then the wavelet data preprocessing algorithm in the algorithm is deleted for 10 times of repeated measurement, and the corresponding experimental results are obtained. The results of the experiment are shown in Table 2.

It can be seen from Table 2 that the AA obtained after data preprocessing with the improved wavelet threshold algorithm proposed in this paper is 99%, 6.4 percentage points higher than that without using the wavelet algorithm.The average operation time of the algorithm is 18.6 ms, which meets the requirement of real-time detection. The results of RMSE obtained by the method in this paper also have great advantages.Figure 12 shows that using the wavelet algorithm can improve AA and reduce RMEA.

Based on the analysis of the experimental process and results, we conclude that the limitations and challenges encountered in the actual application process are as follows:

1) The two-dimensional laser scanner we use has certain systematic errors. This error will increase as the distance between the device and the surface of the material under test increases. The installation position needs to be analyzed during equipment installation to obtain the best results.

2) The material contour is approximated by integral calculation. When the surface shape of the material is too complex, or there are many gaps between the materials, the error of the final result will increase.

3) The device is obtained by scanning the contour curve. The scanning frequency of the equipment is inversely proportional to the sampling accuracy, so the scanning speed and sampling accuracy cannot be taken into account at the same time.

4) This paper uses contact sensor to detect the speed of conveyor belt. The speed sensor is easy to slip during long time operation, which directly affects the accuracy of detection results.

5) When the conveyor belt runs too fast, the conveyor belt will have strong vibration. The results obtained by the system will have a large deviation, which is also the main difficulty to be solved in our future work.

IV. CONCLUSION

In this paper, a two-dimensional laser based coal flow detection method for belt conveyors was proposed. The method collected point cloud data of the conveyor belt surface and the lateral profile of the coal flow by a 2D laser range finder, transferred data through the industrial internet, and performed co-programming using LabVIEW and MATLAB. Additionally, a data preprocessing algorithm based on wavelet threshold was designed to enhance detection accuracy. Then, the online monitoring of coal flow in the conveyor belt was realized. We set up the experimental environment for verification. The results show that the detection accuracy can reach 95% when the conveyor belt running speed was within 2m/s, providing accurate and effective flow data for research on energy-saving speed regulation of conveyor belts. Conditions from test measurements are far from reality. Materials on the conveyor belt and the belt itself moves during transportation. Material in the container can vibrate during movement but its bottom shape is constant and top movements are different than in real conditions. This influences the accuracy and precision of measurements. Tests of the proposed method are in the initial stage of development. In future research, the accuracy of the system will be boosted under the high-speed operation of the conveyor belt, the relationship between the coal flow and the belt speed will be analyzed, realize the material flow monitoring under the real working condition, and finally, the variable-speed operation of the belt conveyor will be realized to curtail energy efficiency.

REFERENCES

[1] K. Zhang, L. Kang, X. Chen, M. He, C. Zhu, and D. Li, "A review of intelligent unmanned mining current situation and development trend," *Energies*, vol. 15, no. 2, p. 513, Jan. 2022, doi: 10.3390/en15020513.

[2] A. Soofastaei, E. Karimpour, P. Knights, and M. Kizil, "Energy-efficient loading and hauling operations," in *Green Energy and Technology*. Cham, Switzerland: Springer, 2018, pp. 121–146.

[3] W. Kawalec, N. Suchorab, M. Konieczna-Fuławka, and R Król, "Specific energy consumption of a belt conveyor system in a continuous surface mine," *Energies*, vol. 13, no. 19, p. 5214, 2020.

[4] N. Suchorab, "Specific energy consumption—The comparison of belt conveyors," *Mining Scince*, vol. 26, pp. 263–274, Jan. 2019.

[5] J. Ji, C. Miao, X. Li, and Y. Liu, "Speed regulation strategy and algorithm for the variable-belt-speed energy-saving control of a belt conveyor based on the material flow rate," *PLoS ONE*, vol. 16, no. 2, Feb. 2021, Art. no. e0247279, doi: 10.1371/journal.pone.0247279.

[6] I. A. Halepoto, M. Z. Shaikh, B. S. Chowdhry, and M. U. H. A. Uqaili, "Design and implementation of intelligent energy efficient conveyor system model based on variable speed drive control and physical modeling," *Int. J. Control Autom.*, vol. 9, no. 6, pp. 379–388, Jun. 2016.

[7] B. Karolewski, "The influence of speed control on the power drawn by motors of the belt conveyor," *Elektrotechniczny*, vol. 9, pp. 76–79, Jan. 2017.

[8] S. X. Li, "Discussion on energy saving of frequency converter of coal mine belt conveyor," *Energy Conservation*, vol. 10, pp. 83–84, Jan. 2018.

[9] R. F. Jia, "Study on energy-saving technology of belt convey or based on frequency conversion and speed regulation," *Mech. Manag. Develop.*, vol 33, no 10, pp. 272–278, 2018.

[10] T. Mathaba and X. Xia, "Optimal and energy efficient operation of conveyor belt systems with downhill conveyors," *Energy Efficiency*, vol. 10, no. 2, pp. 405–417, Apr. 2017.

[11] J. H. Ji, C. Y. Miao, X. G. Li, and Y. Liu, "Research on speed control algorithm of belt conveyor based on controllable parameter PSO-PID," in *Proc. 7th Int. Conf. Inf. Sci. Control Eng.*, 2020, pp. 2136–2140.

[12] W. Daus, S. Koerber, and N. Becker, "Raw coal loading and belt conveyor system at Nochten opencast mine—A new conveying and loading system based on drives controlled and adjusted by frequency converter," *Braunkohle Surface Mining*, vol. 50, pp. 117–130, Mar. 1998.

[13] T. Yamazaki, R. Tasaki, and H. Ohnishi, "Continuous weighing by multi-stage conveyor belt scale," in *Proc. SICE Annu. Conf.*, 2004, pp. 2295–2300.

[14] Y. Tomobe, R. Tasaki, T. Yamazaki, H. Ohnishi, M. Kobayashi, and S. Kurosu, "Continuous mass measurement on conveyor belt," *IEEJ Trans. Electron., Inf. Syst.*, vol. 126, no. 2, pp. 264–269, 2006.

[15] S. Aleksandrovic and M. Jovic, "Analysis of belt weigher accuracy limiting factors," *Int. J. Coal Preparation Utilization*, vol. 31, no. 5, pp. 223–241, Sep. 2011.

[16] M. H. Chen, "Error analysis and application prospect of nuclear belt weigher," *Control Instrum. Chem. Ind.*, vol. 24, no. 5, pp. 38–41, 1997.

[17] K. Gersten, "Flow metering with disturbed inflow," *Acta Mechanica*, vol. 201, nos. 1–4, pp. 13–22, Dec. 2008.

[18] W. J. Liu and S. C. Jin, "Comprehensive comparison of electronic belt scale and nuclear belt scale. Papers of the ninth weighing technology seminar," Changsha China Weighing Instrum. Assoc., Tech. Rep., 2010.

[19] C. Ronsivalle, L. Giannessi, M. Quattromini, A. Bacci, A. R. Rossi, L. Serafini, M. Boscolo, E. Chiadroni, M. Ferrario, D. Filippetto, V. Fusco, G. Gatti, M. Migliorati, A. Mostacci, C. Vaccarezza, C. Vicario, A. Cianchi, and M. Petrarca, "Comparison between sparc e-meter measurements and simulations," in *Proc. IEEE Part. Accel. Conf. (PAC)*, Jun. 2007, pp. 986–988.

[20] F. Q. Meng and Y. C. Wang, "Study of the methods for recognizing the coal flow image of coal mine's conveyor belt," *J. China Coal Soc.*, vol. 28, p. 91, Mar. 2003.

[21] C. Yang, Z. Gu, X. Zhang, and L. Zhou, "Bin ocular vision measurement of coal flow of belt conveyorsbased on deep learning," *Chin. J. Sci. Instrum.*, vol. 41, no. 8, pp. 164–174, 2021.

[22] W. Dai, J. Zhao, C. Yang, and X. Ma, "Detection method of coal quantity in belt conveyor based on binocular vision depth perception," *J. China Coal Soc.*, vol. 42, no. 2, pp. 547–555, 2017.

[23] Z. Liu, X. Ye, T. Qian, and Y. Song, "Application of LabVIEW and MATLAB hybrid programming in unmanned helicopter system simulation," in *Proc. Chinese Intell. Automat. Conf.* (Lecture Notes in Electrical Engineering), vol. 801, 2022, pp. 165–172.

[24] Y. Liu, C. Miao, X. Li, and G. Xu, "Research on deviation detection of belt conveyor based on inspection robot and deep learning," *Complexity*, vol. 2021, pp. 1–15, Feb. 2021, doi: 10.1155/2021/3734560.

[25] Y. Yang, C. Miao, X. Li, and X. Mei, "On-line conveyor belts inspection based on machine vision," *Optik*, vol. 125, no. 19, pp. 5803–5807, Oct. 2014.

[26] N. Singh, V. K. Gunjan, G. Chaudhary, R. Kaluri, N. Victor, and K. Lakshmanna, "IoT enabled HELMET to safeguard the health of mine workers," *Comput. Commun.*, vol. 193, pp. 1–9, Sep. 2022.

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